QATAR UNIVERSITY

COLLEGE OF ENGINEERING

# HYBRID LIFE CYCLE SUSTAINABILITY ASSESSMENT OF LIQUIFIED NATURAL GAS SUPPLY CHAIN

BY

HUSSEIN MOHAMED AL-YAFEI

A Dissertation Submitted to

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in Partial Fulfillment of the Requirements for the Degree of

Doctorate of Philosophy in Engineering Management

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# COMMITTEE PAGE

The members of the Committee approve the Dissertation of
Hussein Mohamed Al-Yafei defended on 10/05/2022.

Dr. Murat Kucukvar
Thesis/Dissertation Supervisor

Prof. Volkan S. Ediger
Committee Member

Dr. Galal Abdella
Committee Member

Dr. Kadir Ertogral
Committee Member

Add Member

Approved:

Khalid Kamal Naji, Dean, College of Engineering

# ABSTRACT

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Title: Hybrid Life Cycle Sustainability Assessment of Liquified Natural Gas Supply Chain

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Integrating sustainability into the distribution network process is a significant problem for any industry hoping to prosper or survive in today's fast-paced environment. Since gas is one of the world's most important fuel sources, sustainability is more important for the gas industry. While such environmental and economic effects have been extensively researched in the literature, there is little emphasis on the full social sustainability of natural gas production and supply chains in terms of the triple bottom line. The basic objective of this dissertation is to perform the first hybrid life cycle sustainability assessment (LCSA) of liquefied natural gas and evaluate its performance from natural gas extraction to LNG regasification after delivery through a maritime transport carrier. LCSA is used for estimating the social, economic, and environmental impacts of processes, and our life cycle model included the multi-region input-output analysis, Aspen HYSYS, and LNG maritime transport operations sustainability assessment tools. The results spot the light on the most contributors of $CO_2$-eq emission. It is found that LNG loading (export terminal) is the source that generated the highest carbon footprint, followed by the MDEA sweetening unit with the contribution of 40% and 24%, respectively. Socially, around 73% of human health impact comes from SRU and TGTU units, which contribute most to particulate matter emissions. Based on the interpretation of life cycle results, the environmental indicators show better performance in the pre-separation unit and LNG receiving terminal

representing a sustainability factor equal to 1. In terms of social and economic impacts, the natural gas extraction stage presents the best performance among all other stages, with a sustainability factor equal to 1. Based on this study's findings, an integrated framework model is proposed. Various suggestions for sustainability strategies and policies that consider business sustainability and geopolitics risk are presented.

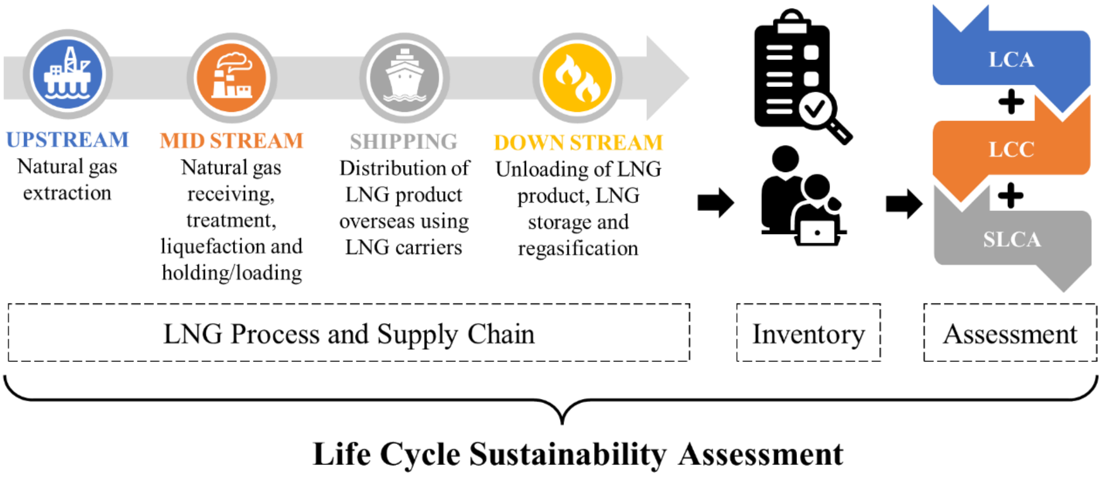

Figure 1. Graphical abstract of the research methodology.

# DEDICATION

*I dedicate this dissertation report to the people working in the oil and gas industries, especially in liquified natural gas production and associated supply chain worldwide, to have a more sustainable world. We need to keep the momentum of assuring minimum environmental impacts to our world, maintain an excellent economy, and social satisfaction for ourselves and future generations.*

Name: Hussein Al-Yafei
Place: Doha, Qatar
Date: June 2022

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| Acronym | Description |
|---|---|
| AGRU | Acid Gas Removal Unit |
| BACT | Best Available Control Technology |
| BOG | Boil-off Gas |
| BTX | Benzene, Toluene, and Xylene |
| $C_3$MR | Propane Pre-Cooled Mixed Refrigerant |
| CAPEX | Capital Expenditure |
| CNG | Compressed Natural Gas |
| CO | Carbon Monoxide |
| $CO_2$ | Carbon Dioxide |
| COx | Carbon Oxides |
| DALY | Disability-Adjusted Life Year |
| EIO | Economic Input-Output |
| GHG | Greenhouse Gas |
| GRI | Global Reporting Initiative |
| GTL | Gas to Liquid |
| GWP | Global Warming Potential |
| HDVs | Heavy-Duty Vehicles |
| HeX | Helium Extraction |
| HHV | Higher Heating Value |
| IMO | International Maritime Organization |
| IPCC AR5 | Intergovernmental Panel on Climate Change - Fifth Assessment Report |
| ISO/14040 | International Organization for Standardization / Environmental Management - Life Cycle |
| ISO/50001 | Energy Management System Standards |
| KPI | Key Performance Indicator |
| kS-bbl | Thousand Standard Barrels |
| LCA | Life Cycle Assessment |
| LCC | Life Cycle Costing |
| LCI | Life Cycle Inventory |
| LCSA | Life Cycle Sustainability Assessment |
| $LN_2$ | Liquid Nitrogen |
| LNG | Liquified Natural gas |
| LPG | Liquefied Petroleum Gas |
| MCDM | Multi-Criteria Decision-Making |
| MCHE | Mixed Cryogenic Heat Exchanger |
| MDEA | Methyl diethanolamine |
| MMBTU | Metric Million British Thermal Unit |
| MMSCFD | Million Standard Cubic Feet per Day |
| MMTA | Million Metric Tonnes Annum |
| MR | Mixed Refrigeration |
| MRIO | Multi-Regional Input-Output |
| NG | Natural Gas |
| NGL | Natural Gas Liquids |

| Acronym | Description |
|---|---|
| NGL | Natural Gas Liquid |
| $NO_x$ | Nitrogen Oxides |
| NR | Nitrogen Removal |
| OPEX | Operational Expenditure |
| PFD | Process Flow Diagram |
| PLCA | Product Life Cycle Assessment |
| PLNG | Pressurized Liquified Natural Gas |
| PMFP | Particulate Matter Formation Potential |
| POFP | Photochemical Oxidant Formation Potential |
| RVP | Reid Vapor Pressure |
| SDGs | Sustainable Development Goals |
| SF | Sustainability Factors |
| SLCA | Social Life Cycle Assessment |
| $SO_2$ | Sulfur Dioxide |
| $SO_x$ | Sulfur Oxides |
| SRU | Sulfur Recovery Unit |
| SSD | Slow Speed Diesel |
| ST | Steam Turbine |
| TBL | Triple Bottom Line |
| TGT | Tail Gas Treatment |
| TLCAM | Tsinghua-LCA Model |
| UNDP | United Nations Development Program |
| UNEP/SETAC | United Nations Environment Programme / Society for Environmental Toxicology and Chemistry |
| US EPA | United States Environmental Protection Agency |
| USD | US Dollar |
| WCED | World Commission on Environment and Development |
| WHO | World Health Organization |
| WSSD | World Summit on Sustainable Development |
| WTW | Well-to-Wheel |

# CHAPTER 1: INTRODUCTION

## 1.1. Background

The World Commission on Environment and Development (WCED) was formed to promote developmental approaches that are attentive to both the existing and future needs globally 1987. WCED issued a report that was titled ‘Our Common Future.’. In this report, the phrase “sustainable development” was first used formally. According to this report, development can be categorized as sustainable if it meets the present needs without harming the capability of upcoming generations to satisfy their necessities. The 2002 World Summit on Sustainable Development (WSSD) borrowed heavily from the concept of sustainable development as defined by WCED. WCED asserts that sustainable development comes in three forms: economic development, environmental development, and social development (Imperatives, 1987).

Sustainability should be at the core of development. Various factors make the sustainability of high relevance in the energy sector. Sustainability is a significant factor for the energy division because of the prevalence of energy demand, the energy sector's relevance to the economy, and the relevant environmental impacts associated with production processes. Concerning the Sustainable Development Goals (SDGs) plan by 2030, numerous goals are directly or indirectly affected by the lengthy processes associated with liquified natural gas (LNG) processing, importation, exportation, and logistic activities.

