COLD UTILIZATION OF LNG: PROCESS MODIFICATION & OPTIMIZATION

A Thesis submitted to
UPES

For the Award of
Doctor of Philosophy
in
Petroleum Engineering

By
Bhalchandra Shingan

December 2023

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DECLARATION

I declare that the thesis entitled **Cold Utilization of LNG: Process Modification & Optimization** has been prepared by me under the guidance of P. Vijay, Controller of Examinations, Graphic Era Hill University, Dehradun & Dr Nilanjana Banerjee, Associate Professor of Energy Cluster, UPES. No part of this thesis has previously been used to grant a degree or fellowship.

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ABSTRACT

This thesis explores the process modification and optimization of cold utilization of liquefied natural gas (LNG). With rising natural gas consumption and increasing environmental concerns, finding innovative ways to maximize the potential of LNG is crucial. Natural gas is generally transported around the world via LNG, which is used extensively in several nations. In the process sector, a significant amount of thermal energy is wasted and released into the environment, rivers, and sea. Pollutant emissions also contribute to global environmental degradation, including the greenhouse effect, acid rain, and ozone layer depletion. Approximately 830 kJ/kg of the energy needed to produce LNG must be stored as cold energy If LNG's cold energy is not captured and used, it will be lost to the vaporizer units' warming mediums (such as air or seawater) and released into the environment. Cold energy is a unique type of energy because, while in a cryogenic state, it may be employed to supply thermal energy for low-temperature applications. Traditionally, power generation, air separation desalination, and food processing are the systems that use LNG cold energy. Since the needed energy form differs in various applications, the LNG cold energy utilisation system generally varies from nation to nation. Therefore, during the past several decades, there has been a lot of focus on developing systems to use LNG cold energy. However, the current processes for cold utilization of LNG have limitations and inefficiencies that can be improved through modifications and optimization.

This research will also describe hotspots and research trends in CULNG technology as well as report on the present state of scientific development using bibliometric analysis. Researchers and manufacturers working on this emerging technology can use the findings to comprehend the current state of the art, the direction of scientific output, the current networks of international organizations, and the authors associated with the CULNG.

Air separation processes are complex and highly energy-intensive. In ASU, the majority of the energy loss happens during air compression. This wastage of energy is utilised for heating LNG. An LNG regasification station is where LNG vessels will eventually halt. Here, the liquefied natural gas is converted back to gas and supplied to the distribution and transmission

infrastructures. Cryogenic LNG has a high potential for cold energy recovery throughout the regasification process. This research examines a novel air separation unit (ASU) design that is combined with LNG's direct expansion cycle (DEC). The study is novel in a way that a performance of an ASU combined with a DEC is analysed through process simulation in Aspen Hysys (12.1) for a 3993-kW power plant. The results of this investigation show that the specific energies needed for the generation of high purity oxygen and high purity nitrogen are, respectively, 0.10 kWh/kg and 0.32 kWh/kg. Additionally, 3993 kW of energy are saved in the system as a result of an adequate system combination of other subsystems and LNG vaporisation. For the system's primary components, exergy destruction and efficiency have been computed. In addition, sensitivity analysis is carried out to explore the effects of crucial factors. In conclusion, to provide the required power for operation and eliminate unnecessary power inputs, a cryogenic ASU is coupled with an LNG-DEC power cycle. Overall, the LNG industry should consider integrating air separation processes and LNG as a viable and appealing option. By using fewer fossil fuels, it also increases the sustainability of the process.

The study on the multistage power generation cycle examines the potential of utilizing the cold energy stored in LNG for power generation. While the efficiency and net power gain of power-generating cycles resulting from cold LNG usage have both increased, there is still room for improvement. An analysis of four alternative systems, combining the rankine cycles (RC) and the direct expansion cycle (DEC), is conducted to determine the net power production and efficiencies of the system. The study is novel in that it uses process simulation in Aspen Hysys (12.1) to examine the performance of an integrated multistage RC and DEC cycle. To evaluate single-stage RC, eleven working fluids have been chosen. In RC, only the thermal exergy of LNG is utilized. The findings demonstrate that when RC combines with DEC, efficiency increases significantly because thermal and mechanical exergies are both utilized for power generation in multistage operations. The DEC and single-stage stage RC have efficiency values of 21.05% and 23.38%, respectively, whereas the efficiencies of the four alternative combinations are 38.78%, 34.93%, 47.52%, and 47.23%. Maximum efficiency and net power gain were achieved when preheated DEC and multistage RCs were coupled. This shows that, without the need for an additional stage, NPG increases dramatically if the LNG stream is preheated before the DEC. Due to Carnot's Theorem, which asserts that power can increase when the temperature difference between cold and hot sources is greater, R1150 was found to produce the best results when 11 different working fluids were examined for the given conditions with single-stage Rankine cycles. This indicates that condensation temperature has a significant influence on the cycle's effectiveness. For multistage rankine cycles, the selection of working fluid depends on the temperature of the LNG stream, which leaves a condenser. Sensitivity analysis reveals that the working fluid pressure, LNG mass flow rate, and turbine output pressure are crucial variables to achieve the best outcomes. Finally, the economic study demonstrated the viability of the suggested power system. The findings show that the suggested modifications and optimizations can improve the efficiency and effectiveness of LNG cold utilisation.

India is currently the fourth-largest LNG importer in the world. Currently, India imports 42.7 MMTPA of LNG, and it is projected to increase its imports to 83 MMTPA by 2030. The cold utilization of LNG is one of the main areas of interest in the Indian LNG market.

This thesis contributes to the development of sustainable energy solutions and provides insights for the design and operation of LNG cold utilization systems. The findings of this research can be useful for industries that utilize LNG as an energy source and can help in achieving energy efficiency and cost savings. In order to increase productivity, future research must prioritize these processes' modification and development. Additionally, it is necessary to conduct an economic study. The integration of various processes and cascade approaches greatly enhances LNG cold energy utilization while lowering energy consumption. Utilizing cold energy could help cut emissions in the industrial sector associated with energy use and consumption. Energy savings and carbon reduction should be the primary determinants of the viability of LNG cold energy utilization projects.

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Notations

W: Work done (kW)

Q: Heat Transfer Rate (kW)

$\dot{X}$: Exergy Rate (kW)

M: Mass Flow Rate(kg/hr)

T: Temperature (° C)

h: Specific Enthalpy (kJ/kg)

s: Specific Entropy (kJ/kg K)

D: Destruction

L: Loss

ph: Physical

ch: Chemical

pt: Potential

h: Enthalpy

s: Entropy

Greek Letters

γ: Specific Energy Consumption (kWh/kg)

η: Efficiency (%)

Abbreviations

ASU: Air Separation Unit

AAV : Ambient Air Vaporizer

AGA: American Gas Association

APA : Aspen parametric analysis

ASA: Aspen sensitivity analysis

ASP: Air Separation Process

BCM: Billion Cubic Meter

BLEVE: Boiling Liquid Expanding Vapor Explosion

BOG: Boil off gas

CBC: Closed Bryton Cycle

CC: Combined Cycle

CCEP: Cool, clean, efficient power

CCGT: Combined cycle gas turbine

CNG: Compressed Natural gas

Comp: Compressor

COP: coefficient of performance

CULNG: Cold Utilization of Natural Gas

DEC: Direct Expansion Cycle

ECA: Emission control areas

EOS: Equation of state

ERR: Energy recovery rate

FLNG: floating LNG

FPSO: Floating production, storage, and offloading

FSRU: Floating sorage regasification unit

GHG: Green House Gas

HPC: High Pressure Column

HX: Heat Exchanger

IEA: International Energy Agency

IFV: Intermediate fluid Vaporizer

IGU : International gas union

kW : kilo Watt

LAES : Liquid Air Energy Storage

LNG: Liquefied Natural Gas

LNGCW: LNG cold warehouse

LOC: loss of containment

LPC: Low Pressure Column

MFC: Mixed Fluid Cascade

MHX: Multi-stream Heat exchanger

MT: Million Tones

MTPA: Million Tonnes per anum

MTPA: Million Tonnes per anum

MW: Mega Watt

NFPA: National Fire Protection Agency

NG: Natural Gas

NGL: Natural Gas Liquids

NPG: Net power gain

ORC: Organic Rankine Cycle

ORV: Open Rack Vaporizer

PDEC: Preheated direct expansion cycle

PEM : Proton exchange membrane

RC: Rankine Cycle

SCV : Submerged Combustion Vaporizer

SEC: Specific energy consumption

SEP: Separator

SMR: Single Mixed Refrigerant

SSLNG: Small-scale LNG

VCE: Vapor Cloud Explosion

VLE: Vapor Liquid Equilibria

Subscripts

i : Number of stage

net: Net Value

th: Thermal

ph: Physical

kn: Kinetic

pt: Potential

ch : Chemical

p: Pump

T: Turbine

c: Compressor

in: Input

out: Output

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Chapter 1: Introduction

Economic and population growth have increased annual energy demand by 2.4 % in the past decade. The emphasis on the utilization of natural gas due to its cleanliness has inreased. Ease of transportability, eco-friendliness and high calorific value have made natural gas one of the primary sources of energy. These user-friendly properties made natural gas a good alternative to conventional resources and potential renewable energy [1]–[3]. Natural gas is a vital non-renewable energy source. It is known as a versatile fuel. It is used as a feedstock in the industrial sector, as a source of fuel in the residential sector, for producing electricity in power plants and in the transportation sector [4], [5]. Natural gas, which is primarily made of methane and is found in large reserves throughout the world, is frequently transferred to consumer markets via piping for gas. The majority of natural gas is being used as fuel; it is only occasionally used as a chemical feedstock [6]. Compared to other fossil fuels, interest in natural gas continues to grow [7]. The World Energy Outlook 2019 estimated that by the year 2040, the global demand for natural gas will increase by an average of 1.4% year [8]. Natural gas can be transported in two ways that are both conventional and popular: pipelines and in liquid form. Natural gas pipeline transportation is cost effective over 2000 kilometers. LNG is frequently regarded as the most efficient option for delivering natural gas across vast distances [9], [10]. LNG is an odorless, colorless, non-corrosive, and non-toxic cryogenic liquid. LNG is cooled to -162°C through the liquefaction process. During the liquefaction process, impurities like water, carbon dioxide, and others are either removed or reduced [9], [10]. Also, the volume occupied by LNG is 1/600 times the volume occupied by its gaseous form, proving LNG to be more advantageous. The risk of LNG spillage during transportation in cargo is less as it floats on the water surface because of its lower density (400 kg/m^3) than water. Thermophysical correlations used to estimate the energy possessed by LNG suggest that the energy possessed is 830 KJ/kg and is often referred to as cold energy [4]. Gradually, there has been a rise in the utilization of LNG as a transportation fuel due to its ease of transportation and shelf life. All these factors have caused a global trend in the trade of LNG. While LNG can be a source of energy, it is therefore necessary to understand its value chain. **Figure 1.1** indicates that its value chain begins with natural gas exploration and production. Following production, the natural gas is transported to central liquefaction facilities using pipelines. The impurities are then removed, and the natural gas is liquefied at -162°C in the liquefaction plants. The liquefied natural gas is transported across long distances by means of cargos and ships in insulated vessels [11]. LNG storage and regasification occur in the last segment of the block chain. Different techniques are applied for regasification to distribute natural gas to customers. This LNG supply chain is frequently large-scale, with vessels with such an average capacity of 145000 m^3[12].

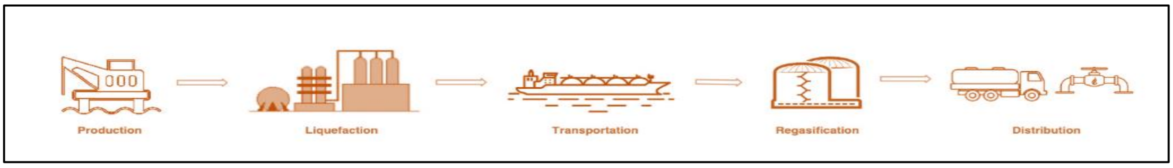

Figure 1.1: LNG Value Chain

The conventional technique of regasification employs heat transfer between seawater and LNG [13]. In this process, not only the cold energy possessed by LNG is wasted but also, the mechanical energy to run seawater pumps [14], [15]. Therefore, techniques are being developed to extract and utilize the LNG's cold energy. In the past two decades, CULNG has attracted a lot of attention, as the LNG trade is predicted to rise to 3.7×10^{11} tons by 2040 [16], [17].

1.1 Background

Utilization of LNG in Japan has drastically increased since the Alaska LNG introduction to Japan in 1969, and Japan will import the world's largest amount of LNG, which is 43 million tonnes per year, in 1990. Under the circumstances, cold utilization of LNG in Japan is aggressively promoted by many enterprises, and the following introduces the current situation and technical subjects to be studied further related to cold utilization [13].

1.2 Motivation for Research

The conversion of energy from one form to other results in global environmental problems. Wastage of a lot of thermal energy and its release into the atmosphere, rivers, and seas occur in process industry. Deterioration of the global environment, such as the greenhouse effect, acid rain, and ozone layer depletion, is also caused by the emission of pollutants. LNG, being a clean source of energy, has become an integral source of energy. This allows the transportation of natural gas in large volumes. Impurities like dust, sulphur compounds, carbon dioxide, and moisture are removed before liquefaction of natural gas to prevent plugging. The boiling point of LNG is around -162°C under atmospheric conditions, making it a worthy refrigerant. By harnessing the cold energy supplied by LNG vaporization, the operational expenses of cold processes have significantly decreased. LNG cold energy can be directly used or indirectly transferred to another working fluid. Some of its direct applications include air separation by cryogenic method, CO_2 liquefaction, the production of dry ice, food freezing, etc. Indirectly, the cold energy of LNG can be transferred to another refrigerant, such as cryogenic nitrogen, oxygen, and carbon dioxide, to serve in heat exchangers [13].

1.3 Objectives

1) To develop novel process for cold utilization of LNG.

2) To simulate process by using available software.

3) To conduct thermodynamic & exergy analysis of the process.

4) To optimize the parameters of process operation.

5) To Carry out economic analysis of the process.

1.4 Natural Gas Liquefaction:

All liquefaction processes, in spite of whatever distinct liquefaction technique is employed, comprise the following stages [13], [14].

i) Natural gas consists of non-hydrocarbons, including hydrogen sulphide, nitrogen, carbon dioxide, and water. These components are removed from natural gas through treatment processes, and the remaining portion is transported through pipelines to the liquefaction facility [15].

ii) Natural gas is cooled to extract heavier hydrocarbons (propane, butane, pentane, etc.). Separated components are utilized in refineries and petrochemical plants to manufacture products such as plastics, resins, etc [16].

iii) After the two steps of purification processes, the natural gas undergoes a cryogenic process to cool down to -162°C where it is converted into liquid [13].

This process is depicted in **Figure 1.2.**

LNG liquefaction methods can be broadly classified into two major types: processes that depend on pure single refrigerants and other processes that depend on mixed refrigerants. Large capacity LNG facilities typically use mixed refrigerant technology [14], [15].

Common Liquefaction processes are explained below.

1.4.1 Single Mixed Refrigerant (SMR)

Linde and APCI companies developed SMR. It is the basic natural gas liquefaction system, and this method is advantageous owing to the minimal number of necessary equipment [13]. In this process, the natural gas is liquefied inside the main cryogenic heat exchanger (MCHE), and the liquefied gas mixture is then expanded by the Joule Thomson Valve to remove non-condensable gases from natural gas and satisfy the needs of a customer. The necessary cold energy is supplied by mixed refrigerants that comprise nitrogen, methane, propane, ethane, and butane. It is renowned for its great flexibility, high dependability, and small capital and operating costs [14].

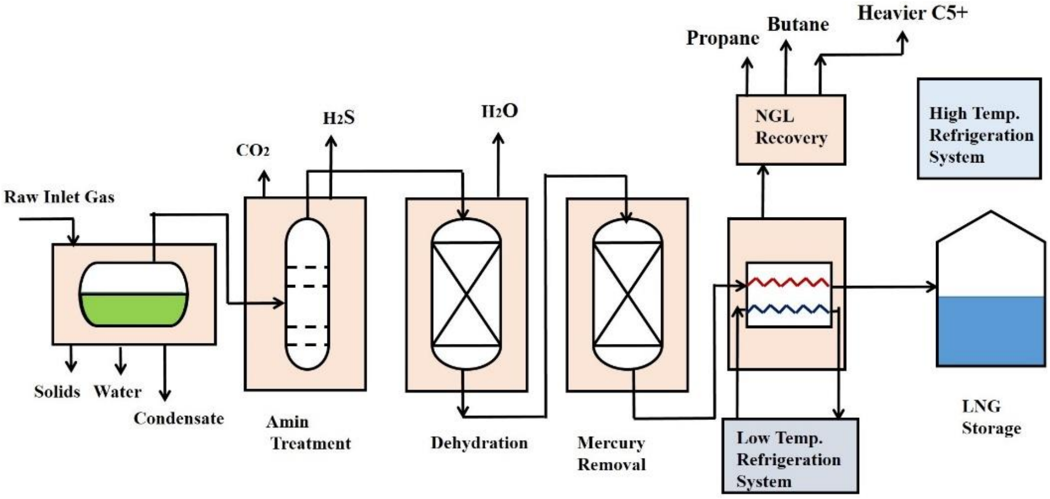

Figure 1.2: Natural Gas liquefaction Process

1.4.2 Propane Precooled Mixed Refrigerant

This process uses two refrigeration cycles, a pre-cooling cycle that uses propane as refrigerant, and a liquefaction sub-cooling cycle that operates using a mixed refrigerant. In the pre-cooling cycle, a multistage refrigeration cycle with 3–4 different pressure levels is used to exchange heat with gas streams and warm mixed refrigerant, so both streams reach a temperature of about

-35°C. In the liquefaction sub-cooling cycle, by using mixed refrigerant, natural gas is further cooled from -35°C to approximately -160°C [13].

1.4.3 Mixed Fluid Cascade (MFC)

In this method, three mixed working fluids are utilized inside three cascade cycles: pre-cool, liquefy and sub-cool the natural gas. A multi-stream heat exchanger is utilized for the three major cycles [13]. The pre-cooling cycle cools the gas stream along with the other two (the liquefaction and sub-cooling refrigerant) to approximately -50°C. The liquefaction cycle refrigerates both the natural gas stream and the sub- cooling mixed refrigerant to about -90°C. In the final section of the exchanger, the sub-cooling refrigerant additionally cools the LNG, guaranteeing its proper outlet temperature of -155°C to -160°C [13], [14].

1.4.4 Nitrogen Expansion Cycle

Nitrogen initially passes through several phases of compression and cooling. Initially, nitrogen is cooled by utilizing water-coolers, and, subsequently, by the pre-cooling refrigerant. After this, natural gas passes a single step of expansion to low pressure, which provides the cooling effect that is needed for liquefaction [13]. Expander operations are simple, dependable, and readily run without hazards connected with flammable working fluid inventories; however, there is a disadvantage as nitrogen expander methods have less energy efficiency than other liquefaction methods [14].International gas union (IGU) reported that global LNG trade has seen a low increase of 1.4 MT from 2019 to 356.1 MT in 2020. Even though there is an increase, the increment is very small. One of the reasons can be due to the fact that a liquefaction plant requires a lot of energy and costs. Therefore, major issues with such plants are to decrease energy input requirements and overall cost [15].

Some of the important investigations in onshore & offshore processes are presented in **Table 1-1** & **Table 1-2**.

Table 1-1: Summary of investigations of onshore Natural Gas Liquefaction Processes

Sr No	Researcher	Method	Result/ Investigation
1	Mehrpooya et al.(2016)[13]	This novel method altered the propane refrigeration cycle by using an ammonia-water absorption refrigeration cycle.	The specific energy usage of this innovative cascade liquefactionmethod was 0.178 kWh/kg LNG, a 30% reduction.

2	Najibullah Khan et al. (2016)[14]	Six case studies were given in order to estimate the greatest energy saving in the cascade liquefaction process	The optimum coefficient of performance (COP) as well as efficiency of exergy were observed in Case 6, where the evaporation temperatures of the low, medium, and high pressure stages were -40°C, 0°C, and 5 °C, respectively.
3	Ding et al. (2017)[15]	The process performance of the mixed fluid cascade process was investigated by varying the LNG storage pressure, feed gas pressure, as well as three mixed refrigerant compositions.	The unit energy consumption may be decreased to 4.655 kWh/kmol and 4.366 kWh/kmol
4	He and Ju (2016) [16]	For a small-scale LNG plant an unsteady state model of single mixed refrigerant liquefactionwas built	Lowering of methane composition and natural gas pressure, and also the rise of natural gas flow rate, had the largest impact on the process stability.
5	Pham et al. (2017) [17]	An optimization research of sin- gle mixed refrigerant liquefaction process improvement was lookedat	The compressor workload was reduced by 30.6 percent, and the heavier component in the mixed refrigerant may improve the energy efficiency of the process.
6	Sanavandi and Ziabasharhagh (2016)[18]	By taking operational limitations into account, created a thorough optimization of the C3MR liquefaction process	According to the findings, the specific energy consumption decreased from 1028.94 kJ/kg in the initial condition to 973.93 kJ/kg in the optimum state.

The liquefaction process and refrigerant in the LNG value chain are both expensive due to the considerable consumption of energy regarding compression power, which is required for refrigeration cycles. So, one method to accelerate worldwide competition and the growth rate of trade in LNG is by decreasing the compression power consumption of the liquefaction process [19]. The necessity of greater compression duty is largely due to reduced energy efficiency, which principally relies on the temperature differential in the primary LNG heat exchanger. These temperature variations are the primary source of energy loss, and hence the energy input requirement is considerable. These variations can be avoided by adjusting the composition, ingredients, and operating pressure of refrigerants . Concerning this, for optimum adjustments, multi-component refrigerators have been used. Exergy destruction in the associated equipment may be identified using traditional analysis. The influence of mixed refrigerant selection on LNG process energy and exergy performance, namely the SMR process, has recently been investigated [19]. However, such research is unable to pinpoint the source of irreversibility or assess the strength of equipment linkages [20].

Table 1-2: Summary of investigations of offshore Natural Gas Liquefaction Processes

Sr.No	Researcher	Method/Investigation	Result
1	Barclay and	For offshore natural gas liquefaction, an improved single	This new cascade liquefaction method used 0.178 kWh/kg LNG,

	Shukri (2000) [21]	mixedrefrigerant liquefaction method was developed.	which was 30% less energy.
2	Lee et al.(2013) [22]	Based on the SMR Liquefaction process, three alternative liquefaction methods for FLNG were designed	When compared to the SMR method, The suggested procedures demonstrated improvements in specific power.
3	Xiong et al. (2016) [23]	For offshore LNG production, carried out the SMR method based on PLNG (Pressurized LNG). To improve the unit energy usage, they used a genetic algorithm.	The energy consumption of single mixed refrigerant based onPLNG would be 50% less than the traditional SMR
4	Remeljej and Hoadley (2006) [24]	Four liquefaction methods were subjected to an exergy study	The nitrogen expansion as well as open-loop expansion processes were the frontrunners for such an offshore LNG facility.
5	Xiong et al. (2015) [25]	Proposed a new cryogenic CO_2 removal method for natural gas pressured nitrogen expansion liquefaction.	The primary benefit of this method was that it saved deck space for offshore LNG production by obviating the need for CO_2 pre-treatment before liquefaction.

In order to efficiently transport and store natural gas in a liquid state, natural gas liquefaction techniques play a critical role in the energy sector. The goal of ongoing research and development has been to make liquefaction processes more energy-efficient. Significant efficiency improvements have been made, lowering both energy consumption and operating costs [26]. These improvements have been made possible by advanced heat exchanger designs, optimized cycle topologies, and the integration of waste heat recovery systems. The use of modular LNG liquefaction units has become more well-known. Shorter building times, flexibility, and scalability are all features of these small, skid-mounted systems [27]. In order to quickly respond to market demands, modularization enables the building of liquefaction plants in remote areas or as additions to existing facilities. Processes for liquefying natural gas have opened up new export possibilities and made it possible to ship natural gas around the world to far-off markets. This has encouraged more international gas trade, enhancing energy security, diversifying the supply, and reducing reliance on particular geographical areas[26]. By removing contaminants and capturing methane, a potent greenhouse gas, during the liquefaction process, natural gas liquefaction techniques can lower greenhouse gas emissions. The use of modern liquefaction technology also reduces energy use and the carbon footprints that go along with it. By making it possible to transport natural gas across large distances in an efficient and economical manner, natural gas liquefaction techniques have completely changed the energy landscape technological developments like increased effectiveness and modular [27].

1.5 LNG-FPSO and FLNG

Although most of the current regasification plants are onshore facilities, with attention towards offshore natural gas resources, floating and offshore LNG production, storage, and offloading (LNG-FPOS and FLNG) have experienced exponential growth over the past period [28], [29]. Won et al.(2014) presented a review of trends in FLNG technologies. The author discusses the benefits and drawbacks of both onshore and offshore NG liquefaction plants. Among other things, plants require both a workforce and equipment to be transported, which increases construction costs and increases difficulty in engineering procurement since they are built in remote locations. Whereas floating (offshore) liquefaction plants are constructed in well-equipped shipyards with easily accessible labor, they also offer huge LNG storage, which is typically less expensive than onshore facilities.

1.6 NGL Recovery by LNG refrigeration system

Natural gas, along with other impurities like heavier hydrocarbons like ethane (C_2) and C_{2+}, is cheaper than lean gas. But there are several problems associated with their presence [28]. To meet the BTU requirement and pipeline standard, the majority of the heavier hydrocarbons must be separated from the natural gas stream in the form of NGLs to meet pipeline specifications. In addition, these compounds have a high freezing point, and to avoid freezing and consequent clogging of process equipment during the liquefaction processes, NGLs must be recovered [29]. The heavy hydrocarbon may be utilized for petrochemical sales or for gasoline blending. Many efforts are made to recover heavy hydrocarbons, as these have several advantages, including recovery. NGL has greater economic advantages than mixing air directly to satisfy pipeline regulations [30]. NGL recovery is typically accomplished in a natural gas processing facility using one or more distillation columns. Another method of extracting ethane and NGL is to segregate them from LNG at the LNG receiving facilities [31].The heavy hydrocarbon may be utilized for petrochemical sales or for gasoline blending. Many efforts are made to recover heavy hydrocarbons, as these have several advantages, including recovery. NGL has greater economic advantages than mixing air directly to satisfy pipeline regulations [30]. NGL recovery is typically accomplished in a natural gas processing facility using one or more distillation columns. Another method of extracting ethane and NGL is to segregate them from LNG at the LNG receiving facilities [31]. Since every component having a different condensation temperature than methane would be liquefied in the liquefaction process, it becomes possible to incorporate NGL recovery into the LNG liquefaction process. Many researchers have investigated a combined system of natural gas liquefaction with NGL recovery [32]. These investigations are presented in the **Table 1-3**.

Table 1-3: Summary of investigations of Integrated natural gas liquefaction & NGL Recovery Method

Sr. No	Researcher	Method/Investigation	Result
1	Vatani et al.(2013) [31]	For NGL LNG coproduction, a new integrated process configuration has been developed.	The method uses 0.414 kWh/kg (LNG) of specific energy and hasa 93.3 percent ethane recovery rate (heavier hydrocarbon in feed gas is 23 percent)
2	Mehrpooya et al.(2014) [33]	C3-MR, DMR, and MFC were used to introduce and evaluatethree processes for LNG and NGL co-production	The suggested methods recover more than 90% of ethane
3	He et al.(2014) [34]	A new mixed refrigerant cycle (MRC) LNG coupled with NGLrecovery method was optimized using a genetic algorithm	Ethane product purity is over 99.5%, with an ethane recovery rate of over 99.5%. Optimizedspecific energy consumption is approximately 0.44 kWh/Nm3 (natural gas), with a 47% energy efficiency
5	Ansarinasab et al.(2016)	From an energy and economic standpoint, we examined an LNG and NGL co-productionmethod based on MFC refrigerants	Because it has a large amount of energy destruction, the efficiencyof the demethanizer column has increased.
6	Ghorbani et al. (2018) [35]	An absorption refrigeration system was used to investigate a new LNG-NGL recovery method	Reduced system energy consumption also opens up the option of using waste heat energy.

International criteria and regulations are met since NGLs are removed from the natural gas stream when LNG is produced. The energy and sulphur content of LNG are decreased by removing the heavier hydrocarbon components, resulting in LNG that satisfies the standards for international trade and consumption. The recovery of NGLs during LNG production can benefit the environment [36]. In comparison to other hydrocarbon fuels, NGLs, in particular ethane, have a lower carbon intensity. The overall carbon footprint of the LNG production process can be decreased by removing NGLs from the natural gas stream, aiding in the drive to reduce greenhouse gas emissions. In order to remove useful byproducts from the natural gas stream, NGL recovery using LNG refrigeration systems is crucial to the LNG production process [37]. The effectiveness of NGL recovery is increased by the employment of technology like fractionation towers and turbo-expanders, which also maximize the economic feasibility of LNG projects and guarantee adherence to quality standards. By lowering the carbon footprint connected to LNG production, NGL recovery also benefits the environment [38].

1.7 LNG Storage & Transportation

As the LNG market is growing, LNG carriers are experiencing remarkable growth. An LNG ship or carrier is a tanker intended to carry LNG at a temperature of -162°C. Generally, LNG carriers may range in size from 1000 to 267,000 m^3, although most contemporary boats are between 125,000 and 150,000 m^3 [39]. Smaller LNG carriers (1000-25,000 m3 capacity) are still operational in certain regions, such as Norway and Japan [40]. A typical contemporary LNG ship is about 300 m long and 43 m broad and it has a draft of around 12m. 'Mozah' a Q-Max LNG carrier built in 2008 by Samsung Heavy Industries and operated by Qatargas II is reported to be the biggest LNG carrier with capacity of 266,000m^3. Only 13 shipyards in the world were capable of constructing LNG carriers in 2016. An LNG storage is a specialized storage used to store LNG at very low temperature of -162 °C [41]. LNG can be stored in a variety of ways like above ground, underground, or LNG tankers. LNG carriers provide a link between the liquefaction plant of natural gas and regasification plant. LNG carriers facilitate the transport of massive quantities of natural gas over long distances to consumers [42].

Typical LNG carriers are shown in **Table 1-3**

Figure 1.3: Typical Carriers for LNG [72]

Five common designs of LNG storage containers are single containment, double containment, full containment, membrane, and pressure vessels [43]. A typical vessel design includes an internal shell and an external shell. In between the inner and outer shells of an LNG storage tank, thermal insulation is made mainly of expanded perlite and fibreglass panels [44]. For LNG storage pressure vessels, this insulation may be a vacuum insulated jacket or a high performance insulation (like aerogel) with metal jacketing [45].

These massive LNG storage tanks are always exposed to the atmosphere. Due to the exchange of heat with the environment, it causes the evaporation of LNG, which may result in a large number of vapours accumulating in the storage tank [46]. Incidents may lead to a rupture of the tank, and an unintentional leak of LNG might take place. When the released vapours come into contact with the air, a combustible vapour cloud may probably form. If an ignition source is available in the vicinity of a flammable cloud, it may lead to a fire or vapour cloud explosion [47]. Feed Natural Gas provides a substantial portion of the fuel needed to convert natural gas throughout the base load LNG chain's many operations. The combustion of this fuel leads to the production of a considerable amount of CO2 and other polluting gases (e.g. Sox , NOx etc.)[48]. Apart from these disadvantages, LNG development is linked to additional environmental concerns, which include solid waste and water discharges. Improvements in operations at different points along the chain may have a significant impact. Improving energy efficiency has the advantage of reducing energy consumption, which in turn lowers environmental issues by lowering gas emissions. Savings in fuel usage may also assist in achieving greater LPG production with fewer resources and a lower environmental impact [49].

LNG storage areas, because of the escalation scenario and chain reaction effect triggered by fire, have high vulnerability. Many eventualities might end in the fire engulfment of LNG tanks, e.g. Leaks from tank connection pipes, pools of diesel fuel catch fire as a result of traffic accidents, causing liquid spills to ignite [50]. The heat from the fire is transferred to the tank through the tank walls and insulating layer, causing the LNG to heat up and increase pressure. Due to the rise in pressure and weakening of the vessel shell produced by fire explosions, exposed equipment may collapse, leading to critical situations such as fast phase transition or boiling liquid expanding vapour explosions (BLEVE) [51]. When exposed to fire, the thermal behaviour of LNG improves as it improves equipment protection against industrial fires and aids in the development of safe storage and transportation systems [52].

The schematic of LNG storage tank is presented in **Figure 1.3**.

Infrastructure for LNG transportation and storage has facilitated the diversification of natural gas supply sources, enhancing global energy security. LNG makes it possible to transfer gas from far-flung areas to areas with strong demand, minimizing reliance on particular producing areas and boosting energy resiliency [53]. The efficient and secure distribution of natural gas is made possible by the storage and transportation of LNG, which is a critical component of the global energy landscape. The availability of dedicated LNG ships, bunkering infrastructure, and advanced storage technologies has increased the use of LNG as a flexible energy source. LNG storage and transportation continue to influence the direction of the energy sector while putting an emphasis on security, environmental sustainability, and energy diversification [54].

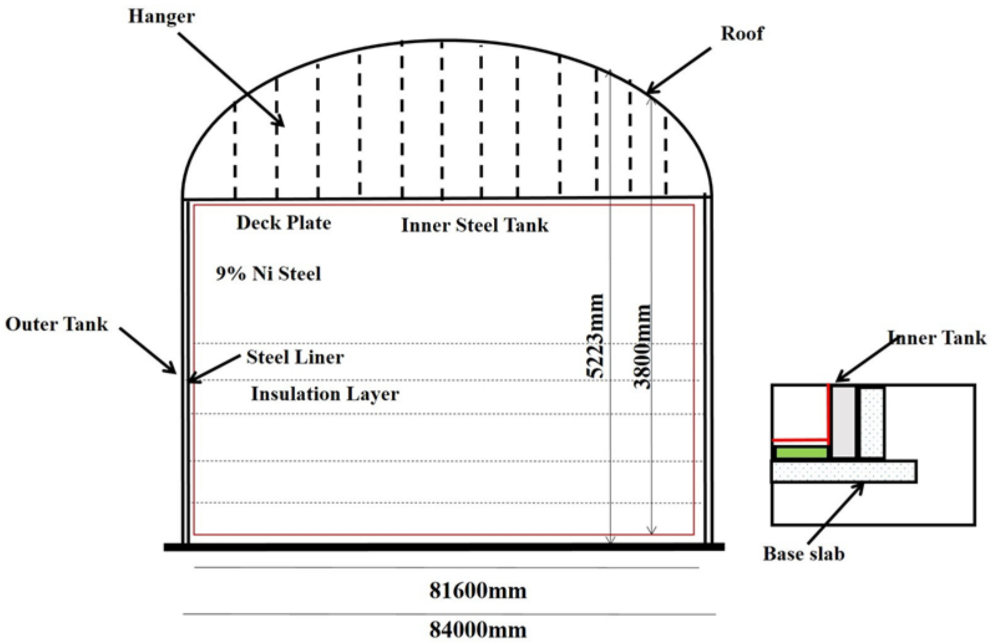

Figure 1.4 : LNG Storage Tank Schematic

1.8 Boil-off Gas (BOG)

Even though tankers are constructed with insulation to prevent external heat from entering, even a little quantity of warmth will cause minor evaporation of cargo. Because the temperature differential between LNG and ambient air is approximately -83.15 °C, boil-off gas is produced [55]. Therefore, the performance of LNG ships can be measured by the evaporation rate of the cargo tanks. Accurate BOG generation prediction under different operational circumstances may have considerable commercial and scientific significance [56]. These methods are presented in **Table 1-4**.

For LNG to have the greatest economic value, the least amount of energy waste, and the least amount of negative environmental effects, BOG recovery is essential. Recovered BOG could be re-liquefied as well as returned to a storage system, obviating the need for additional LNG production [57]. It can also be used as a valuable fuel source. Effective BOG recovery techniques aid in energy efficiency, cost reduction, and LNG operations that are sustainable [58].

1.8.1 BOG Recovery Methods

1.8.1.1 BOG Reliquefication

Reliquefaction entails employing onboard reliquefaction equipment to cool the BOG back to its liquid condition. These systems use refrigerants or cryogenic techniques to compress and cool the BOG, allowing it to be returned to the LNG storage tanks. Reliquefaction keeps the LNG in a condensed state by reducing BOG losses during storage and transit [58].

1.8.1.2 BOG Utilization

BOG is a useful fuel source that can be used for onboard operations or power generation. It can be burned in specialised BOG-fueled engines, used as fuel for gas turbines or boilers, or used as fuel for both, supplying electricity for a number of onboard systems. In comparison to conventional marine fuels, using BOG as fuel minimises pollution as well as energy waste [59].

1.8.1.3 BOG Compression

The vaporized gas is compressed during BOG compression and then delivered back to the LNG storage system. This technique keeps the pressure in the storage tanks and prevents BOG loss. The BOG's pressure is raised using compressors, enabling its reintroduction into the LNG system for re-liquefaction [60].

Table 1-4: Summary of investigations of BOG Recovery Methods

Sr. No	Researcher	Method/Investigation	Result
1	Sayyaadi and Babaelahi (2010) [61]	Claude refrigeration was used to optimize the LNG-BOG reliquefication system	Energy and energy analysis were used to create thermodynamic modeling.

2	Gomez et al. (2015) [62]	A thermodynamic analysis of a BOG re-liquefaction facility for LNG carriers equipped with a dual-fuel high-pressure gas supply engine was performed.	SEC of 0.64 kWh/kg LNG was achieved with a COP of 0.22, an energy efficiency of 37 percent, and a coefficient of performance (COP) of 0.22.
3	Ghorbani et al. (2017) [63]	An absorption refrigeration system was used to investigatea new LNG-NGL recovery method.	Reduce the amount of energy used by the system, as well as thepossibility of using waste heat energy.
4	Kwak et al. (2018) [64]	A novel boil-off gas re-liquefaction technology for LNG carriers has been designed based on a dual mixed refrigerant cycle.	The lowest specific power for a cycle without compression is pre dicted to be 1.27 kWh/kg LNG as a consequence of optimization.
5	Tan et al. (2018) [65]	A novel boil-off gas re-liquefaction technology for LNG carriers was proposed which is based on a dual mixed refrigerant cycle.	Exergy efficiency was 41%.
6	Yin and Ju (2019) [66]	Two nitrogen expansion cycles have been compared and evaluated for BOG re-liquefaction systems for small LNG ships.	Focusing on energy and exergy analysis, the performance of the serial nitrogen expansion is bet- ter, with an SEC of 0.73 kWh/kgLNG and an exergy efficiency of 28%.
7	Kim et al.(2019) [67]	The Joule-Thomson (J-T) process was used to optimize and assess a reference fuel supply system and its changes as a result of BOG liquefaction.	Total yearly cost was minimized by optimization of cycle.

Reliquefaction systems have become more effective and compact as a result of technological improvements. Modern refrigeration cycles, like mixed-refrigerant and cascade systems, optimize BOG cooling and recondensation, increasing reliquefaction effectiveness and consuming less energy [68], [69]. BOG compression system improvements have produced more dependable and effective compression procedures. The efficiency of compression has increased, reducing energy losses during the compression stage thanks to high-performance compressors, sophisticated control systems, and integrated heat exchangers [70], [71]. Floating sorage regasification unit (FSRUs) use BOG recovery techniques to increase their overall effectiveness as they transform LNG back into natural gas for onshore delivery. Systems for reliquefaction and compression are built into FSRUs to collect BOG during regasification, minimizing losses and improving operational efficiency [72], [73].

BOG recovery techniques help make LNG plants economically viable. Operators can maximise the amount of LNG that is available for sale and enhance income by minimising BOG losses. Utilizing BOG as onboard fuel also lessens the need to purchase additional fuel, which saves money for LNG carriers and ports [74]. The use of BOG recovery techniques benefits the environment. Reducing BOG losses lowers greenhouse gas emissions and helps mitigate climate change. The use of BOG as fuel also lessens the need for other fossil fuels, which lowers the emissions of air pollutants like sulphur oxides (SOx) and nitrogen oxides [75]. All prior research on BOG production and management relied only on one factor: heat loss. Only a few studies have quantified the role of mechanical vibrations in BOG production. Essentially, the constant mechanical vibration of storage tanks of LNG is comparable to the input of a thermal source owing to LNG viscosity, which can also cause BOG production. However, BOG generation will be more susceptible to heat leakage when compared with vibrational impact. In some situations, such as LNG marine or road transportation, significant LNG vibrations may occur, and the vibration-induced BOG generation must be taken into account so that the complete BOG production can be accurately predicted and the BOG managing facilities can be designed properly and preserved [76].

1.9 Small Scale LNG Carriers

Small scale LNG vessels typically transport no more than 30,000 m^3. LNG transportation via tiny LNG ships is still uncommon, but as global trade grows, these small-sized LNG ships give remote areas access to natural gas. They are mostly intended for inland use, as well as massive LNG power generating systems for peak demand or secondary cycles. The usage of LNG on a modest scale is becoming more popular, carriers depend on importer- exporter market shares. Because its lower vessel dimensions satisfy sea depth restrictions for transport routes, the LNG Carrier offers operational convenience [77].

1.10 LNG as a shipping fuel

LNG as a fuel offers several advantages, including the fact that it is non-corrosive, non-toxic, and odorless. When related to other types of hydrocarbons, LNG is highly economical in the worldwide market for energy because of its vast reserves and relatively cheap costs. As a result, the use of LNG as a marine fuel substitute on board ships is gaining popularity among stakeholders. LNG was initially utilized on LNG carriers in the 1960s, but it was not employed on other kinds of ships until 2000 owing to technical and safety concerns [78]. Maritime air pollution prevention is a worldwide problem that is now in the spotlight. As public concern about air pollution has grown, so has public knowledge that LNG tankers are polluting the environment. The IMO's environmental rules include sulfur oxides (Sox), carbon dioxide (CO_2), and the creation of emission control areas (ECAs), among other things. Even if LNG may replace current fuels, it still has certain drawbacks, such as a lack of LNG infrastructure, a costly capital investment. LNG, on the other hand, may decrease emissions significantly due to lower peak temperatures during burning, which complies with IMO environmental standards [11].

International shipping has become more difficult related to current binding legal air quality regulations and a 50% decarbonization target by 2050. International shipping has become more difficult as a result of new legally enforceable air quality standards and a 50 % decarbonization goal by 2050. Although LNG is a popular substitute for liquid hydrocarbon fuels, methane emissions decrease LNG's total climatic benefit [79]. To investigate the effect of new emission assessments and supply-chain data to perform an environmental life cycle and cost evaluation of LNG as a marine diesel oil (MDO), methanol, heavy fuel oil (HFO), and prospective renewable fuels (hydrogen, ammonia, biogas, and biomethanol). To make use of the advantages of LNG, such as better air quality, lower fuel costs, and mild climate benefits, large differences among various LNG engine types are created. When coupled with the best-case supply chain, the use of the best-performing LNG engine may reduce global warming potential by up to 28% [80]. Methane leakage from certain engines is unwelcome. To ensure environmental benefits across all timescales compared to current liquid fuels, total methane emissions must be decreased to 0.8–1.6%, but, it is not only to match incumbent fuels; steps should be taken towards decarbonization targets. To achieve a 50% decarbonization goal, energy efficiency must improve to 30%, and methane emissions must be reduced to 0.5% throughput [81]. Iannaccone et al. (2020) evaluated the long-term sustainability of alternative fuel methods for big cruise ships utilizing a variety of technologies depending on LNG and traditional fuels, such as marine gas oil and conventional diesel fuel [82]. LNG-based technologies outperform MGO in terms of sustainability. Due to the applicable environmental advantages (44% environmental index reduction) and reasonable costs, the low-pressure dual fuel system proved to be the most sustainable option, with a decrease in total sustainability impact of 35% when compared to MGO. However, safety concerns penalize technical solutions that process natural gas at high pressure, such as high-pressure dual-fuel systems. In this instance, the increased inherent safety index (62% greater than MGO) results in a depleted sustainability performance, with only a 29% decrease in the total sustainability index when compared to MGO [83].

1.11 LNG Regasification

Regasification stations convert LNG to natural gas and put it into the gas grid. They are usually near ports to assist in the transfer of LNG from ships to storage tanks. There are now 133 regasification terminals in service, with another 29 under construction (including both onshore and off-shore terminals). As of February 2021, worldwide regasification capability has risen to 850.1 MTPA [84]. There are over 100 on-shore facilities, with more than a handful under development, that are better suited for greater integration with port energy infrastructures. It is also worth noting that more than 33% of current onshore terminals and more than 70% of those currently under development have a nameplate reception capacity of fewer than 3 MMTPA. In contemporary times, there is the possibility of the construction of bigger terminals. Because of the presence of maritime oil and gas and industrial sectors, harbours and ports have been identified as sources of air pollution. In ports, pollutant emissions such as NOx, SOx, and PM are important. Shipping accounts for 2-3% of worldwide greenhouse gas emissions, with ports accounting for 2-5% of this. This is the reason the IMO has established a greenhouse gas plan to cut absolute emissions by half by 2050 [85].

There are different modes on which LNG regasification terminals operate [86].

i) Holding mode: LNG is shifted to and from LNG tanks in this mode.

ii) Unloading mode: Tanks collect LNG from tankers in this mode.

iii) Reloading mode: Tanks deliver LNG to the tanker in this mode.

However, irrespective of the type of operation selected, LNG re-gasification at the appropriate rate and cooling of transfer lines linking tanks and jetties are done continually. The LNG used to cool the transfer lines is returned to the tank, generating inline BOG as well as in-tank BOG and changing the temperature of the tank’s vapor phase. This alters the transfer of heat from the vapor to the liquid phase, influencing BOG production in the tank [87].

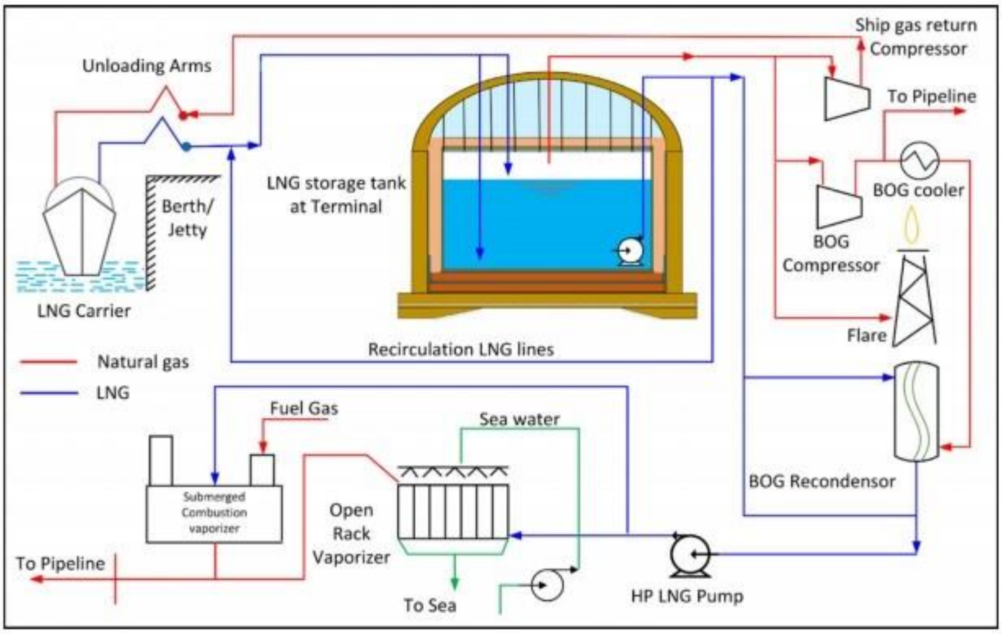

Figure 1.5: LNG Regasification Terminals [88]

Regasification, the process of converting LNG from liquid to gas, is a key operational procedure at LNG receiving facilities. Generally, depending on various heat sources, there are four types of LNG vaporizers [89].

1.11.1 Open Rack Vaporizer (ORV)

It is extensively used. It heats LNG with saltwater (at a temperature close to that of the surrounding environment).

1.11.2 Submerged Combustion Vaporizer (SCV)

It converts LNG using gas combustion as a source of heat. It feeds flue gases via a water bath where LNG is first heated and regasified bypassing via bundles.

1.11.3 Intermediate fluid Vaporizer (IFV)

It entails the use of a third fluid (such as glycol, propane, or other similar substances) to transfer heat from various sources. (e.g., salt water, gas combustion, ambient air etc.) to LNG to convert its phase back to gas.

1.11.4 Ambient Air Vaporizer (AAV)

It makes contact with LNG by passing ambient air via vertical finned tube heat exchangers.

The crucial role that LNG regasification plays in supplying the rising demand for natural gas worldwide. LNG is delivered across vast distances in its liquefied form using specially constructed ships. LNG is converted back into gas at regasification terminals at import ports or onshore facilities, enabling pipeline distribution to a variety of end customers, including power plants, industrial facilities, and residential consumers. The procedure guarantees a consistent and adaptable supply of natural gas, enhancing energy security and source diversity [90].

1.11.5 LNG Regasification Advantages

1.11.5.1 Energy Security

By gaining access to international LNG markets, LNG regasification enables nations to diversify their energy sources. It improves energy security by reducing reliance on a single domestic gas source and by supplying a steady energy supply [91].

1.11.5.2 Environmental Considerations

When compared to other fossil fuels, natural gas burns cleaner, which reduces the emissions of greenhouse gases and air pollutants. Natural gas utilization is facilitated by LNG regasification, which lowers carbon intensity and improves air quality [92].

1.11.5.3 Flexibility and Versatility

LNG regasification installations offer supply-and-demand flexibility for LNG. They make regasification processes quick to start up and stop, which makes natural gas suited for peak power generation, seasonal demand, and market swings [93].

1.11.6 Challenges for LNG Regasification

1.11.6.1 Infrastructure Investment

Significant capital investment is needed to establish LNG regasification terminals, particularly for building storage facilities and pipeline networks. Long-term LNG supply contracts and high upfront prices might be financially difficult [94].

1.11.6.2 Safety and Environmental Concerns

Regasification procedures include the handling of cryogenic materials and call for appropriate safety precautions to avoid mishaps or leakage. Additionally, regasification facilities' potential to harm marine ecosystems or cause thermal discharge should be properly evaluated and addressed [86].

1.11.6.3 Market Dynamics

The market for LNG is impacted by variables like price volatility, geopolitical tensions, and shifting regulatory landscapes. Regasification projects' long-term profitability is reliant on obtaining a competitive LNG supply, market demand, and efficient gas pricing mechanisms [95].

1.12 LNG as a fuel for Natural Gas Vehicles

Due to the increase in demand for energy in the recent past, it is very important to shift towards alternate fuel technologies. The main issue that these alternative fuels confront is the significant limitations that they encounter when utilized in heavy-duty vehicles and long-distance transportation [96]. Currently, electric vehicles are replacing routine vehicles, but their major drawback is the continuous recharging, and they are also suitable for short distances. Hydrogen has a great potential for decreasing greenhouse gas emissions; however, the generation of hydrogen is expensive as compared to other sources. The usage of biofuels is difficult owing to their scarcity, which arises as a result of land use devoted mainly to food production. Natural gas vehicles were first used in the year 1930. Unlike other technologies, it is considered a mature technology and has applications in a wide range of vehicles [97]. Natural gas can be used as vehicle fuel in two different states. One is in a compressed form, known as CNG (compressed natural gas), while the other is in a LNG form. While CNG is widely used in passenger cars, LNG’s considerably higher energy density makes it ideal for heavy-duty vehicles [98]. This may be accomplished by reducing the volume of the liquefaction process. The only source of fuel that can be comparable to diesel (used for heavy- duty vehicles) is LNG. It is the most viable and mature technology used for long-distance transport. When compared to diesel, using LNG as a substitute fuel is environmentally friendly because it does not cause pollution and includes clean combustion, which produces around 80% less nitrogen oxides (NOx), nearly 99% less particulate matter(PM) and sulfur oxide (SOx) emissions, and around 20% less carbon dioxide [99]. By incorporating liquefied bio-methane into gasoline, we may further reduce emissions. Also, the LNG fueled vehicles reduced noise levels, allowing for competitive advantages via inner-city and late-night delivery services [96].

1.12.1 Challenges for LNG as a Fuel

1.12.1.1 Infrastructure Development

Significant upfront investments are needed to build the LNG infrastructure for NGVs, which includes liquefaction plants, storage facilities, and refuelling stations. For the widespread use of cars fueled by LNG, a robust and easily accessible refuelling infrastructure is essential. The expense and complexity of building infrastructure continue to be major obstacles that must be overcome in order to promote market expansion [100].

1.12.1.2 Vehicle Conversion and Availability

Vehicle Conversion and Availability Costs may increase if more NGVs are produced or if existing cars are converted to run on LNG. The use of LNG as a fuel could be hampered by the limited availability of NGV vehicles, particularly in certain vehicle classes or locations. To increase the selection of NGV options and guarantee vehicle availability, cooperation between vehicle makers, regulators, and the LNG sector is crucial [101].

1.13 Safety Aspects in LNG Sector

If any accident occurs, there is a huge waste of money and infrastructure, so safety aspects play an important role in the manufacturing, storage, loading, unloading, transportation/ shipping, and regasification of LNG. Recognizing the dangers of LNG not only helps to ensure the appropriate safety and dependability of the R&D system, but also improves the efficiency of asset protection, fire prevention, and disaster response [102]. Maintaining the proper LNG temperature is critical since a very low temperature may pose a major danger, resulting in fractures and frostbites in both materials (tanks and ship construction) and humans within reach [103]. As a result, tanks, pipes, and valves that come into contact with LNG must be constructed of specific cryogenic materials that can resist extreme cold. LNG is a highly flammable substance that may quickly catch fire. In certain instances, explosions may occur as a result of leaks and spills in the presence of ignition sources, necessitating appropriate LNG storage

[104]. LNG will evaporate, spread, and ultimately create a vapor cloud that will scatter in the atmosphere if there is no ignition. In the event of ignition, LNG offers four possible danger scenarios: flash fire in a vapor cloud, jet fire, pool fire, and vapor cloud explosion. Furthermore, the effects of LNG fires and explosions are dependent on the original LNG temperature and composition, as well as the diameter of the pool fire [105]. The following are the most significant features coming from rules and guidelines on LNG operating ports, based on the distinctions provided in the bunkering modes [106].

i) Tanks for storing LNG must meet the Seveso III regulation, as well as EN 1473 and NFPA 59A requirements.

ii) Bunker trucks should follow the ADR agreement, while buffer ships should be built to the IGC code, fulfilling the ADN agreement's safety criteria as well as the ISO 28460 and EN 1532 standards.

iii) For safety, LNG-fueled ships must be constructed in line with the IGF code to attain a high degree of safety in LNG bunkering, ISO 18683, 16901, and 20519 requirements should be considered.

1.13.1 LNG Spillage

LNG is transported in liquid form, so there are chances that it could be spilled and interact with seawater to accelerate the vaporization process. The series of occasions for an LNG spill comprises several steps. The first stage requires a regulatory spill, which involves breaking the confinement of LNG in a tank or transfer line. If the loss of containment (LOC) occurs above sea level, the LNG will descend to the water's surface, and the LNG jet will break apart as it collides with the water surface. When the velocity of the jet is high enough, the droplets may penetrate the surface and get submerged in water, resulting in a chaotic mixing zone [107]. Because water is approximately twice as heavy as LNG, it is buoyant and floats to the top. The spill eventually creates a pool that extends over the water's surface. Because LNG has a boiling point of -162°C, the pool begins to boil as it spreads. The resulting vapor consists primarily of methane due to its highest volatility among all other components. As a result, a gradual compositional change is observed, and this leads to increases in the proportion of heavier alkanes like ethane, propane, and butane [108]. There is a risk of a minor mishap at a floating liquefied natural gas terminal that has the potential to turn into a more catastrophic event (FLNG). For example, an unintentional release of LNG in a manufacturing facility could cause fire, blast, fragile breakage, asphyxiation, and frost, among other hazards [109]. The LNG leakage may appear to be a single minor event at first, but because of the instantaneous vaporisation caused by the water-LNG contact near the surface, when the vapour is ignited, it is likely to result in a fireball, flash fire, Vapor Cloud Explosion (VCE), and pool fire. If the aforementioned events are escalated to a storage facility, a Boiling Liquid Expanding Vapor Explosion (BLEVE) [110] may occur.The National Fire Protection Agency (NFPA) and American Gas Association (AGA) suggest high expansion usage of foam in case of an accident resulting in LNG leakage. It is generally recommended to reduce the risk due to a cryogenic vapor cloud. Krishnan et al. studied the role of exfoliated zirconium phosphate (ZrP) nanoplates in the stabilization of high expansion foam. Experiments show that exfoliated ZrP nanoplates may maintain high expansion foam under forced convection (from the wind) and heat radiation. When exfoliated ZrP nanoplate stabilized foam was used, a nearly 40% reduction in the foam breakage rates was noted. The main advantage of using this foam is that it may lengthen the time it takes for it to be refiled while allowing rising LNG vapors to exchange heat with the foam, making it lighter and ensuring effective vapor dispersion [111].

1.13.2 Risk Management and Hazard Mitigation

1.13.2.1 LNG Release and Dispersion

The potential leak of LNG is the main safety concern in the LNG industry. Although LNG is not flammable when it is in its liquid condition, it can quickly vaporise in the presence of ambient heat and produce a dangerous gas cloud. To stop LNG releases and control the dangers involved, thorough risk assessments, hazard identification, and mitigation techniques are essential [112].

1.13.2.2 Fire and Explosion Hazards

Although LNG itself is not explosive, under some circumstances, the vapour cloud that results from its emission might catch fire or explode. To reduce the risk of fire and explosion, it is crucial to put in place efficient fire prevention and protection measures, such as fire-resistant barriers, detection systems, and emergency shutdown systems [113].

1.13.3 Safety Measures and Best Practices

1.13.3.1 Design and Engineering

When designing and building LNG facilities, certain safety regulations must be followed. Double containment systems, high-integrity pressure protection systems (HIPPS), and emergency isolation valves are examples of safety measures that can be incorporated to help reduce hazards and improve operational safety [114].

1.13.3.2 Operational Safety

Safe LNG operations depend on effective operational procedures, training, and maintenance programmes. The dependability and integrity of the LNG infrastructure are ensured through routine inspections, equipment integrity checks, and preventive maintenance [115].

The thorough analysis of the LNG value chain brings to light the complex procedures needed to harness natural gas and convert it into LNG for use on a worldwide scale. Several important conclusions can be reached from an analysis of each stage, from exploration and production to end-use applications:

i) LNG is now recognized as a key element in supplying the world's rising energy needs while attempting to cut carbon emissions. It is a desirable replacement for conventional fossil fuels because of its adaptability and better burning qualities.

ii) Innovations in liquefaction technologies, including conventional techniques, floating LNG (FLNG), and small-scale LNG (SSLNG) plants, are highlighted in the review. These developments have increased productivity, decreased prices, and increased the possibility of producing LNG in previously unreachable locations.

iii) Due to its cryogenic nature, LNG poses special difficulties in terms of transportation and storage. The research looks at a number of techniques, including LNG ships, barges, trucks, and storage possibilities like on-land tanks and offshore alternatives. The necessity of strict safety regulations and environmental considerations in these processes is emphasized.

iv) A crucial stage in getting LNG back into a gaseous condition for distribution and consumption is regasification. Traditional onshore terminals, floating storage and regasification units (FSRUs), and land-based facilities are examined in detail, with an emphasis on their operational merits. Due to this diversity, it is possible to be flexible and adaptable in order to satisfy various market demands. While CNG is widely used in passenger cars, LNG’s considerably higher energy density makes it ideal for heavy-duty vehicles.

v) Applications for LNG include transportation, industrial processes, home heating, and power generation. Due to its adaptability, it may be integrated into a variety of industries, promoting energy diversification and lowering reliance on conventional fuels. To realize its full potential in each area, however, specialized infrastructure and regulatory frameworks are required.

vi) Despite the fact that LNG is a cleaner option than other fossil fuels, the assessment stresses how crucial it is to solve environmental issues. To guarantee the long-term viability of the LNG value chain, attention must be paid continually to methane emissions, carbon footprints, and greenhouse gas mitigation techniques.

1.14 Thesis Outline

Chapter 1 provides a basic overview of the LNG processes. The production, processing, liquefaction, storage, transportation, and regasification of natural gas are all briefly described.

The literature review on the cold utilization of LNG is described in Chapter 2 and was used to inform the research concept and problem findings. Various research papers, research articles, as well as book chapters were examined to determine the issue and chosen remedy.

The novel cold utilization processes for air separation and multistage power generation are described in Chapter 3. This study looks at a new air separation unit (ASU) design paired with LNG's direct expansion cycle (DEC). The study is unique in that it analyzes the performance of an ASU paired with a DEC for a 3993-kW power plant using process simulation in Aspen Hysys (12.1). According to the findings of this study, the specific energies required for the creation of high purity oxygen and high purity nitrogen are 0.10 kWh/kg and 0.32 kWh/kg, respectively. Furthermore, the system saves 3993 kW of energy as a result of an appropriate system combination of other subsystems and LNG vaporization.

It was discovered that the current power generating cycles employing CULNG have low efficiency and NPG during problem development. To increase efficiency and NPG, four different modified cycles are described. The largest net power improvement can be achieved by integrating DEC and multistage Rankine cycles. With RC, only cold energy is used by the condenser to separate LNG from the gas. Cold exergy as well as mechanical exergy can be recovered if DEC and RC are combined. Various parallel and series configurations for RC and DEC are feasible. DEC can be used at the start, middle, or end of a multistage cycle. In the proposed integrated power cycle, energy equations and exergy equations are established with minimal pressure drop and heat loss in evaporators, condensers, and heat exchangers.

Chapter 4 describes the simulation software ASPEN Hysys (12.1) and research methodology.

Results and discussions are outlined in Chapter 5. The results show that, the least amount of energy is consumed by optimising an air separation process that is coupled with LNG regasification. Using an exergy analysis and parametric optimisation, an optimum design is generated after examining the impacts of altering the number of equipment components. In conclusion, the integration of LNG cold energy with the ASP provides an efficient option for improving ASP efficiency, reducing energy consumption, and lowering greenhouse gas emissions when compared to standard air separation procedures because no fuel is burned in this process.

The results of multistage power generation power cycle show that net power gain and power cycle efficiency significantly increase when the DEC and RCs are coupled. The efficiencies of the DEC and single-stage stage RC are 21.05 % and 23.38 %, respectively, whereas they are 38.78 %, 34.93 %, 47.52 %, and 47.23 % for the four alternative combinations. Preheated DEC and multistage RCs were linked to provide maximum efficiency and net power gain. When 11 different working fluids were tested for the given conditions with single-stage Rankine cycles, R1150 was determined to produce the best results. This suggests that the effectiveness of the cycle is significantly influenced by the condensation temperature. The working fluid pressure, LNG mass flow rate, and turbine output pressure are significant factors in getting the optimum results, according to sensitivity analysis. The economic analysis also showed the proposed power system's viability.

The research's conclusion and its future directions are covered in Chapter 6.

Chapter 2: : Literature Review

A cold is an essential form of energy. In the past decades, governments have developed policies leading to most energy sectors: oil and gas, coal, renewable, heat, and transport. However, the energy required for cooling gets much less attention. There are growing appeals for cooling in many forms, like air conditioning, the data industry, food, and medicine, worldwide [116]. Systems that require refrigeration or cooling are being developed in such a way that the cold energy possessed by LNG can be utilized [117], [118]. Power generation, desalination, air separation and fractionation, and carbon dioxide liquefaction are examples of these systems [119], [120].

Figure 2.1 illustrates the variety of CULNG applications that are accessible [121].

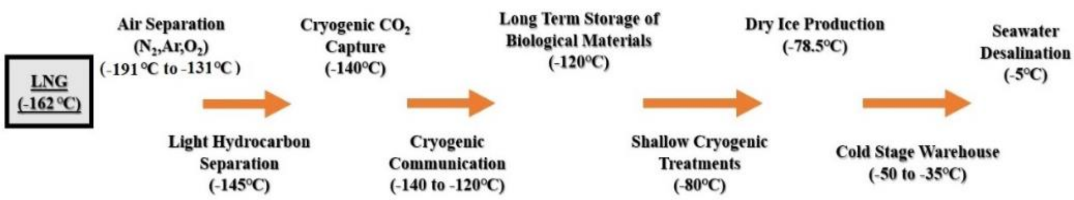

Figure 2.1: Temperature level for several applications[121]

Table 2-1:Implementation of cold utilization of LNG in different countries

Process	Country
Air Separation	China, France, South Korea, and Japan
Electricity Generation	Japan
Hydrocarbon Liquefaction	Japan
Cryogenic Comminution	Japan, South Korea
Liquid CO_2 / Dry Ice	Japan
Refrigeration / Cold Storage	Japan, South Korea
Seawater Desalination	United States
Gas Turbine inlet cooling	India, Japan

More detailed applications of CULNG are discussed in the following sections.

2.1 Power Generation

Power can be generated effectively by utilizing the potential of cold energy [30]. The CULNG application for power generation has been most famous for decades. Hence, systems that utilize cold energy for power generation are getting developed across nations. The main advantages of power generation using cold energy are [122].

1) While the cold energy of LNG is comprehensively utilized, its economic advantages are also promoted.

2) As no fuel is burned to produce energy, the process of power generation becomes eco-friendly. Also, the LNG does not come in association with any inflammable gases.

3) The electricity generated using LNG cold energy can be utilized effectively by receiving terminals, as each terminal uses 40–50 kW of energy.

4) The amount of electricity production can be increased as the capacity of electricity generation changes with a change in the consumption of natural gas in downstream receiving terminals.

2.1.1 Methods of Power Generation by CULNG

Power generation through CULNG follows three major theoretical frameworks. The first method uses a direct expansion cycle (DEC), while the second method uses cycles like the organic rankine cycle (ORC), Bryton cycle, and Kalina cycle [33]. The third method is a combination of ORC and DEC. In the first technique, LNG is vaporized directly into gaseous form. The gas is passed through turbines to recover pressure energy, also known as exergy. The second method uses refrigerants like ammonia-water and propane, which are cooled by LNG. In the third method, the combination of ORC and DEC improves efficiency [123].

In DEC, the liquid natural gas is first compressed to high pressure, followed by heating and regasification, as shown in **Figure 2.2**. The gas produced through regasification is used to run the turbine generator. After passing through the expansion system, the gases are reheated to reach the surrounding temperature. This cycle is the most inefficient method of all cycles [124].

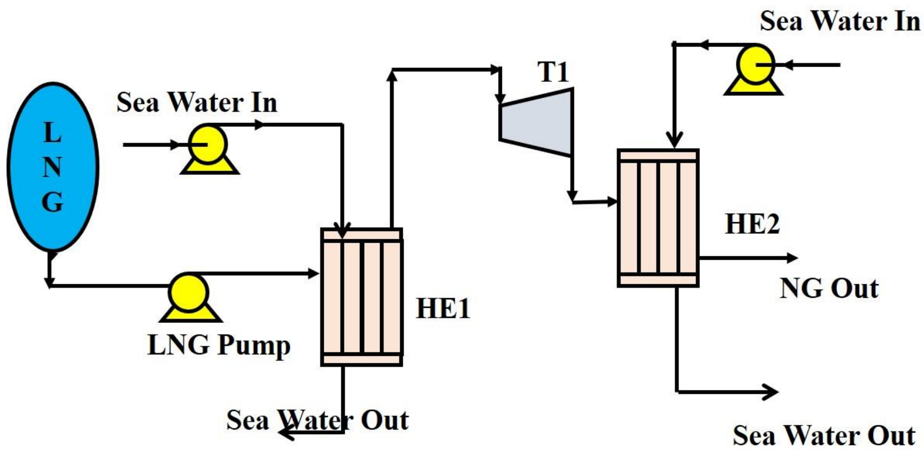

Figure 2.2: Direct Expansion Cycle

Figure 2.3 shows the organic rankine cycle, which has two stages. LNG and working fluids are in stages 1 and 2, respectively. In later stages, the working fluid enters the pump, where it is pressurized to the operating pressure of the vaporizer. The working fluid is heated by the heating medium in the vaporizer. The vapor produced is expanded in the expander turbine to generate power. Following this, the vapors are cooled in the condenser evaporation using cryogenic LNG, and the cycle is completed [125].

A schematic diagram of the combined DEC-ORC is represented in **Figure 2.4**. The stages for LNG and working fluids are connected to a condenser. The LNG turbine pressurizes the LNG to a greater pressure than the LNG pump. The energy output from combined cycles is greater than that from individual ORC and DRC cycles [126] .

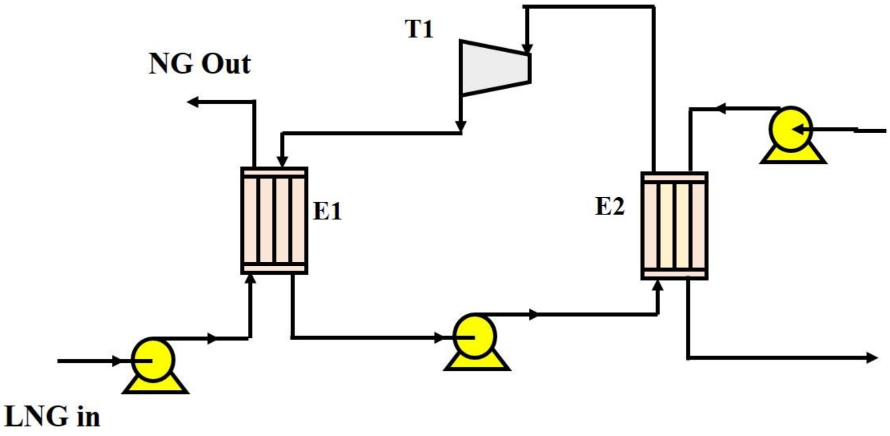

Figure 2.3: Organic Rankine Cycle

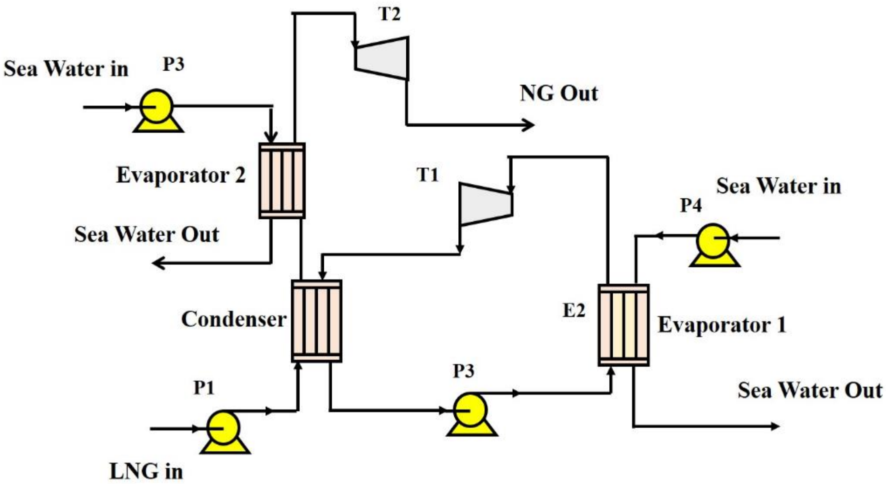

Figure 2.4: Combined Cycle

The Brayton cycle utilizes the thermal exergy possessed by LNG for cooling gases in the compressor, which causes a drop in the work required for compression because the compressor is related to the gas's specific volume. Kalina developed a kind of power cycle utilizing working fluids with different vaporization temperatures [127]. The Kalina cycle had greater efficiency due to greater energy utilization as compared to the RC. It is because of the closeness of the temperature profile of the mixture to the heat source temperature. Nevertheless, the Kalina cycle functions by utilizing waste heat at high temperatures, such as that released from flue gas from the turbines. Also, the efficiency of the cycle is limited because of the lower pressure ratio across the turbines. In the Kalina cycle, the LNG's cold energy is utilized to condense the ammonia at the turbine outlet and cool the absorber [128].

The CULNG can be used in the Sterling cycle as well. The primary determinants of the Stirling cycle method’s generating capacity and cryogenic generation efficiency are LNG vaporization pressure, LNG mass flow rate, and heat source temperature. Utilizing a high-temperature heat source, such as exhaust gas, and controlling the LNG evaporation pressure and mass flow rate in an appropriate range would improve the performance of the fundamental process [129].