Regarding the Paris Agreement, which aimed to promote global temperature stabilization according to the SDGs framework brought in place by the United Nations Development Program (UNDP), natural gas (NG) can be considered a suitable transition source of energy. Its low carbon emission implies that when it is used together with a renewable source of energy, there will be a significant improvement in the programs that aim to reduce global warming (Safari, Das, Langhelle, Roy, & Assadi, 2019).

NG has undergone tremendous transformations all around the world. Due to industry changes, heavy investment in supply chains is required to reach the global supply of LNG efficiently. LNG trading is undergoing a rapid transformation from regional, bilateral trade flows to local and, eventually, the global economy. Many countries that rely on coal for electricity generation have increased their demand for NG to lessen the causes of environmental challenges. NG customers assessed that LNG is a viable and promising alternative to coal to restore coal and meet energy requirements, including power generation (EIA, 2010).

The global LNG sector has seen fast expansion, with commerce reaching a new high of 355 million tons in 2019 (up 13% from 2018) (Roman-White et al., 2021). LNG exports are expected to continue expanding, with predicted worldwide demand estimates ranging from 450 to 700 million tons per annum by 2040. At the same time, considerable reductions in greenhouse gas (GHG) emissions must be reduced to accomplish the Paris Agreement's goal of maintaining the greenhouse effect far below 2 degrees Celsius.

### 1.2. LNG's environmental, social, and economic impacts

The whole supply of NG is reliant on the distribution and pipeline networks that connect the demand and supply fields. Manufacturers of LNG are currently focusing on a more advanced liquefaction and regasification process in order to comply with a more ecologically acceptable working environment (Oliver, 2015). The conversion of NG through the various stages of the LNG production chain involves the usage of a significant amount of fuel, which is mostly derived from the NG feed. The combustion of this fuel produces a considerable amount of carbon dioxide ($CO_2$) and other pollutants such as sulfur dioxide ($SO_2$) and nitrogen oxides ($NO_x$). As long as LNG production continues, the expectation of industrial air pollutants being ventilated into the atmosphere will exist. To verify the economics of LNG management and supply networks and evaluate the LNG product's sustainability, comprehensive accounting and tracking of the midpoint air pollution footprint are required (Whitmore, Baxter, & Laska, 2009). Furthermore, the LNG sector's waste consumption and land usage area are critical resources for assessing the environmental impact of any similar industry.

It is hard to deny that the industrial activity-to-trade revolution is assisting countries in growing and meeting numerous social status requirements, such as job creation, alleviating poverty, labor standards, gender equality, and exceptional access to health care and education. On the other hand, industrial methods may have disastrous impacts on the environment, resulting in numerous serious and international challenges such as global warming, natural resource loss, water, and air pollution, and biological degradation. The increase in air pollution is one of the most serious impacts of LNG industrial expansion. Humans, plants, and the ecosystem are all harmed in different ways by air pollution and resource usage. Exposure to a specific subject matter raises the risk of lung cancer and cardiovascular disease in people. Ground-level ozone, eutrophication, and acidification are all effects of air pollution on ecosystems (Agnolucci & Arvanitopoulos, 2019). More societal ramifications are associated with employment, salary and benefits, total taxation and other expenses, and total man-hours completed for a certain activity or process chain.

Since the Fukushima nuclear disaster in 2011, the need for LNG, which is a preferred mode of transport for offshore NG shipments, has risen rapidly (Hayashi & Hughes, 2013). Bjørndal, Bjørndal, Pardalos, and Rönnqvist (2010) estimated that the LNG production line represents 30-40% of the cost in the LNG value chain. It has been recommended that pressurized LNG (PLNG) be used as a solution to the issue of high LNG manufacturing costs. According to the Oxford Center for Energy Studies research, the cost analysis per LNG plant area (LNG liquefaction facility) can be separated into various cost variables. The cost variables are capital expenditure (CAPEX) and operational expenditure (OPEX), which are related to site preparation, gas treatment, fractionation, liquefaction, refrigeration, utilities, and offsite storages and tanks (The Oxford Institute for Energy Studies, 2014). Pre-operational economic factors include the project's magnitude and sophistication and maritime facilities such as jetties (Eikens & Møller, 2020).

CAPEX for regasification plants generally includes the costs of vessel drydock, storage vessels, regasification systems, transfer pipelines, and metering of new facilities (Zhongming, Linong, Wangqiang, & Wei, 2017). As a result, this valuation chain-link exposes the cost considerations associated with the contact between LNG ships and onshore facilities. Although CAPEX makes up a significant amount of a project's budget, it's also critical to assess overall OPEX across the entire distribution network to identify possible investment risks. Based on PwC data and a report published in the journal of Industrial & Engineering Chemistry Research (I&EC) (PwC, 2014), the operational costs for a general value chain are as follows; upstream development accounts for 10-11% of costs, refrigeration, and liquefaction for 40-42% of costs, shipping and transportation for 20-30% of costs, and regasification and distribution for 20-27% of costs.

## 1.3. LNG uses in the world

### *1.3.1. Coal to gas-switch*

Because burning NG in combined gas-fired power plants has shown to be more efficient and cleaner than burning other fossil fuels, such as coal, NG plays a vital role in electricity generation. Studies have found that when LNG is burned to generate energy, it releases about half the GHG emissions that coal does. When combusted in a new efficient NG power plant, NG releases 50 to 60% less $CO_2$ than a typical new coal plant. NG would minimize $CO_2$ emissions by 1,200 MT if it were used to replace all coal in power generation. The Asia Pacific, in particular, has a lot of conversion potential. However, GHG emissions are a problem for the gas sector throughout its whole value chain's lifecycle. Some argue that upstream methane ($CH_4$) emissions and, in the case of LNG, the extra energy required for liquefaction reduce or even negates gas's basic benefits (GIIGNL, 2020).

Most of the world's countries have substantial reserves of NG. That abundance, combined with its low emissions and reliability, makes NG a building block of the easy power future cheaper and low-carbon energy preference for consumers at home and across the globe. Residences use NG for heating and cooking, the industry for manufacturing imperative merchandise as assorted as steel, scientific equipment, and fertilizer, and with the aid of grocery stores, lodges, and restaurants for heat, power, and dehumidification. Moreover, it is used by the automobile as a cleaner fuel and utilized utility to generate power as a reliable energy source with low emissions.

In addition to the numerous uses for NG, LNG, in its liquid structure, can be used in the marine and mining sectors as fuel. The beauty of LNG is that it enables herbal gas to be safely and economically transported to other countries considering the distance, bringing environmental benefits and more suitable exceptional of life. NG is used for many applications, such as fuel for transportation and electricity generation in addition to many domestic uses like the heating sector and chemical industry. The following are brief details for each use.

### *1.3.2. LNG used as a transportation fuel*

Using LNG for transportation has significantly increased in various parts of the world over the past few years (De Carvalho, 1985). LNG is the most used source of energy that is categorized as a greener source of energy for powering Heavy-Duty Vehicles (HDVs) such as trucks and buses. Using LNG needs a storage facility that will ensure that low temperatures of -162$^{o}$C are maintained to make sure that it does not turn into gas (Newsletter, 1991; NGVGlobal, 2022). Additionally, vehicles running on LNG need to have a unique duel engine. Furthermore, their tanks should be made to match the conditions that LNG needs to be in for it to be useful in the production of energy. Such requirements have often made the use of LNG for transportation economically unsuitable.

LNG has higher thermal efficiency as compared to the other available alternatives, which allows meeting the energy needs with a reduced quantity of fossil fuel. Higher thermal efficiency is a desirable factor for energy-intensive industries. It also has lower specific energy as compared to other options such as oil and coal. Therefore, there is a possibility that technologies and innovations might make the use of LNG more energy efficient in the future. Many academics have focused on the use of LNG as oceanic energy because of the sulfur-based emission limits that the International Maritime Organization (IMO) introduced. The limits were aimed at reducing the extent to which the operation of ships leads to the emission of GHG (Angelino, 1978; Burel, Taccani, & Zuliani, 2013).

### *1.3.3. Electricity production*

LNG can also be used in the production of electricity. Using LNG's cryogenic energy in the production of electricity has been addressed in various studies (Benham, 2017; Gao & You, 2017; Raghoo, Surroop, & Wolf, 2017; Ren & Lützen, 2017). Some studies suggest the introduction of a Rankine and Braytone combination cycle, with $CO_2$ as a working fluid. Further heating source is needed and can be obtained by burning $CH_4$ in the presence of oxygen, leading to the production of gases with large quantities of $CO_2$. When heat is transmitted to the LNG that is undergoing evaporation, the resultant process is irreversible (Aspelund & Gundersen, 2009; Karashima & Akutsu, 1982; C. Kim, Chang, & Ro, 1995; Oliveira & Marreco, 2006). LNG has turned out to be a primary transportation energy source in Japan. Such a development has led to a significant reduction in carbon emotion. The same benefits could be achieved if LNG were used in the production of electricity.

### *1.3.4. Other domestic uses of LNG*

There are many other uses of NG. It is used for houses and commercial buildings. It can be used for heating, air conditioning, food cooking, lighting, etc. LNG is also applicable in the production of fertilizers and increasing in popularity as far as household activities such as cooking and heating are concerned (Khalilpour & Karimi, 2011; Kotzebue & Weissenbacher, 2020; Okamura, Furukawa, & Ishitani, 2007; Oshima, Ishizaki, Kamiyama, Akiyama, & Okuda, 1978). Furthermore, it is used as an industrial utility for heating, firing, flare systems, steam generation, and cooling in some cryogenic industries (Hydrocarbon Processing Staff, 2021).

#### *1.3.4.1. Heating use*

Residential and commercial uses of NG account for more than a third of total consumption in the United States, as gas is utilized in buildings for space and water heating as well as cooking. In 2013, NG was used to heat around half of all United States residences, and 70% of all new homes were built using gas heating systems. Home furnaces can achieve an efficiency of more than 90%. Building efficiency improvements are typically regarded as the most cost-effective technique to minimize NG consumption (Union of Concerned Scientists, 2015).

#### *1.3.4.2. Chemical industry use*

According to studies that have recently been undertaken, LNG can be used for feedstock for chemical, power, fertilizer, and petrochemical plants (Schinas & Butler, 2016). Huge business organizations using a large amount of energy are gradually opting for LNG at the expense of coal. LNG can potentially replace naphtha as a preferred source of energy for industries (S. Kumar, Kwon, Choi, Lim, et al., 2011).

Chemical techniques based on methane activation are becoming more economically viable as methane is the principal component in LNG. Methane is currently converted into bulk chemicals in the industry via an indirect process. Methane is converted to syngas at a high temperature, and the syngas is then utilized to manufacture a variety of hydrocarbons or alcohols using various catalysts types. Lowering the reaction temperature for the transformation of methane into chemicals would be beneficial because the process is energy-intensive and expensive. The direct conversion of methane to derivatives is feasible, and methanol is one of the final products from the syngas reaction (Tang, Zhu, Wu, & Ma, 2014).

### 1.4. Problem statement

The conception of sustainable development is executed at the policy level. Still, it must be extended in the business context and encourage evidence-informed decision-making connecting the two levels. Given this, the oil and gas industrial sector has integrated sustainability in their growth map due to more conscious purchasers' boosted need for sustainably manufactured goods. Moreover, corresponding to the Global Reporting Initiative (GRI) guidelines (GRI, 2021), from a sustainable development standpoint, the gas industry must identify and disclose the substantial consequences of its many processes on the environment and various stakeholders. The progress in the direction of sustainability necessitates improving the approaches for evaluating the life cycle and aiming for sustainable products (Sala, Farioli, & Zamagni, 2013). Aside from environmental preservation, the approach also includes economic and social safeguards. Accordingly, this research framework of LCSA was established as it combines environmental protection, economic outlook, and social equity. The LCSA model is the brightest and offers the highest level of assessment among the sustainable assessment methods (Janjua, Sarker, & Biswas, 2020).

### 1.5. Research objectives

The primary aim of this dissertation is to examine and identify the LNG product's sustainability in relation to the LNG value chain, which includes natural gas extraction, treatment, liquefaction, transportation, and regasification at receiving ports. The approximate air pollution footprint is used to obtain the endpoint effect on human health based on ReCiPe 2016 characterization parameters. Other numerous quantification technologies such as the EXIOBASE multi-regional input-output (MRIO) database, Aspen HYSYS (Al-Yafei, Kucukvar, AlNouss, Aseel, & Onat, 2021), and LNG Maritime Transport Operations LCSA tools (Aseel, Al-Yafei, Kucukvar, Onat, & Bulak, 2022) have been used to identify the environmental, social and economic impact. This hybrid model is then used to build the principal LCSA for LNG businesses.

This research is motivated by the need to assess LNG within sustainability pillars encompassing each stage of the value chain, considering a global energy environment that strives towards sustainability by supporting gas as an energy transition fuel and the integration of renewable energy sources. In this regard, a functional and new model for the LNG value chain has been developed in this research to assess LNG's long-term viability. The proposed model considers environmental, social, and economic assessments. The followings present the main objectives:

- Introducing a novel system for calculating the hybrid LCSA of LNG processing and distribution.
- Developing and implementing a hybrid LCSA model that incorporates MRIO models, HYSYS simulation tool, LNG Maritime Transport Operations LCSA tool, and data from a variety of sources and domains.

- Developing a sustainable impact assessment tool that can be used by a variety of gas and oil process-related professions.
- Developing the basis for evaluating the holistic sustainability of the LNG value chain considering both processing and shipping stages.

### 1.6. Dissertation outline

This dissertation report is organized in chapters way with six chapters in total. Chapter 1 presents general information about the current and predicted energy demand, the background of the LNG as a clean energy source, and its environmental, social, and economic impacts. Moving forward, LNG applications and uses have been addressed, such as transportation fuel, electricity production, and other domestic uses like heating and chemical industry. Later, the problem statement of this research is provided and followed by this research objectives.

Chapter 2 aims to start with conducting a comprehensive global review of the sustainability of the LNG industry using SCOPUS databased for the studies from 2010 until 2020. The main outcomes from the review are presented based on a) country, b) scope margin, and c) analysis performed. Later, the integrated sustainability assessment is presented. Each component of the sustainability pillars is part of the literature review, including environmental life cycle assessment (LCA), social life cycle assessment (SLCA), and life cycle costing (LCC), followed by a general literature review on the life cycle sustainability assessment. LNG process chain overview is presented, considering the main operation stages followed by the research gaps found from the literature review.

Chapter 3 presents the methodology of hybrid LCSA. This chapter starts with developing the research flow chart and visualized research method. Also, the LCAS goal and scope are provided, including all assumptions, limitations, and constraints considered in the research. As part of the inventory analysis, life cycle inventory is prepared for all LNG process chain stages. A total of three main tools are followed in this research to achieve the hybrid

LCSA of LNG, 1) MRIO database, Aspen HYSYS, and LNG maritime transport operations LCSA tool. Later, the interpretation methodology of the hybrid LCSA model is illustrated in detail.

Chapter 4 aims to present the results, discuss these results, and the policy implications related to the research outcomes. The chapter started with clustering the LNG supply chain stages based on life cycle indicator results, followed by LCA, LCC, and SLCA analysis results. Then, the cumulative triangle chart and sustainability assessment results are presented as part of the interpretation of the results. Later, policymaking implications related to the research outcomes are illustrated, and more focus is given to human heath impact and associated ways to control it.

Chapter 5 aims to summarize the lessons learned from the research outcomes. This chapter explains the good practices that need to be considered part of the LNG trading and operations, and they are as follows; 1) challenges for using LNG as a transportation fuel, 2) selecting the LNG supply option, 3) designs of LNG refueling stations, 4) energy security of LNG, 5) sustainability and safety, 6) sustainable development strategy of LNG, and finally, 7) natural gas liquefaction design and optimization of future research directions.

Chapter 6 provides the summary of the research's key findings and presents their significance for the LNG importers and exporters. Limitations of the current research based on the research and results are discussed. Later, recommendations for future work are pointed out for further consideration.

# CHAPTER 2: LITERATURE REVIEW

## 2.1. Sustainability of LNG industry: a global review

A review of the literature is carried out with the intent of investigating the application-based and methodological gaps. Filtering and specific keywords were used for the purpose of reviewing literature from the Scopus database. A structured review consisting of 4 phases was used. The first phase entails a general search of the literature to identify the total number of articles that were focused on the sustainability of the development of LNG industries. The keywords: sustainability, sustainable, liquefied natural gas, and LNG were used in the first phase to search articles that were published between 2010 and 2020. The first phase led to the retrieval of 467 documents. The accessed literature materials included journal articles, books, conference papers, and letters. After identifying the total number of literature materials that were based on this study's topic, a search was narrowed down to those found on macro-level estimations for the LNG sector. The list of these studies is available in the supplementary information (SI) file No. 1 belongs to Al-Yafei, Aseel, et al. (2021). The use of automatic filtering made it possible for the narrowing down to be based on the sector at large. Most of the identified studies focused on specific traits of the LNG industry, and thus, there was no focus on macro-level sustainability development estimations. As a result, there was a need to carry out a comprehensive review in phase 2 and manually filter the materials that were not within the scope of this study. The primary focus of the research is the suitability of the developments in the LNG industry. Therefore, there was an exclusion of LCA-based environmental focusing on biofuels, technical and design studies, and materials based on risks and safety issues of LNG production.

Table S1 in SI file No. 1 belongs to Al-Yafei, Aseel, et al. (2021), avails details of the studies that were excluded and the reasons behind their exclusion. In phase three, there was an inclusive review of 168 literature materials. In this phase, the sources were categorized based on various factors such as author, year of publication, title, journal, methodology, country studied, analyzed system, the scope of the analysis, and period. Table S2 in the SI file No. 1, which belongs to Al-Yafei, Aseel, et al. (2021), gives comprehensive details of the categorization of the sources. After the narrowing down had taken place, there was a detailed analysis of the 168 literature materials. Appendix A presents the LNG's bibliometric analysis and relevant sustainability studies between 2010 and 2020.

The visualized form of the results from the bibliometric analysis can be found in Figure 2 for various studies based on the year. There has been a noticed increase in the studies recently, and that provides evidence of the importance of using LNG fossil fuel sustainably in the coming future.