Thermodynamics of potential of cold energy can be explained by **Table 2 2.** The liquefaction process consumes 2900 kJ/kg, with approximately 2070 kJ/kg wasted as heat. The remaining "cold energy" (830 kJ/kg) is kept in the LNG. Theoretically, regasifying LNG to an ambient temperature of 15°C can recover approximately 830 kJ per kg of LNG from the liquefaction process. Natural gas output pressure from LNG vaporizing terminals varies based on pipeline needs. The ultimate pressure ranges from 25-30 bar for integrated cycle stations to 60-80 bar for long-distance distribution. Table 2 2 provides an estimated maximum available power based on distribution needs [124].

Table 2-2 : Required pressure for a variety of NG applications, as well as accompanying theoretical work [124]

Use	Pressure (bar)	Temeprature (°C)	h (kJ/kg)
LNG reference condition	1.013	-161.5	-286.50
Environmental Conditions	1.013	15	601.20
Combined cycle power plant	27	15	573.40
Local Disrtibution	35	15	525.50
Long distance pipeline	70	15	442.80

There are growing appeals for combined cycles and multistage cycles. There have been numerous studies to investigate and develop systems to run on cold energy. Also, there has been a comparison between the efficiencies of the proposed methods. Some of the most popular proposals are summarized below.

Shi et al. gave an idea to increase the work output of conventional cycles. The proposal suggested utilizing integrated thermal power plants, which are advanced. Using this method, the net electrical efficiency and overall performance increased by 2.8% and 76.8 MW, respectively. While 0.9 MW of electrical power was saved, the system delivered 75.8 kg/s of natural gas. The use of these previously eliminated the need for seawater pumps. However, the suggested technique is sensitive to the surrounding temperature, which is not evident in the conventional cycles [130].

Zhang et al. suggested that three processes: single-stage expansion, single-stage expansion with recycling of gases, and multi-stage expansion with recycling of gas could be used to utilize the LNG's cold energy. A comparison of the energy produced using three systems was made for the same initial conditions. While the multistage model had an efficiency of 28.7% in saving energy, the single-stage model with and without gas recycling had an efficiency of 20.1% and 19.1%, respectively. Even if the efficiency of the multistage model is high, the setup of this model is complex. Therefore, single-stage expansion is proposed for small power generation and multistage gas recycling models in large-scale power generation systems [131].

A proposal for a power plant containing a RC)and a closed Brayton cycle (CBC) was given by Gomez et al. The model utilizes LNG to cool the CBC compressor section. In this study, the best working fluids used in the proposed model were also identified, along with their operating conditions. While RC worked best with carbon dioxide, ammonia, water, and ethanol, helium and nitrogen were considered the best working fluids for the Brayton cycle. The comparison among the different working fluids highlighted that the CBC running on helium gas and carbon dioxide for the RC gave maximum efficiency to the proposed system. A thermal efficiency of 67.6 % and an overall efficiency of 55.13 % were achieved with a specific power of 2.465 MW/Kgs of LNG [132].

Many researchers have given suggestions for producing power using integrated systems.

The efficiency of a gas turbine plant working on a combined cycle gas turbine (CCGT) was examined by Stradio et al. The cold energy produced during the regasification process was utilized in the cycle. Natural gas was supplied to adjacent CCGT plants from LNG import terminals. The study emphasized integrating, proposing, and simulating two systems working on LNG cold energy. System one requires heat exchange between LNG and the Brayton cycle air intake. The second cycle added a condenser working on the Rankine cycle to the first system to increase the recovery of heat. Both systems rejected heat from CCGT at the lower temperature. The electrical efficiency is increased to 6.32% and 9.09%, respectively, for both systems [132]. Zao et al. investigated power generation by applying a thermoelectric semiconductor to an LNG vaporizer. The study involved designing a special, unique tube that was incorporated in the power generation system. Upon comparison, it was found that the results from an air gasification tube are 15.8% less efficient than a flue gas designed tube. The system is 3.48% more efficient in generating power. The outside length of the thermoelectric power generation device is maintained at 42°C ambient temperature. The increase in output was 3.24 times [133]. Ma et al. examined a five-stage rankine cycle system to determine the variables that affected the system. In conclusion, it was discovered that a grading model might significantly enhance the use of cold energy. Improvements in cold energy use were accompanied by increases in the energy recovery rate (ERR) and net power gain (NPG). Comparing the recovery rate to a single-stage Rankine cycle revealed an increase of 35.47 %. Also, the net power gain and cold energy utilisation have increased to 281.7% and 19.5%, respectively. Effective reductions in the cold energy losses were made [134]. A system involving cold and power generation based on the energy of cryogenic LNG was proposed by Li et al. Ammonia water is utilized as a working fluid in the cycle. Ammonia and natural gas were heated in a low-temperature heat source, and these two were expanded. Simulation of the system showed good thermal performance. The higher exergy efficiency of 36.1% was indicated. The key parameters affecting the power generation were analyzed by sensitivity analysis [135]. The study to optimize the net power output using different combinations of single and two-stage Rankine cycles was carried out by Bao et al. In this study, eight different combinations of single and double-stage Rankine cycles were proposed. The combinations involved series and parallel arrangements. In conclusion, it was found that the increase in vaporization pressure decreased the net power output. The working fluids in this cycle are R41/R14 [136]. An LNG regasification power plant with liquid air energy storage (LAES) was proposed by Qi et al. The proposal has several pros, like increased operational profits and increased power generation, yet issues regarding flexibility and safety are present. The regasification is carried out using two approaches. In the first approach, LNG is passed through a two-stage Rankine cycle. The second approach involved a transfer of high-grade LNG cold energy to LAES. The pressure is minimized to 0.15 MPa in storage vessels. LNG-LAES method is found to be the best system to generate power according to market analysis. The increase in power generation is 94.8 KJ/kg using this system. The round-trip electrical efficiency of the system is is very high as compared to conventional. In order to make the system technically and commercially acceptable for industrial usage, the amount of cold energy utilization in LNG can be fixed while designing [137]. Tianbiao He et al. performed the analysis of cooling and heating source properties and working fluid selection for the ORC. The effects of LNG vaporization pressure, seawater temperature, and a minimum temperature approach on performance were studied. This study is performed for nine different working fluids; out of the nine, the working fluid R-1270 has the highest net power output and exergy efficiency of 18.96%. The study also found a significant increase in net power output, thermal efficiency, and exergy efficiency while using a binary mixture of R-1270 and Ethane [138]. Alam cycle power plant with CO_2 capture integrated with LNG cold utilization by Haoshui Yu et al. They studied the best way to integrate LNG cold utilization into an Allam cycle power plant and found that for a standalone power generation cycle, the cold energy of LNG was used to liquefy the captured flue gas. It is noted that integration of the ORC had only a marginal increase in exergy efficiency, which in terms increases the capital cost, but in a co-generative system with an increase in LNG input, the ORC has a significant benefit with a 10.45% increase in exergy efficiency of 10.45 % [139].

The power generation using CULNG is summarized in **Table 2-3**

Table 2-3: Summary of investigation of power generation from CULNG by different Researchers.

Sr.No	Researcher	Method	Investigation/ Result
1	Shi et al. (2010) [49]	Integrated thermal power system which is advanced was analyzed	The efficiency of the system increased to 2.8 %.
2	Zhang et al. (2012) [140]	Three processes involving single-stage expansion, single and multistage expansion with gas recycling were compared	The efficiency of the three systems were 19.1 %, 20.1 %, 28.7 % respectively
3	Gomez et al. (2014) [141]	This approach studied combination of Brayton Cycle and Rankine Cycle	Maximum efficiency was recovered for using Helium gas in CBC and CO2 for the RC. Thermal efficiency of 67.60 % and 55.13 % overall efficiency with a specific power of 2.465 $(MW(kg.s)^{-1})$ LNG was achieved
4	Wang et al. (2014) [131]	Integrated carbon dioxide cycle with geothermal resources.	Exergy efficiency maximized with greater CO_2 turbine inlet temperature or a lower back-pressure with a reduction in the heat exchange area.
5	Stradio et al. (2015) [132]	The energy utilization was proposed through a combined-cycle gas turbine plant	This approach increased the electrical efficiency to 6.32 %.

6	Xue et al.(2017) [142]	The proposal involved analysis of a double and three-stage Rankine cycle followed by their optimization.	Thermal and exergy efficiencies were increased to 17.33 % and 25.7 % with the help of optimization
7	Ma et al.(2018) [143]	This approach studied multistage Rankine system (MSRC) containing 5 stages	The energy recovery, net power gain along with exergy and cold energy utilization were increased using the system..
8	Pattanayak and Padhi(2018) [144]	The proposal analyzed a combined Cycle Power Plant using triple pressure system	The system showed an increment of 2.2 % exergy efficiency as compared to the standard conditions
9	Le et al.(2019) [94]	An absorption regeneration cycle was proposed.	The exergy efficiency for the model was 36.1 %.
10	Bao et al.(2019)[145]	Different (8) combination (in series and parallel) method were studied	At a vaporization of 3.0 MPa to 7.0 MPa, there is highest power output. The working fluid in this cycle is R41/R143.
11	Qi et al. (2020) [137]	The proposal studied combination of LAES and LNG regasification process	LNG-LAES method is found to be the best system to generate power with increment of power generation to 94.8 KJ/kg.
12	Tianbiao He et al. (2021) [138]	Cryogenic ORC cooling and heating source properties as well as working fluid selection	Significant increase in net power output, exergy efficiency, and thermal efficiency while using binary mixture of R-1270 and Ethane

2.1.2 Selection of Working Fluid for RC

One of the most important steps in developing RC power generation cycles is selecting the working fluid. Several aspects need to be considered for selection: ozone depletion, the global warming effect, safety, the critical temperature and pressure of a working fluid, environmental sustainability, and thermal stability. In addition, the working fluid must be non-toxic, non-flammable, and non-corrosive. Hydrochlorofluorocarbon (HCFC) and chlorofluorocarbons have not been considered due to environmental constraints. H. Yu et al. [66] reviewed the literature and addressed criteria for working fluid selection for ORC with CULNG. Their analysis showed that the condensation temperature of working fluids had a great impact on the performance of power cycles. It should be significantly lower than the ambient temperature. However, the configuration of the cycle and the pressure of natural gas are also important for the selection of working fluids. They compared 22 working fluids using a simulation-based optimization strategy below and across ambient temperature. Below ambient temperature, the most energy-efficient working fluids were R125, R143a, R290, and R1270, and across ambient temperature, R170, R134a, and R290 gave maximum energy efficiency [146].

The following section describes the application of CULNG in air separation.

2.2 Air Separation

Various technologies, like adsorption, distillation, or membranes, can be used for the separation of air. Cryogenic air separation should be the primary choice if the requirement for a high-purity product is in large volumes [67]. In a cryogenic ASU, the feed air is compressed with the removal of contaminants in the first stage. These contaminants include water, other hydrocarbons, and carbon dioxide. The resulting mixture produced consists of oxygen, nitrogen, argon, and traces of some noble gases. The next stage involves cooling the cleaned air to low temperatures in the main heat exchanger (MHX) and feeding it into the distillation unit. The air is separated into oxygen and nitrogen inside the distillation column. A stream of argon gas is also sometimes produced. The product streams are recycled through the MHX. Produced gases are compressed to pressures that are required by consumers for the ASU [147].

There are many industrial applications for the constituents of air. Therefore, ASU has become an important process in many industries. Prominent constituents of air are used for several processes, including oxygen, nitrogen, and argon. Oxygen is used in the medical industry. In other industries such as metal refining, glass manufacturing, ammonia production, and oxy-fuel combustion, oxygen is used on a large scale. Oxygen is also utilized for power generation through the use of an IGCC. Nitrogen is used in large-scale applications for the petroleum and chemical industries. It is currently considered a carrier of energy. Nitrogen is also used in the metal and electronics industries because of its inert nature. Argon finds use in welding as an inert shielding gas. It has been used for growing silicon crystals. The light bulb also uses argon gas as its filler gas. A large amount of electricity is consumed by cryogenic air separation plants. Cryogenic separation of air produces various products in both gaseous and liquid states. Intelligent utilization of liquid products can also be a boon to the industry because of their economic value. The operational cost incurred for the separation of gases can be reduced by proper exploitation of the cold energy of LNG [148].

Nakaiwa et al. investigated an energy supply system with high-performance using LNG. Significantly fewer pollutants were emitted, making this a promising eco-friendly energy supply system. The amount and generation are nil due to the use of methane and high purity oxygen. Recycling carbon dioxide as a dilution gas from the flue gas helps to control the combustion temperature. Separation, isolation, and treatment of carbon dioxide from the exhausted gas are easy due to the presence of only CO_2 and water. A cryogenic ASU is used to manufacture high purity oxygen at an economical rate through the utilization of LNG cold energy. 66% of the electric power consumption is reduced compared to the conventional system. However, a reduction in performance efficiency of the system to 10% can be ignored as the system contributes toward environmental preservation [149]. A novel single-column ASU equipped with a heat pump and CULNG was studied by Jieyu et al. Simulation on the Aspen Hysys software was done to verify and conclude the most optimized parameters. A power consumption of 0.281 kWh/kg of the liquid product with a total exergy efficiency of 0.575 was obtained from the simulation. The literature study showed that a saving of 39.1% of energy is achieved in comparison to conventional double-column air separation units. The system efficiency effectively increased due to the utilization of LNG cold energy [150] . Mehrpooya et al. proposed a coal gasification system integrated with a double-column ASU. The system utilizes LNG cold energy recovery for the air separation unit. The trans-critical CO_2 power generation cycle has a shift converter unit, and a cryogenic CO_2 capturing system is present in the system. High-purity oxygen (99.99 %) and nitrogen (99.99 %) were produced using an air separation unit. The specific power demand was 0.11 kWh/kg of pure oxygen. Proper integration of the two distillation columns results in the effective exchange of the latent heat of the high-pressure condenser with the low-pressure reboiler column. The condenser in the trans-critical CO_2 power cycle utilizes the cold energy of the LNG stream produced at the outlet of the ASU. The results indicate a savings of 2301.6 kW of energy and a trans-critical power generation of 14,217.6 kW. The purity gaseous oxygen produced is sent to a coal gasifier for the gasification process. The system requires a power of about 0.10 kWh/kg to capture about 99.83 % of carbon dioxide with high purity [151]. Donghoi K. et al. developed and compared two different novel air separation processes to achieve maximum use of CULNG. In the first configuration, the CULNG was used as an extra refrigerant in the liquid nitrogen production cycle, and in the second configuration, the CULNG was used for precooling air or liquid nitrogen. To evaluate and compare the performance of two configurations, energy and exergy analyses were conducted. The result indicated that specific power consumption was lower in configuration two (0.28 kWh/kg) than in configuration one. Configuration 2 also had higher exergy efficiency because it had improved heat integration, which resulted in smaller temperature differences in heat exchangers [152]. Wu et al. investigated a novel three-column cryogenic ASU combined with CULNG. The results of the simulation specify that, power consumption of liquid nitrogen and liquid oxygen is 0.258 KWh/kg and 0.252 KWh/kg, respectively, which is lower than traditional plants. In addition, the overall exergy efficiency and the CULNG exergy efficiency reach 0.71 and 0.53, respectively [153]. Four external circulation techniques for air separation utilizing CULNG were proposed by Fenghui Han et al. and contrasted with the current air separation systems. These design schemes were proposed for different matching pressures. One of the systems has an energy consumption of 41.1 % less than the existing CULNG–air separation process and 66 % more than the traditional air separation process. These results were concluded by analyzing exergy efficiency, energy consumption, and heat loads at different pressure matching conditions.

Table 2-4 reveals information about research in the area of air separation by using CULNG

Table 2-4: Summary of investigations of air separation plant from CULNG by different Researchers

Sr. No	Researcher	Method	Investigation/ Result
1	Nakaiwa et al. (1996) [149]	Energy supplying system with high-performance ability using LNG for air separation.	66 % of the electric power consumption is reduced.
2	Yongqiang and Ben Hua(2014) [154]	Introduced and simulated air separation process with CULNG	58.2 % energy saved above 6.5 MPa pressure of recycled Nitrogen.
3	Jieyu et al. (2015) [150]	An innovative one column air separation plant by using CULNG	Saving of 39.1 % of energy is achieved in comparison to the conventional double-column air separation units.
4	Mehrpooya et al.(2017)[151]	A coal gasification system integrated with a double-column cryogenic air separation	Saving of 2301.6 kW of energy and trans-critical power generation of 14,217.6 kW
5	Donghoi K.et al.(2018) [79]	Developed and Compared two novel ASU with CULNG	Second configuration had a lower specific power consumption due to improved heat integration.
6	Zhang et al.(2019) [80]	Integrated with light hydrocarbons separation plant	The ratio of CULNG is raised by 35.77 %.
7	Wu et al. (2020) [81]	A novel three column cryogenic ASU combined with CULNG was proposed	The overall and CULNG exergy efficiency risen to 0.7165 and 0.5318, respectively.

8	Fenghui Han et al. (2021) [82]	Proposed four external circulation systems for air separation	One of the systems has energy consumption 41.1 % less than the existing CULNG air separation process

Air separation processes are complex and require high capital investments. One way to overcome these problems is to integrate with other applications [155].

2.3 Desalination

Due to the massive consumption of electricity in the refrigeration system, the freeze desalination method is not much preferred. However, the LNG regasification process generates a large amount of cold energy that can be used as a refrigerant. While gasifying LNG, the two processes of seawater freezing and LNG vaporization can be combined to create freshwater. Therefore, a more economical and environmentally friendly way to produce freshwater from saline water can be through a combination of saline water freezing and LNG vaporization methods. **Figure 2.5** represents the desalination process flow diagram by CULNG [156].

Freezing, washing, and melting are the three steps involved in cryogenic desalination. Pure water is frozen using LNG as a refrigerant at the LNG import terminal. Gravity is then utilized to transfer the ice and salt solution to a washer. Freshwater is utilized by the washer to remove brine. After cleaning, the ice is melted in a melter. Waste heat available in the plant can also be used to melt the ice. A part of the freshwater used for washing the pure ice crystals is recirculated. The efficiency of the desalination process is increased by cooling the saline feed water in a heat exchanger [157].

CULNG employed for clathrate hydrate desalination (ColdEn-HyDesal) was presented by He et al. This process could overcome the limitation of high energy consumption in the traditional

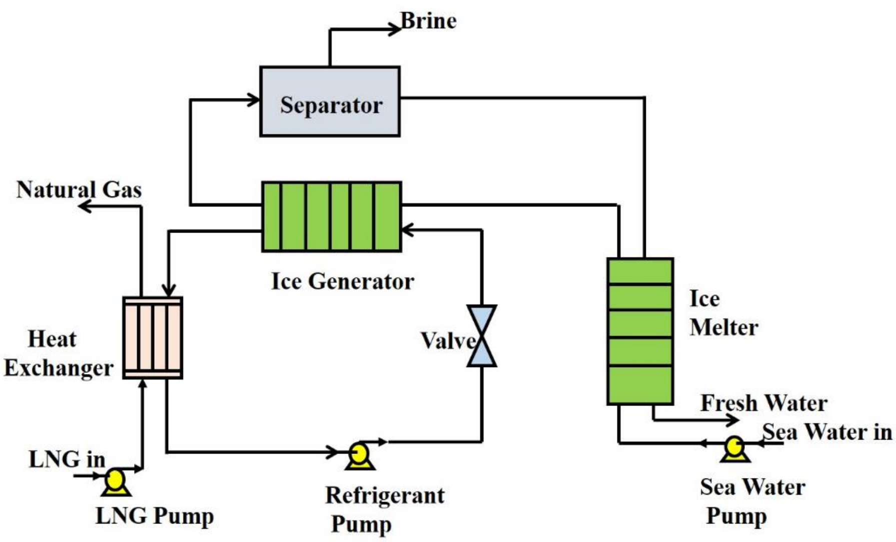

Figure 2.5: Process Flow Diagram of Desalination by CULNG

process. A significant advantage of the novel design was the utilization of cold energy to replace the external refrigeration cycle. A heat exchanger network working under optimum conditions is obtained for the ColdEn-HyDesal process using mathematical programming at a flow rate of 1000 kg/hr in an LNG regasification terminal. The simulation indicated that the specific energy consumption (SEC) is 65.29 and 0.6 of potable water for the HyDesal and ColdEn-HyDesal processes, respectively, when the hydrate is not recycled. If hydrate former is recycled, the SEC for HyDesal and ColdEn-HyDesal processes are 65.13 and 58.7% respectively. The effects of water recovery rate, recovery pressure, and concentration of NaCl in seawater on SEC and the flow rate of potable water were analyzed and discussed. The results suggested a substantial decrease in SEC (27.42%) with an increase from 40 to 70% in water recovery. Further, an increase in NaCl concentration from 3.5 to 7.0 wt% in the feed increases SEC by 2.81%. Therefore, the proposed model can be employed for the efficient desalination process in LNG regasification terminals [158]. Mehdi Salakhi et al. performed analysis of heat and mass transfer and optimization on the double pipe container in the proposed freeze desalination of seawater using CULNG. They integrated the CULNG directly into the system, thus eliminating a secondary refrigerant. In the double-pipe container, the LNG flows in the inner tube and seawater flows in the outer cylinder. Their results displayed that the decrease in LNG temperature from -10°C to -60° C increased the ice mass production by 15 times and increased salinity by 90%. The increase in Reynolds number increased the ice mass production but led to a slight decline in the quality of the ice; on the other hand, the increase in length of the container improved ice mass production and also the ice quality. The system was then optimized to get optimal conditions [159].

2.4 CO_2 Capture

One of the main reasons behind the changes in climate globally is the emission of carbon dioxide (CO_2). CO_2 is primarily produced due to the burning of fossil fuels for power generation. Installation of efficient CO_2 capture techniques in power plants ensures power generation with reduced CO_2 emissions [91]. Also, the CO_2 that is recovered has considerable economic value. For example, oil production from reservoirs that have very low reservoir pressure can be enhanced by the injection of CO_2 gas, which is also known as CO_2 enhanced oil recovery. This is one of the perfect applications of captured CO_2 . Natural gas, also known as NG or LNG, has a clean and simple composition, making it more superior fuel than coal. The two major products obtained after the combustion of natural gas are water and CO_2. Therefore, after water removal, CO_2 can be liquefied very easily. Hence, there will be zero carbon and pollutant emissions [160].

The application of CULNG for power generation ensures CO_2 capture. This is done by condensing CO_2 in flue gas at low temperatures by using CULNG.

Zhang N. et al. proposed a COOLCEP (cool, clean, efficient power) system in which power is produced with CULNG, which has almost zero CO_2 emissions and higher efficiency. They developed two configurations, COOLCEP-S and COOLCEP-C, where the inlet turbine pressure level was different. The effect of important parameters like turbine inlet pressure and backpressure on the system was studied. The result indicated that, the efficiency of the system was 59 % at the turbine inlet temperature of 900°C for the COOLCEP-S system, which was higher than the COOLCEP-C [161]. Xiong Y. et al. examined a novel CO_2 capture gas combined power plant. The combined power cycle plant was designed with an LNG mass flow rate of 159 T/hr. Their simulation results showed that exergy efficiency reached 54.9 % with 90.6 % CO_2 recovery [162] . The carbon capture system using CULNG to the O_2 /H_20 combustion was developed by Yenwen et al.[163]. For this system, a mathematical model was developed to calculate thermal and exergy efficiency. The suggested system was then compared to the COOLCEP technology, which also captures carbon using the cold energy of LNG. The combustion process is carried out under high pressure in this system, with air serving as the medium of circulation. LNG is used in a cascade design to minimize energy usage for oxygen production through air separation and carbon capture. In addition, the system's power generation efficiency is boosted, and it is done at a cheap cost with high carbon dioxide capture. As the intake temperatures of the gas turbine rise, so does the thermal efficiency and energy efficiency. When the circulating water flow rate is 13.5 kmol/sec and the combustion pressure and input temperature of the gas turbine are 1.6 MPa and 1328.1°C, respectively, thermal efficiency and exergy efficiency of 57.9% (at maximum) and 42.7% are achieved. In compared to the COOLCEP system, the combustion system consumes significantly less energy. The thermal and exergy efficiencies were 6.3% and 5.4% higher, respectively, than the COOLCEP system [164]. Wu et al. studied a new power generation system having pure oxygen (NG/O_2) combustion gas and a steam mixture cycle (GSMC). Water is circulated as the turbine's working medium. This system implements efficient power generation with CO_2 capture with the help of the energy possessed by LNG and liquefied oxygen. A detailed analysis of CO_2 capture schemes improves both CO_2 capture and system efficiency. Capturing CO_2 over a wide range can be efficiently carried out by including a reduction of the CO_2 liquefaction enthalpy drop. Cooling energy for CO_2 /moisture separation can be conserved efficiently in this system. Higher condenser outlet temperatures often lead to lower CO_2 capture efficiencies. Different conditions for the turbine inlet, cooling water, and CO_2 liquefaction can be analyzed to determine the optimized conditions. When the turbine has an inlet pressure of 30 MPa at 1000°C and the condenser has an outlet pressure of 18 kPa at 38°C, there is an efficiency drop of 1.18 % for the total CO_2 capture. For this input variable, the CO_2 capture ratio of the original GSMC is less than 60 [160].

2.5 Dry Ice Production

The generation of liquid CO_2 and dry ice using CULNG is one of the most traditional methods. In this method, CO_2 stored at high pressure is cooled and then finally liquefied. LNG's cold energy helps to achieve the temperature needed for cooling and liquefaction of CO_2. As a result, the operating pressure can be reduced considerably using CULNG. The load for power consumption is reduced by 30 to 40 % using LNG. The temperature of the second level of LNG cold energy matched the temperature of dry ice, i.e., -78.5°C. Energy is transferred from LNG to Freon, and then finally to CO_2 . This transfer of cold energy liquefies CO_2 . Then dry ice can be produced by sending it into the machine. Dry ice is produced for a variety of applications, including industrial cleaning, artificial rainfall, and food refrigerant [165].

2.6 Potential Applications of CULNG

The following part of this paper moves on to new areas that have emerged from the cold utilization of LNG.

2.6.1 NGL Recovery

Adsorption, oil absorption, and mechanical refrigeration are currently the leading natural gas liquid (NGL) recovery techniques used in the industry. The conditioning process mainly occurs by using two methods. One method involves operating within a temperature range of 20°C and 30°C. This method is suitable for extracting heavier hydrocarbons apart from ethane and methane [100]. The other method of natural gas conditioning involves operations below 45° C. The process is successful in extracting the heavier hydrocarbon components, along with ethane. However, the process of gas conditioning requires a lot of energy consumption, as the refrigeration cycles operate primarily on electricity. In such conditions, cold energy from LNG can be utilized as a refrigeration medium [166].

2.6.2 Recovery of Light Hydrocarbons

CULNG can also be utilized for the separation of light hydrocarbons like ethane from LNG. A cascade system of CULNG can be carried out through a combined process of air and hydrocarbon separation. This creates a greater economic benefit. Sensitivity analysis can be performed over different temperature ranges of LNG regasification to separate air from light hydrocarbons. Experiments suggest an increase in CULNG efficiency of 35.77%. This method can be miniaturized and installed at LNG terminals [167].

2.6.3 Liquid Air Energy Storage

Liquid Air Energy Storage (LAES) has attracted much attention as a way to shift the load on fossil fuels by employing renewable sources of energy. One of the greatest advantages of LAES is its capability to store a large amount of cold energy and its fast response. The system is also not bound to any geographic locations, making it more advantageous. However, in comparison to other large-scale energy storage technologies, LAES has a lower round-trip efficiency of around 50 %. The amount of compression heat is also excessive in LAES. Integration of LAES and LNG can lead to the usage of much of these energies. The work proposed by She et al. (2019) ensured power production through the usage of compression heat and wasted LNG cold exergy in the Brayton cycle. The integrated model with the LAES had a round trip power production efficiency of around 72%. This proposal ensured a wide application of LAES [168].

2.6.4 Hydrogen Production

Electrolysis is a standard method to produce hydrogen. Electrolysis of water is carried out by passing electricity through it to split water molecules into two hydrogen atoms and an oxygen atom. The latest trend in the electrolysis process utilizes a solid electrolyte membrane for hydrogen production, also known as a proton exchange membrane (PEM). Utilization of this membrane cuts off applications of acidic electrolytes while increasing the lifetime of the process. The amount of hydrogen production can be increased by incorporating CULNG in the conventional electrolysis process. Emadi et al. proposed such a prototype with a geothermal-assisted cooling system for hydrogen production. Along with PEM, the proposal consisted of Sterling, Kalina (KCS-34), and LNG cycles to obtain hydrogen. Geothermal energy acts as the main heat source for the prototype. The renewable thermal energy of the source is passed to the Kallina cycle in the evaporator, which helps in the generation of electricity in the turbine. The working fluid for the Kallina cycle is the ammonia-water mixture, which has a temperature of about 65°C. The sterling cycle is incorporated with the Kalina cycle to produce more electricity. Also, in addition to the two cycles, it is highly preferred to have a cold energy source to achieve greater efficiencies. A cycle containing LNG as a working fluid can fulfil two purposes: as a cold energy source and for LNG re-gasification. The products in the output stream are used as cooling agents in domestic sectors along with electricity generation for PEME [169].

2.6.5 LNG Cold Warehouse

The LNG cold warehouse (LNGCW) system is utilized to a large extent for saving energy. Li et al. proposed a model after analyzing the regasification taking place at different operating pressures. An LNGCW system with three parallel stages was chosen for the work, with R23 acting as the intermediate working fluid. With an operating pressure of 7 MPa, the LNGCW system had 64.75 % of exergy efficiency and a COP of 1.41. Additionally, an increment in COP and exergy efficiency occurred with a rise in LNG regasification pressure. It was also found that subsequent stages were more favorable for the LNGCW system [170].

2.6.6 Agro Food industry

Cold energy usage in the agro-food industry is quite interesting. The food industry utilizes cold energy as a refrigerant. The cold energy can be used for conservation and loops in the cold chain. The requirement for a high amount of mechanical energy increases unavoidably as the temperature decreases. Employing the cold energy of LNG can save considerable energy and benefit the economy while reducing greenhouse gas emissions [171].

2.6.7 Ice Making

The procedure for creating ice is straightforward, easy to maintain, and widely used. The ability to open and close the ice-maker device allows for variable and controllable timing of the ice-making process. This capability also complies with the requirements of discrete manufacturing and makes the ice-maker device suitable for building in urban areas nearby. The use of LNG cold energy in the satellite station for the ice-making business is a realistic and practical approach because the requirements and characteristics of the operating background of the ice-making industry correspond with those of LNG satellite. Yun et al. proposed a novel technology to make ice with CULNG. Refrigerant circulation, LNG vaporization, and ice-making systems were three parts of the process. The refrigerant helped deliver the cold energy to the ice-maker. The design and optimization of the process identified the optimum temperature for ice formation, along with the calculation of power savings. Exergy analysis highlighted the efficiency of energy usage. Vaporization of 1000 Kg/hr of LNG released energy to produce 1.59 t/hr of ice. The change in temperature of the ethylene glycol aqueous solution from -15 to -6°C increased energy efficiency. The novel process saved 112 kW of electricity with a 5.52% of cold exergy efficiency. The technology could be imposed on a skid-mounted setup for flexible operation across different LNG vaporization stations [172].

2.6.8 Boil off Gas Recovery

Boil off gas (BOG) can be efficiently recovered by CULNG. To increase the energy effectiveness of the current system, an ejector-enhance LNG boil-off gas re-liquefaction system is suggested by Tan et al. The new system uses two ejectors to prevent energy loss during the pressured BOG's expansion and to inject some fuel BOG into the compression system. A recuperator is used to recover the cold energy of the BOG that has been removed from the LNG tank. On the basis of the simulation in Aspen HYSYS, the proposed system's performance increase is examined. The SEC is decreased from 0.756 to 0.59 kWh/kg compared to the standard BOG re-liquefaction system, and the coefficient of performance (COP) and energy efficiency can both be raised by 28% in the case of the 4557.6 kg/hr re-liquefaction capacity[173]. Liang Yin et al. proposed a novel BOG treatment process with CULNG; this work was done to improve the existing BOG supply system and re-liquefaction systems in LNG transportation ships. By utilizing the CULNG in a closed air cycle to compress the air to a supercritical state, the energy output after the regasification of liquefied air was used for the re-liquefaction of BOG, thus reducing the energy consumption when compared to existing techniques of BOG re-liquefaction [174].

2.6.9 Cascade System for CULNG

Developing a cascade for the utilization of cold energy can result in extensive economic benefits. Also, there has been a considerable decrease in the cost of LNG cold utilization. The work proposes a novel system for using the CULNG reasonably. The design and simulation of the system are carried out using ASPEN Plus. According to the simulation results, the cascade utilization system is efficient. This system unifies the cryogenic processes of waste rubber comminution, liquid CO_2, dry ice production, and cold storage, as shown in **Figure 2.6**. The cascade system saves much energy and increases the efficiency of LNG cold energy utilization [175].

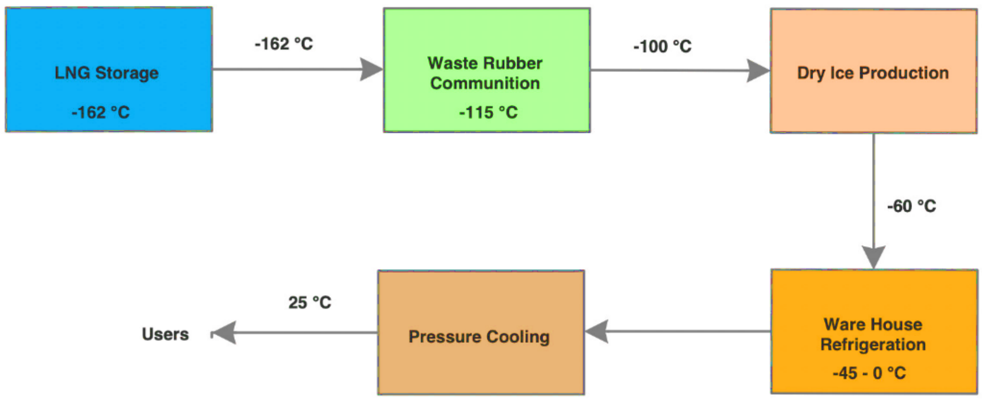

Figure 2.6: Cascade System for CULNG

2.7 Bibliometric Analysis of CULNG

Numerous academics have been interested in the features and benefits of the CULNG, which has sparked a quick rise in the amount of research on this technology. CULNG's promise has not really been realized yet, though. This demonstrates the potential for fresh difficulties in advancing this technology. The current technological level can only be advanced with infrastructure financing for this technology and close collaboration between academia and industry. Bibliometric analysis approaches offer a statistical method that enables the growth and scientific advancement of a given topic to be examined, giving an overall view of current research, and are used to evaluate both the research pattern and the future views on CULNG. Additionally, bibliometric analysis improves research as a mechanism for producing knowledge [176].

As a result, this work studied the trajectory of the scientific investigation involved in the study of CULNG using bibliometric analysis methodologies in order to identify the prospects and the new obstacles to utilizing waste energy through CULNG. In order to enable researchers and industrialists interested in CULNG technology to comprehend the state-of-the-art literature and identify potential hotspots for CULNG research in the future, the results of the bibliometric analysis provided in this study can be helpful.

2.7.1 Methodology

The database Scopus was utilized as a reference in the bibliometric analysis examined in this paper in April 2023. In contrast to other databases like Web of Science, Scopus has a sizable amount of work pertaining to technological topics [177]. The keywords and abstract from the study that dealt with CULNG were used to help build the query, which was based on important terms that were frequently used there. The cold and utilization and LNG were formulated as a query because it is usually used as a key term or keyword in the research papers related to CULNG. Other key terms "cryogenic energy storage" and "waste energy utilization" were not included because they lead to other research papers but were not related to CULNG. The findings were analyzed to determine the distribution of research articles by author, country, institution, journal, and kind of subject. An analysis of the keywords was done to determine. the major themes and critical subjects in relation to CULNG. VOS viewer software was used to assess the relationship between the authors, keywords, and nations, and the results were illustrated graphically. **Figure 2.7** illustrates how the chosen query returned 486 items. It's likely that a small number of documents went unnoticed because keywords lacked critical terms. When the search engine's output from the Scopus database was analyzed, it was discovered that the articles had a strict connection to the CULNG. This confirms that the question was phrased correctly. The outcomes of evaluating all 486 papers are displayed graphically and in charts.