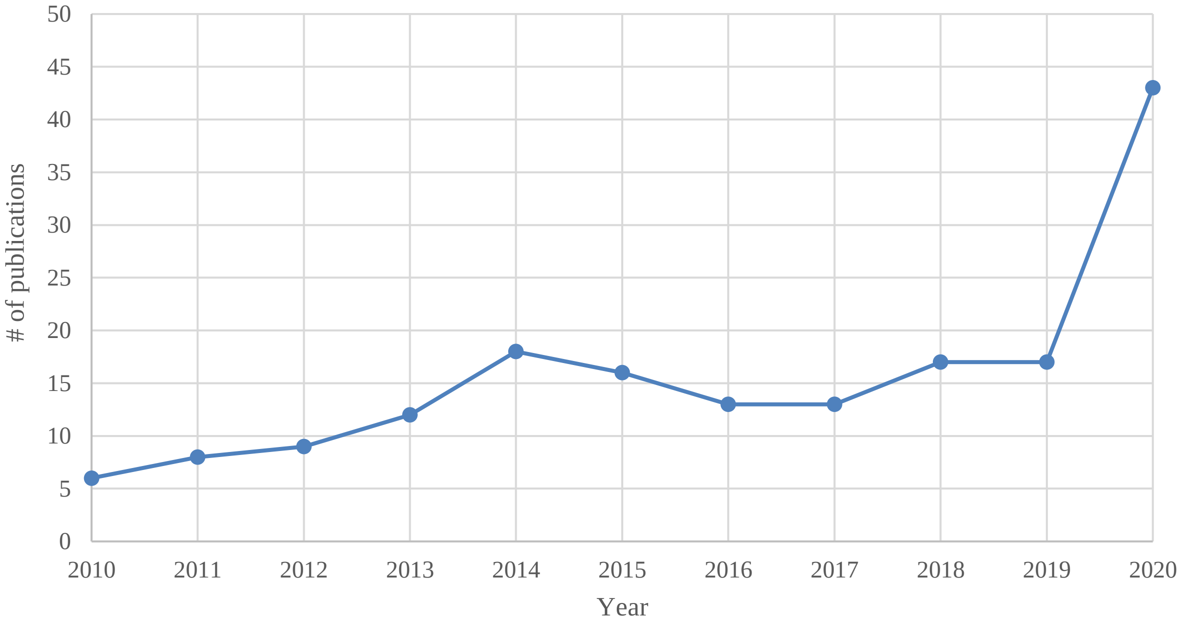

Figure 2. Search results from SCOPUS (2010 until 2020).

The bibliometric analysis results are analyzed in-depth and illustrated more in Figure 3 for the various studies conducted for the last ten years based on the scope margin, country, and systems. If all the samples of the studies were focused on the field of LNG sustainability overview, the number of micro-level studies would be just 36% of the total studies. Of the 36% of the studies, the results revealed that an average of 7 nations were close to 46 other nations in the research that had been undertaken about the suitability of the LNG industry. The 7 nations claimed almost half of the studies that had been undertaken concerning the suitability of the LNG industry. More deals can be found in Figure 3a. As seen in Figure 3b, most of the studies (48%) undertook an analysis at the national level. (40%) of the studies took place at the global level, focusing on the manufacturing and production of LNG. City-level and regional-level studies accounted for 5% and 7% of the reviewed studies, respectively. Figure 3c reveals that 29% of the reviewed materials focused primarily on the general energy sector. The general energy sector is followed by the LNG sector specifically with 19%, LNG fueled ships with 15%, and the LNG industry with 13%.

For top-down methods, most of these studies cover the review and analysis part of the LNG industry, LNG sector, and energy sector in general. The energy sector can be defined as any energy trading and business, including LNG and other energy supply industries. It is considered the broader sector among the other systems. The LNG sector in this review covered the LNG trading and business that include all the operational stages (from natural gas extraction until the delivery to the intended destination). The process of LNG manufacturing is considered here as the LNG industry. Also, many studies were found illustrating the LCA of LNG utilization either in power generation, fueled ships, fueled vehicles, and aircraft. However, after a comprehensive literature review, no complete LCSA for the LNG industry (from extraction until customer use) has been found. Further consideration of LNG transportation, sustainability, and associated emissions is illustrated in Appendix B.

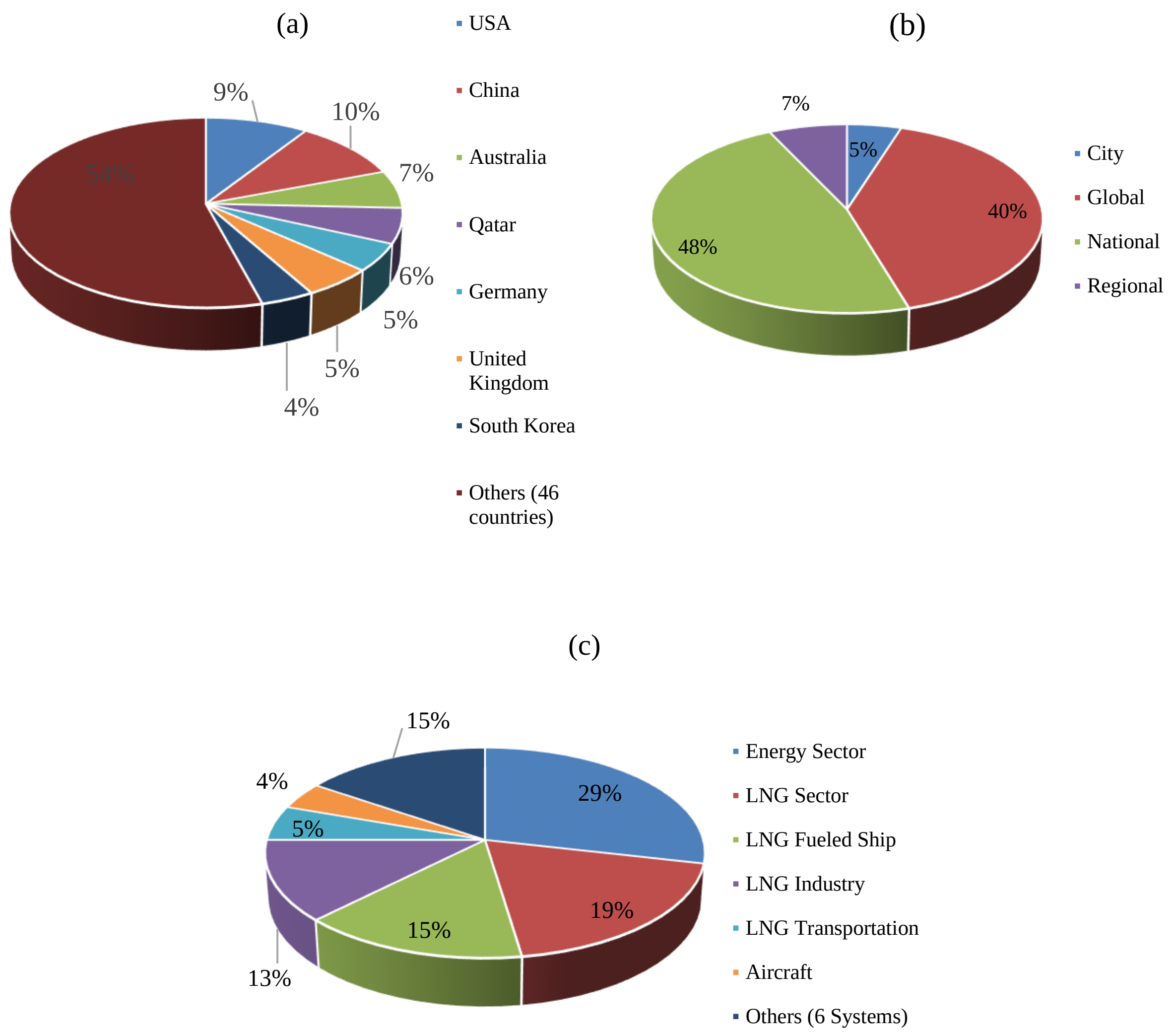

Figure 3. Literature review analysis of nominated articles based on a) country, b) scope margin, and c) analysis performed.

## 2.2. Integrated sustainability assessment

### *2.1.1. Environmental life cycle assessment*

The LCA method aims to assess the product's impact from environmental perspectives, such as pollution, resources consumption, and waste. For instance, Aberilla, Gallego-Schmid, Stamford, and Azapagic (2020) established an integrated environmental and economic assessment model in order to provide water and energy applications with the most sustainability options that satisfy the community's current and future needs. Barnett (2010) studied the environmental implications of LNG liquefaction, regasification, and shipping operations. Tamura et al. (2001) focused on carbon footprints as well as other atmospheric pollutants during LNG production, where the study considered these pollutants during the delivery of LNG. In Western Australia, Biswas, Engelbrecht, and John (2013) examined carbon emissions throughout LNG production and supply chain, considering Australia's LNG exports to customers, such as China.

Compared to the other processes, such as separation and exploration, the proportion of carbon footprint emitted during the LNG delivery process is significantly lower. For example, Jaramillo, Griffin, and Matthews (2007) estimated emissions from LNG-based electricity generation, linking $SO_x$, $NO_x$, and GHG emissions to the life cycle of the gas, especially those originating from sources of energy. The study conducted a life cycle based comparison of air pollutants for electricity generation from various energy sources such as coal, domestic NG, LNG, and synthetic NG.