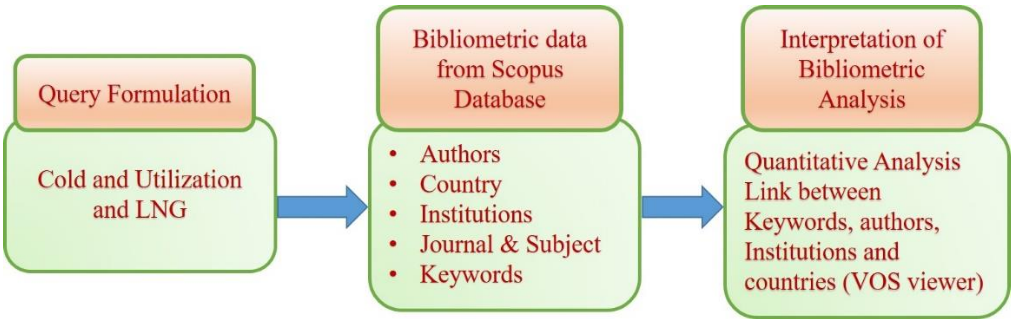

Figure 2.7: Method used for Bibliometric Analysis

2.7.2 Publication Trends

Figure 2.8 illustrates the trend in articles from the Scopus database year over year. The first research paper appears to have been published in 1977. Ushiba K.K. published this study in Proceedings of the American Gas Association [178]. Three more research articles were published in 1978, and twelve more were published in 1984. The research first concentrated on the power generation industry. It is interesting to note that from 1985 to 1993, no research papers were published. One research paper was published in 1994, and three more were seen in 1998. There was no appreciable increase in the quantity of research papers in the CULNG field prior to 2003. This graph demonstrates the increase that has continued since 2003, reaching its first peak in 2004 with 14 publications and then again in 2009 and 2017. Publications have grown more rapidly in recent years. The number of publications reached its peak in 2022 with 63, up from 61 in 2021.

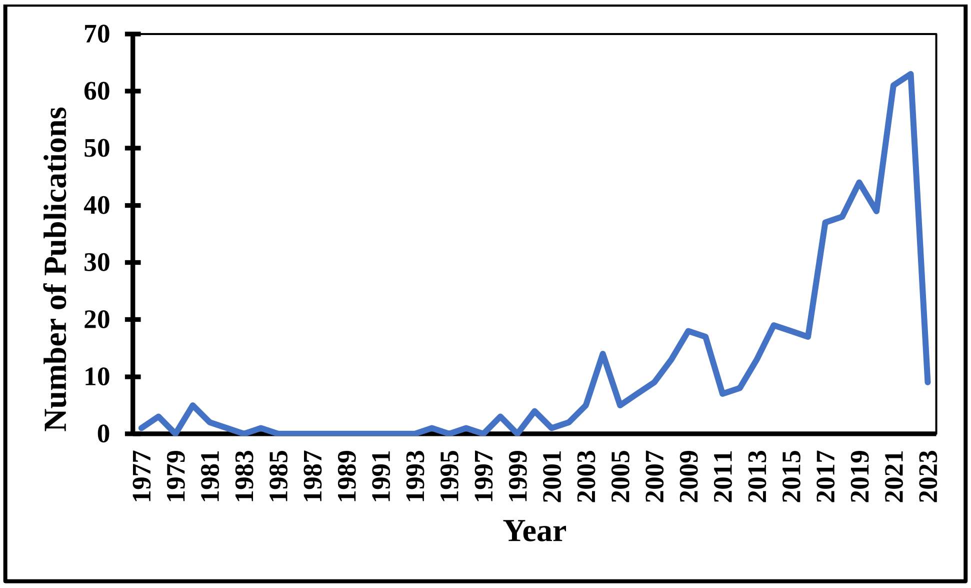

Figure 2.8: Trend of publication from 1977 to 2022

2.7.3 Type of Publications

The publications from the Scopus database are shown in **Figure 2.9**. According to the figure, the majority of publications were classified as articles and conference papers (347 & 115 papers respectively). Review papers, conference reviews, and book chapters only cover a small part of the overall number of published articles.

When a search for the CULNG was made in the Scopus database, a total of 140 journals and proceedings were discovered. The number of articles in journals and proceedings that are restricted to at least 9 documents is shown in **Figure 2.10**. Energy was the journal with the most articles relating to CULNG (43 articles), followed by Energy Conversion & Management (28 publications). Applied Thermal Engineering (21 publications), Natural Gas Industry (16 publications), Applied Energy (15 publications), Huagong Xuebao Ciesc Journal (11 publications), and International Journal of Hydrogen Energy were other journals with a respectable amount of articles (11 publications). the 10 articles that Energy Procedia published. 9 publications were published in the international journal of energy research, Journal of Cleaner Production, and Kung Cheng Je Wu Li Hsueh Pao Journal of Engineering Thermophysics.

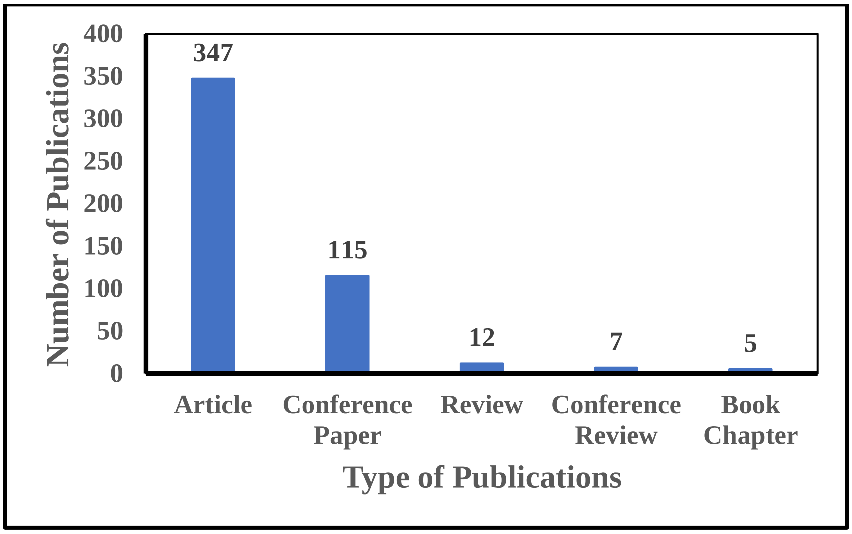

Figure 2.9: Type of Publications

The journals and proceedings with at least two articles are shown in **Table 2-5**, along with their primary characteristics. The majority of publications were not open access and were published in reputable journals (Q1). The lowest category (Q4) belonged to the Huagong Xuebao Ciesc Journal and Kung Cheng JeWu Li Hsueh Pao Journal of Engineering Thermo-physics. Among the other journals included in **Table 2-5**, Energy Conversion & Management had the highest impact factor. It is noteworthy that many papers on CULNG have appeared in conference proceedings, emphasizing the fact that some of the relevant content is accessible in open access form. Only a small number of publications were found in the open access journals (Huagong Xuebao Ciesc Journal) that were not included in the proceedings.

Table 2-5: List & Features of the journals with nine publications minimum

Journal	Number of Publications	Category	Impact Factor (2022-23)	Full Open Access
Energy	43	Q1	8.857	No
Energy Conversion & Management	28	Q1	11.53	No
Applied Thermal Energy	21	Q1	6.465	No
Natural Gas Industry	16	Q2	1.69	Yes
Applied Energy	15	Q1	11.45	No
Huagong Xuebao Ciesc Journal	14	Q4	0.73	Yes
International Journal of Hydrogen Energy	11	Q1	7.139	No
Energy Procedia	10	-	-	Yes
International Journal of Energy Research	9	Q1	5.164	No
Journal Of Cleaner Production	9	Q1	9.29	No
Kung Cheng JeWu Li Hsueh Pao Journal Of Engineering Thermo-physics	9	Q4	0.32	-

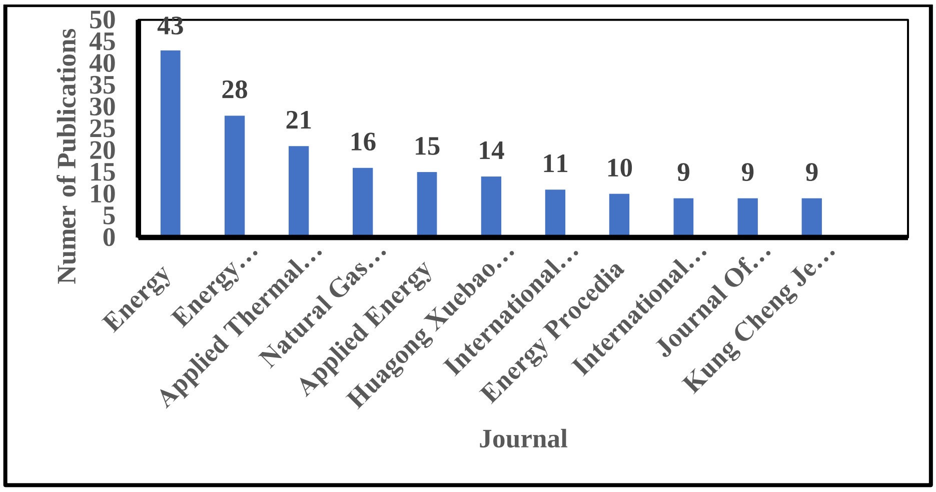

Figure 2.10: Journals with articles in the area of CULNG

Table 2-6: List & Features of the journals with nine publications minimum

Journal	Number of Publications	Category	Impact Factor (2022-23)	Full Open Access
Energy	43	Q1	8.857	No
Energy Conversion & Management	28	Q1	11.53	No
Applied Thermal Energy	21	Q1	6.465	No
Natural Gas Industry	16	Q2	1.69	Yes
Applied Energy	15	Q1	11.45	No
Huagong Xuebao Ciesc Journal	14	Q4	0.73	Yes
International Journal of Hydrogen Energy	11	Q1	7.139	No

Energy Procedia	10	-	-	Yes
International Journal of Energy Research	9	Q1	5.164	No
Journal Of Cleaner Production	9	Q1	9.29	No
Kung Cheng JeWu Li Hsueh Pao Journal Of Engineering Thermo-physics	9	Q4	0.32	-

Information from the Scopus database is shown in Figure 16, regarding the number of publications in various subject categories. More than 50% of publications are published in the primary topic areas of energy and engineering. Environmental science (108) and chemical engineering (108) make up a sizable part as well. Earth and planetary sciences (41 each) and chemistry (102), which made up a small percentage.

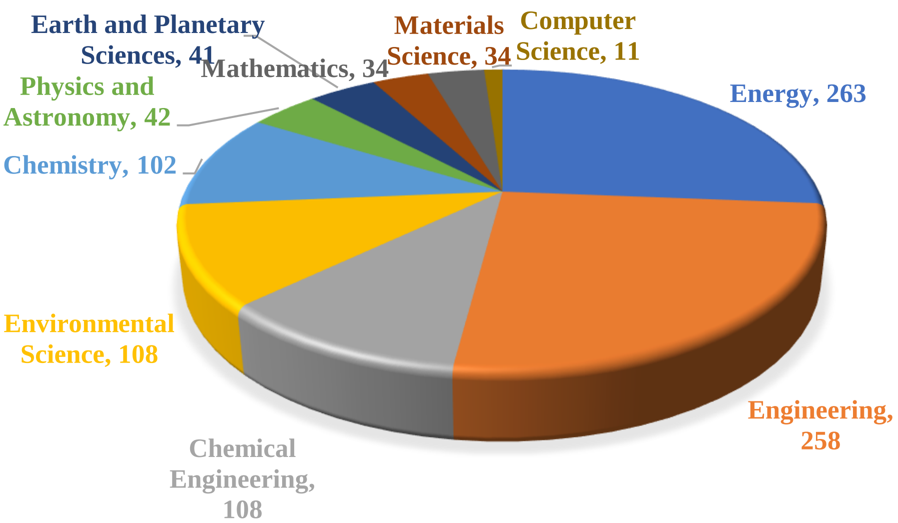

Figure 2.11:Number of publications in the different subject areas

2.7.4 Distribution of publications by Institutions

As was previously mentioned, the first paper on CULNG was published in 1977 in the American Gas Association sessions. Less than ten publications were released annually up until 2003. Finding the institutions of some researchers from 1977 to 2003 can be challenging. The top 10 institutions with the most documents published in the field of CULNG are shown in **Figure 2.12**. We can observe from this number that universities make up the majority of the institutions. The Ministry of Education of China is the best institution, nevertheless. It is significant to note that the Chinese Ministry of Education issued 31 research papers between 2010 and 2023.

The top ten institutes with their respective nations that have produced the most research articles in the field of CULNG are listed in. It's noteworthy to observe that China and Singapore have two of the top ten institutes. Some institutions may not be on the list because they may have searched for a different term than "Cold LNG Utilization".

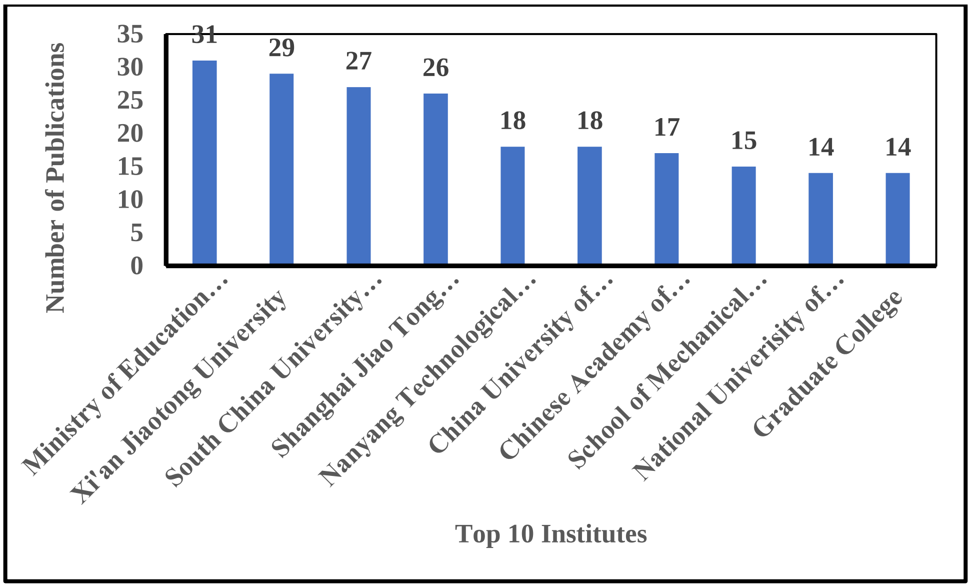

Figure 2.12: Publications in top 10 Institute

Table 2-7: List of the institutions and their associated nations

Affiliations	Countries	Publications
Ministry of Education China	China	31
Xi'an Jiaotong University	China	29
South China University of Technology	China	27
Shanghai Jiao Tong University	China	26
Nanyang Technological University	Singapore	18
China University of Petroleum East	China	18
Chinese Academy of Sciences	China	17
School of Mechanical and Aerospace Engineering	Singapore	15
National University of Singapore	Singapore	14
Graduate College	Singapore	14

2.7.5 Distribution of Countries

The quantity of publications for various nations is shown in **Figure 2.13**. It's interesting that China has published more research papers than any other country (270), accounting for more than half of all publications (486). The figure also shows that Singapore is the third country (with 30 publications) and South Korea is the second (29 publications). Singapore is a smaller nation with a higher concentration of publications, as can be seen. In the CULNG field, the

United States published 27 research publications, whereas the other countries on the list only produced less than 20 documents.

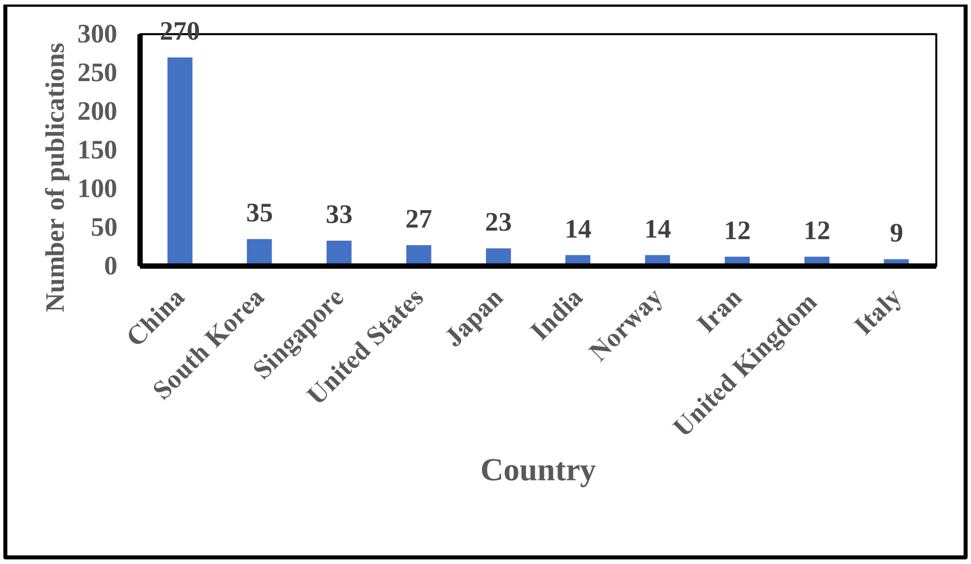

Figure 2.13: Publications for top 10 countries

2.7.6 Bibliometric Analysis by using VOS viewer software

A software programme for creating and visualizing bibliometric networks is called VOSviewer. The Centre for Science and Technology Studies (CWTS) at Leiden University in the Netherlands, led by Nees Jan van Eck and Ludo Waltman, created it. This software programme, which you may download for free, is frequently used for bibliometric analysis. Analysis of big bibliographic databases, selection of the most pertinent articles, and relationship visualization are the main tasks of VOSviewer. Co-citation networks, bibliographic coupling networks, and bibliographic networks can all be created using the software. The bibliographic networks assist scholars in comprehending the organization of research areas and the connections between various articles.

The network can be viewed using a variety of layouts, including circular, grid, and global maps, using VOSviewer. It also provides a variety of clustering methods, like as density-based clustering, hierarchical clustering, and k-means clustering, which aid academics in locating collections of similar articles. Analysis and visualization of citation data is one of VOSviewer's key capabilities. Citation maps, which display the links between citations in various papers, can be produced by the software. Citation maps assist scholars in locating significant papers as well as the contributions of various researchers and research organizations in a certain topic. Co-authorship networks can also be analyzed and displayed using VOSviewer. Co-authorship networks display the connections and partnerships between various writers. Additionally, the software allows for the analysis and visualization of keywords and journals. Numerous disciplines, including scientometrics, the social sciences, and computer science, have made extensive use of VOSviewer. Over 1,000 scholarly papers have referenced the software, highlighting its significance in the bibliometrics community.

2.7.6.1 Network of different countries

The outcomes of using the software VOSviewer to expand on the data from Scopus are shown in **Figure 2.14**. The chart, in particular, highlights the connections between different countries and their co-authorship relationships on published works. This graph demonstrates the large number of countries that were unconnected to one another. As we have already discussed, China has published over fifty percent of all research articles and has close ties with numerous other countries. It is represented as a blue cluster. The red and purple cluster represent the several countries that Singapore as well as the United Kingdom are connected to. For CULNG study, some countries only have a single connection to another. For example, there exist ties between Poland and the UK, Japan and China, and Iran. Norway enjoys relations with both China and the US.

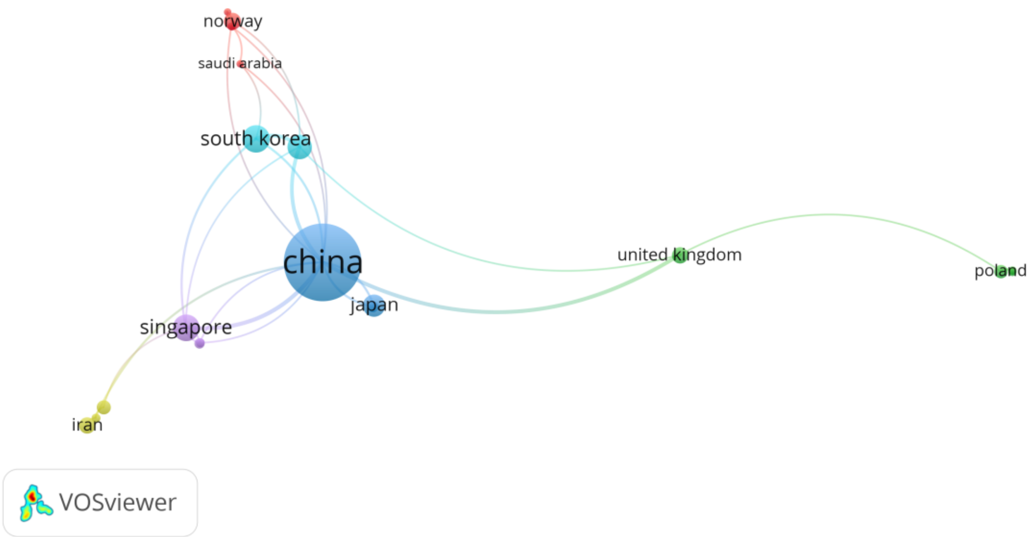

Figure 2.14: Network of the countries elaborated with VOSviewer

2.7.6.2 Analysis of Authorship

The top 10 authors of research publications in the topic of CULNG are shown in of the Scopus database. A closer examination of the data reveals that China and Singapore are the countries with the most researchers. The eighth-ranked researcher, T. Gundersen, is affiliated **Table 2-8** with Norway's Norwegian University of Science and Technology and has ten published research articles. Hua, B., is ranked first with 16 research papers, followed by Duan, F., with 13 papers. Although they have published 13 research publications, Duan F., Dubey S., and Kanbur B.B. have a distinct h-index. Authors with the same number of publications are ranked using the h-index. This table is significant due to the affiliation of Zhang N. & Lee I. with the same organization. Their H-index and overall quantity of research articles are also the same.

Data from Scopus was enhanced using the programme VOSviewer to demonstrate a connection between authors for at least two papers, as shown in **Figure 2.15**. As observed from this figure, there are four major clusters. The first cluster, indicated by the red cluster, has authors who are connected to Li Y from the South China University of Technology. The strongest connections are with Wang S., Zhang Y., Tan H., and Yang J. Blue is used to indicate the second cluster, which includes writers connected to Hua B from the South China University of China. The strongest connections are with Xiong Y., Jia D., and Xue D. The third cluster is indicated by the colour brown and consists of Zhang N. from the Chinese Academy of Science, Song C., Bao J., Lior N., and Zhang R. Authors associated with Zhang Z. from Xi'an Jiaotong University can be found in the fourth cluster, which is indicated by the colour sky blue.

Table 2-8: Details of top 10 Authors from Scopus Database in the area of CULNG

Author	Institution	Country	Publication on the CULNG	Total Documents	H index in Scopus
Hua, B.	South China University of Technology	China	16	230	19
Duan, F.	School of Mechanical and Aerospace Engineering	Singapore	13	195	32
Dubey, S.	Energy Research Institute NTU	Singapore	13	60	18
Kanbur, B.B.	Singapore Centre for 3D Printing	Singapore	13	35	10
Lin, W.	Shanghai Jiao Tong University	China	12	106	15
Gu A.	Shanghai Jiao Tong University	China	11	171	21
Gundersen, T.	Norwegian University of Science And Technology	Norway	10	169	29
Choo, F.H.	Graduate College	Singapore	9	74	26
Lee, I.	University of Chinese Academy of Sciences	China	9	137	25
Yao S.	Jiangsu University of Science and Technology, Zhenjiang	China	9	149	12

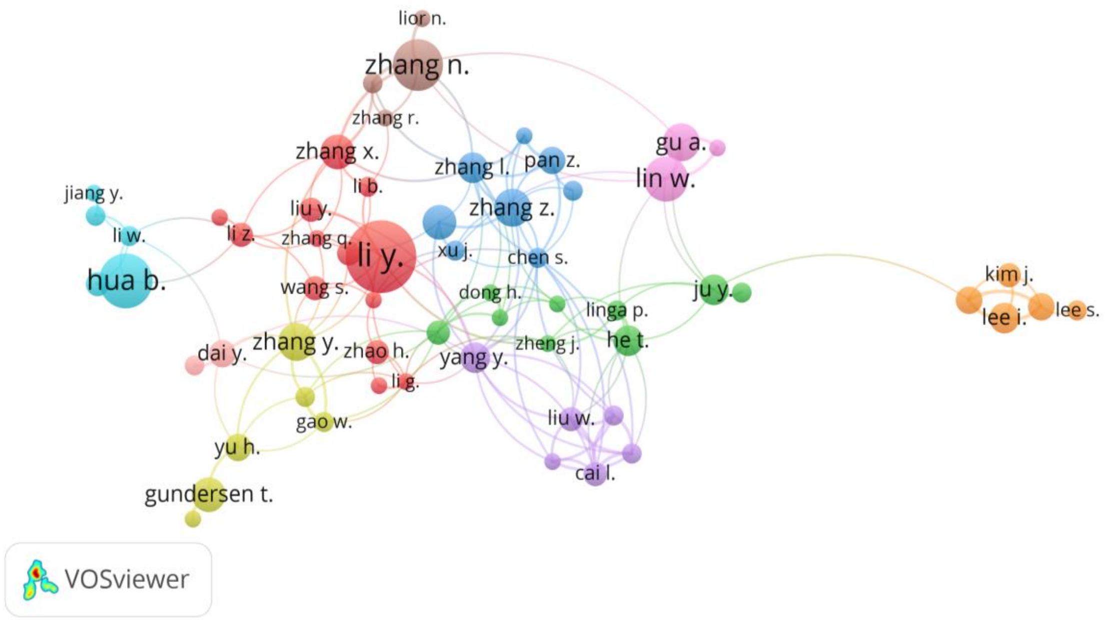

Figure 2.15: Network of Authors elaborated with VOSviewer

2.7.6.3 Analysis of Keywords

Figure 2.16 displays the network of keywords produced by the Vosviewer programme. The keywords are found to be organized into multiple clusters and highlighted in different hues.

When the Vosviewer programme was given a query with at least 5 keyword occurrences, a total of 289 matches were discovered. In particular, there are strong connections between the terms "LNG," "cold energy," "cold energy usage," and "exergy". This shows that these keywords are used most frequently by researchers. It links to "liquefied natural gas," "air separation," "waste heat recovery" and "exergy" when "cold energy utilization" is underlined.

As we have demonstrated in the aforementioned sections, the approaches of exergy analysis and thermodynamic analysis are most commonly utilized in the study of CULNG. Indeed, the researchers' main objectives are to boost thermodynamic and exergy efficiency. Numerous keywords have been related to the phrase "Multiobjective Optimization". This shows that the multiobjective optimization is heavily used for optimization in the CULNG field. It is observed that also observed that the terms "desalination," "organic Rankine cycle," "combined power cycle," and "carbon capture" are frequently used, all of which are CULNG uses.

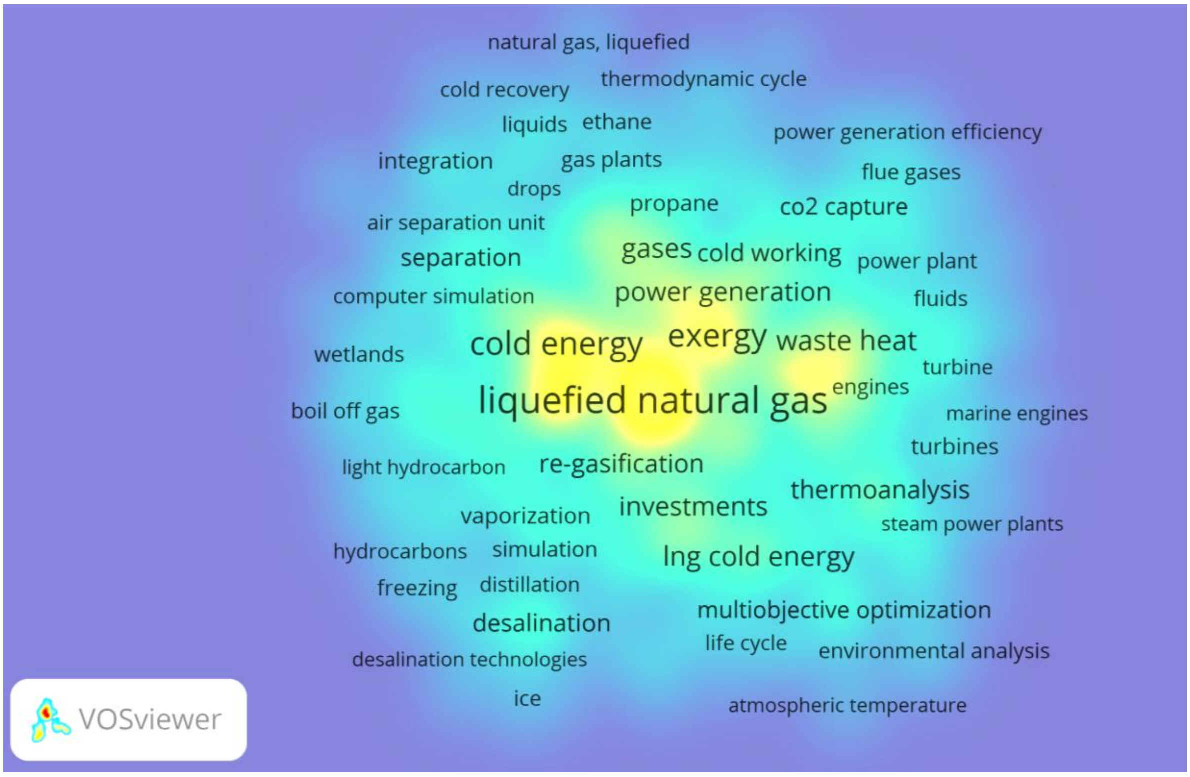

Figure 2.16: Network of keywords elaborated with VOSviewer

2.7.6.4 Citation Analysis of Publications

Citation analysis is a technique for assessing the significance and influence of research by looking at how frequently it has been referenced by other scholars. When using VOSviewer to analyze citation data for sources, data on the total number of citations each source has received as well as the total number of co-citations (i.e., the total number of times two sources are cited simultaneously in the same paper) are analyzed. The relationships between the sources in the network can be mapped out using this data and VOSviewer's network visualization features. Citation analysis for sources used in the CULNG research is shown in **Figure 2.17**. 24 documents out of 172 were received when the query was given the minimal requirements of 5 papers and 2 citations. It is evident that the most significant sources in the field of CULNG are energy, applied thermal energy, energy conversion, and energy management. Some journals, such as, have fewer documents but more citations. In comparison to energy conversion and management, applied thermal energy has fewer documents.

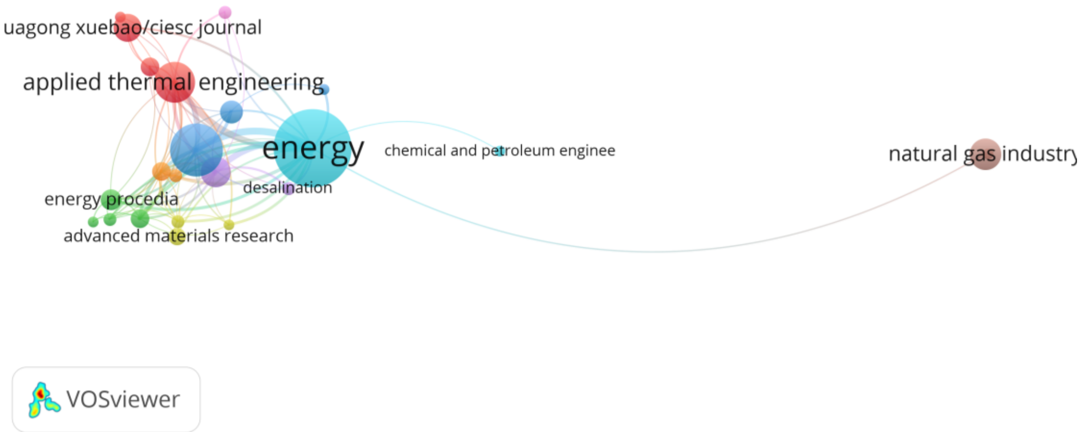

Figure 2.17: Citation Analysis for Sources elaborated with VOSviewer software

Table 2-9: Top 10 cited Journals

No	Journal	Number of Publications	Citations	Total Link strength
1	Energy	43	2047	247
2	Applied Thermal Energy	21	955	115
3	Energy Conversion & Management	28	846	135
4	Applied Energy	15	607	96
5	International Journal of Hydrogen Energy	11	265	23
6	Desalination	06	205	12
7	Journal Of Cleaner Production	9	161	49
8	International Journal of Energy Research	9	151	34
9	Cryogenics	6	117	16
10	Energy Procedia	10	87	31

Table 2-9 lists the top 10 cited journals together with the total number of links. The total link strength in citation analysis is the total number of incoming links or citations that one publication or author receives from other publications or writers. A publication or author's total link strength will increase with the number of citations they earn, showing how well-respected and significant their work is in their industry. Some publications, it can be seen, have fewer citations but stronger links. For example, journal of cleaner production has more link strength than cryogenics.

2.8 Indian Perspective

India is currently the fourth-largest LNG importer in the world. Currently, India imports 42.7 MMTPA of LNG, and by 2030, it is expected to import 83 MMTPA of LNG. To decrease its reliance on polluting fuels like coal and oil, the nation is implementing a number of measures to increase the proportion of natural gas in its energy mix. In order to promote the use of LNG, which is anticipated to be essential in accomplishing this aim, the Indian government has taken a number of actions. Applications for the cold use of LNG in India include air separation, power generation, and sea water desalination. The industry of refrigeration and air conditioning, where LNG is increasingly employed as a refrigerant, is one of the most significant uses. Compared to conventional refrigerants like hydrofluorocarbons (HFCs) and chlorofluorocarbons (CFCs), using LNG as a refrigerant has a number of benefits. LNG is an environmentally favorable choice because it is non-toxic, non-flammable, and has no potential to deplete the ozone layer [179]. In India, the power generation industry is one of the main areas where LNG is used cold. Through a procedure known as liquefied natural gas-fired combined cycle (LNG-CC), LNG can be utilized to produce electricity. In this procedure, a gas turbine that produces energy is fueled using LNG. After that, the gas turbine's exhaust gases are used to heat water, which creates steam, which powers a steam turbine and produces more energy. When compared to conventional power production methods, LNG-CC technology has a number of benefits, including greater efficiency, lower emissions, and cheaper costs.

The rule of thumb states that industrial gas will increase by 1.5 to 2 times GDP, or 12 to 15 percent. To meet the demand for gasoline, the refining capacity needs to be increased in nations like India over the next 20 years. Due to India's recent transition from Bharat IV to Bharat VI, there is a good chance that industrial gas usage and refining capacity would increase. India, which has the fifth-largest coal reserves in the world, is concentrating on coal exploitation to promote the use of this sustainable source of energy [180]. These elements could therefore be considered driving the industrial gas market's expansion. In order to meet the demand for industrial gases, cryogenic air separation using LNG cold energy is the best alternative because it is more effective and uses less power than conventional air separation plants.

For the fishing industry, LNG's cryogenic cold energy can be used. The value of the Indian fishing market in 2019 was Rs 1,233 billion. Six percent of the world's shale production comes from India. As a result, India ranks as one of the world's top producers of fish. India has experienced a rapid rise in both domestic consumption and exports of fish over the last few years. 18% or so of India's harvested fruits and vegetables are lost due to a lack of post-harvest storage facilities. The Food and Agricultural Organization of the UN has estimated that roughly 40% of fresh fruits and vegetables, which cost $8.3 billion, perish in India before reaching consumers. Despite being the second-largest producer of fruits and vegetables, with an annual production of 83 million tonnes of fruits and 121 million tonnes of vegetables, only 2% of it is stored or transported in cold storage facilities, compared to 85% in the US, which results in a 25 million tonne gap between supply and demand.

Desalination plants in India were first started in the state of Tamil Nadu. In 2010 and 2013, desalination facilities were built close to Chennai. Gujarat, Andhra Pradesh, and Maharashtra are three other states with plans to build desalination facilities. There are LNG import terminals in each of these states. Due to the proximity of LNG terminals and desalination plants to the shore, CULNG may be the best option for desalination [179].

2.9 Global Perspective of LNG:

During the first three quarters of 2023, the global supply of liquefied natural gas (LNG) increased by 3% over the previous year, totaling 11 billion cubic meters (bcm). This expansion was mostly driven by the United States and Algeria, who together provided 85% of the extra LNG supply. In the United States, dry natural gas output increased by roughly 5% year on year, totaling over 32 billion cubic meters during the same time. This rise was mostly due to increased associated gas output from oil-driven shale developments. In simple terms, the increase in LNG supply was mostly driven by increasing production in the United States and Algeria, with the United States seeing considerable expansion due to higher output from shale gas extraction connected with oil production operations. Global gas liquefaction capacity in December 2022 was 478.4 MMTPA & global regasification capacity was 970 MMTPA. In addition, Global floating and offshore regasification capacity in April 2023 end was 177.2 MMTPA. There were 668 LNG vessels available for transporting LNG. In As previously discussed, 830 kJ/kg cold energy is available in LNG. Therefore, equivalent power output per ton of LNG is (830*1000/3600) = 230.55 kWh. If LNG cold energy is fully utilized huge amount of power can be produced [179].

Chapter 3: Developing a Novel Process of Integration with CULNG

Air separation processes are complex and highly energy-intensive. In an air separation unit (ASU), the majority of the energy loss happens during air compression. This waste of energy is utilized for heating LNG. An LNG regasification station is where LNG vessels will eventually halt. This research examines a novel ASU design that is combined with LNG's direct expansion cycle (DEC).

3.1 A Novel Air Separation Process Integrated with CULNG

The objective of this research on the cold utilization of LNG integrated with air separation processes is to investigate the feasibility of using the cold energy contained in LNG to partially or fully replace the electrical energy required for air separation processes. The research aims to optimize the design and operation of LNG cold energy utilization systems for air separation, and to assess their potential to reduce energy consumption. This research will examine the potential for improving energy efficiency as well as net power improvement in a cryogenic ASU that used a double-stage air compressor integrated with heat recovery from the compressor discharge that used an LNG vaporization system. In contrast to the traditional system, which uses water as the cooling medium. The study is novel in a way that a performance of an ASU combined with a DEC is analyzed through process simulation in Aspen Hysys (12.1) for a 3993-kW power plant. The results of this investigation show that the specific energies needed for the generation of high purity oxygen and high purity nitrogen are, respectively, 0.10 kWh/kg and 0.32 kWh/kg. Additionally, 3993 kW of energy are saved in the system as a result of an adequate system combination of other subsystems and LNG vaporization. For the system's primary components, exergy destruction and efficiency have been computed. Additionally, sensitivity analysis is performed to investigate the impacts of critical parameters. In conclusion, to provide the required power for operation and eliminate unnecessary power inputs, a cryogenic ASU is coupled with an LNG-DEC power cycle. Overall, the LNG industry should consider integrating air separation processes and LNG as a viable and appealing option. By using fewer fossil fuels, it also increases the sustainability of the process.

3.1.1 General Air Separation Process

The separation of air can be accomplished using a variety of technologies, including distillation, membranes, and adsorption. If significant amounts of a high-purity product are required, cryogenic air separation should be the first option [181]. The feed air is compressed in a cryogenic ASU, and impurities are removed in the first stage. These pollutants include carbon dioxide, water, and other hydrocarbons. The resulting combination contains traces of various noble gases as well as oxygen, nitrogen, and argon. The cleaned air is then fed into the distillation unit after being cooled to low temperatures in the multistream heat exchanger (MHX). In the distillation column, the air is divided into nitrogen and oxygen. Sometimes, argon gas is indeed generated. The MHX is used to recycle the product streams. Produced gases are compressed to the pressures necessary for users' ASU requirements [182]. **Figure 3.1** illustrates the general cryogenic air separation process. The components of air have a wide range of industrial applications. As a result, ASU has emerged as a crucial procedure in numerous sectors. Significant air constituents, including oxygen, nitrogen, and argon, are utilized in a number of processes [183]. As observed, in the medical field, oxygen is used.

Oxy-fuel combustion is widely employed in numerous industries, including the production of ammonia, glass, and metals for refining. Through the utilization of a mixed integrated gasification cycle, oxygen is also used for power generation (IGCC). The petroleum and chemical industries make extensive use of nitrogen. It is currently thought of as a transporter of energy. Nitrogen is also used in the metal and electronics industries since it is inert. Argon is used in welding as an inert shielding gas. This technique has been used to generate silicon crystals. The light bulb also uses argon gas as a filler gas. As per [184], cryogenic air separation facilities need a lot of power.

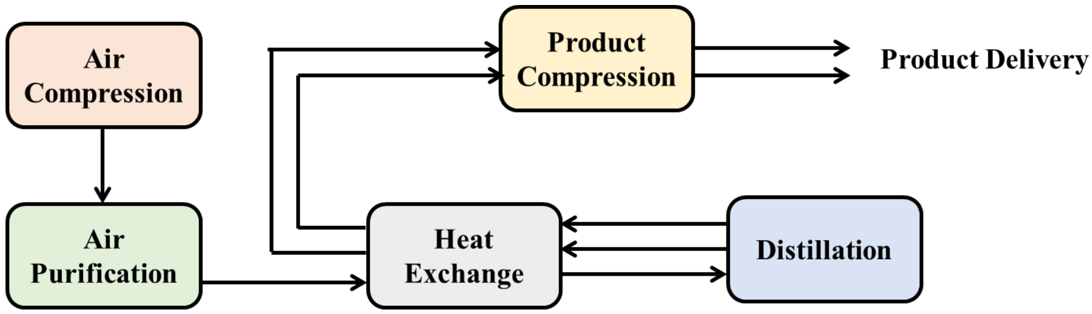

Figure 3.1: General Air Separation Process

3.1.2 Cold Energy Utilization in the Air Separation Process

Plants for cryogenic air separation require a lot of electricity. The cryogenic separation of air results in a variety of gaseous and liquid compounds. Because of their economic worth, the wise use of liquid products can also be beneficial to the sector. By properly utilizing the cold energy of LNG, the practical costs associated with the separation of gases can be decreased [185]. One of the most promising ways to use the cold energy contained in LNG is to incorporate it into the air separation process (ASP) in order to increase the operation's effectiveness. This literature review aims to provide an overview of the recent research on the cold utilization of LNG integrated with the air separation process.

The mathematical model of the procedure is simplified by the following assumptions: Steady-state conditions govern the process' operation. The entire process operates in an adiabatic state. The fluctuations in kinetic and potential energy are neglected. There is hardly any pressure loss inside the heat exchangers. The compressor and pump isentropic efficiencies remain constant at 0.80 and 0.85, respectively.

3.1.3 Industrial Air Separation Process

The term "Air Separation Process" describes a method for dividing air into its constituent gases, notably nitrogen, oxygen, and argon. When these gases are needed in large quantities for industrial applications, this cycle is frequently used. Compression, cooling, and expansion are often included in the cycle of air separation. The procedure makes use of the various components' air boiling points. The gases can be separated depending on their boiling points by first liquefying them in the air at very low temperatures. Through a series of compression, cooling, and distillation phases, the air separation cycle is a complicated process that separates air into its various components, notably nitrogen, oxygen, and argon. It is essential for the production and utilization of these gases in the sectors that need huge amounts of them [186]. **Figure 3.2** is a schematic illustration of depiction of the double-column cryogenic air separation procedure. Two distillation columns that operate under various pressures are used in the procedure [187]. The lower column (HPC) has higher operational pressure than the top column. (LPC). Liquid nitrogen and oxygenated liquid air are present in the lower column. The distillation process uses this liquid nitrogen as reflux. The compressor (C1) compresses the feed air before splitting it into two streams. The product streams in the primary heat exchanger are used to cool a sizeable portion of the compressed input stream (stream 6), which reaches the lower column bottom stage at a temperature close to the dew point (MHX1). After being subsequently compressed in a booster air compressor (C2), the leftover feed stream (Stream 5) undergoes cooling by the primary heat exchanger (HX2). This stream is expanded in the turbine (T) before being used as feedstock at a later period in the top distillation column. (LPC). The turbine's mechanical energy stream is used by the compressor. The lower distillation column HPC produces oxygen-enriched liquid air (stream 18) and high-purity nitrogen (stream 21), while the distillation column LPC creates high-purity nitrogen (stream 11), high-purity oxygen (stream 24), and liquid high-purity oxygen (stream 26).

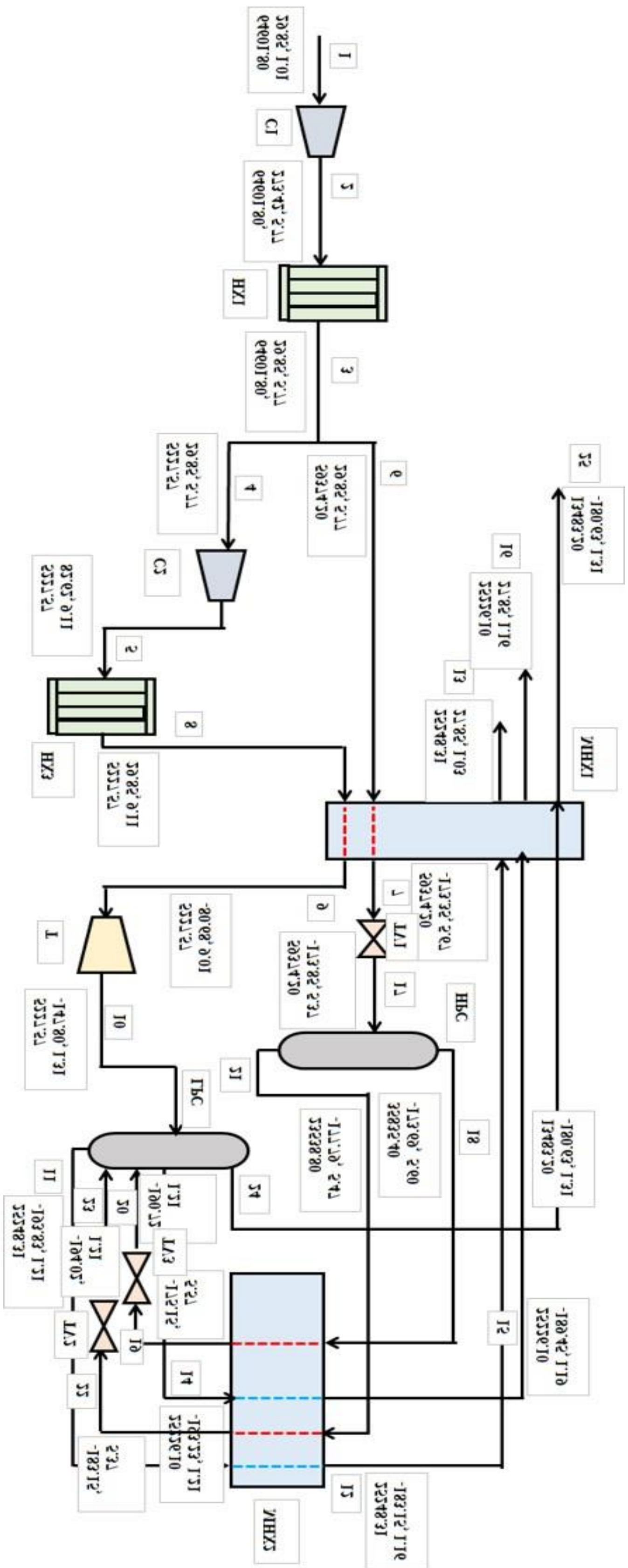

Figure 3.2: Two Column Air Separation Process

3.1.4 Simulation of Direct Expansion Cycle

The term "Direct Expansion Cycle of CULNG" describes a method for using LNG's cold energy for power generation. The simplest configuration for power production is the direct expansion cycle. For small LNG regasification plants that feed low pressure natural gas, the LNG direct expansion cycle is thought to be straightforward and appropriate. However, gasified LNG is typically demanded at supercritical conditions, allowing it to be sent via long distance pipelines and causing the maximum pressure. Its pressure drops to the gas-supplying pressure following expansion in the turbine, which is where power is produced [124].

Figure 3.3 depicts the LNG pump pumping LNG (-161°C and 1.01 bar) to a pressure of 40 bars. It is heated to a temperature of 10 °C in heat exchanger HX1. At this temperature, LNG is undergoing full regasification. The stream is then routed via turbine T1 for power production after regasification. The generated power is 3993 kW. The temperature of the stream is lowered to -87.20°C and the required 5 bar pressure for gas as a result of the gas expanding. As a result, the stream is routed to heat exchanger HX2, where it is kept at room temperature.

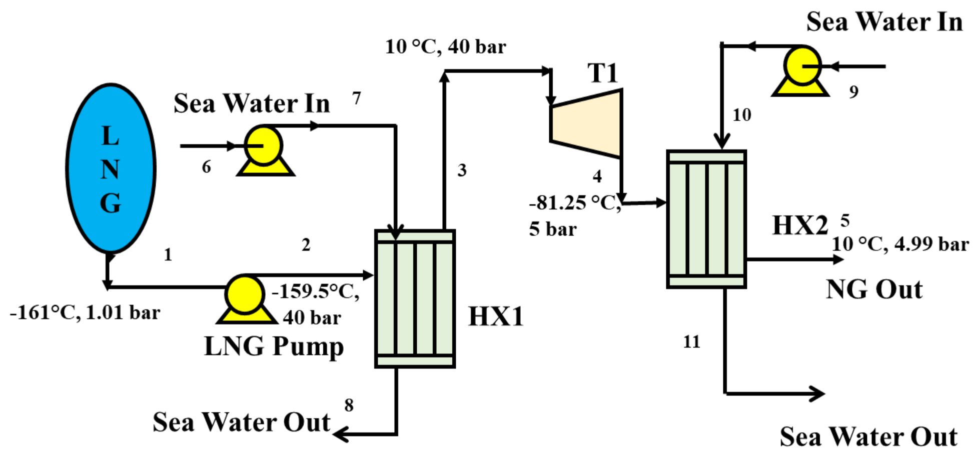

Figure 3.3: Simulation of direct expansion cycle

3.1.5 A novel contribution of this research

In normal cryogenic ASUs, low-grade heat is generated during the air compression process. The heat generated during compression lowers the compressor's efficiency. In order to keep the compressor operating efficiently, cooling is required. In industrial settings, the compressor intercooler and heat exchangers now use water as their cooling medium. Since water is used as the cooling medium, the low-grade heat that is removed does not help the process. But when converting to LNG vaporization, compressor waste heat is transformed into electricity, which is advantageous to the process since it can be used to balance the ASU's electrical needs. This research's novelty lies in this.

3.2 A Novel Proposed Air Separation Cycle

Based on the literature, a significant amount of energy loss, occurs during air compression. Because 90% of the electrical input used in a normal compression operation is wasted as heat, this is the cause. The ambient air is compressed in the standard cryogenic ASU under examination in this work to a pressure of approximately 5.53 bar in C1 and 9.11 bar in C2. Intercoolers, which help remove heat from the compressor effluents, are typically used in conjunction with multistage compressors to accomplish this compression. The air is around 275.3°C and 91.47°C, respectively, in the moments following the first and second compressors. These air temperatures must be lowered using intercooler and aftercooler heat exchangers. Typically, water is used at ambient temperature to provide intercooling. **Figure 3.2** illustrates how using water as a cooling medium limits the usage of the extracted heat to only heat integration because the intercooler's output water temperature is unsuitable for any utilization. Due to the possibility that such heat is not required elsewhere in the plant, this could not be advantageous in a stand-alone cryogenic ASU. Because the recovered compressor heat might not be utilized elsewhere in the process, the transformation of heat to electricity via the LNG vaporization process will be the most advantageous to the process.

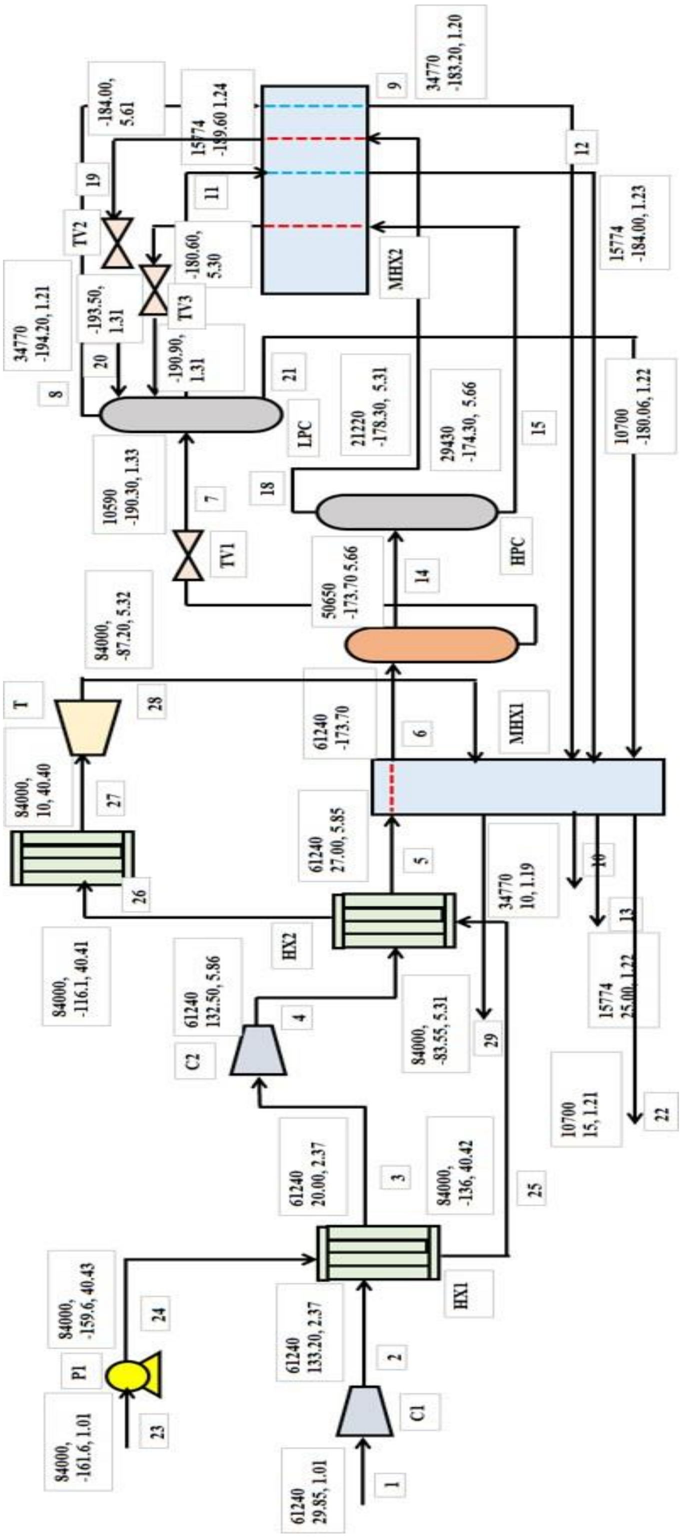

Figure 3.4: Proposed novel air separation process integrated with CULNG

Figure 3.4 depicts the proposed novel cryogenic air separation cycle following the integration of LNG. Distillation columns are used in the procedure, and they may work under various pressures. In this figure, the lower column (HPC) has a higher operational pressure than the top column (LPC). Liquid nitrogen and liquid oxygenated air are present in the lower column. The distillation process uses this liquid nitrogen as a reflux. The compressor compresses the feed air (stream 1) at 1.36 bars (C1). The product streams in a major heat exchanger (MHX1) substantially cool the compressed input stream (stream 5) as it enters the separator (SEP). Feedstock is fed into the bottom distillation column from the top product stream (HPC). The bottom stream of the separator is introduced to the upper column (LPC). While the distillation column LPC yields high-purity nitrogen (stream 8), waste nitrogen (stream 11), high-purity oxygen (stream 21), and liquid high-purity oxygen, the lower distillation column HPC produces oxygen-enriched liquid air (stream 15) and high-purity nitrogen (stream 18). The temperature of the stream increases to 132.2°C when air is compressed and must be cooled to 40°C. In the proposed cycle, air temperatures are lowered using LNG's cold energy. Using a pump, the LNG stream is compressed to 40 bars. Heat exchanger HX1 raises the temperature of the pressurised LNG stream (26) to -136.0°C as it passes through it. The temperature of the air is reduced to 27°C, and the temperature of the LNG stream (28) is elevated to -116.1°C as this stream is once again transported through heat exchanger HX2. The stream 28 is heated to 10°C and then routed through an expander in order to use CULNG for power generation through DEC. The 3993 kW of electricity that the turbine (T) produces is enough to power the air separation operation. Gas expansion causes a decrease in temperature of -87.20°C. In MHX1, this cold energy is once again used. The expander is taken out after using the LNG stream in the ASU cycle, and the throttle valve prior to the HPC is also taken out. NG exit temperature from MHX1 is -83.55°C. General assumptions about simulations are presented in **Table 3-1**.

.

Table 3-1: General assumptions of system simulation

	Pressure Ratio	Isentropic Efficiency
Compressors		
Comp 1	5.81	0.80
Comp 2	1.57	0.80
Exp	0.13	0.80
Pump 1	40	0.85
Expansion Valves		**Pressure Difference (atm)**
Ex2		4.27
Ex3		4.16
Distillation Columns	Number of Stages	Pressure Drop(atm)
HPC	12	0.2
LPC	33	0.1

3.3 Advanced Multistage Power Generation Cycle

Since 1976, the CULNG schemes have been functional in power generation applications. The CULNG systems were presented by Griepentrog and Sackarendt for the first time in 1976 [188]. They represented the significance of the energy during the LNG regasification, and different closed-cycle turbine alternatives were discussed for the CULNG [189]. Xue et al. (2016) introduced and summarized cryogenic power generation cycles with CULNG in the review paper. The performance of the power generation cycle can be improved in two ways. The first is to modify and optimize key factors for the design of the power production cycle, and the second is structural enhancement [190]. Prior research has mostly focused on multistage rankine cycles and how well they perform with various working fluids. The integration of the direct expansion cycle with the multistage rankine cycles has not been the subject of many investigations. The performance of the power generation cycle is enhanced in this work by both of the approaches described by Xue et al. (2016). First, the efficiency of the single-stage Rankine cycle and the DEC with various working fluids is assessed. An innovative advanced integrated DEC with RC cycle (ORC-RC-PDEC) is presented to recover the maximum cold utilization of LNG. The LNG stream is heated in this setup before entering the DEC. Cold-use NH_3 working fluids are chosen for the multistage Rankine cycle based on performance. Aspen Plus (v.12.1) software is used for the design and analysis of proposed system. Additionally, economic research is done to assess performance.

DEC and multistage RCs can be integrated to produce the greatest net power gain. In RC, the condenser solely uses cold energy to recover LNG from the gas. Mechanical energy can be recovered with cold exergy if DEC and RC are combined, as was explained in earlier sections.

Different series and parallel arrangements of RC and DEC are possible. DEC may be used at the beginning, middle, or end.

3.3.1 ORC-DEC-RC

In this combination, the LNG cold energy is utilized by ORC with R-1150 as the working fluid, DEC with LNG and RC with ammonia as working fluid as shown in **Figure 3.5**. The working fluid R-1150 is pumped by pump P2 and vaporized through exchanger E4 and this high-pressure gas is sent to a turbo-expander T2 and depressurized where the work is extracted and the working fluid is liquefied again by utilizing LNG cold energy. The LNG is pumped by pump P1 to the exchanger at E3 pressure where it is vaporized by liquefying the working fluid R-1150. Then the high-pressure natural gas is depressurized to by extracting work from turbo expander T3. Due to expansion, the natural gas temperature drops to -138°C. This cold is used to liquefy the NH_3 in another Rankine cycle where the working fluid NH_3 is pressurized by pump P3 and vaporized in exchanger E2 and depressurized in turbo-expander (T3). The Net-Power extracted from this combination is 2841 kW and has an efficiency of 47.52%.

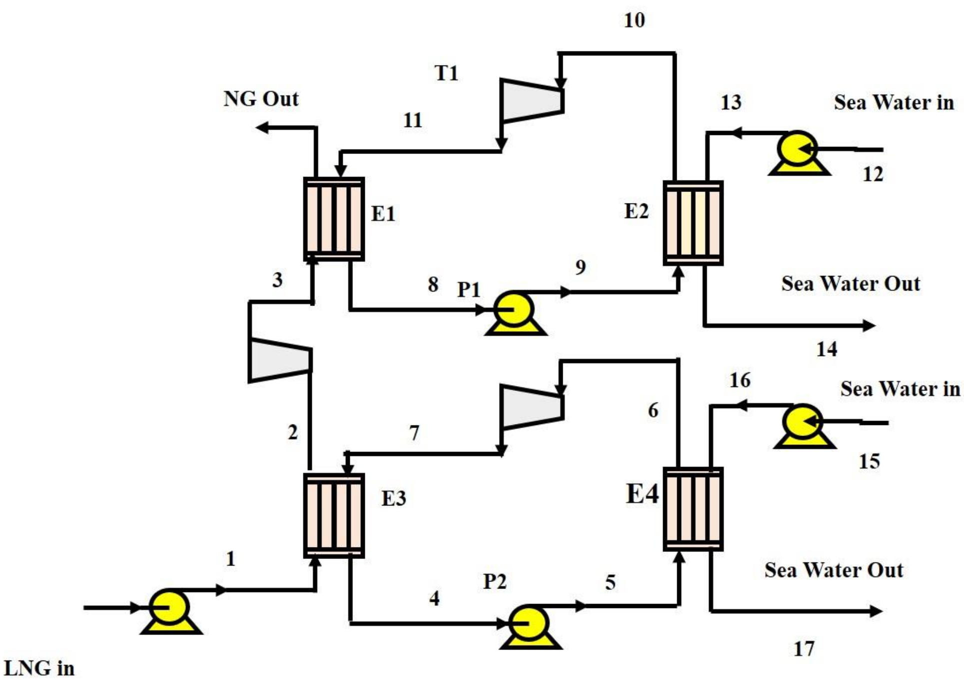

Figure 3.5: ORC-DEC-RC Combination

3.3.2 ORC-RC-DEC

In this combination, The ORC and RC make use of LNG cold energy in series with R-1150 and NH_3 as their working fluids respectively and Direct expansion of LNG as presented in **Figure 3.6**. The working fluids in ORC and RC are pressurized by pumps P2 and P3 and vaporized in exchangers E2 and E3, the high-pressure gases are expanded through turbo-expanders T-1 and T-2 respectively. The exchanger E2 is vaporizer in ORC and condenser in RC. The LNG is pumped to exchanger E1 at by Pump P1, the high-pressure natural gas is expanded in turbo-expander T3. The net power from this combination is 2961 kW and has thermal efficiency of 38.8 %.

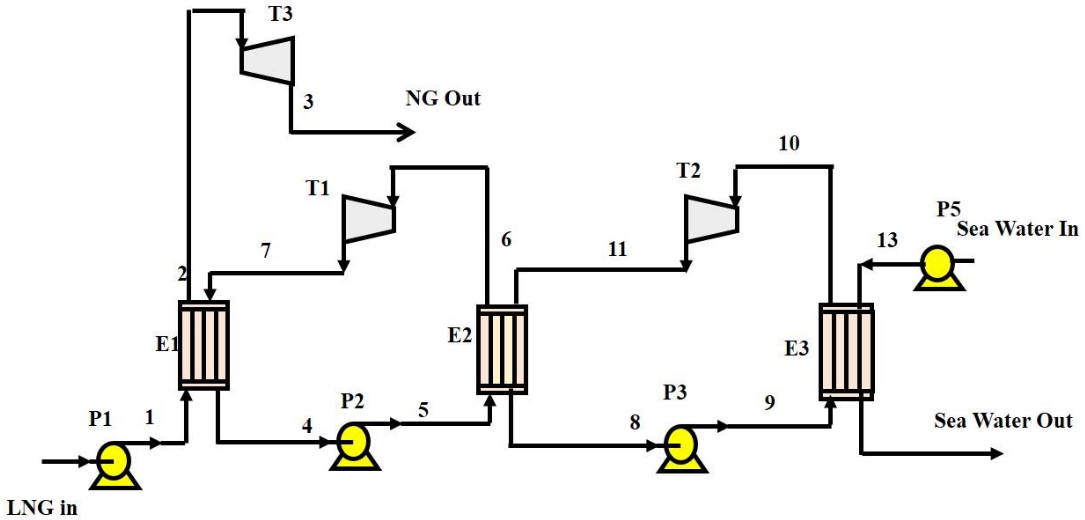

Figure 3.6: ORC-RC-DEC Combination

3.3.3 ORC-RC-DEC-RC

Figure 3.7 represents the ORC-RC-DEC-RC combination. The ORC and RC use LNG cold energy in series with R-1150 and NH3 as working fluids, respectively, and by the direct expansion of LNG and Rankine cycle with NH_3 as working fluid. The LNG is vaporized in exchanger E-1 of ORC by liquefying R-1150. The working fluids in ORC and RC are pressurized by pumps P2 and P3 and vaporized in exchangers E2 and E3 respectively. The exchanger E2 vaporizes R-1150 by liquefying NH3, thus exchanger E2 acts as a condenser in RC and a vaporizer in ORC. The high-pressure natural gas is expanded in turbo-expander T3 and sent to exchanger E5 to liquefy NH_3 in the final RC. The NH3 in this cycle is pumped by pump P5 and vaporized in exchanger E4 and expanded in turbo-expander T4. The net-Power from this combination is 3340 kW and has a thermal efficiency of 34.9 %.

3.3.4 Proposed Multistage Power Generation Cycle

After evaluation of six different cycles, a novel ORC-RC-PDEC configuration is proposed for power production by cold utilization of LNG.

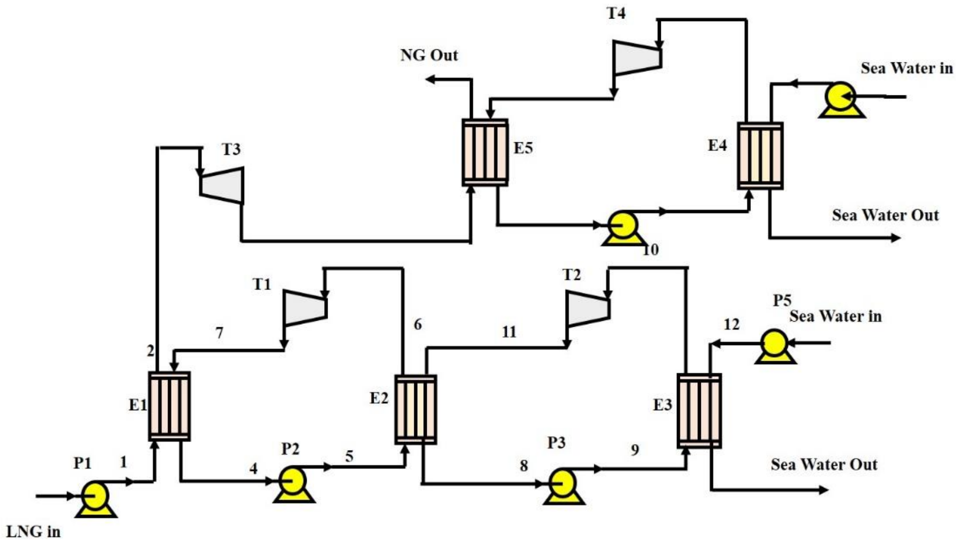

Figure 3.7: ORC-RC-DEC-RC Combination

ORC-RC-PDEC

In this combination, the LNG cold energy is utilized by the ORC and RC in series with R-1150 and NH3 as their working fluids respectively, and direct expansion of LNG with Pre-heating as presented in **Figure 3.8**. The working fluids in ORC and RC are pressurized by pumps P2 and P3 and vaporized in exchangers E2 and E3, the high-pressure gases are expanded through turbo-expanders T1 and T2 respectively. The exchanger E2 is a vaporizer in ORC and a condenser in RC. The LNG is pumped to exchanger E1 by Pump P1. Natural gas from exchanger E1 is again heated to 25° C in E4, and the high-pressure natural gas is expanded in turbo-expander T3 to 5 bars. The net-power from this combination is 3826 kW and has a thermal efficiency of 47.23%.

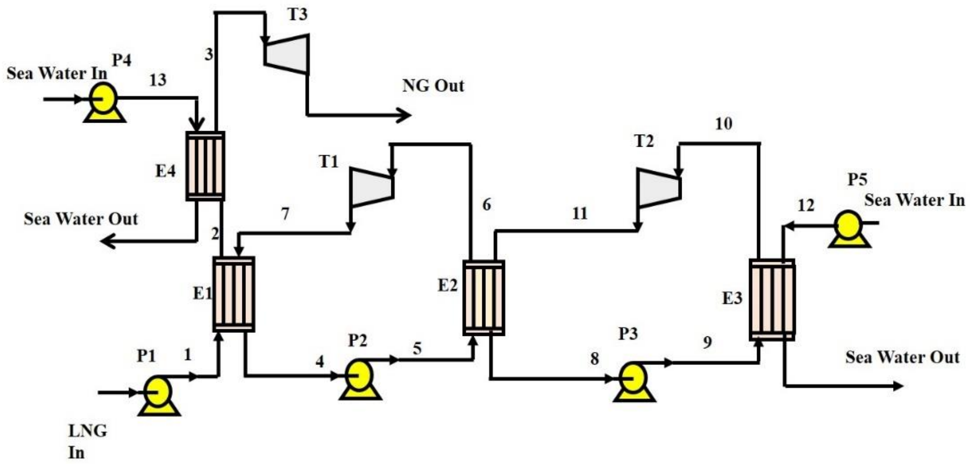

Figure 3.8: ORC-RC-PDEC Combination

Chapter 4: Simulation Tools & Research Methodology

Simulation is the technique of employing a computer programme to mimic the behaviour of a system or process in the actual world. Users can examine the system in various environments without having to interact with it physically. Engineering, healthcare, finance, and education are just a few of the many industries that might benefit from simulation [191]. In engineering, simulation can be used to assess a new product design's performance, forecast how a structure will respond to certain loads, or model fluid movement in a system. Simulation can be used in the healthcare industry to teach medical staff in a secure and controlled environment or to model the outcomes of various therapies on a virtual patient. In the field of finance, simulation can be used to replicate the performance of various investment strategies or to model the behaviour of financial markets. Simulated environments can be used in the classroom to generate engaging learning opportunities. For instance, students can investigate historical events, develop their problem-solving abilities, or imitate scientific investigations using simulations [192]. In engineering, simulation can be used to evaluate how well a new design performs. Simulated environments enable users to study complicated systems in a controlled setting, which is one of the benefits of simulation. This can be especially helpful when studying the system in the actual world is challenging or dangerous. For instance, without exposing researchers to radiation, simulation can be used to examine the behaviour of a nuclear reactor. Discrete event simulation, continuous simulation, and agent-based simulation are only a few of the numerous simulation subtypes. Different kinds of systems and processes are best suited to particular simulation types. As computer technology advances, simulation is expected to be used even more frequently in the future. It has already become a significant tool in many industries [193].

Aspen Hysys (12.1) software, which is frequently used for process modelling, design, and optimisation, was employed in this investigation.

4.1 Aspen Hysys Simulation Software

Software for process simulation called Aspen Hysys is widely used in the petrochemical, oil, and gas, and chemical sectors. One of the most potent and complete simulation tools for building and optimizing process plants was created by Aspen Technology [191]. Users of Aspen Hysys can simulate and model the behaviour of various complicated process systems, such as chemical processes, heat exchangers, distillation columns, and other unit activities. The software employs a meticulous modelling methodology that considers the behaviour of individual components and their interactions in addition to the physical and thermodynamic characteristics of the process stream.

Aspen Hysys's user-friendly interface, which enables users to rapidly and simply develop models using pre-built templates and drag-and-drop capability, is one of its primary strengths. Along with an extensive collection of physical attributes and process components, the software also has strong optimization tools that may be used to optimize plant designs and increase process efficiency [194]. Numerous applications of Aspen Hysys have been made use of, such as the design of chemical and petrochemical plants, process optimization in refineries, and modelling of offshore oil and gas production facilities. It has also been applied to academic research and instruction, where it is a useful tool for examining new process technologies and evaluating process systems. Aspen Hysys is an all-around effective and adaptable instrument that is frequently utilized in the process industries. Process engineers and designers depend on it heavily due to its sophisticated modelling capabilities and user-friendly interface, and its optimisation tools can help businesses cut costs and increase process efficiency [195].

4.2 Thermodynamic Packages in Aspen Hysys

Several thermodynamic software from Aspen Hysys are available for modelling the behaviour of process streams. These packages include, among others, the NRTL activity coefficient model, UNIQUAC activity coefficient model, Soave-Redlich-Kwong equation of state (EOS), and Peng-Robinson equation of state (EOS). The exact application and the characteristics of the process stream being modelled will determine which thermodynamic package is best. One of the most popular thermodynamic models in Aspen Hysys is the Peng-Robinson EOS. It is founded on the idea that a fluid's behaviour can be predicted based on its composition, pressure, and temperature. The Peng-Robinson EOS accurately predicts the behaviour of mixes of various components because it takes into consideration the intermolecular interactions between the fluid's molecules.