### *2.1.2. Social life cycle assessment*

SLCA is a method followed to adequately assess and evaluate manufactured products' beneficial and adverse impacts on society. Social concerns have been shown to substantially impact the successful deployment of various technologies and systems. For instance, when analyzing emerging technologies, Lehmann, Zschieschang, Traverso, Finkbeiner, and Schebek (2013) recognized the importance of addressing the social determinants in the early stages of technological innovation as well as in the decision-making phase of businesses. The authors investigated how the UNEP/SETAC recommended SLCA approach can be used to study the social aspects of new technologies.

The current external context and circumstance, such as policy initiatives, affect the integration of social aspects in the technology development cycle, such as the implications on employees, community, and society, as well as the overall productivity of an organization and their intrinsic behavior in selecting a technology (García-Ramírez, Balcázar, & de Freitas, 2014; Hannouf & Assefa, 2018). By legislating the eradication of specific environmental impacts and supporting the development and deployment of new, improved technology, policymakers can contribute to creating a sustainable regulatory environment (Duch & Costa-Campi, 2015). International, regional, and state climate regulations, for example, have attempted to regulate GHG emissions, compelling firms to change their activities in order to reduce pollution (Hickmann, Widerberg, Lederer, & Pattberg, 2021). Additionally, by offering incentives or fines, environmental regulations can encourage the growth and acceptance of innovative technology. For instance, given the carbon tax imposed by the State of Alberta on large emitters through the Climate Crisis and Emissions Monitoring Fund, the Emissions Reduction Alberta funding supports the momentum and increased capacity of technological developments that contribute to a lower carbon industry (ERA, 2021). In addition, policymakers can support the development of ecologically superior technologies that reduce environmental repercussions by promoting appropriate social conditions that facilitate the deployment of these innovations.

### *2.1.3. Life cycle costing*

The abundance of fossil fuels is currently one of the key drivers for being the most utilized energy source. Fossil fuels satisfy 85% of the world's commercial energy demand. As a result, it has the potential to be a catalyst for a country's long-term development. There are few extensive studies on the LNG distribution network LCC and economics due to the system's sophistication and insufficient information. For example, Jokinen, Pettersson, and Saxén (2015) suggested a computational formula to aid in creating LNG supply chains. However, their central emphasis was on cutting gasoline procurement prices, with only the regasification-to-end-users segment of the chain receiving attention. Raj, Ghandehariun, Kumar, and Linwei (2016) research focused on the comprehensive GHG emissions and delivery costs of Canadian LNG to China from well to wire; nevertheless, the study did not account for the chain's strong properties.

Sapkota, Oni, and Kumar (2018) investigated the NG supply chain's techno-economic and life cycle GHG emissions from Canadian manufacturing locations to European receivers. Nonetheless, their study relied on estimations and ranges rather than detailed equipment modeling and emission measurement. J. Kim, Seo, and Chang (2016) proposed a novel LNG distribution network that relied on liquid nitrogen ($LN_2$) for liquefaction, and they looked at the supply chain's LCC and profit. Despite this, they did not include NG preprocessing or any other important processing components in their study. The cost of a pressurized LNG distribution chain, which comprised maritime development, transportation, and consumption, was studied by I. Lee, Park, and Moon (2017). They also looked at the chain's LCC to see the economic feasibility. The focus of the investigation was on the hydrolysis reaction, which is the most significant step in non-baseload LNG networks.

### 2.3. Life cycle sustainability assessment

The scope of traditional LCA has been expanded from considering environmental consequences alone to the integration of the three dimensions of sustainability (environmental, economic, and social). Furthermore, a more comprehensive and long-term answer for life cycle analysis can be acquired by combining the three aspects of sustainability, namely environmental, economic feasibility, and social for any product. The product life cycle assessment (PLCA) is a tool for determining the influence of a manufacturing distribution network on sustainability (of varying lengths). The PLCA model was used to investigate environmental damage and remediation costs. PLCA later created the concept of SLCA to explore the consequences of the production process on social organization (Mesaric, Šebalj, & Franjkovic, 2016). The LCA's definition has been expanded to include the three elements of sustainability (planet, profit, and people). People refer to the societal dimension, Planet to the ecological extent, and Profit to the economic aspect (Heijungs, Huppes, & Guinée, 2009). At the UN Sustainable Development Summit in South Africa, the 3Ps were renamed People, Planet, and Prosperity. The contrast between profitability and prosperity highlights how economic evaluation incorporates more than business aims. More LCA variables help determine whether commodities, operations, and services are progressing toward sustainable development and allow proactive decisions to be made (De Benedetto & Klemeš, 2009).

From the start, it was evident that a comprehensive assessment of sustainable development would include two additional factors: monetary and social (Kloepffer, 2008). Environmental LCA for environmental implications, economic performance for measuring the LCC, and SLCA for analyzing social effects are the methods used to examine the three principles of sustainability. LCSA is the outcome of merging the three strategies mentioned above. LCSA provides a holistic view of supply network sustainability to policymakers and decision-makers, increasing their support (Ciroth et al., 2011). Today, the bulk of LCSA publications consist of literature reviews, operational improvements, and comments, suggesting that LCSA's conceptual base is still being formed (Costa, Quinteiro, & Dias, 2019). Despite the fact that the LCSA approach is still in its inception, a number of scholars have contributed to it have made use of it in their research to investigate the potential of self-sufficiency in all three components: environmental, economic, and social (Ferrari et al., 2019; Settembre-Blundo et al., 2018; Shrivastava & Unnikrishnan, 2021).

Elhuni and Ahmad (2017) presented key performance indicators (KPIs) for evaluating sustainable manufacturing in Libya's oil and gas industry. The performance indicators for all three dimensions of sustainability were assessed, although there was no framework in place to evaluate sustainable output. Hannouf and Assefa (2017) provided a systematic method for performing an LCSA of polyethylene in Canada, outlining difficulties in defining the interrelationships between the three pillars of sustainable development (LCA, LCC, and SLCA). Several authors discussed above stated that the absence of a relationship between the three dimensions of sustainability was a significant study gap (Guinée, 2016; Zamagni, Pesonen, & Swarr, 2013). There was also a lack of evidence of the interaction of three sustainability characteristics in the gas industry. According to Costa et al. (2019), the bulk of the LCSA research articles were from countries like the United States and Germany. Case studies are required for all industries and sectors to raise awareness of developing challenges and develop techniques for adopting LCSA.

Evidently, the full breadth of sustainability has not been considered in previous LNG studies, as concluded from the literature review assessment on LCSA. As such, this dissertation is novel as it is the first to incorporate all aspects of sustainability within the LNG industry. The emphasis of this research is on implementing the LCSA on the LNG processing chain. Using data from manufacturing, use, input materials requirements, and emissions during a given time period, an LCA, LCC, and SLCA are undertaken. An effort has been made to combine the aspects of sustainable development through a theoretical foundation. Sustainability improvement initiatives and strategic framework proposals are also provided in order to attain sustainability objectives. The study has some assumptions, such as a lack of environmental LCA data, numerous overhead charges, and a few cultural subcategories. Secondary data are acquired from databases, resource integration assessments and annual reports, and research articles when primary information is not available.

## 2.4. LNG process chain

In this research, a flow block diagram of the LNG process chain is considered in Figure 4. The processing train of LNG is portioned into two different subsections: cold and hot (Katebah, Hussein, Shazed, Bouabidi, & Al-musleh, 2020). The divisions are classified into the NG obtained from the well, NG pre-separation, sweetening, sulfur recovery unit (SRU) in the acid gas removal unit (AGRU), and dehydration units for the hot section and Natural Gas Liquids (NGL) fractionation and recovery, Helium Extraction (HeX), liquefaction, and Nitrogen Removal (NR) units, and the cold section loading terminals. Associated utilities and electrical power are required for both sections. After the process of liquefaction, the shipment of LNG takes place to the importing terminal for it to be regasified. The main terminal utility import is the electrical power developed by employing the LNG gasified portion.

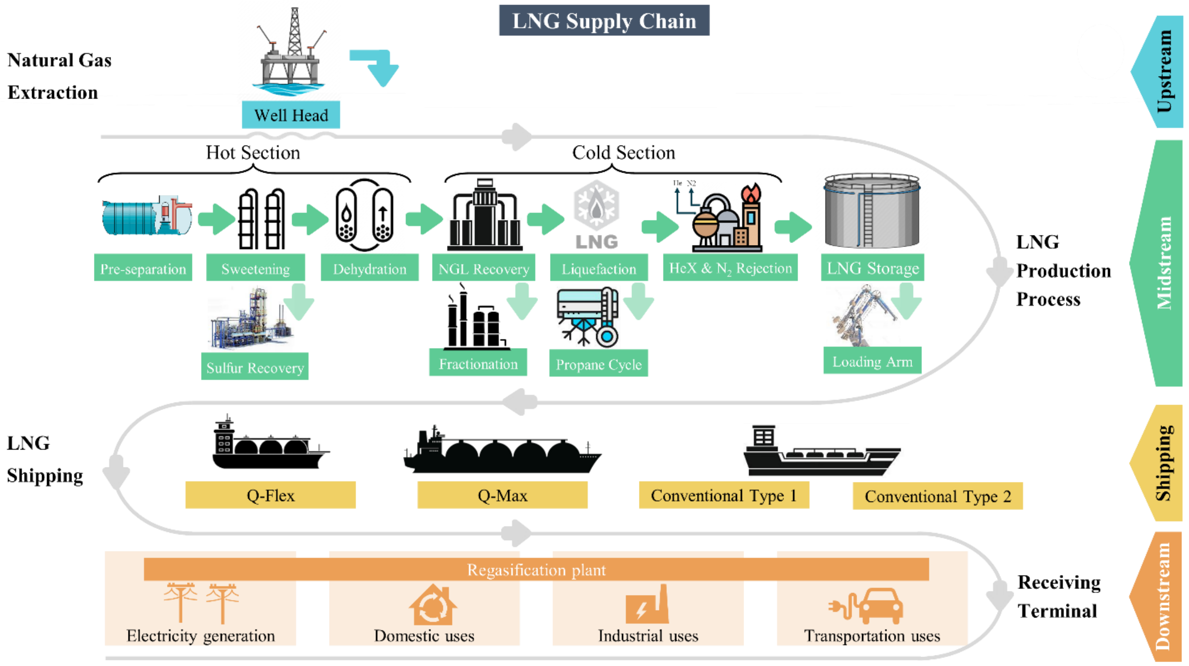

Figure 4. LNG process chain.