The NRTL activity coefficient model is a crucial thermodynamic package in Aspen Hysys. The activity coefficients of the components in a mixture are determined using this model. When predicting the behaviour of mixes, such as the degree of phase separation and the distribution of ingredients between the liquid and vapour phases, activity coefficients are crucial. Additionally, Aspen Hysys offers a variety of choices for specifying a wide range of physical characteristics, such as density, viscosity, and thermal conductivity. To accurately mimic the behaviour of process streams, these features are employed in conjunction with thermodynamic models. The chemical and petroleum sectors have several uses for Aspen Hysys' thermodynamic packages. It can be used to design and improve process components like reactors, heat exchangers, and distillation columns. Additionally, it can be used to mimic and optimise large processing facilities, such as chemical and oil refineries. In conclusion, precise process simulation and optimization require the use of thermodynamic packages in Aspen Hysys. The individual application and the characteristics of the process stream being modelled will determine which thermodynamic model is best. In order to accurately simulate and optimise complicated process systems, Aspen Hysys offers a wide range of options for selecting physical parameters [191].

The mathematical model of the procedure is simplified by the following assumptions: Steady-state conditions govern the process's operation. The entire process operates in an adiabatic state. The fluctuations in kinetic and potential energy are neglected. There is hardly any pressure loss inside the heat exchangers. The compressor and pump isentropic efficiencies remain constant at 0.80 and 0.85, respectively.

4.3 Simulation of CULNG processes

Aspen Hysys is often used to simulate LNG processes, such as cold LNG utilisation. This section will go over the use of Aspen Hysys in cold utilization processes as well as its applications. The cold utilisation of LNG refers to the use of LNG's cold energy can provide refrigeration and otherwise cooling services. To simulate and optimize the performance of cold utilization processes, Aspen Hysys can be used. It can also be used to design and optimize the process equipment, such as heat exchangers, compressors, and turbines [196].

The design and optimization of the LNG regasification process is one of Aspen Hysys' primary applications in cold utilization processes. Regaining LNG's gaseous state for use in power production or other purposes is a process known as regasification. The performance of the LNG regasification process, including the design of the heat exchangers utilized in the process, can be simulated and optimized using Aspen Hysys.

The design and optimization of LNG refrigeration systems is a significant use of Aspen Hysys in cold utilization operations. Utilizing LNG's cold energy, these systems offer cooling or refrigeration services. The performance of these systems, including the design of the compressors, turbines, and other components, may be simulated and optimized using Aspen Hysys. Additionally, Aspen Hysys offers a variety of alternatives for simulating the behaviour of LNG, including thermodynamic models for computing its physical characteristics. This makes it possible to simulate and optimise cold utilisation processes with accuracy. The LNG sector has various uses for Aspen Hysys in cold utilization processes. It can be used to plan and improve LNG refrigeration and regasification systems as well as other process-related machinery. Additionally, it can be utilized to improve the efficiency of LNG production facilities, including the liquefaction process as well as LNG storage and transportation [197].

Aspen Hysys is a crucial software for the simulation and improvement of cold utilization processes in the LNG sector, to sum up. It enables the design and optimization of the equipment used for these processes as well as the precise modelling of LNG behaviour.

4.4 Selection of Thermodynamic Package

The Peng Robinson equation of state is a widely accepted model for determining the thermodynamic properties of a fluid. Peng and Robinson proposed it as an improvement to a Soave-Redlich-Kwong (SRK) equation in 1976. The law of comparable states, which asserts that all fluids behave similarly when compared at the same lowered temperature and reduced pressure, forms the basis for the equation [198]. The adjustable parameter and acentric factor, two variables that can be changed in the Peng Robinson equation, allow it to be used with a variety of fluids. The interaction parameter compensates for the impacts of molecular interactions, such as hydrogen bonding, that are not included in the ideal gas model, while the acentric factor represents the divergence of a fluid from an ideal gas. Numerous experiments have been conducted using the Peng Robinson equation on a range of fluids, including water, alcohols, and hydrocarbons. For forecasting thermodynamic parameters like compressibility, density, and vapour pressure, it has been demonstrated to be reliable. The equation has also been applied to the design and improvement of industrial processes such as gas processing, liquefaction, and distillation [199].

However, it is important to note that the accuracy of the Peng Robinson equation is limited by the complexity of the fluid being modelled. Other equations of state might be more appropriate for fluids that are extremely polar or that associate. Inaccuracies in the adjustable parameters and restrictions on the experimental data used for calibration can also have an impact on how accurate the equation is. Overall, the Peng Robinson equation continues to be an invaluable resource for forecasting the thermodynamic characteristics of fluids and has a wide range of real-world uses. As a result, we decided to use Peng Robinson's equation in our research.

The Peng Robinson equation is given by,

$$P = ((RT/V - b) - a\alpha/V(V + b) + b(V - b))) \tag{1}$$

where P denotes pressure, R denotes the gas constant, T denotes temperature, V denotes molar volume, a and b are adjustable parameters, and is a temperature dependent parameter. The Peng-Robinson equation's adjustable parameters a and b are related to the fluid's critical properties and its acentric factor, which is a measure of its deviation from spherical symmetry. The mixing rule used to determine the adjustable parameters is determined by the method used to combine the pure-component parameters. The Van der Waals mixing rule, which assumes a linear combination of the pure-component parameters, is the most commonly used mixing rule. The Peng-Robinson equation is commonly used to predict the thermodynamic properties of a wide range of fluids, including hydrocarbons, polymers, and electrolytes. It has been shown to accurately predict vapor-liquid equilibria for many fluid mixtures, particularly at low to moderate pressures. However, its accuracy is limited at high pressures and for fluids with large acentric factors.

4.5 Selection of Working Fluid

One of the most important steps in the design of multistage RCs is indeed the selection of working fluid. Several aspects need to be considered for selection: Ozone depletion, global warming effect, safety, critical temperature, critical pressure of the working fluid, environmental sustainability, thermal stability. Working fluid must be non-toxic, non-corrosive and non-flammable. Hydrochlorofluorocarbon (HCFC) and chlorofluorocarbons have not been considered in this study due to environmental constraints [200]. In addition, thermodynamic properties like critical temperature and pressure, condensation temperature and pressure, wet dry properties are important properties of refrigerants because it has serious effect on NPG [143].

Considering these aspects, eleven working fluids have been selected for evaluation of single-stage RC. **Table 4-1** provides thermodynamic properties of the working fluids.

Table 4-1: Properties of Working Fluid

Fluids	Chemical Formula	Critical Pressure (bar)	Critical Temperature(°C)	Condensation Temperature(°C) at 1.31 bar
R1150 (chloropentafluoroethane)	C_2ClF_5	50.42	9.2	-99.48
R170 (Ethane)	C_2H_6	48.72	32.17	-83.79
R23(Fluoroform)	CHF_3	26.1	48.32	-77.36
R1270(Propene)	C_3H_6	45.6	91.1	-42.08
R143a(1,1,1-Trifluoroethane)	$C_2H_3F_3$	37.8	72.9	-41.51
Propane	C_3H_8	43.01	97	-36.1
R22 (Chlorodifluoromethane)	$CHCIF_2$	49	96	-35.55
Ammonia	NH_3	132.4	112.8	-33.34
R134a(1,1,1,2-Tetrafluoroethene)	CF_3CH_2F	101.06	40.59	-27.7
R600a(2-methylpropane)	C_4H_{10}	134.98	38	-5.99
R600 (n-butane)	C_4H_{10}	152.01	37.96	6.54

4.6 Sensitivity Analysis

Sensitivity analysis is an important tool for assessing how input factors affect a model's or system's performance. Aspen software is frequently used in chemical engineering for process simulation and design, and it offers a number of tools for sensitivity analysis. With references to pertinent literature, this article will go over sensitivity analysis in Aspen software, its significance, and its uses in chemical engineering [191].

Different techniques for conducting sensitivity analysis are provided by Aspen software, including the parameter estimation, Aspen Sensitivity Analysis (ASA), and Aspen Parametric Analysis (APA) tools. By comparing model predictions to experimental data, parameter estimation enables engineers to estimate the values of parameters that are challenging to measure or uncertain. By performing a one-at-a-time (OAT) analysis or a global sensitivity analysis, ASA is a tool that aids engineers in understanding the impact of input parameters on model outputs. Engineers can utilize APA, a tool that enables simultaneous variation of numerous input parameters, to explore the design space of a process. Finding the input factors that have the most effects on process performance is one of the main advantages of sensitivity analysis in Aspen software. Engineers can optimize the process and enhance its effectiveness, safety, and environmental impact by changing these factors. Engineers can increase the precision of their forecasts and identify the sources of uncertainty in their models with the aid of sensitivity analysis [201].

Chemical engineers use sensitivity analysis for a variety of purposes, such as process control, process optimisation, and safety analysis. Sensitivity analysis, for instance, can assist in process optimisation by assisting in the identification of the crucial operational parameters that influence the process performance, such as temperature, pressure, and flow rate. Engineers can boost process effectiveness, lower energy usage, and enhance product quality by optimising these factors. Sensitivity analysis in process control can assist in determining the variables, such as response rate constants, that affect the stability of the process and improve the control techniques to maintain stable operation. Sensitivity analysis in safety analysis can assist engineers design safer processes by identifying the most important factors that have an impact on the process' safety, such as the rate at which hazardous compounds are released [202].

To sum up, the Aspen software's sensitivity analysis feature is crucial for chemical engineers to comprehend how input factors affect process efficiency. Engineers can optimise the process, raise its effectiveness, and lessen its environmental impact by finding the crucial parameters. Chemical engineers can use sensitivity analysis in a variety of ways to create safer, more effective, and environmentally friendly processes.

4.7 Methodology used for Simulation

The methodology used in Aspen Hysys involves several key steps.

4.7.1 Importing the CULNG process model:

The first step is to import the LNG regasification process model into Aspen Hysys. This includes specifying the process streams, equipment, and operating conditions as shown in **Figure 4.1**

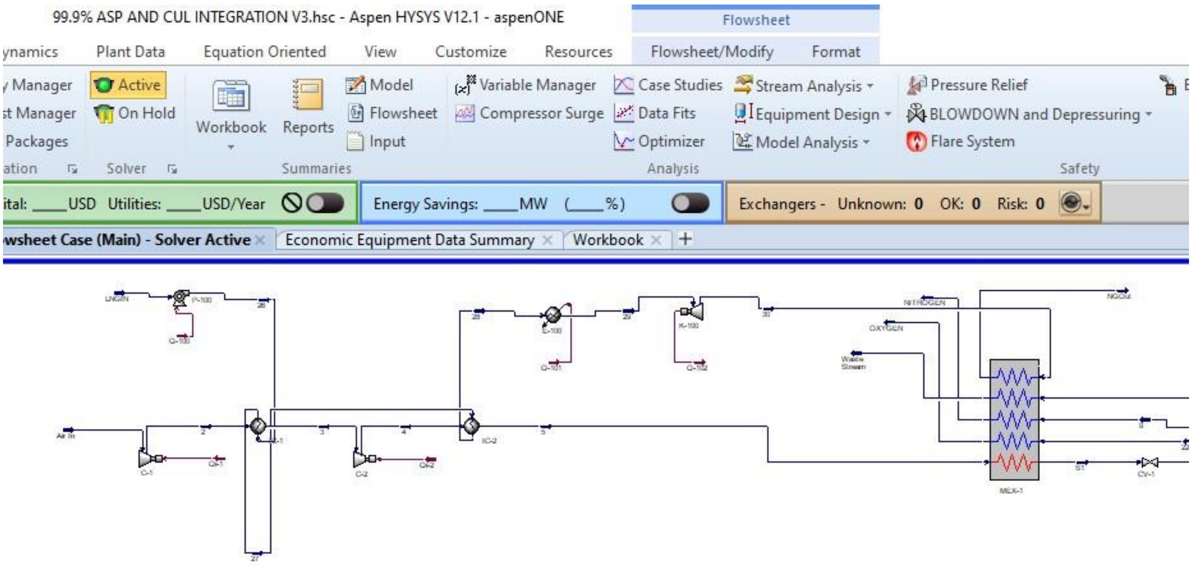

Figure 4.1: Importing the CULNG process model

4.7.2 Adding the cold utilization equipment

Next, the cold utilization equipment is added to the model. This could include heat exchangers, refrigeration units, or power generation equipment as shown in **Figure 4.2**.

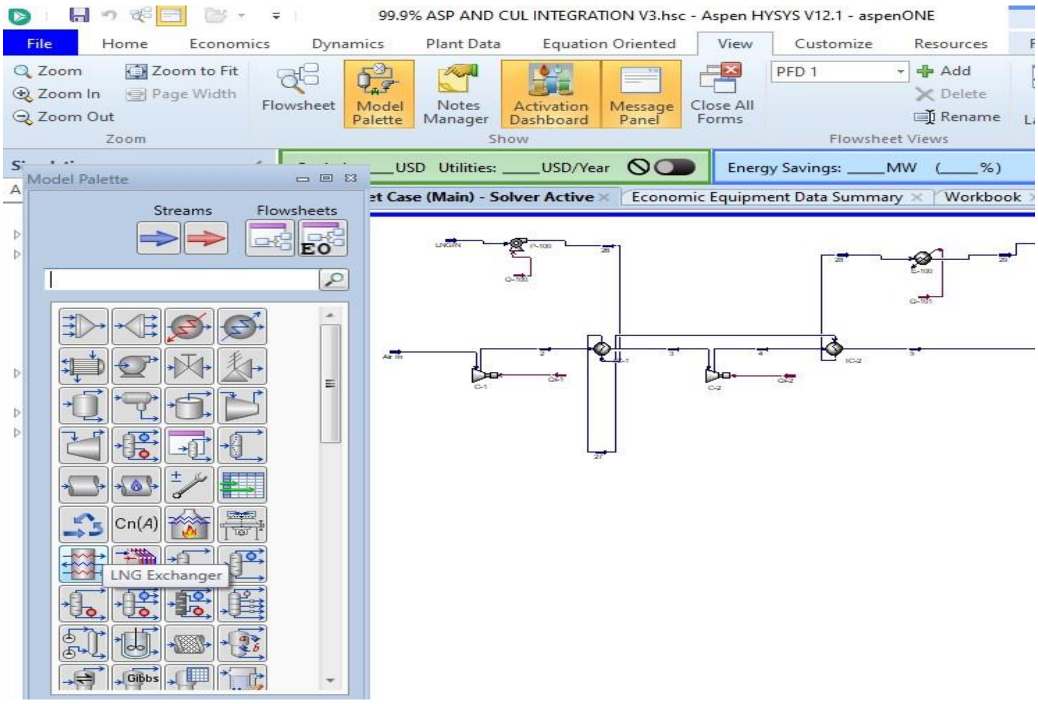

Figure 4.2: Adding the cold utilization equipment

4.7.3 Running the simulation

The simulation is then run in Aspen Hysys to determine the performance of the cold utilization process. This includes calculating the amount of cold energy available for utilization, the efficiency of the cold utilization equipment, and the overall energy balance of the system as shown in **Figure 4.3**

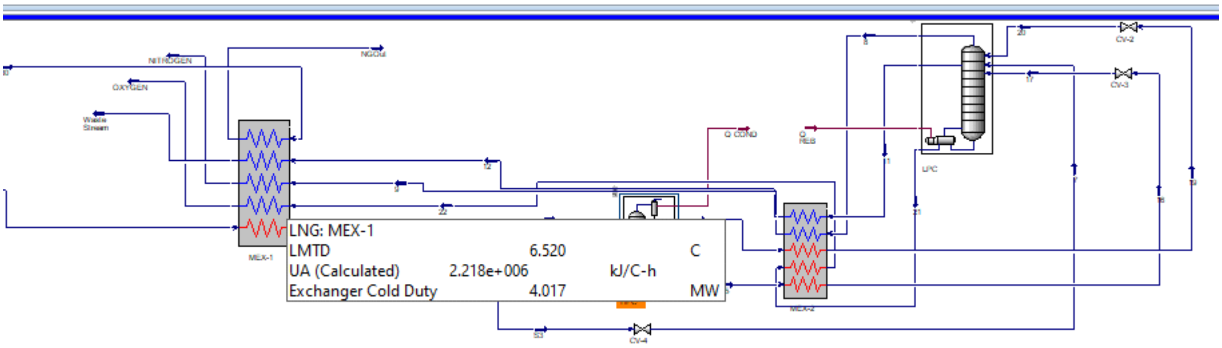

Figure 4.3: Running the Simulation

4.7.4 Analysing the results:

Finally, the results of the simulation are analysed to optimize the cold utilization process. This could involve changing the operating conditions, adjusting the equipment sizing, or selecting different refrigerants to improve the efficiency and overall performance of the system as shown in **Figure 4.4**.

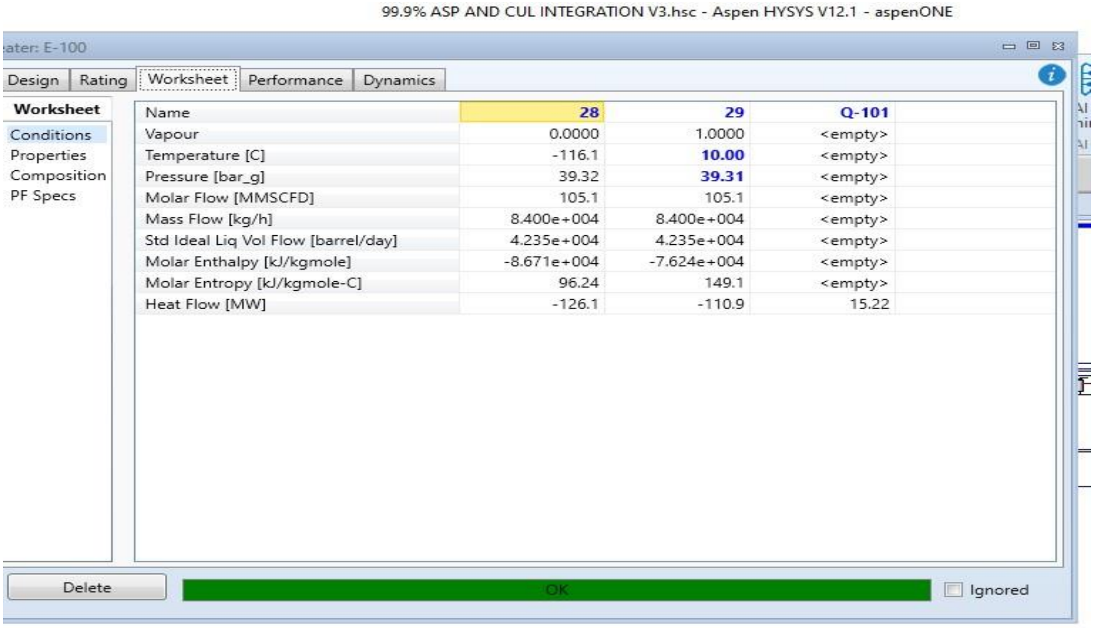

Figure 4.4: Analysing the results

4.8 Thermodynamic Analysis

In this section, thermodynamic analysis for different components is discussed in detail.

4.8.1 Air Separation Unit

The power consumed by air separation unit can be calculated based on number of compressors and turbines used in the process [182].

$$W_{total,ASU} = \Sigma W_{comp} - \Sigma W_T \tag{2}$$

There are two established specific energy consumptions (SECs) for the air separation process. Both the ratio of overall power consumption to the flow rate of pure oxygen ($\gamma_{O2;ASU}$) and the ratio of net power consumption to ($\gamma_{O2N2;ASU}$) stand for power consumption per the sum of the flow rates of pure oxygen and pure nitrogen.

$$\gamma_{O2;ASU} = \frac{W_{TOT,ASU}}{M_{O2}} \tag{3}$$

$$\gamma_{O2N2;ASU} = \frac{W_{TOT,ASU}}{M_{O2} + M_{N2}} \tag{4}$$

4.8.2 Power Generation Cycles

Energy equations for the suggested integrated power cycle are designed with minimal pressure drop as well as heat loss in evaporators, condensers, and heat exchangers. For the purposes of this study, steady-state flow and LNG as pure methane were assumed [203].

$$W_{net,i} = \sum W\ output, i - \sum W\ input, i \tag{5}$$

$$W_{net} = W_{net,i} \tag{6}$$

$$\eta_{th} = \frac{W_{net}}{Q_{Source}} \tag{7}$$

4.9 Exergy Analysis

Exergy and sensitivity analysis are the two key techniques for assessing the outcomes of process and component performance. The engineering tool of exergy analysis is adequate to specify the maximum work that each subsystem can accept. Additionally, sensitivity analysis is used to examine the impact of important parameters on the effectiveness of the unit [204].

The exergy analysis equation is given below [205].

$$\dot{X}_{in} + \dot{X}_Q = \dot{X}_{out} + \dot{X}_w + \dot{X}_D + \dot{X}_L \tag{8}$$

$$\dot{X}_Q = \left(1 - \frac{\dot{T}_O}{T_i}\right) Q_i \tag{9}$$

For a single component exergy loss is zero.

$$X_L = 0 \tag{10}$$

The sum of exergies can be presented by following equation

$$\dot{X} = \dot{X}_{ph} + \dot{X}_{kn} + \dot{X}_{pt} + \dot{X}_{ch} \tag{11}$$

For a pure substance exergy can be written by,

$$\dot{X} = m\ [(h - h_0) - T_0(s - s_0)] \tag{12}$$

An equation for exergy destruction for pump, turbine, heater, condenser and compressor are represented as follows

$$\dot{X}_{D,P} = \dot{W}_P + \sum X_{in,p} - \sum \dot{X}_{out,p} \tag{13}$$

$$\dot{X}_{D,T} = \sum \dot{X}_{in,T} - \sum \dot{X}_{out,T} - \dot{W}_T \quad (14)$$

$$\dot{X}_{D,H} = \sum \dot{X}_{in,H} - \sum \dot{X}_{out,H} \quad (15)$$

$$\dot{X}_{D,Cd} = \sum \dot{X}_{in,Cd} - \sum \dot{X}_{out,Cd} \quad (16)$$

$$\dot{X}_{D,C} = \sum \dot{X}_{in,C} - \sum \dot{X}_{out,C} + \dot{W}_C \quad (17)$$

Eq. (18) is used to determine the overall exergy efficiency of the cold utilization process.

$$\dot{X}_{Eff} = \frac{\dot{X}_{Out}}{\dot{X}_{In}} \quad (18)$$

Chapter 5: Results & Discussions

The results of an integrated air separation process, encompassing the cold utilization of LNG and the incorporation of multistage power generation units, are discussed in this section. Within this holistic strategy, the effective separation of air components, leveraging the cryogenic properties of LNG for enhanced performance, and the optimization of power generation at multiple stages are addressed. The synergy generated by the integration of these technologies is underscored by the results, highlighting their potential to boost energy efficiency and mitigate environmental impact across various industrial applications. A more sustainable and economically viable solution is demonstrated by this cutting-edge integration, showcasing its potential to revolutionize the field of energy and resource utilization.

5.1 Results of Air Separation Process Integrated with CULNG.

Table 5-1 lists the physical properties and composition of the double-column air separation process. The simulation's findings are in good agreement with the existing source [206]. **Table 5-1** demonstrates that air enters the process under typical temperature and pressure conditions. The temperature of the compressed air reached 273°C, indicating that heat was being produced. Usually, water is utilized to bring the air temperature back down to normal. This heat is being lost. Multistream heat exchangers, expanders, and J-T valves are used to cool the air to cryogenic temperature (-173 °C). At -193.83°C and -183.15°C, respectively, nitrogen and oxygen are liquid, and they are separated in the upper column. As can be observed, this technique results in products of higher purity (nitrogen 99.12% and oxygen 98.43%). To bring incoming air down to cryogenic temperatures, the nitrogen and oxygen streams are recycled. Nitrogen and oxygen are regasified during this process.

5.2 Model Validation

To verify the correctness of the cryogenic air separation process, a similar process[206] is modelled, and the simulation outcomes are compared. This procedure generates high-purity oxygen (99.51 mol%) from 64601.80 kg/hr (50000 m^3/hr) of air supply that contains 78.11 mol% nitrogen, 20.95 mol% oxygen, and 0.93 mol% argon at standard pressure and temperature (29.85 °C) (1.01 bar). The major data's standard deviation (SD) is shown in **Table**

5-2. The simulation's results can be inferred to be in strong agreement with the existing literature.

Table 5-1: Simulation Results of air separation process

No	**Flow Rate (kg/hr)**	**Temperature (°C)**	**Pressure (bar)**	**Nitrogen (Mole Fraction)**	**Oxygen (Mole Fraction)**	**Argon (Mole Fraction)**
1	64601.80	29.85	1.01	0.7811	0.2095	0.0093
2	64601.80	273.42	5.77	0.7811	0.2095	0.0093
3	64601.80	29.85	5.77	0.7811	0.2095	0.0093
4	5227.57	29.85	5.77	0.7811	0.2095	0.0093
5	5227.57	82.62	5.77	0.7811	0.2095	0.0093
6	59374.20	29.85	5.77	0.7811	0.2095	0.0093
7	59374.20	-173.35	5.67	0.7811	0.2095	0.0093
8	5227.57	29.85	9.11	0.7811	0.2095	0.0093
9	5227.57	-80.68	9.01	0.7811	0.2095	0.0093
10	5227.57	-147.80	1.31	0.7811	0.2095	0.0093
11	25248.31	-193.83	1.21	0.9872	0.0086	0.0040
12	25248.31	-183.15	1.16	0.9872	0.0086	0.0040
13	25248.31	27.85	1	0.9872	0.0086	0.0040
14	25226.10	-193.23	1.21	0.9586	0.0297	0.0115
15	25226.10	-189.45	1.19	0.9568	0.0297	0.0115
16	25226.10	27.85	1.16	0.9568	0.0297	0.0115
17	59374.20	-173.35	5.67	0.7811	0.2095	0.0093
18	35835.40	-173.69	5.60	0.6357	0.3497	0.0144
19	35835.40	-175.15	5.57	0.6357	0.3497	0.0144
20	35835.40	-190.72	1.21	0.6357	0.3497	0.0144
21	23538.80	-177.79	5.47	0.9912	0.0068	0.0019
22	23538.80	-183.15	5.37	0.9912	0.0068	0.0019
23	23538.80	-194.02	1.21	0.9912	0.0068	0.0019
24	13483.20	-180.63	1.31	0	0.9843	0.0156
25	13483.20	27.85	1.01	0	0.9843	0.0156
26	644.15	-180.63	1.31	0	0.9892	0.010

Table 5-2: Model validation between reported results and simulated results

Parameter	**Reported Results**	**Simulation Results**	**Standard Deviation**
Feed (kg/hr)	64601.80	64601.80	0
O_2 Purity (%)	99.51	98.43	1.08
O_2, T (° C)	301	301	0
O_2, P (atm)	1	1	0
O_2, Flow Rate(kg/hr)	13483.2	13483.2	0
N2 Purity (%)	95.68	94.94	0.77
N2 T (° C)	301	301	0
N2 P(atm)	1	1	0
N_2 Flow Rate(kg/hr)	25226.1	25226.1	0
LP Column number of stages	33	33	0
HP Column number of stages	12	12	0

5.3 Performance of the DEC

Table 5-3 displays the DEC simulation results. It shows that the stream's temperature enters at -161°C and exits at 10°C.

Table 5-4 shows the duty needed for the regasification process and the power the expander produces. The total duty required is 19070 kW, while the power produced is 3993 kW. DEC has a 20.65% efficiency, which can be improved by integrating it with the air separation process.

Table 5-3: Simulation results of DEC

No	Flow Rate (kg/hr)	Temp (°C)	Pressure (bar)
1	84000	-160.16	1
2	84000	-159.50	40
3	84000	10	39.99
4	84000	-81.25	5
5	84000	10	4.99

Table 5-4: Duty required for equipment in DEC

No	Equipment	Duty (kW)
1	Pump (P)	268.5
2	Heater (H1)	19070
3	Turbine (T)	-3993
4	Heater(H2)	4657

Table 5-5 reveals the distillation column's operating conditions.

Table 5-5: Operating conditions of distillation column

Column	Number of Stages	Feed stage	Reflux Ratio	Top Pressure (bar)	Bottom Pressure(bar)	Column Type
HPC	20	20	1.454	6.57	5.25	Refluxed Absorber
LPC	13	40	0.5463	1.31	1.21	Reboiled Absorber

Table 5-6: Simulation results of proposed system

No	Flow Rate (kg/hr.)	Temperature (°C)	Pressure (bar)	Nitrogen Mole Fraction	Oxygen Mole fraction	Argon Mole Fraction	Methane Mole Fraction
Air In	61240	29.85	1.03	0.7812	0.2095	0.0093	0.0000
2	61240	133.20	2.37	0.7812	0.2095	0.0093	0.0000
3	61240	20.00	2.36	0.7812	0.2095	0.0093	0.0000
4	61240	132.50	5.86	0.7812	0.2095	0.0093	0.0000
5	61240	27.00	5.85	0.7812	0.2095	0.0093	0.0000
6	61240	-173.70	5.84	0.7812	0.2095	0.0093	0.0000
7	10590	-190.30	1.33	0.6345	0.3526	0.0129	0.0000
8	34770	-194.20	1.21	0.9990	0.0004	0.0006	0.0000
9	34770	-183.20	1.20	0.9990	0.0004	0.0006	0.0000
10(Nitrogen)	34770	10.00	1.20	0.9990	0.0004	0.0006	0.0000
11	15774	-189.60	1.24	0.7644	0.2010	0.0345	0.0000
12	15774	-184.00	1.23	0.7644	0.2010	0.0345	0.0000
13(Waste Stream)	15774	25.00	1.22	0.7644	0.2010	0.0345	0.0000
14	50650	-173.70	5.66	0.8111	0.1803	0.0086	0.0000
15	29430	-174.30	5.61	0.6687	0.3167	0.0145	0.0000
16	29430	-180.60	5.57	0.6687	0.3167	0.0145	0.0000
17	29430	-190.90	1.31	0.6687	0.3167	0.0145	0.0000
18	21220	-178.30	5.31	0.9990	0.0002	0.0008	0.0000
19	21220	-184.00	5.26	0.9990	0.0002	0.0008	0.0000
20	21220	-193.50	1.31	0.9990	0.0002	0.0008	0.0000
21	10700	-180.6	1.31	0.0000	0.9990	0.0010	0.0000
22(Oxygen)	10700	15	1.21	0.00	0.9990	0.0010	0.0000
23 (LNG in)	84000	-161.6	1.01	0.0000	0.0000	0.0000	1.0000
24	84000	-159.6	40.53	0.0000	0.0000	0.0000	1.0000
25	84000	-136.00	40.52	0.0000	0.0000	0.0000	1.0000
26	84000	-116.1	40.51	0.0000	0.0000	0.0000	1.0000
27	84000	10	40.40	0.0000	0.0000	0.0000	1.0000
28	84000	-87.20	5.32	0.0000	0.0000	0.0000	1.0000
29(NG Out)	84000	-83.55	5.20	0.0000	0.0000	0.0000	1.0000

5.4 Assessment of Energy Consumption

The quantity of heat required for LNG regasification in the proposed cycle is shown in **Table 5-7**. The total energy required for vaporization of LNG is 19070 kW. Heat is produced during the air compression process and is utilized to vaporize LNG. As a result, 20% less energy is used during the vaporisation of LNG, and the temperature of the compressed air is lowered to ambient levels. It is clear that the air compression process uses 3982.73 kW of energy, as represented in **Table 5-8**. Additionally, DEC generates 3993 kW of power, which is provided to run the air separation process.

Table 5-7: Heat Duty in different heat exchangers in proposed system

Parameter	HX1	HX2	HX3	MHX1
Mass Flow rate (kg/hr)	84000	84000	84000	84000
Duty(kW)	1960	1837	15220	190

Table 5-8: Specification of power components

Equipment	Pressure Ratio	Power (kW)	Adiabatic Efficiency (%)
C1	2.34	1785.70	80
C2	2.57	1940.33	80
T	0.13	3993.00	80
Pump	40	256.70	85

5.5 Exergy Analysis

Along with having excellent chemical exergy LNG also has a lot of physical exergies. Cold exergy and pressure exergy make up physical exergy. Sensible and latent cold exergy are the two components of cold exergy. The physical exergy of LNG may be recovered and used, which not only saves a lot of energy but also protects the environment. The location of the greatest exergy destruction is shown by the exergy analysis based on equipment. Equipment used in this research includes compressors, turbines, J-T valves, heat exchangers, pumps, and distillation columns.

The exegetic efficiency of the components is shown in **Figure 5.1**. The best performance is provided by the expansion valves (TV2 and TV3) and multistream heat exchanger (MHX2), which follow heat exchangers (HX1 and HX2) with the greatest values compared to other elements. The compressors have the third highest efficiency. **Figure 5.2** shows the exergy destruction of individual components. The multi-stream heat exchangers (MHX1) & (HX3) had a maximum exergy destruction throughout the operation. Expansion valves are typically isenthalpic systems that transfer little to no heat and no work to the surrounding environment. J-T valve expansion efficiencies are therefore the highest, at 99.62% and 99.19%. **Figure 5.3** displays the percentage of exergy destruction for each component in relation to the system's overall exergy destruction rate. Heat exchangers and multistream heat exchangers account for the majority (42.93% and 26.47 %, respectively) of the process's overall irreversibility.

Exergetic efficiency and exergy destruction both need to be taken into account when assessing a unit's performance in the process. For instance, compared to other pieces of equipment, the highest energy destruction occurs in MHX1 (7523.19 kW) and HX3 (7679 kW). This shows that the significant temperature difference between the hot stream and the cold stream is what is responsible for the high exergy destruction of MHX1. One solution is to maintain the temperature of the air. The distillation column (LPC) also has a high rate of exergy destruction despite having a 61% energy efficiency (4354.32 kW). In the end, this integrated process's overall energy efficiency is over 85.08 %.

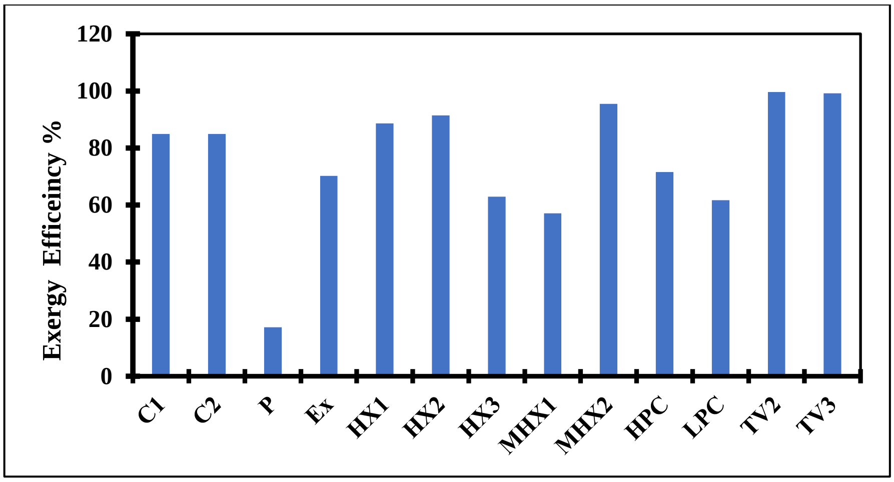

Figure 5.1: Exergy efficiency of the equipment

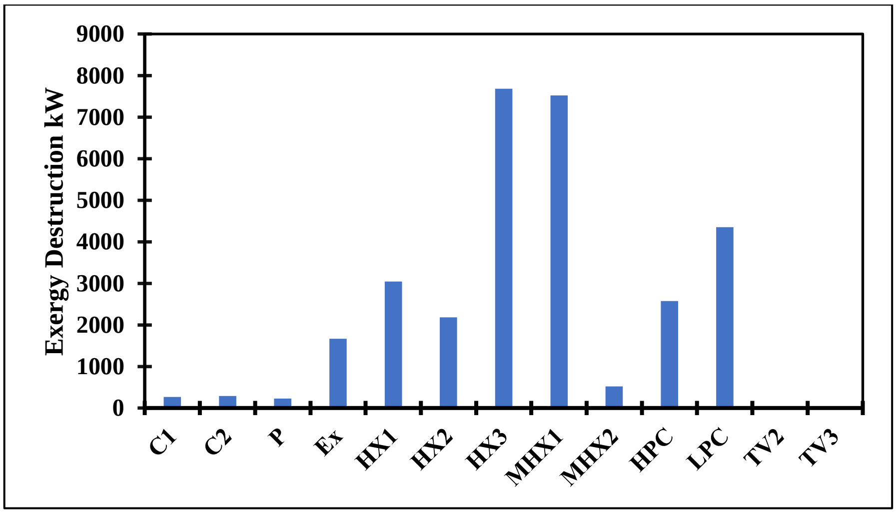

Figure 5.2: Exergy destruction of equipment

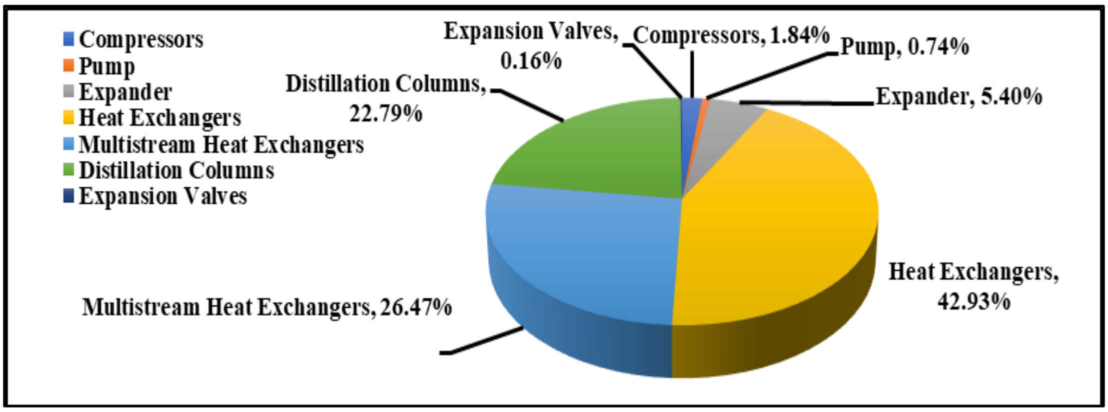

Figure 5.3: Analysis of the total exergy destruction over various processes

5.6 Parametric Optimization

The primary objective of metric optimization is to find the best settings to optimise the process's performance. At this stage, the implementation is carried by using a sensitivity analysis to investigate how some essential factors affect the process's efficiency.

5.6.1 Effect of turbine pressure differential on Turbine power production

The impact of the turbine pressure differential on energy production is seen in **Figure 5.4**. The turbine power increases linearly at first and then starts to gradually grow after 36 bars. The estimated outcomes show that when the difference in LNG turbine pressure rises, the net electrical efficiency increases. This is so that the LNG turbine can operate at a higher-pressure ratio, which increases the work output from LNG turbines.

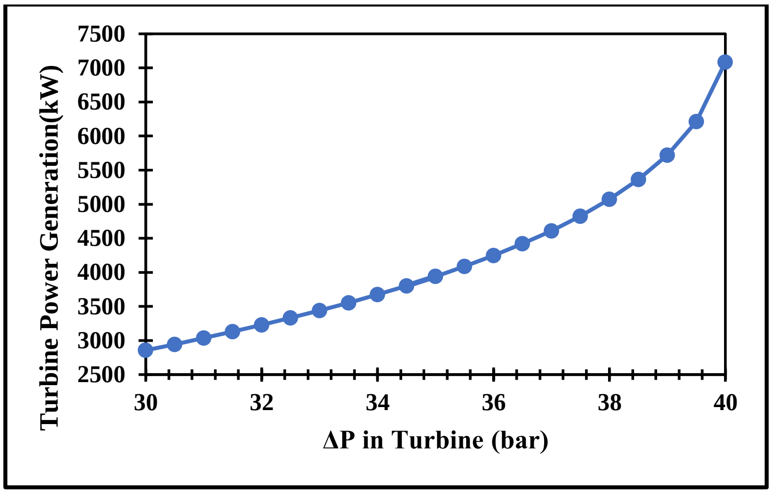

Figure 5.4: Effect of turbine pressure differential on Turbine power production

5.6.2 Effect of inlet temperature of turbine on power generation

The power generated by the turbine (T) is affected by the LNG inlet temperature, which is represented in **Figure 5.5**. The rate of power generation rises as temperatures rise. This is done so that, according to Carnot's theorem, the power can be greater whenever the temperature difference between both the cold and hot sources is larger.

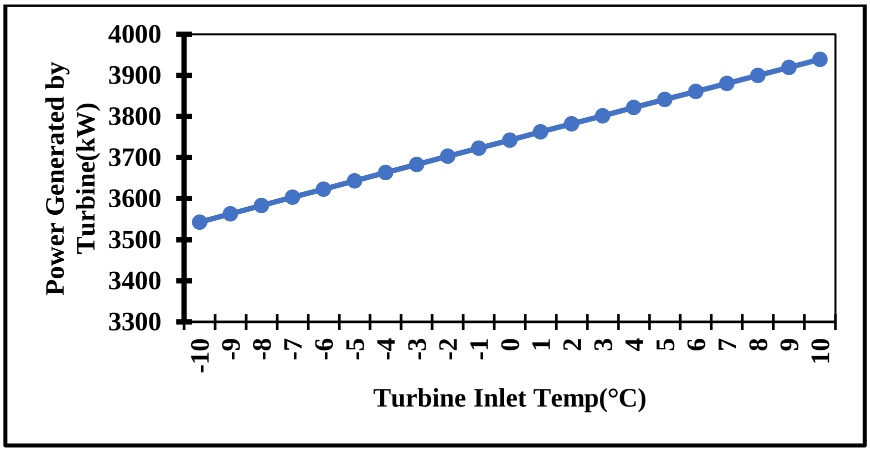

Figure 5.5: Effect of inlet temperature of turbine on power generation

5.6.3 Effect of Adiabatic Efficiency on power consumption

Figure 5.6 shows the precise power consumption of the air separation unit when the adiabatic efficiencies of the compressors range from 75% to 95%. C1 compressor uses electricity. The power consumption (C1) declines linearly with adiabatic efficiency. The power consumption of compressors declines as adiabatic efficiency increases, due to the fact that adiabatic efficiency is a measure of the compressor's ability to convert the input power into useful compression work without any loss of energy as heat. In other words, adiabatic efficiency measures how well the compressor can compress the gas without generating any heat that needs to be removed. When the adiabatic efficiency of the compressor increases, it means that the compressor is able to compress the gas more efficiently and with less energy loss due to heat generation. This reduces the energy required to remove the heat generated during the compression process, which leads to a decrease in power consumption. Thus, a compressor with a higher adiabatic efficiency is able to achieve the same level of compression with less energy input, resulting in lower power consumption.

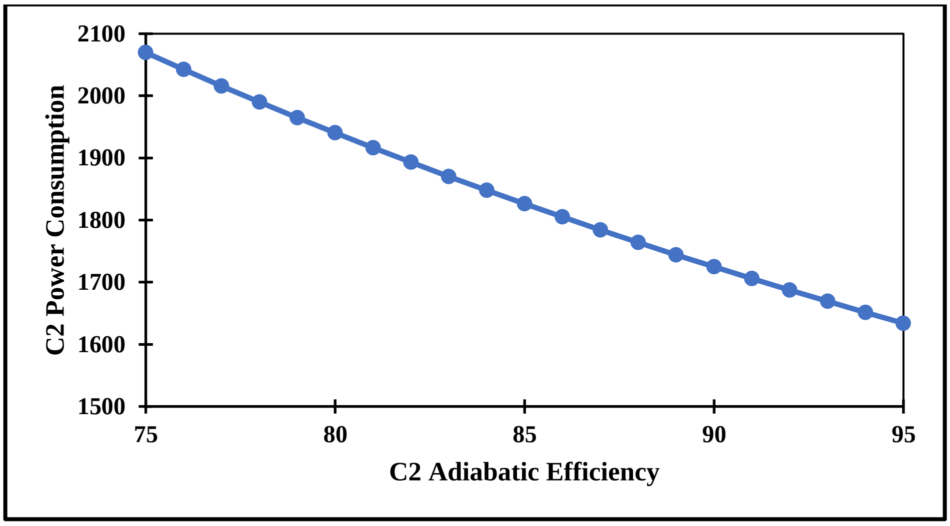

Figure 5.6: Effect of adiabatic efficiency on power consumption

5.6.4 Effect Air Temp on Heat Duty of multi stream heat exchanger

Figure 5.7 illustrates how the temperature of the air, which is introduced to the MHX1 unit, affects the duty cycle of the MHX1. Duty consumption (MHX1) is shown to increase with increasing air incoming temperatures, owing to the desire to achieve the highest cold recovery in the ASU. This means that maintaining air temperature is crucial to getting the best performance out of a multistream heat exchanger.

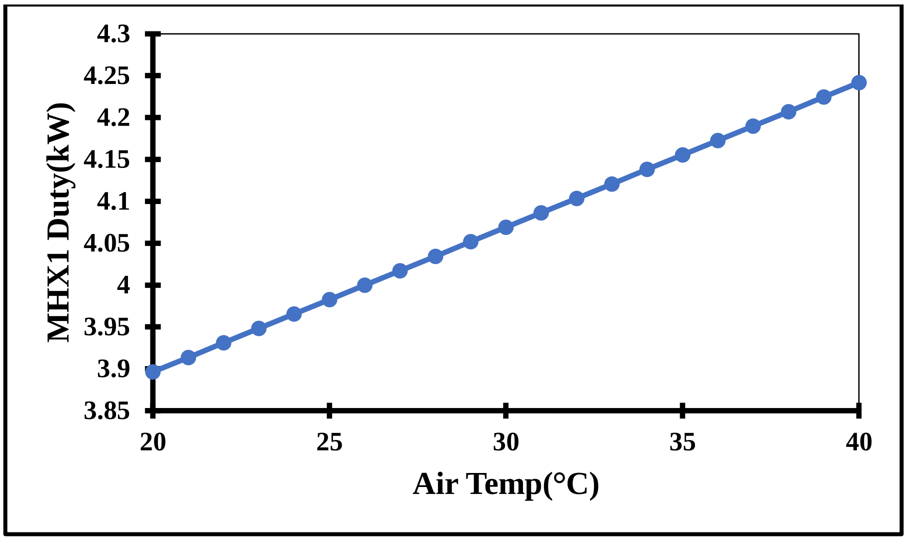

Figure 5.7:Effect Air Temp on Heat Duty of multi stream heat exchanger

5.6.5 Effect of HPC Flowrate on Product Purity

Figure 5.8 illustrates how the change in distillate flow rate of HPC affects the purity of the products since the distillate of HPC is used as reflux in LPC. This variation can be understood from **Figure 5.9**. As the HPC distillate flowrate increases, nitrogen composition in the reflux decreases, which results in a decrease in nitrogen purity when the distillate flowrate is above 22000 kg/h, whereas oxygen purity increases and remains steady with an increase in distillate flowrate.

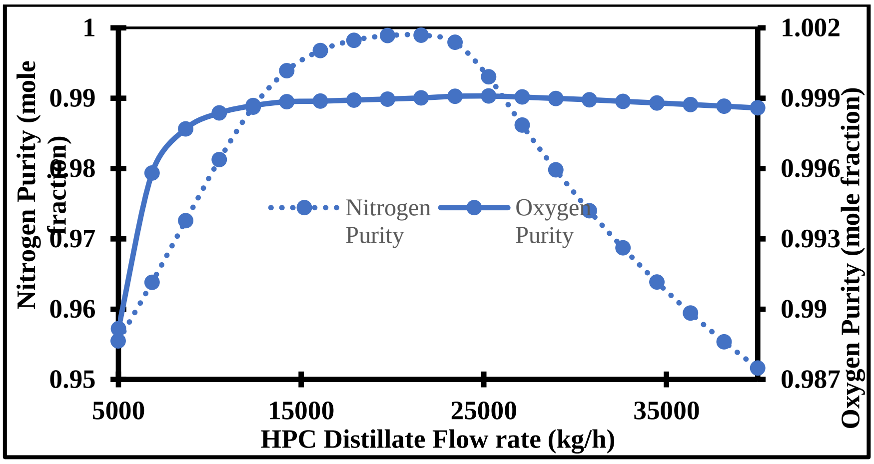

Figure 5.8: Effect of HPC flow rate on product purity

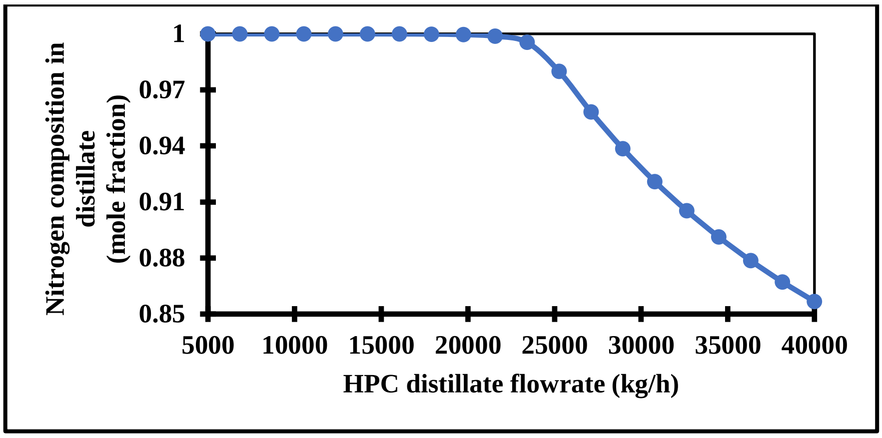

Figure 5.9: Effect of HPC flow rate on Nitrogen Purity

5.6.6 Effect of Waste Stream on Product Purity

Figure 5.10 and **Figure 5.11** display how product purity and flow rate change with variations in waste stream flow rate. It can be noted that an increase in waste stream flowrate increases nitrogen purity and decreases nitrogen flowrate. since the oxygen impurities in the nitrogen stream decrease with an increase in waste stream flow rate. On the other hand, oxygen purity decreases slowly with an increase in waste stream flowrate, and oxygen flowrate drops suddenly and increases steadily with an increase in waste stream flowrate.

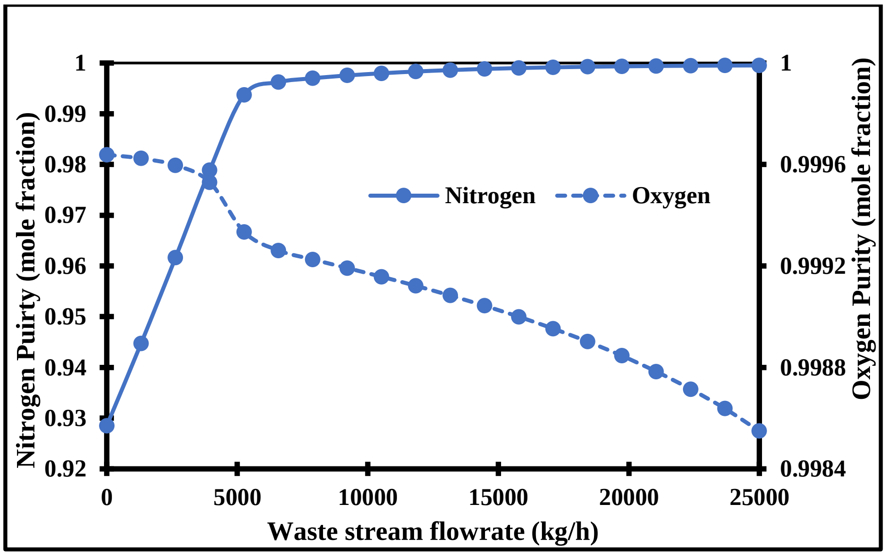

Figure 5.10: Effect of waste stream flow rate on product purity

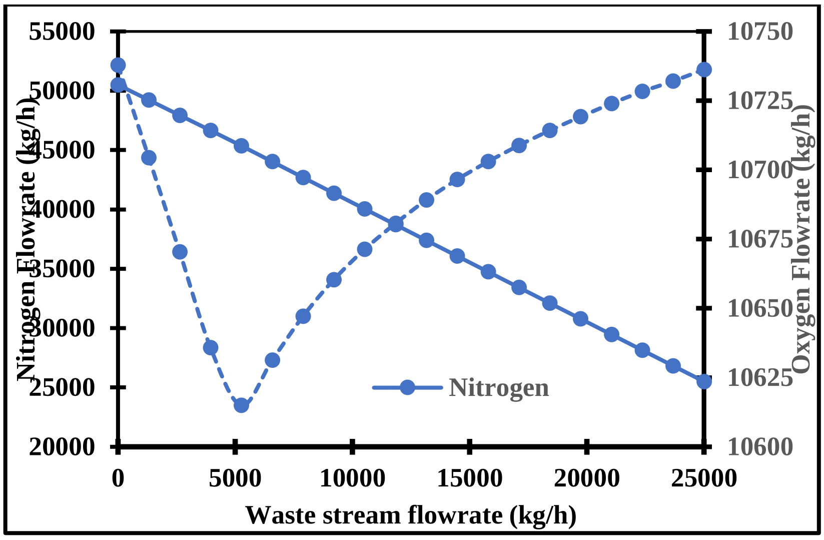

Figure 5.11: Effect of waste stream flow rate on product flow rate

5.7 Results of Multistage Power Generation Systems

The main simulation parameters of the proposed systems are shown in **Table 5-9** and **Table 5-10** for ORC-RC-DEC-RC and ORC-RC-PDEC cycles respectively. Mass flow rate, temperature, and pressure for every stream are presented in these tables.

Table 5-9: ORC-RC-DEC-RC Simulation Results

No	Fluid	Mass Flow Rate (kg/hr.)	Pressure (bar)	Temperature (°C)
LNGIN	LNG	36000	1.01	-162.00
1	LNG	36000	25.01	-160.70
2	LNG	36000	25.01	-98.60
3	NG	36000	25.01	-138.00
NGOUT	NG	36000	4.99	-28.57
4	NH_3	8300	1.51	30
5	NH_3	8300	8.51	-29.81
6	NH_3	8300	8.51	25.00
7	NH_3	8300	1.51	-24.61
8	R-1150	48810	19.01	-100
9	R-1150	48810	19.01	-28.58
10	R-1150	48810	19.01	1.16
11	R-1150	48810	1.66	-95.06
12	NH3	19340	1.51	-30
13	NH3	19340	9.94	-29.81
14	NH3	19340	9.94	25
15	NH3	19340	1.51	-24.70
Sea Water In-1	Sea Water	110000	1.51	30
16	Sea Water	110000	2.51	30.01

Sea Water Out-1	Sea Water	110000	2.51	24.02
Sea Water In-2	Sea Water	550000	1.51	30.00
17	Sea Water	550000	1.51	30.01
Sea Water Out-2	Sea Water	550000	1.51	24.02

Table 5-10: ORC-RC-PDEC Simulation Results

Stream	Fluid	Mass Flow rate (kg/hr.)	Pressure(bar)	Temperature (°C)
LNGIN	LNG	36000	1.01	-162.00
1	LNG	36000	25.01	-160.70
2	LNG	36000	25.01	-99.99
3	NG	36000	25.01	25
NG OUT	NG	36000	4.99	-60.70
4	R-1150	48810	1.51	-100
5	R-1150	48810	19.01	-98.76
6	R-1150	48810	19.01	-28.68
7	R-1150	48810	1.51	-96.85
8	NH3	19350	1.51	-30.00
9	NH3	19350	9.51	-29.82
10	NH3	19350	9.51	23.57
11	NH3	19350	1.51	-24.69
Sea Water In-1	Sea Water	500000	1.01	30
12	Sea Water	500000	2.51	30
Sea Water Out-1	Sea Water	500000	2.51	30.01
Sea Water In-2	Sea Water	110000	1.01	30
13	Sea Water	110000	2.51	30.01
Sea Water Out-2	Sea Water	110000	2.51	24.50

5.7.1 Model Verification

To verify the results of simulations, a two-stage condensation Rankine cycle is reproduced under the same conditions and compared with ref [207]. The simulation results are represented in **Table 5-11**. It can be seen that the results of the simulation is close to [207].

Table 5-11: Results of two-stage ORC compared with reference

Parameters	In study	In Reference[207]
Working Fluid(left Cycle)	R170	R170
Working Fluid(Right Cycle)	R290	R290
TE1	6.631	6.631
TE2	15.00	14.99
Tcond1	-88.73	-88.51
Tcond2	-42.40	-42.41
Wnt (kW)	1745.97	1763

5.7.2 Analysis of working fluid selection

The single-stage Rankine cycle is used as an illustration to examine how working fluid performance varies. Pressure, temperature, and flow rate are all constants for LNG streams, while the working fluids are simulated altered. Using simulation software, NPG, efficiency, working fluid flow rate, and NG exit temperature are determined.

R1150 has the highest NPG (1635.51 kW), according to **Figure 5.12**, while R600 has the lowest NPG (246.81 kW). This means that, the condensation temperature of working fluids has a significant impact on NPG. NPG values for R170 and R23 are 1452.07 kW and 1433.32 kW, respectively. NPG decreases as the condensation temperature drops. The condensation temperature of working fluids should be lower because LNG evaporates at low temperatures. The effect of condensation temperature on efficiency is comparable to that of NPG. When R1150 is used in single-stage RC, efficiency is higher and for R-600 efficiency is lower. For multistage rankine cycles selection of working fluid depends on the efficiency of the systems as shown in **Figure 5.13**.

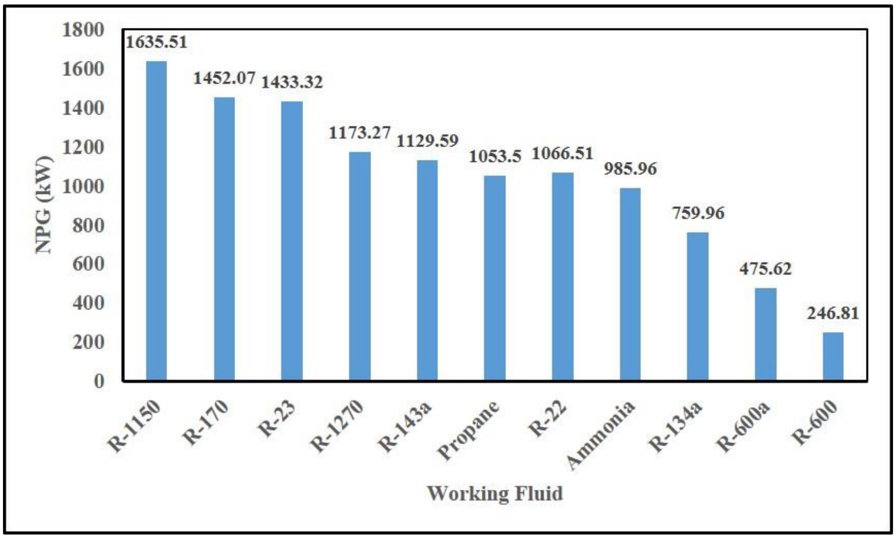

Figure 5.12: Net Power Gain for working fluids in single-stage RC system

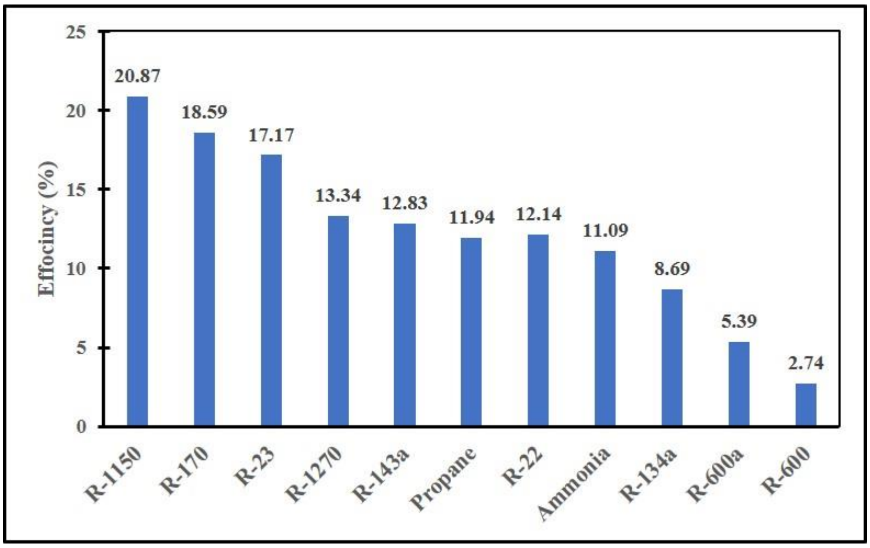

Figure 5.13: Thermal Efficiency in single-stage RC system for refrigerants

5.7.3 The Efficiency of the systems

At first, the efficiencies of the power cycles are compared as listed in **Table 5-12**. There are limitations of single-stage RC and DEC power generation cycle. Single-stage DEC has an efficiency 21.05% which is the least for any power cycle. This is because thermal exergy is wasted in the vaporization process. single-stage RC a have lower efficiencies as compared to multistage cycles. In addition, NG leaves at -108°C. So cold exergy above -108°C is wasted in the vaporization process. In RC, only thermal exergy of LNG is utilized. It is observed that, when RC combines with DEC efficiency increases significantly because thermal and mechanical exergies are utilized for power generation in multistage operation. The efficiency of ORC-DEC-RC cycle is largest followed by ORC-RC-PDEC. Both the ORC-DEC-RC and ORC-RC-PDEC are two-stage RCs combined with DEC.

Table 5-12: Efficiencies of the Power Cycle

Power Cycle	Thermal Efficiency (%)
DEC	21.05
RC	23.78
ORC-ORC	19.98
ORC-RC-DEC	38.78
ORC-RC-DEC-RC	34.93
ORC-DEC-RC	47.52
ORC-RC-PDEC	47.23

5.7.4 Net Power Gain (NPG)

Utilizing LNG cold energy is primarily done to improve the turbine's expansion work, which in turn improves the system's NPG. **Figure 5.14** displays the NPG for each cycle of power generation. The NPG of single-stage RC and DEC are 1795.84 kW and 1867.67 kW respectively. For two-stage RC NPG is 2268.94 kW. It can be observed that, when DEC is connected to multistage RC, NPG increases remarkably. The NPGs of ORC-DEC-RC and ORC-RC-DEC configurations are 2840.89 kW. and 2961.45kW respectively. When one more stage is added to ORC-RC-DEC configuration NPG is 3340.71 kW. NPG of ORC-RC-PDEC is 3826.28kW, higher than any other configuration. This indicates that if LNG stream is preheated before DEC, NPG increases significantly without the addition of a one more stage. This is because, Carnot's theorem states that, when the difference in temperate between the cold and heat sources is higher the power can be more.

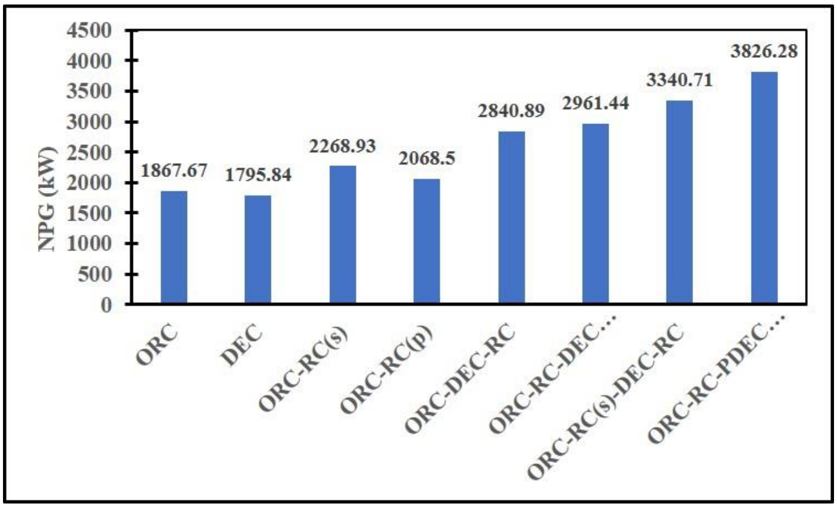

Figure 5.14: NPG for different power generation cycles

5.7.5 Parametric Optimization of ORC-RC-PDEC cycle

LNG mass flow rate, working fluid outlet temperature and turbine outlet pressure are key parameters for designing a multistage power generation system. A sensitivity analysis is carried out for working fluid pump outlet pressure for ORC-RC-PDEC cycle.

5.7.5.1 Effect of LNG mass flow rate on power output for DEC

Figure 5.15 displays the effect of LNG mass flow rate on the performance of net power output. It can be seen that, in the feasible range of the LNG mass flow rate net power output increases linearly because work output varies directly with mass flow rate of the fluid. The power output changes from 3173 kW to 4243 kW in the range of mass flow rate from 30000 kg/hr to 40000 kg/hr.

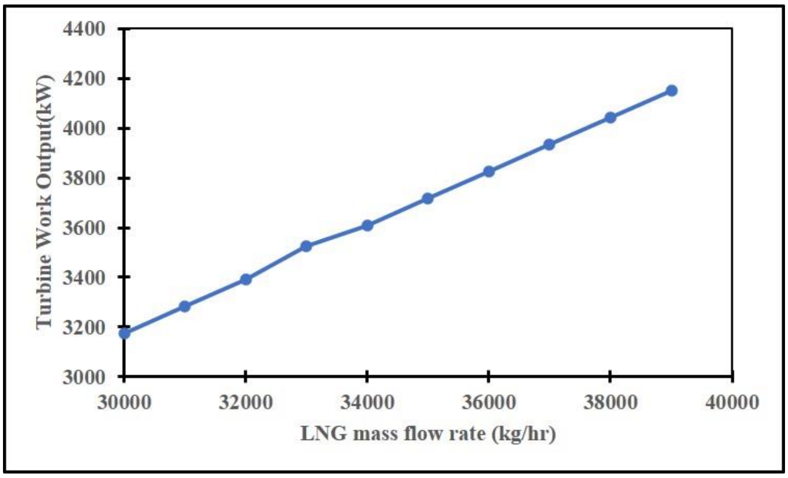

Figure 5.15: Effect of LNG mass flow rate on power output for DEC

5.7.5.2 Effect of working fluid pressure on power output for ORC

Figure 5.16 depicts how ORC-RC-PDEC stage I Rankine cycle performance was impacted by the working fluid's pump output pressure. The turbine output work initially rises swiftly and then swings to a moderate climb at around 14bar, the ideal pump outlet pressure found at 18 bar. Outlet pressure of the turbine depends on the end user of the natural gas.

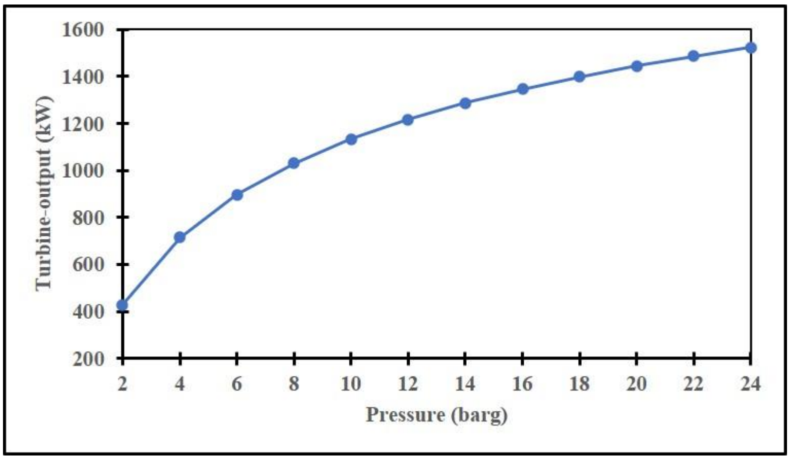

Figure 5.16: Effect of working fluid pressure on power output for ORC

5.7.5.3 Effect of turbine outlet pressure on power output for DEC

Figure 5.17 reveals the performance of the power cycle as the turbine outlet pressure increases from 3.5 to 5 barg for DEC. The inlet turbine pressure is 25 barg which is constant. According to the simulation results, the net power output decrease as the turbine work output increases. Because as the pressure ratio of the turbine decreases the power output also decreases.

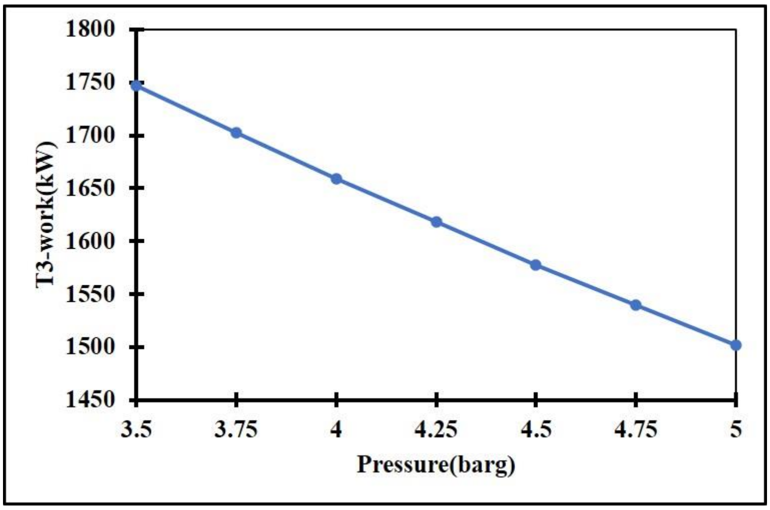

Figure 5.17: Effect of turbine outlet pressure on power output for DEC

5.8 Economic Analysis of Air Separation Unit

The Aspen Hysys Economic Analyzer is an essential component of the Aspen Hysys process simulation software, and it is well-known for its ability to assess the economic feasibility of different chemical and engineering processes. This sophisticated tool enables engineers and analysts to do rigorous cost calculations, profitability analyses, and optimization studies for projects ranging from oil and gas to petrochemicals. Aspen Hysys Economic Analyzer helps users make educated decisions by evaluating multiple design options, analysing cost drivers, and estimating project financial performance by including specific cost data. Its easy-to-use interface and powerful modelling capabilities make it an invaluable resource for organisations looking to maximise efficiency and profitability while minimising risk in their process engineering endeavours[191]. **Table 5-13** presents investment options pertaining to the air separation plant. We have established a nominal operational lifespan of 25 years for the air separation plant, encompassing 8,766 operational hours per year. In

Table 5-14, critical parameters and costs associated with the feed steam are delineated. It is noteworthy that, given the ready availability of atmospheric air and the cold energy harnessed from liquefied natural gas (LNG), the associated cost of the feed stream has been conservatively assessed at zero. Moreover, in **Table 5-15**, the cost of the feed stream has been ascertained via reference to data procured from the Indian Mart website. It is essential to underscore that the cost of oxygen and nitrogen is contingent upon their respective purities. **Table 5-16** encapsulates the outcomes of the economic analysis, which were meticulously evaluated through the utilization of ASPEN HYSYS software. This analysis encompasses the estimation of the total capital cost, the operational expenditure, and the pay-off period. The results unequivocally indicate a favourable pay-off period of **6.79** years, signifying the economic viability of the integrated air separation process with CULNG.

Table 5-13: Investment Options

Operating plant of life	25 Years
Length of Plant start up	05 Years
Start of Basic Engineering	10/12/2024
Operational Years	8766 Hrs.

Table 5-14: Cost of Feed Stream

Name	Air In	LNGIN
Pressure (barg)	0.1	0.1
Temperature (°C)	29.85	-161.59
Mass Flow (kg/hr)	61239.58	84000
Vapor / Phase Fraction	1	0
Molar Enthalpy (kJ/kgmole)	133.11	-89504.40
Stream Price	0	0.45
Stream Price Basis	Mass Flow	Mass Flow

Table 5-15: Cost of Product Stream

Name	NITROGEN	OXYGEN	Waste Stream	NGOut
Pressure (barg)	0.0567	0.1168	0.0376	5.3
Temperature (°C)	10	15	25	-82.37
Mass Flow (kg/hr)	34767.66	10703.48	15768.43	84000
Vapor / Phase Fraction	1	1	1	1
Molar Enthalpy (kJ/kgmole)	-445.53	-302.33	-8.52	-78817.25
Stream Price	8.58	2.1	2.1	0.70
Stream Price Basis	Mass Flow	Mass Flow	Mass Flow	Mass Flow
Cost Rate [Cost/$]	**298306.54**	**22477.32**	**33113.71**	**75600**

Table 5-16: Results of Economic Analysis for Air Separation Process

Total Capital Cost (mUSD)	28.38
Total Operating Cost [mUSD/Year]	10.61
Total Raw Materials Cost [mUSD/Year]	33.13
Total Product Sales [mUSD/Year]	3764.95
Total Utilities Cost [mUSD/Year]	7.95
Desired Rate of Return [Percent/'Year]	20
P.O.Period [Year]	**6.79**
Equipment Cost [mUSD]	7.14
Total Installed Cost [mUSD]	9.13

5.9 Economic analysis of power generation cycles

Net power gain can be improved through the integration of Rankine cycles and direct expansion cycles. However, as stages increase, the capital investment cost will increase. Therefore, economic evaluation is essential for examining the feasibility of the project. Economic evaluation is carried out, which depends on the cost of purchased equipment (PEC). The PEC is found by the Aspen Hysys v.12.1 economic analyzer, which is represented in **Table 5-17**. A certain percentage of PEC is used for the estimation of other investment costs, which is shown in **Table 5-18**. **Table 5-19** includes several factors that are supplied for the economic analysis's convenience. For evaluation of economic feasibility, payback period is considered an indicator [208].