LNG technique includes a given number of units, and a brief explanation of the units is as follows; First, impurities and hydrocarbon are the elements present in NG. The liquids from

NG divided at this phase must be transferred for recovery to a processing plant. The pre-separation unit is where feed sour NG is passed through to remove water and condensate. Then the divided sour NG gets into the sweetening unit, where undesired components like $H_2S$ and $CO_2$, known as acidic gases, benzene, toluene, xylene (BTX), and mercaptans, are removed. The steams of acid gas by-products departing from the sweetening unit are routed into the SRUs to generate sulfur allotropes from $H_2S$.

Similarly, the appearance of $SO_x$ is a result of the combustion of acid gas. Before NG leaves the sweetening unit, it should be treated to remove dehydration water hence minimizing downstream corrosion and preventing the formation of hydrates. The functional and recovery unit of NGL is crucial because it helps to recover NG steam leftover condensate, providing propane and ethane the refrigerant make-up for the system liquefaction when required, and generating standard LNG specifications. The primary fractionation unit has three conventional distillation sections to fraction the NGL into propane, butane-rich streams, ethane, and unwanted condensate. The propane pre-cooled mixed refrigerant ($C_3MR$) process of liquefaction and cooling is utilized with the considered chain. It entails compressing vapor in two cycles that subcool, condense, compress, and throttles the refrigerants, providing the necessary cooling primarily via the evaporation process. Once liquefaction is done, the HP LNG passes via an integrated NR and HeX departments to regain the helium and meet the specifications of LNG, such as higher heating value (HHV) and nitrogen content. Later on, LNG is immediately loaded into their maritime transport carriers by using LNG loading arms or compiled in holding tanks. The carriers of LNG are generally categorized based on their boil-off gas (BOG) presence, propulsion systems and containment types, and capacity of reliquefication unit (Anderson et al., 2009; Romero Gómez, García, Gómez, & Catoira, 2014). The currently importing facilities and regasification plants consist basically of the supporting utilities, LNG storing tanks, and the regasification unit. The terminals work either on LNG tanks' holding mode or loading mode.

Up to this juncture, according to the studies on the energy sustainability valuation, it is clear that there has been a scarce study on adequate energy, and a lot of the researchers have fastened on formulating models of sustainability assessment with scarce precedence on environmental impacts with the introduced investigation. Also, the literature does not have an LCSA of oriented pool chains and its foreign pool chains of LNG. Besides, the triadic - lowermost lines of the sustainable development, integration of the life cycle environmental, social, and economic range is still required for the LNG industry.

### 2.5. Research gap

Following a detailed review of the literature, it was found that many studies on the energy sources used around the world either for transportation, electricity generation, LNG transportation, etc. However, a rare number of papers cover LNG's LCA as a reliable, promising, and more environmentally friendly energy source than other energy sources, and no study conducted the entire LCSA from natural gas extraction until arrival to the end-user. Moreover, the economic, environmental, and social LNG impacts illustrate the better performance and less pollution to the environment significantly compared with other energy sources.

Furthermore, there is no comprehensive work found offering or gathering the best practices related to LNG production and supply chain that covers the transportation, selecting supply options, designs of refueling stations, energy security, LNG sustainability and safety, sustainable development strategy of LNG, policymakers' opportunities, and natural gas liquefaction design and optimization.

# CHAPTER 3: MATERIAL AND METHODS

## 3.1. Research flow chart

According to UNEP/SETAC standards, the approach for analyzing the LNG LCSA involves four steps: LCSA purpose and range, evaluation methods, impact analysis, and LCSA interpretation (see Figure 5). LCSA is the result of combining three life cycle characteristics: LCA, LCC, and SLCA. LCA is the only one of these that is ISO-14040-44 certified. Further research and clarity on the technique of the LCC and SLCA tools are required (Guinée, 2016). The following are the steps involved in LCSA:

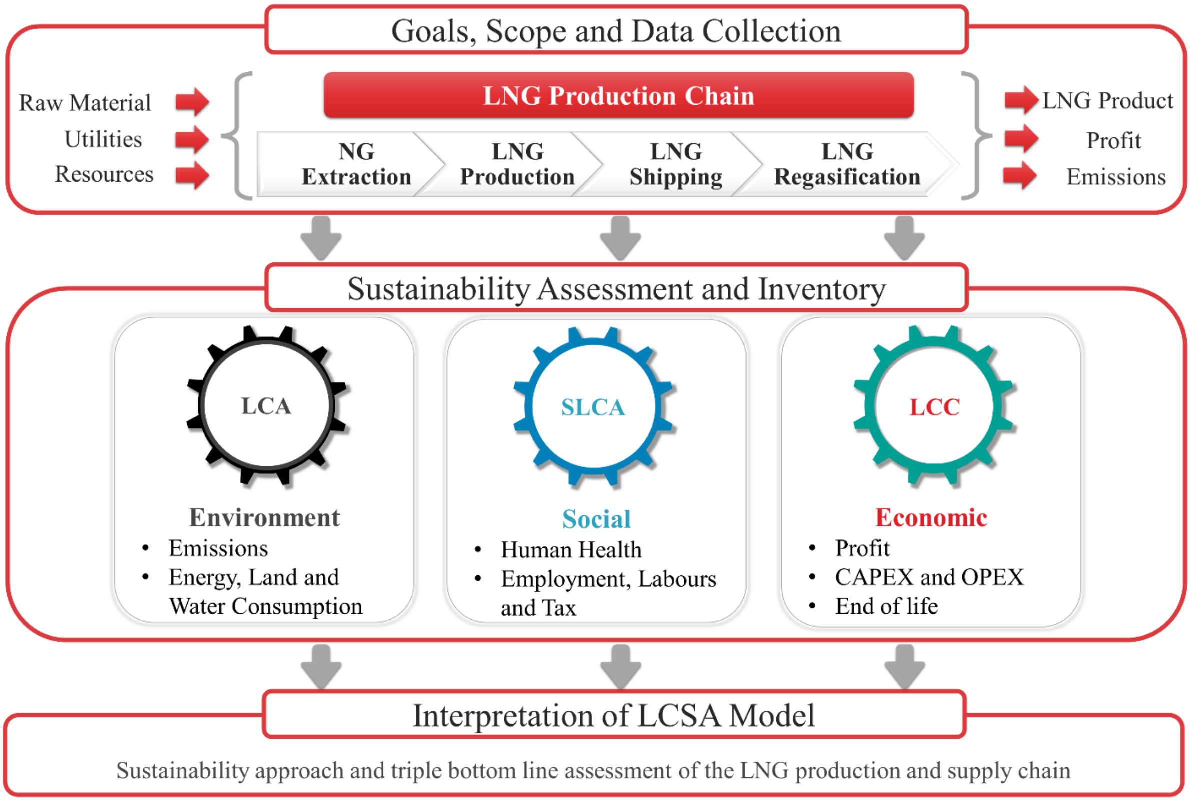

Figure 5. Research method.

## 3.2. LCSA goal and scope

The research's purpose is to conduct an LNG LCSA and evaluate its performance from start to end or from the extraction of raw materials to final LNG dispatch from holding and regasification. One metric ton (MT) of LNG generated was utilized as the functional unit for the LCA and LCC assessments. Because empirical information is recorded for SLCA and subsequently translated into quantitative data for evaluation, there is no need for a fundamental structure; nonetheless, UNEP/SETAC advice states that a primary structure should be chosen for conducting SLCA. The factor chosen was one MT of LNG. According to the UNEP/SETAC report, “establishing a base structure for SLCA is as important as establishing a fundamental structure for LCA because it is the offset for establishing a product line” (Initiative, 2009).

Table 1 presents some assumptions and constraints in the LNG process were considered in this simulation to comply with the environmental protection requirements, minimize environmental pollution and apply the best operational practices:

Table 1. Various Assumptions, Limitations, and Constraints made in the Study.

| Process stage | Assumptions / Limitations / Constrains |
|---|---|
| All stages | − Minimum flaring is anticipated.<br>− Utility allocation is achieved based on availability and cost.<br>− Water withdrawal is assumed for the seawater intake with a once-through concept.<br>− Water consumption is assumed to be associated with fresh cooling water.<br>− Taxes are assumed to be 10% of total revenue.<br>− LNG price is assumed to be 35 USD/ MMBTU (FRED Economic Data, 2021)<br>− Point sources stack emissions shall not exceed the limits set by the authorities.<br>− Zero liquid discharges of treated industrial water to the sea. |
| LNG manufacturing, LNG loading, LNG unloading, and regasification | − BOG flaring while holding and loading modes is reliquefied and reused to the maximum extent.<br>− The capital cost is approximated using Aspen HYSYS based on the purchase and installation costs of equipment, civil, instrumentation and electrical, and administration costs.<br>− Operating cost is approximated using Aspen HYSYS based on the consideration of operational and labor charges, maintenance, plant overhead, and administration costs. |

| Process stage | Assumptions / Limitations / Constrains |
|---|---|
| | − Seawater cooling water intake and outfall differential temperature are assumed to be within three degrees Celsius for heating/cooling purposes. |
| LNG loading | − LNG product holding mode is assumed in this research. However, another assumption is that all LNG products are loaded and distributed to customers throughout the year by LNG carriers. |

## 3.3. Inventory analysis

For the assessment, a life cycle inventory (LCI) is generated for every phase of the LNG processing chain. Qatar is used as a case study, and Qatar-United Kingdom trade is the case selected for LNG trade and shipping. To achieve this goal, consider the LNG process chain domain, which is previously established as the estimation's functional and boundary unit system. NG extraction from offshore to onshore, gas processing, liquefaction and LNG storage in acquiring stations, maritime product transport, and regasification are all part of the process chain. Second, the sustainability indicators that must be recognized, showing environmental, social, and economic factors, are briefly outlined in Table 2. The MRIO sector used for the upstream unit is namely natural gas and services related to natural gas extraction, excluding surveying.

Table 2. LCI of the Study.

| Impact area | Impact/Indicator | Unit | Description | Source of data |
|---|---|---|---|---|
| Environmental | Global Warming Potential (GWP) | kg $CO_2$-eq. | Total GHG emissions based on IPCC's factors for GWP100 according to Assessment Report 5 (AR5) | Upstream: MRIO<br>Midstream: HYSYS<br>Shipping: LNG Maritime Transport Operations LCSA Tool<br>Downstream: HYSYS |
| | Particulate Matter Formation Potential (PMFP) | kg $PM_{2.5}$-eq. | Total criteria air pollutant emissions | Upstream: MRIO<br>Midstream: HYSYS<br>Shipping: LNG Maritime Transport Operations LCSA Tool<br>Downstream: HYSYS |
| | Photochemical Oxidant Formation Potential (POFP) | kg $NO_x$-eq. | Amount of airborne substances able to form atmospheric oxidants | Upstream: MRIO<br>Midstream: HYSYS<br>Shipping: LNG Maritime Transport Operations LCSA Tool<br>Downstream: HYSYS |
| | Energy consumption | TJ | The entire amount of energy is derived from natural resources. | Upstream: MRIO<br>Midstream: HYSYS<br>Shipping: LNG Maritime Transport Operations LCSA Tool<br>Downstream: HYSYS |
| | Use of water | $m^3$ | The volume of water is permanently withdrawn from its source for use. | Upstream: MRIO<br>Midstream: HYSYS<br>Shipping: LNG Maritime Transport Operations LCSA Tool<br>Downstream: HYSYS |
| | Land used | $Km^2$ | The set of activities done by humans on land to get benefits from the | Upstream: MRIO<br>Midstream: HYSYS and google earth<br>Shipping: LNG Maritime Transport |

| Impact area | Impact/Indicator | Unit | Description | Source of data |
|---|---|---|---|---|
| | | | use of land resources. | Operations LCSA Tool<br>Downstream: HYSYS and google earth |
| | Removal of water | $m^3$ | The amount of water that has been taken from a source of water for private use and subsequently returned to the source. | Upstream: MRIO<br>Midstream: HYSYS<br>Shipping: LNG Maritime Transport Operations LCSA Tool<br>Downstream: HYSYS |
| Social | Employment | person | The number of employees in each industry in Qatar and worldwide, | Upstream: MRIO<br>Midstream: HYSYS<br>Shipping: LNG Maritime Transport Operations LCSA Tool<br>Downstream: HYSYS |
| | Compensation of employment | USD | The monetary value assigned to a service, loss, accident, debt, or other events. | Upstream: MRIO<br>Midstream: HYSYS<br>Shipping: LNG Maritime Transport Operations LCSA Tool<br>Downstream: HYSYS |
| | Total tax | USD | The entire tax income is generated by each industry, both within and outside Qatar. | Upstream: MRIO<br>Midstream: HYSYS<br>Shipping: LNG Maritime Transport Operations LCSA Tool<br>Downstream: HYSYS |
| | Man-hours | hours | Total number of working hours throughout the year. | Upstream: MRIO<br>Midstream: HYSYS<br>Shipping: LNG Maritime Transport Operations LCSA Tool<br>Downstream: HYSYS |
| | Human health | DALY (Disability- | The number of years of life lost as a result of | Upstream: MRIO<br>Midstream: HYSYS |

| Impact area | Impact/Indicator | Unit | Description | Source of data |
|---|---|---|---|---|
| | | Adjusted Life Year) | infirmity, illness, or death at a young age. | Shipping: LNG Maritime Transport Operations LCSA Tool<br>Downstream: HYSYS |
| Economic | Net profit value (Revenue – Total annualized cost) / Gross operating surplus | USD | Corporations' available capital allows them to pay taxes, reimburse creditors, and support their investments. | Upstream: MRIO<br>Midstream: HYSYS<br>Shipping: LNG Maritime Transport Operations LCSA Tool<br>Downstream: HYSYS |
| | Operational cost (utilities, maintenance, operating cost) | USD | The expenses a business incurs in their normal day-to-day operations. | Upstream: MRIO<br>Midstream: HYSYS<br>Shipping: LNG Maritime Transport Operations LCSA Tool<br>Downstream: HYSYS |
| | Equipment cost | USD | The purchase price therefore paid by the Owner to install the equipment | Upstream: MRIO<br>Midstream: HYSYS<br>Shipping: LNG Maritime Transport Operations LCSA Tool<br>Downstream: HYSYS |
| | Salvage value (End of life) | USD | The book value of an asset after all depreciation has been fully expensed | Upstream: MRIO<br>Midstream: HYSYS<br>Shipping: LNG Maritime Transport Operations LCSA Tool<br>Downstream: HYSYS |

Finally, the environmental LCA data connected with each unit's processes is collected for each life cycle stage. The data are extracted from a variety of places, including the LNG Marine Transport Operations LCSA tool, Aspen HYSYS, oil and gas yearly sustainability reports, and the MRIO database. The human health impact endpoint is derived from Al-Yafei, Kucukvar, et al. (2021). Finally, the functional unit will be defined as one ton of LNG output.

## 3.4. Impact assessment tools

### *3.4.1. MRIO database and analysis*

The Economic Input-Output (EIO) criterion is essential in the LCA research's industrial ecology toolkit. Jeswani, Azapagic, Schepelmann, and Ritthoff (2010) stress the necessity of combining input-output analysis with LCA to create a hybrid model that can portray the impacts of LCA inter- and intra-sectoral events. When working with complex systems like LNG supply chains, IO-developed LCA models can be quite valuable in assisting the process-based assessment. The database, including the obligations of trade-based economic exchanges between different sectors (Onat, Kucukvar, & Tatari, 2014a), provides a comprehensive impact assessment, which is a critical contributor.

In this context, IO-based LCA models provide a top-down analysis using a dealing financial matrix between sectors of the economy, taking into account sophisticated interactions across sectors within a single country. MRIO models are included since they advanced within the examination of the triple bottom line (TBL) consequences of consumption and production on a global scale (Kucukvar, Haider, & Onat, 2017; Zhao, Onat, Kucukvar, & Tatari, 2016). Previous research studies (Onat, Kucukvar, & Tatari, 2014b) have extensively employed single-region IO models. Many studies on the carbon impact of consumption (Galli, Weinzettel, Cranston, & Ercin, 2013), manufacturing (Kucukvar, Cansev, Egilmez, Onat, & Samadi, 2016), commerce (Andrew & Peters, 2013), and countries (Hertwich & Peters, 2009) employed MRIO datasets. In comparison to the traditional EIO-LCA model, EXIOBASE 3.41 is the favored option due to improvements made by Carnegie Mellon University's EIO-LCA in the 2015 model compared to the 2007 model. The EXIOBASE 3.41 is a high-resolution global MRIO resource covering 90% of the world's marketplace. It summarizes all that EIO-LCA provides for the 2015 database (Stadler et al., 2018), including the most up-to-date data (material satellite and socio-economic data). The development of a multinational life cycle framework sustainability assessment using the most extensive EXIOBASE 3.41 database is regarded as revolutionary and unique in the LNG industry. However, for a global life cycle sustainability analysis of power production sectors and energy management in many regions throughout the world, the MRIO database indicated above is insufficiently integrated. According to a review of MRIO studies, the energy sector's sustainability impacts must be assessed using the TBL measure, which includes the entire world and reveals as many countries and sectors as feasible (Wood et al., 2015). The main steps of midpoint air emissions calculation using the MRIO database are illustrated in Figure 6.