Results of overall economic analysis of various power generation cycles are shown in **Table 5-20**. ORC-RC, ORC-RC-DEC, ORC-RC-PDEC and ORC-RC-RC-DEC are the cycles that are being taken into account. According to, the ORC-RC power generation cycle requires the least amount of capital expenditure, or 1.82 million USD. The ORC-RC-PDEC cycle, on the other hand, calls for the largest capital outlay of 6.75 million USD because the equipment cost of pumps and turbines depends on the total power generated. For example, the cost of turbine T3 is higher in ORC-RC-PDEC cycle than the ORC-RC-DEC-RC cycle. However, the ORC-RC-PDEC cycle's net power gain is 3826 kW, which is much larger than that of any other cycle. Even though the ORC-RC-RC-DEC cycle has an extra stage above the ORC-RC-PDEC cycle, the net power gain is lower. This is because, despite having fewer stages, the preheated cycle (PDEC), according to the Carnot theorem, generates greater power. Additionally, the ORC-RC-PDEC cycle has a larger initial capital investment requirement than other cycles, but it generates significantly more net revenue annually. As a result, the project has a short payback period, which makes it commercially viable. The economic study shows that as the number of stages in the power generation cycle increases, performance generally improves. This improvement, though, comes at the expense of higher capital and operating expenditures. In order to find a balance between performance and economic viability, the number of stages can be reduced by taking the economic analysis into account. Although ORC-RC-PDEC requires a higher initial capital investment than other examples, the net revenue per year is significantly higher, resulting in a quick payback period for the project. This is clearly demonstrated in **Table 5-20**. However, with ORC-ORC, the annual net revenue is frequently lower and the required capital expenditure is less expensive. Because the net power output and cooling have better thermodynamic performance than other examples, ORC-RC-PDEC clearly outperforms them in terms of the dynamic payback period.

Table 5-17: Costs of Purchased Equipment (USD)

Name of Equipment	ORC-ORC	ORC-RC-DEC	ORC-RC-PDEC	ORC-RC-DEC-RC
P1	24100	75000	75000	75000
P2	102300	64700	64700	64700
P3	51000	18600	18600	18700
P4	13300	33600	33600	33600
P5	7300	-	18100	18100
T1	155700	61500	619500	602400
T2	16877	84900	85100	85100
T3	-	377600	737098	381000
COND1	44500	112000	112000	120800
COND2	33800	124200	124200	125300
EV1	85800	119000	119000	133200
EV2	28600	69800	67200	67200
COND3	-	-	-	18800
T4	-	-	-	238200
P6	-	-	-	18700
Total	**562377**	**1629100**	**2076498**	**1999600**

Table 5-18: Total Capital Investment (million USD)

	ORC-ORC	ORC-RC-DEC	ORC-RC-PDEC	ORC-RC-DEC-RC
A. Direct Costs				
1. Onsite Costs				
Total Purchased Equipment Costs (PEC)	0.56	1.62	2.07	1.99
Purchased Equipment	0.18	0.53	0.68	0.65
Installations (33% of PEC)	0.18	0.53	0.68	0.65
Piping(33% PEC)	0.19	0.56	0.72	0.69
Instrumentation and control(12% of PEC)	0.06	0.19	0.24	0.23
Electric Equipment and	0.07	0.21	0.26	0.25
materials(13% of PEC)				
Total onsite costs	1.08	3.12	3.99	3.84
2. Offsite Costs				
Land, Civil, Structural and	0.14	0.40	0.51	0.49
Architectural work(25% PEC) Service Facilities (35% of PEC)	0.19	0.56	0.72	0.69

Total offsite costs	0.33	0.97	1.24	1.19
Total Direct Costs	1.33	4.09	5.23	5.03
B. Indirect Costs				
Engineering and Supervision(8% of DC)	0.11	0.32	0.41	0.40
Construction Price and	0.21	0.61	0.78	0.75
Contractor profit (15% of				
DC)				
Sum	0.32	0.94	1.20	1.17
Contingency(15% of the	0.04	0.14	0.18	0.17
above)				
Total Indirect Costs	0.37	1.08	1.38	1.33
Fixed Capital Investment	1.79	5.18	6.62	6.36
Other outlays(2% of fixed	0.03	0.10	0.13	0.12
Total capital investment	**1.82**	**5.28**	**6.75**	**6.49**

Table 5-19: Parameters used in economic evaluation

Annual Operating Hours	7300 h/year
Rate of discount	10%
Life time of power plant	15 years
Price of electricity	7.18 INR/kWh
Exchange Rate	1 USD = 74.42 INR

Table 5-20: Results of Economic Evaluations (million USD) of Multistage power generation unit

Factor	**(ORC-ORC)**	**(ORC-RC-DEC)**	**(ORC-RC-PDEC)**	**(ORC-RC-RC-DEC)**
Initial capital Investment (mil-	1.82	5.28	6.75	6.49
lion USD)				
net power output(kW)	1916	2961	3826	3340.71
Revenue of net power output	1.34	2.08	2.69	2.35
(million USD/year)				
Operation and Maintenance	0.11	0.32	2.01	2.01
Cost (20% of PEC) (million				
USD/year)				
Other expense (million	0.012	0.032	0.20	0.20
USD/year) 2% of PEC				
Total Costs	1.94	5.63	8.96	8.70
Payback time (years)	**1.45**	**2.70**	**2.67**	**3.10**

Chapter 6: : Conclusions & Future Scope

Natural gas requires approximately 830 kJ/kg of energy to liquefy, and this energy can be stored as cold energy. Regasification terminals that need cooling or refrigeration can make use of this energy. A review of power generation shows that multistage compound cycles increase the processes thermodynamic, exergy efficiency, and NPG, but they require a significant capital outlay. This element advises that the ideal multistage cycle be created. Power generation can be combined with other applications including air separation, water desalination, and NGL separations, and new processes can be created. A number of researchers proposed CULNG-based technologies for producing hydrogen, recovering NGLs, storing air-liquids, storing food in cold storage, and transporting it. There has been a lot of research done on the potential of CULNG, but there is still room for improvement. The integration or cascade of the processes to increase efficiency is a crucial research subject. It requires a more thorough, theoretical investigation. In addition, an economic analysis needs to be done. The cascade method and integration of different processes significantly improve LNG cold energy use while reducing energy consumption. Utilizing cold energy could aid in the reduction of energy and consumption-related emissions in industry. The main criteria for determining whether LNG cold energy utilization projects are feasible should be energy savings and carbon reduction.

CULNG has gained popularity as a substitute for waste energy utilization systems in the recent past due to its high energy density and capacity to be combined with different applications of CULNG. As a result, the amount of scientific research on CULNG has rapidly increased, and an increasing number of international organizations are looking into the potential of this technology. Despite the fact that the first CULNG publication appeared in 1977, the trend of publication started to quickly increase after 2003. In the categories of "engineering" and "energy," scholarly journals and conference proceedings held the most publications on this subject in Q1. In order to discover research gaps and potential future trends that could serve as inspiration for further research, the most pertinent elements of the current body of work were examined using bibliometric techniques in the analysis of the keyword data. The following is a summary of the key findings that can be drawn from the research on CULNG, backed by the bibliometric analysis done.

- The majority of methods used to research CULNG have been focused on exergy and thermodynamic analyses of the system, with the goal of estimating CULNG efficiency and suggesting ways to improve the performance of the system, which is presently the primary shortcoming of this technology.
- The keyword analysis also revealed that a portion of the research on CULNG was interested in examining the system's economic viability. However, compared to phrases connected to the thermodynamic analysis, keywords relating to the economic side were less relevant, indicating the first research gap.
- One of the most important study topics is the integration, or cascade, of processes to improve efficiency. It necessitates a deeper, more theoretical analysis. In order to increase productivity, future research must focus on these processes: modification and development. Additionally, it is necessary to conduct an economic study. The cascade method dramatically reduces energy usage while improving the use of LNG cold energy. Utilizing cold energy could help cut emissions associated with energy use and consumption in business.
- When the keywords were analyzed, there were few references to experimental investigations that showed the system functioning in practice. This demonstrates how this component is unreliable and has not been well examined. This is the primary research gap that has to be filled in order for the CULNG technology to advance to a substantial stage.

In general, bibliometric analysis offers insightful information about the state of research in the area of LNG cold utilization at this time. The results of this study could assist future research and development activities focused on improving the use of LNG as a cold source as the globe continues to move towards more environmentally friendly and sustainable energy sources.

In the study of air separation integrated with CULNG, the least energy consumption is determined by optimizing a process for the air separation process integrated with LNG regasification. An optimized design is created after investigating the effects of changing the number of equipment components using an exergy analysis and parametric optimization. The integration of LNG cold energy with the ASP offers an effective solution to improve the efficiency of the ASP, reduce energy consumption, and reduce greenhouse gas emissions compared to traditional air separation processes, as no fuel is burned in this process. The recent studies reviewed in this literature have demonstrated the feasibility of using subcooled LNG to pre-cool the air feed to the ASP, producing high-purity oxygen and nitrogen.

Some of the most significant outcomes of this integration are as follows.

- The use of a DEC system and the incorporation of ASP with waste heat recovery led to a substantial reduction in power consumption and an increase in system efficiency. With the help of LNG vaporization (DEC) technology, the compressor waste's low-grade heat is converted into electricity.
- In the cryogenic ASU, high-quality gaseous oxygen (99.99 mol%) and nitrogen (99.99 mol%) are produced. The SEC is approximately 0.32 kWh/kg-O_2 for pure oxygen and 0.10 kWh/kg-N_2.
- ASU requires around 3982.73 kW of power, which is produced by DEC. Energy savings in HX1 and HX2 are 1960 kW and 1837 kW, respectively, which are utilized for LNG vaporization.
- The output of electricity generation and the liquefaction process are both enhanced by the cold exergy of LNG. The expander and the throttle valve prior to the high-pressure distillation column (HPC) are both removed after utilising the LNG stream in the ASU cycle. The suggested new cycle efficiently uses low-grade energy while recovering LNG's cold and pressure exergy.
- Exergy analysis findings revealed that the multi-stream heat exchanger (MHX1), heat exchanger (HX3), and distillation column (LPC) had higher exergy destruction rates than the other components. Depending on the requirement and location, the NG outflow stream's temperature (-83.55°C), can be further used for any other purpose.
- A comprehensive parametric analysis was conducted to elucidate the critical factors governing the design of an air separation system integrated with the CULNG processes. The study highlighted several key parameters, including LNG flow rate, LNG inlet temperature, pressure, air inlet parameters, and high-pressure column flow rate, as pivotal in shaping the system's performance and efficiency. Through rigorous parametric analysis, we were able to optimize essential variables, such as air inlet temperature, HPC flow rate, turbine outlet pressure, and waste stream flow rate, contributing to the enhanced design and operation of the integrated CULNG and air separation system. These findings underscore the significance of parameter

optimization in achieving optimal performance and efficiency in such complex industrial processes.

- A payback period of 5.12 years is regarded as economically acceptable in this scenario, suggesting that the investment is projected to create adequate returns to refund the initial cost within a reasonable duration, making it a financially sensible option.

Overall, LNG and air separation process integration is a viable and appealing option for the LNG industry. However, the integrated process has some technical and operational challenges, such as the need for careful control of temperatures and pressures, but these can be overcome with proper design and operation. Further research is required to investigate the economic feasibility and practical implementation of this process.

The study of multistage power generation cycles presents a cold LNG usage direct expansion cycle coupled with two-stage RC cycles. The following are some of the most significant outcomes of this integration.

- The ORC-RC-PDEC system's efficiency is enhanced by 23.45% and NPG is increased by 213.06% when compared to single-stage RC systems, which is a considerable improvement.
- On multistage RC systems, the choice of working fluid has a significant influence. R1150 produces better results in terms of efficiency and NPG when used as a working fluid. This demonstrates that the condensation temperature of the working fluids is an important selection factor. The choice of working fluid relies on the temperature of the NG outflow when a further stage is introduced. The most suitable working fluid for second is NH3, according to an examination of the selection criteria.
- Given that work output fluctuates with changes in these parameters, the findings of the sensitivity analysis show that the LNG mass flow rate, working fluid pump outlet pressure, and turbine outlet pressure are crucial parameters for the design of the power system.
- Economic analysis of power generation cycles demonstrates that performance improves with stage number but increases capital and operating investment as well. As a result, the stage number can be restricted by considering the economic analysis. One of the

most important findings of the study is that if the LNG stream is preheated before DEC, the NPG increases dramatically without the need for an additional stage.

The study's findings imply that the proposed power system in this work is feasible. An economic analysis based on thermodynamic data and a more thorough design are needed for further evaluation and for a viable system.

Currently, India imports 42.7 MMTPA of LNG annually; by 2030, that figure is expected to rise to 83 MMTPA. Around 10 million people will have access to electricity if CULNG is properly implemented, which is a sizable figure. India is becoming increasingly interested in the cold utilisation of LNG, which has a number of uses in the transportation, power production, refrigeration, and air conditioning industries. For a nation wanting to lessen its reliance on more polluting fuels, using LNG presents a number of benefits, including lower emissions, lower costs, and increased energy efficiency. With the assistance of the government and the rising need for sustainable energy sources, LNG is anticipated to become a more substantial component of India's energy mix over the next few years.

6.1 Future Scope

It is possible to significantly improve energy efficiency and cut greenhouse gas emissions by using the cold energy from LNG. A more sustainable future may result from research in this field, which could lead to the creation of new technologies and uses for LNG's cold energy. A review of power generation shows that multistage compound cycles increase the processes thermodynamic, exergy efficiency, and NPG, but they require a significant capital outlay. This element advises that the ideal multistage cycle be created. Power generation can be combined with other applications including air separation, water desalination, and NGL separations, and new processes can be created. A number of researchers proposed CULNG-based technologies for producing hydrogen, recovering NGLs, storing air-liquids, storing food in cold storage, and transporting it. There has been a lot of research done on the potential of CULNG, but there is still room for improvement. The process integration or cascade of the processes to increase efficiency is a crucial research subject. It requires a more thorough, theoretical investigation. Future research must prioritise the modification and improvement of these processes in order to boost productivity. In addition, an economic analysis needs to be done. The cascade method and integration of different processes significantly improve LNG cold energy use while reducing energy consumption. Besides, individual analyses, multi-objective optimization studies can be used as an optimization technique to determine the LNG cold utilization systems' optimal operation point from the viewpoints of thermodynamics, economics, and the environment. Utilizing cold energy could aid in the reduction of energy and consumption-related emissions in industry. The main criteria for determining whether LNG cold energy utilization projects are feasible should be energy savings and carbon reduction.

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Chapter 7: Appendices

7.1 Performance of MHX1

Table 7-1: Performance of MHX1

Sr No	**Parameter**	**Results**
1	Duty	4.01 MW
2	Heat Leak	0.00 MW
3	Heat Loss	0.00 MW
4	UA	2217756.61 kJ/C-h
5	Min. Approach	2.00 °C
6	LMTD	6.52 °C

7.2 Side Results of MHX1

Table 7-2: Side Results of MHX1

Pass Name	**Inlet T° C**	**Outlet T° C**	**Mass Flow(kg/hr.)**	**Duty (kW)**	**Hot/cold**
5-6	27	-173.75	61240	-4.01	Hot
21-22(Oxygen)	-181.28	15.00	10700	1.018	Cold
09-10(Nitrogen)	-183.15	10.00	34770	1.917	Cold
12-13 (Waste Stream)	-184.00	25.00	15774	0.89	Cold
28-29 (NG Out)	-80.00	-77.17	84000	0.19	Cold

7.3 Performance of MHX2

Table 7-3: Performance of MHX2

Sr No	**Parameter**	**Results**
1	Duty	0.2524 MW
2	Heat Leak	0.00 MW
3	Heat Loss	0.00 MW
4	UA	301254.16 kJ/C-h
5	Min. Approach	0.454 °C
6	LMTD	3.038 °C

7.4 Side Results of MHX1

Table 7-4: Side Results of MHX1

Pass Name	**Inlet T° C**	**Outlet T° C**	**Mass Flow(kg/hr.)**	**Duty (kW)**	**Hot/cold**
15-16	-174.28	-186.00	29430	-0.182	Hot
18-19	-178.32	-184.00	21220	-0.071	Hot
11-12	-194.19	-175.00	15774	0.193	Cold
08-09	-189.61	-175.43	34770	0.061	Cold

7.5 Parameters for HPC

Table 7-5: Parameters for HPC

Stage	**Pressure(barg)**	**Temperature (° C)**	**Net Liquid (kg/hr)**	**Net Vapor (kg/hr)**
0.00 (Condenser)	4.300	-178.33	30853.32	0
1.00	4.30	-178.32	30852.27	52069.5
2.00	4.31	-178.27	30866.04	52068.45
3.00	4.33	-178.22	30879.01	52082.23
4.00	4.34	-178.17	30890.67	52095.2
5.000	4.36	-178.11	30900.28	52106.85
6.00	4.37	-178.05	30906.82	52116.46
7.00	4.39	-177.98	30908.86	52123
8.00	4.41	-177.89	30904.43	52125.04
9.00	4.42	-177.8	30890.95	52120.61
10.00	4.44	-177.68	30865.07	52107.13
11.00	4.45	-177.54	30822.71	52081.25
12.00	4.47	-177.37	30759.25	52038.89
13.00	4.48	-177.15	30670.07	51975.44
14.00	4.50	-176.88	30551.51	51886.25
15.00	4.52	-176.55	30402.34	51767.69
16.00	4.53	-176.17	30225.29	51618.53
17.00	4.55	-175.73	30027.87	51441.47
18.00	4.56	-175.26	29821.83	51244.06
19.00	4.58	-174.77	29620.78	51038.01
20.00	4.60	-178.33	29428.95	50836.96

7.6 Parameters for LPC

Table 7-6: Parameters for LPC

Stage	Pressure(barg)	Temperature (° C)	Net Liquid (kg/hr)	Net Vapor (kg/hr)
0	0.2026	-194.19	19001.6	34767.66
1	0.2051	-194.15	18998.45	32553.08
2	0.2076	-194.09	18988.05	32549.93
3	0.2101	-193.99	18962.35	32539.53
4	0.2126	-193.82	18906.81	32513.83
5	0.2151	-193.5	18799.54	32458.29
6	0.2176	-192.95	18619.43	32351.02
7	0.2201	-192.09	46530.95	32170.91
8	0.2226	-192.07	46536.72	30653.48
9	0.2251	-192.04	46542.05	30659.26
10	0.2276	-192	46545.04	30664.59
11	0.2301	-191.93	46538.12	30667.58
12	0.2326	-191.72	46495.38	30660.66
13	0.2351	-191.15	46354.92	30617.91
14	0.2376	-189.61	46065.66	30477.45
15	0.2401	-187.52	45849.32	45956.63
16	0.2426	-185.59	45746.2	45740.29
17	0.2451	-184.34	45664.9	45637.17
18	0.2476	-183.7	45563.06	45555.87
19	0.2501	-183.4	45452.69	45454.03
20	0.2525	-183.24	45348.68	45343.66
21	0.255	-183.15	45257.5	45239.65
22	0.2575	-183.09	54013	45148.47
23	0.26	-181.85	54058.35	43309.52
24	0.2625	-181.32	54039.63	43354.86
25	0.265	-181.1	53991.68	43336.14
26	0.2675	-181	53938.43	43288.19
27	0.2675	-180.95	53889.08	43234.94
28	0.27	-180.91	53846.09	43185.6
29	0.2725	-180.87	53809.69	43142.6
30	0.275	-180.84	53779.32	43106.2
31	0.2775	-180.81	53754.28	43075.83
32	0.28	-180.78	53733.84	43050.79

33	0.2825	-180.76	53717.36	43030.35
34	0.285	-180.73	53704.25	43013.87
35	0.2875	-180.71	53694.02	43000.76
36	0.29	-180.68	53686.21	42990.53
37	0.2925	-180.66	53680.47	42982.72
38	0.295	-180.64	53676.48	42976.98
39	0.2975	-180.62	53676.56	42972.99
40 (Reboiler)	0.3	-180.62	10703.49	42973.07

7.7 Simulation Results of Single Stage RC

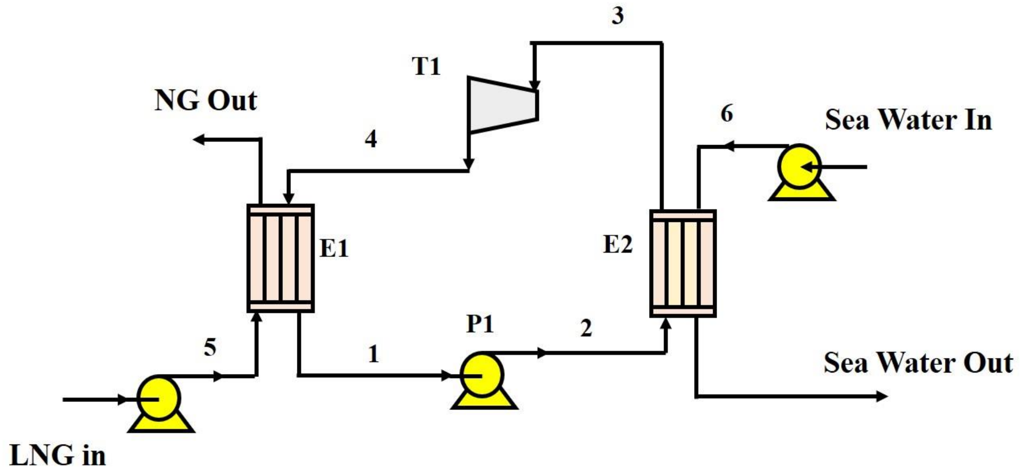

Figure 7.1: Single Stage RC

Table 7-7: Simulation Results of Single Stage RC

Stream	Fluid	Mass Flow Rate (kg/hr)	Pressure (barg)	Temperaure (° C)
1	R-1150	52000	0.50	-100.00
2	R-1150	52000	36.00	-97.47
3	R-1150	52000	35.90	25.00
4	R-1150	52000	0.5	-96.85
LNG In	LNG	36000	0.1	-162
5	LNG	36000	3.98	-161.87
NG out	NG	36000	3.97	-105.10
Sea Water In	Water	100000	0.1	30.00

6	Water	100000	1.5	30.01
Sea Water Out	Water	100000	1.5	23.22

7.8 Simulation results of two Stage Rankine Cycle

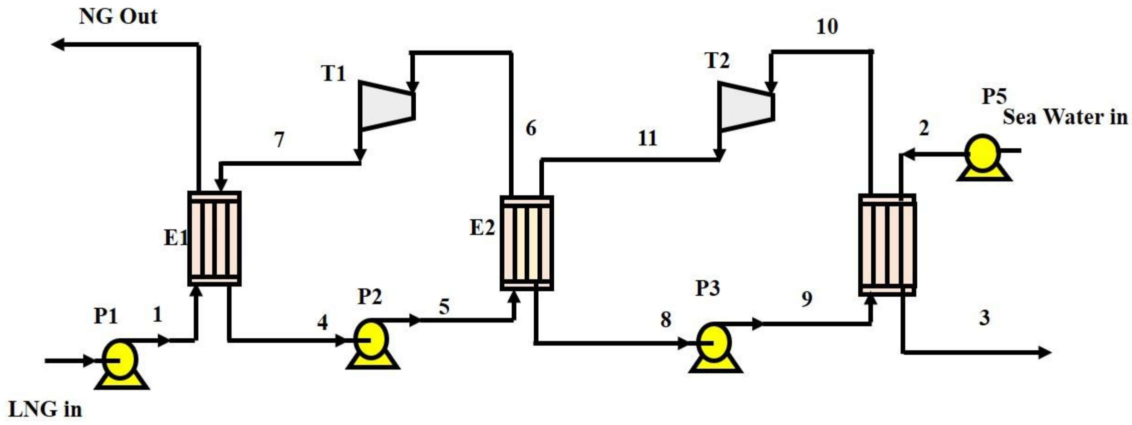

Figure 7.2: ORC-RC combination

Table 7-8: Simulation Results of ORC-RC combination

Stream	Fluid	Mass Flow Rate (kg/hr)	Pressure (barg)	Temperaure(° C)
LNGIN	LNG	36000	0.10	-162.00
1	LNG	36000	24.00	-160.7
NGOUT	NG	36000	24.00	-99.99
Sea Water In	Water	1100000	0.10	30.00
2	Water	1100000	1.50	30.01
3	Water	1100000	1.50	24.50
4	R-1150	48810	0.50	-100.00
5	R-1150	48810	18.00	-98.76
6	R-1150	48810	18.00	-28.68
7	R-1150	48810	0.50	-96.85
8	NH_3	19350	0.50	-30.00
9	NH_3	19350	8.50	-29.82
10	NH_3	19350	8.50	23.57
11	NH_3	19350	0.50	-24.69

7.9 Simulation Results of ORC-DEC-RC

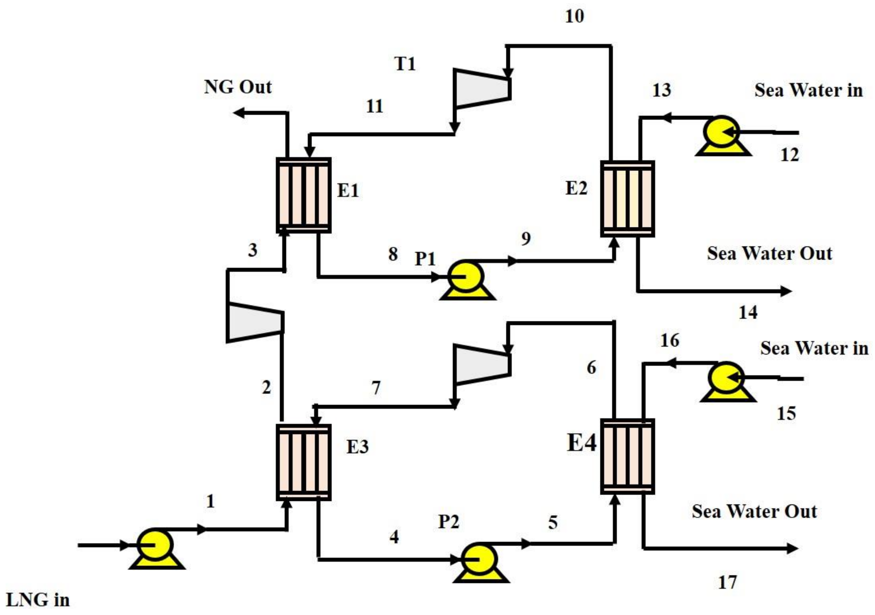

Figure 7.3: Simulation of ORC-DEC-RC

Table 7-9: Simulation of Results ORC-DEC-RC

Stream	Fluid	Mass Flow Rate (kg/hr)	Pressure (barg)	Temperaure(° C)
LNGIN	LNG	36000	0.10	-162
1	LNG	36000	24.00	160.70
2	NG	36000	24.00	-99.26
3	NG	36000	3.98	-138.00
NG Out	NG	36000	3.98	-30.28
4	R-1150	47000	0.50	-100.00
5	R-1150	47000	36.00	-97.49
6	R-1150	47000	36.00	25.00
7	R-1150	47000	0.5	-96.85
8	NH_3	8350	0.5	-30.00
9	NH_3	8350	8.5	-29.82
10	NH_3	8350	8.5	23.57
11	NH_3	8350	0.50	-24.69
12	Water	1000000	0.1	30.00
13	Water	1000000	1.5	30.01

14	Water	1000000	1.5	23.92
15	Water	700000	0.1	30.00
16	Water	700000	1.5	30.01
17	Water	700000	1.5	25.97

7.10 Simulation Results of ORC-RC-DEC

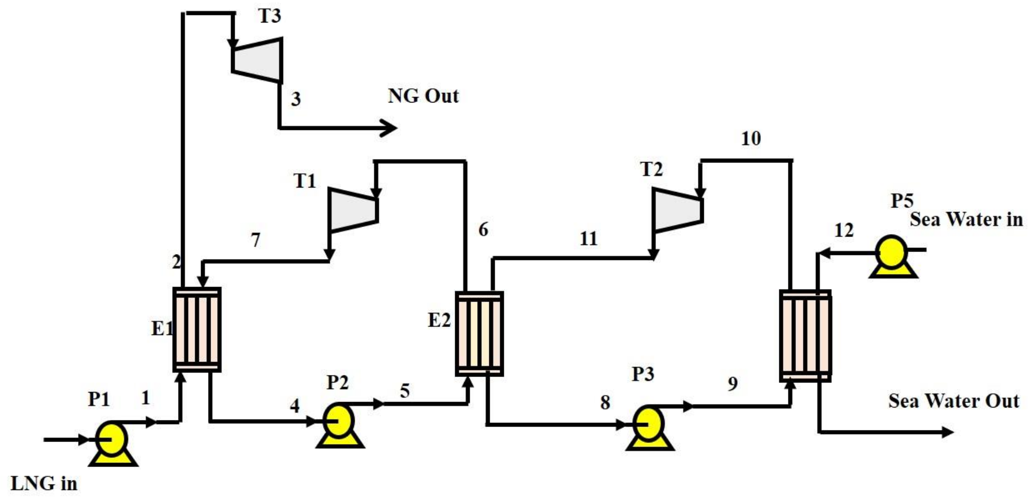

Figure 7.4: Simulation of ORC-RC-DEC

Table 7-10: ORC-RC-DEC

Stream	Fluid	Mass Flow Rate (kg/hr)	Pressure (barg)	Temperaure(° C)
LNGIN	LNG	36000	0.5	-162.00
1	LNG	36000	24.00	-160.7
2	NG	36000	24.00	-99.99
3	NG	36000	3.98	-138.00
4	R-1150	48810	0.50	-100.00
5	R-1150	48810	18.00	-98.76
6	R-1150	48810	18.00	-28.68
7	R-1150	48810	0.50	-96.85
8	NH_3	19350	0.50	-30.00
9	NH_3	19350	8.50	-29.82
10	NH_3	19350	8.50	23.57
11	NH_3	19350	0.50	-24.69
Sea Water In	Water	1100000	0.1	30.00
12	Water	1100000	1.50	30.01
Sea Water Out	Water	1100000	1.50	24.05

7.11 Performance of different working fluids in single stage cycles

Table 7-11: Performance of different working fluids in single stage cycle

S.No	Working Fluid	Flowrate kg/hr	WO	WI	NPG	Qh	Efficiency	Cond Temp @0.3barg	Vap Pres (barg) @25degC	NG Temp
1	R-1150	50000	1774	138.49	1635.51	7833	20.88	-99.48	36	-103.6
2	R-170	55000	1688	235.93	1452.07	7809	18.59	-83.79	41.07	-109.5
3	R-23	110000	1601	167.68	1433.32	8347	17.17	-77.36	30	-80.46
4	R-1270	64000	1302	128.73	1173.27	8792	13.34	-42.08	10.57	-45.1
5	R-143a	120000	1258	128.41	1129.59	8802	12.83	-41.51	11.68	-42.91
6	Propane	65000	1192	138.5	1053.5	8819	11.95	-36.1	8.51	-38.57
7	R-22	125000	1196	129.49	1066.51	8784	12.14	-35.55	9.45	-40.78
8	Ammonia	22000	1094	108.04	985.96	8887	11.09	-27.7	8.932	-32.25
9	R-134a	130000	892	132.04	759.96	8737	8.7	-20.21	5.62	-28.8
10	R-600a	80000	623	147.38	475.62	8814	5.4	-5.19	2.5	-12.27
11	R-600	80000	401	154.19	246.81	8998	2.74	6.548	1.415	6.245

List of Publications

1. B. Shingan, V. Parthasarthy, N. Banerjee, VP. Singh “Liquefied Natural Gas Value Chain- A Comprehensive Review & Analysis” Chem. Eng. Technol. December 2023, **(SCI, IF 2.26).**

2. Shingan, B., Vijay, P., & Pandian, K. (2023). Advanced Design of Power Generation Cycle with Cold Utilization from LNG. Arabian Journal for Science and Engineering, 1–16. **(SCI, IF 2.90)**

3. B. Shingan, V. Parthasarthy, K. Pandiyan “Cryogenic Air Separation Process Integrated with Cold utilization of Liquefied Natural Gas: Design, Simulation and Performance Analysis,” Arabian Journal for Science & Engineering, August 2023. **(SCI, IF 2.90)**

4. B. Shingan and V. Parthasarthy, “Recent Progress in Cold Utilization of Liquefied Natural Gas,” Chem Eng Technol. May 2023. **(SCI, IF 2.25)**

5. S. Rajput, N. Sabharwal, A. Singh, B. Shingan, BP Yadav “City gas distribution Incident Analysis in India using Pareto Principle-A comprehensive analysis, Journal of Failure Analysis & Prevention”, 1-13, 2022 **(SCI, IF 0.94)**

6. Bhalchandra Shingan, Karthikraja Pandiyan, Brahminder Singh ‘Design, Simulation & Optimization of Multistage Power Generation Cycle from Cold Utilization of Liquefied Natural Gas’ AIP Conference Proceedings 2023 **(Scopus)**

7. Shingan, B., Harshita, M., Verma, N., Joshi, M., Vishwakarma, H. (2023). Comprehensive Review on the Selection of Materials in City Gas Distribution Value Chain. In: Sahu, A.K., Meikap, B.C., Kudapa, V.K. (eds) Energy Storage and Conservation. MESC 2022. Springer Proceedings in Energy. Springer, Singapore. https://doi.org/10.1007/978-981-99-2870-5_2. **(SCOPUS).**

8. B. Shingan, K. Pandiyan, B. Singh, and R. Gore, “An exergy analysis of boil-off gas recovery process,” Mater Today Proc, 2022, doi: https://doi.org/10.1016/j.matpr.2022.11.460. **(Scopus).**

9. Shingan, B., Harshita, M., Verma, N., Joshi, M., Vishwakarma, H. (2023). Comprehensive Review on the Selection of Materials in City Gas Distribution Value Chain. In: Sahu, A.K., Meikap, B.C., Kudapa, V.K. (eds) Energy Storage and Conservation. MESC 2022. Springer Proceedings in Energy. Springer, Singapore. https://doi.org/10.1007/978-981-99-2870-5_2 **(Book Chapter)**

10. B. Shingan “Cold Utilization of LNG: Indian Perspective “Gas Statistics Review, July 2023

11. Bhalchandra Shingan , P. Vijay A Critical Review and Future Perspective of Hydrate Mitigation Technologies, Test Engineering & Management 82 (January-February 2020), 3621 – 3628, 2020 **(Scopus).**

12. AK Arya, B Shingan, PC Varaprasad Seismic design of continuous buried pipeline International Journal of Engineering and Science 1 (1), 6-17, 2015

13. AK Arya, B Shingan Scour-mechanism detection and mitigation for subsea pipeline integrity International Journal of Engineering Research & Technology, 2012

Under Revision

1) B. Shingan, V. Parthasarthy, N. Banerjee, A. K. Arya, V.P. Singh "Conceptual Design & Analysis of Air Separation Process Integrated with Cold utilization of Liquefied Natural Gas" Energy Sources Part A: Recovery, Utilization and Environmental Effects. **(SCI, IF 2.90)**

Book Edition

S. Timung, B. Shingan, M. Pujari "Microfluidics in Petroleum Engineering" Taylor & Fransis

Book Chapter

B. Shingan, A. K. Arya "Efficiency Meets Innovation: City Gas Systems in Modern Buildings" Sustainable Technologies for Energy Efficient Buildings, CRC Press, Taylor & Fransis group.

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