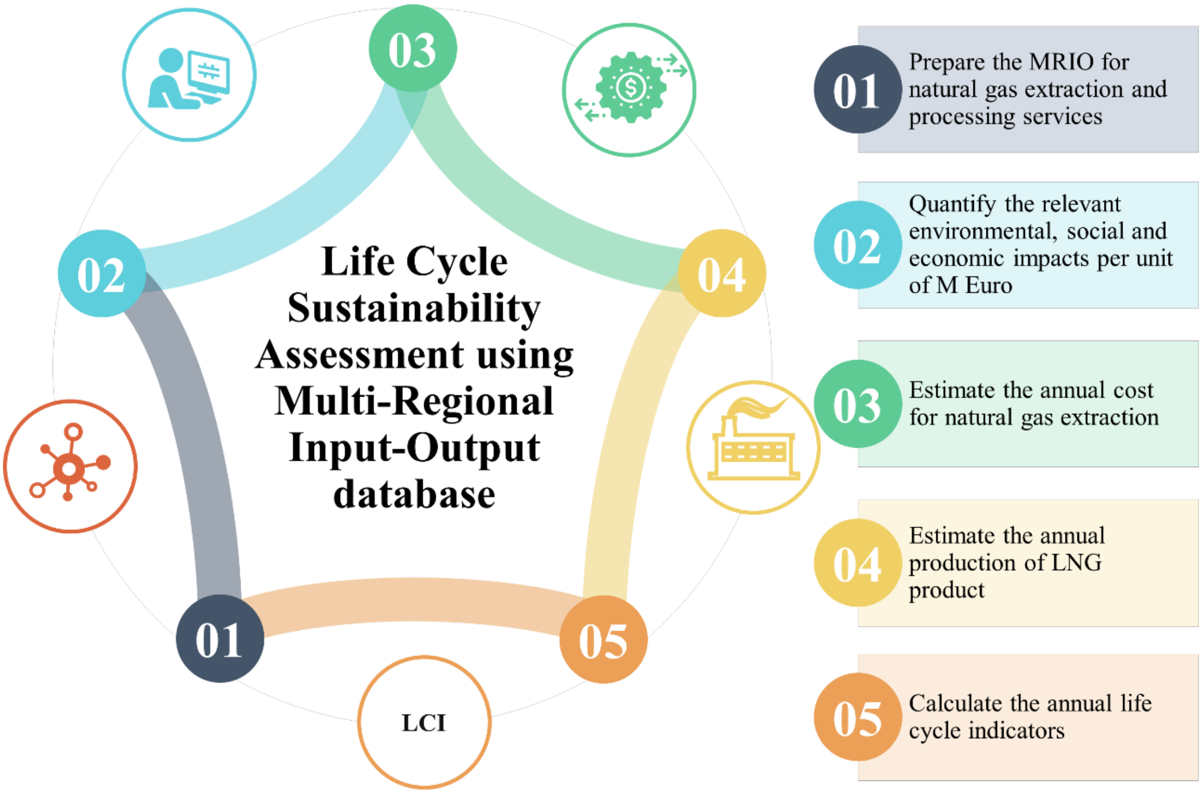

Figure 6. Steps of life cycle air emissions using MRIO database.

The parameter factors relevant to this work are $CO_2$, $CH_4$, $N_2O$, $NH_3$, $PM_{2.5}$, $SO_x$, $NO_x$

($SO_x$ and $NO_x$ are considered as $SO_2$ and $NO_2$, respectively), energy inputs, operating surplus, employment, compensation of employment, total tax, and employment hours, according to the MRIO table for NG extraction and processing. The elements are weighed in different units per million euros as an annual expenditure. The annual investment in NG extraction and processing per million Euros must be estimated to calculate the yearly values. The cost of NG extraction has been estimated to be USD 4 per MMBTU NG (Foss, 2011). Designers employed the unit conversion method ("Chapter 1 - LNG Fundamentals," 2014) to convert the NG to LNG factors. The following Equations (1) and (2) were used to compute the price of each ton of LNG in Euro:

$$Unit\ cost_{Natural\ gas\ extraction} = Cost\ per\ MMBTU\ natural\ gas\ \times Conversion\ factor \tag{1}$$

$$Unit\ cost_{Natural\ gas\ extraction} = \frac{4.0\ USD}{MMBTU\ natural\ gas} \times \frac{EURO}{1.21\ USD} \times \frac{1 \times 10^6\ MMBTU}{TriBTU\ natural\ gas} \times \frac{0.021\ TriBTU\ natural\ gas}{1{,}000\ ton\ LNG} = 0.0694 \frac{USD}{Ton\ LNG\ Produced}$$

$$Annual\ cost_{Natural\ gas\ extraction} = Annual\ LNG\ production \times Unit\ cost \tag{2}$$

$$Annual\ cost_{Natural\ gas\ extraction} = 126 \times 10^6\ Ton \times 0.0694\ \frac{EURO}{Ton} = 8.75\ M\ EURO$$

To calculate the annual parameters, each MRIO factor is multiplied by the annual cost of NG extraction, as per Equation (3).

$$Annual\ impact_{Natural\ gas\ extraction} = Annual\ cost_{Natural\ gas\ extraction} \times MRIO\ factor \tag{3}$$

### *3.4.2. Aspen HYSYS modeling*

This model is a widely used simulation program within the energy industry. The optimization process is the primary purpose of this software; it involves the downstream, upstream, and midstream processes. The flow process for many industrial operations might include hydrocarbon processes, gas flue enumeration for emission reporting, wastewater treatment among other operations, process performance troubleshooting and monitoring, and a commonly utilized promising equipment for over 35 years (AspenTechnologyInc, 2021).

In this research, the stages starting from the pre-separation unit until the regasification unit in the receiving terminals are simulated in the Aspen HYSYS chemical process simulator except for the transportation stage. Two subsections of the LNG transformation train are considered; hot and cold. The hot section operates above the ambient temperatures and includes the NG pre-separation, sweetening, SRU, and dehydration sections. On the other hand, the cold part comprises recovery and fractionation of NGL, nitrogen/mixed-refrigerant coolant cycle liquefaction, HeX, NR facilities, and export terminal. Cooling, heating, power, and shaft work supplies are required for the hot and cold portions. Most are produced and delivered via the plant's utility area, fueled by hot and cold waste hydrocarbons. The LNG is sent to the exporting terminals after liquefaction, where it is shipped to the end-users. Receiving terminal at the end-users side takes care of regasifing the LNG by heating for future customer distribution. Approximately 126 MMTA of LNG were provided for the end-user during tank holding mode with an 18,146 MMSCFD NG feed based on a simulation for the whole LNG chain. The NG feed terms and product specifications are listed in Table 3.

Table 3. Chain Feed Conditions and Products' Specifications.

| NG feed parameters | Specifications |
|---|---|
| Temperature (°C) | 27 |
| Pressure (bar) | 84.5 |
| Flowrate (MMSCFD) | 18,146 |
| Composition (mol%) | |
| $N_2$ | 3.78 |
| $H_2S$ | 0.80 |
| $CO_2$ | 2.43 |
| C1 | 81.3 |
| C2 | 4.84 |
| C3 | 1.84 |
| C4 | 1.03 |
| C5+ | 2.93 |
| BTX | 0.24 |
| Mercaptans | 0.04 |
| $H_2O$ | 0.74 |
| He | 0.04 |
| **LNG Product Parameters** | **Specifications** |
| Temperature (°C) | -161 |
| Higher heating value (BTU/SCF) | 1,040 |
| Flowrate (MMTA) | 126 |
| Composition (mol%) | |
| $N_2$ | 0.70 |
| C1 | 93.4 |
| C2 | 5.90 |
| C3 | 0.03 |
| $H_2S$ (ppm) | ≤4 |
| $CO_2$ (ppm) | ≤59.2 |

The rough feed-acid NG on the LNG train passes first via the condensate and water pre-separation section. For the simulation technique and the Process Flow Diagram (PFD), see Figure 7. The principal limitation of the method is the Reid Vapor Pressure condensate product (RVP). The reboiler duty of C1 was thus changed in the simulation, producing 9.4 psi of RVP condensate. The model shows that about 336 thousand standard barrels of stabilized condensate (kS-bbl/day) are generated from the specified NG feed, which is equal to approximately 91% of feed pentane plus recovery. The rest of the conditions specific to the pre-separation unit are illustrated in Table 4.

Table 4. Pre-separation Unit Conditions and Specifications.

| Specification \ Stream | Feed from off-shore | Sour NG to AGRU | Condensate | Sour water |
|---|---|---|---|---|
| Temperature ($^{o}$C) | 27.00 | 34.50 | 40.24 | 28.64 |
| Pressure (bar) | 84.50 | 74.66 | 74.66 | 28.00 |
| Flowrate (MMSCFD) | 18,145.67 | 17,658.50 | 368.79 | 135.21 |
| Composition (mol%) | | | | |
| $N_2$ | 3.78 | 3.88 | | |
| $H_2S$ | 0.80 | 0.82 | 0.01 | 0.05 |
| $CO_2$ | 2.43 | 2.49 | | 0.06 |
| C1 | 81.30 | 83.32 | | |
| C2 | 4.84 | 4.96 | 0.02 | |
| C3 | 1.84 | 1.87 | 0.50 | |
| C4 | 1.03 | 0.96 | 9.13 | |
| C5+ | 2.93 | 1.47 | 82.46 | |
| BTX | 0.24 | 0.10 | 7.80 | |
| Mercaptans | 0.04 | 0.04 | 0.08 | |
| $H_2O$ | 0.74 | 0.07 | | |
| He | 0.04 | 0.04 | | 99.89 |

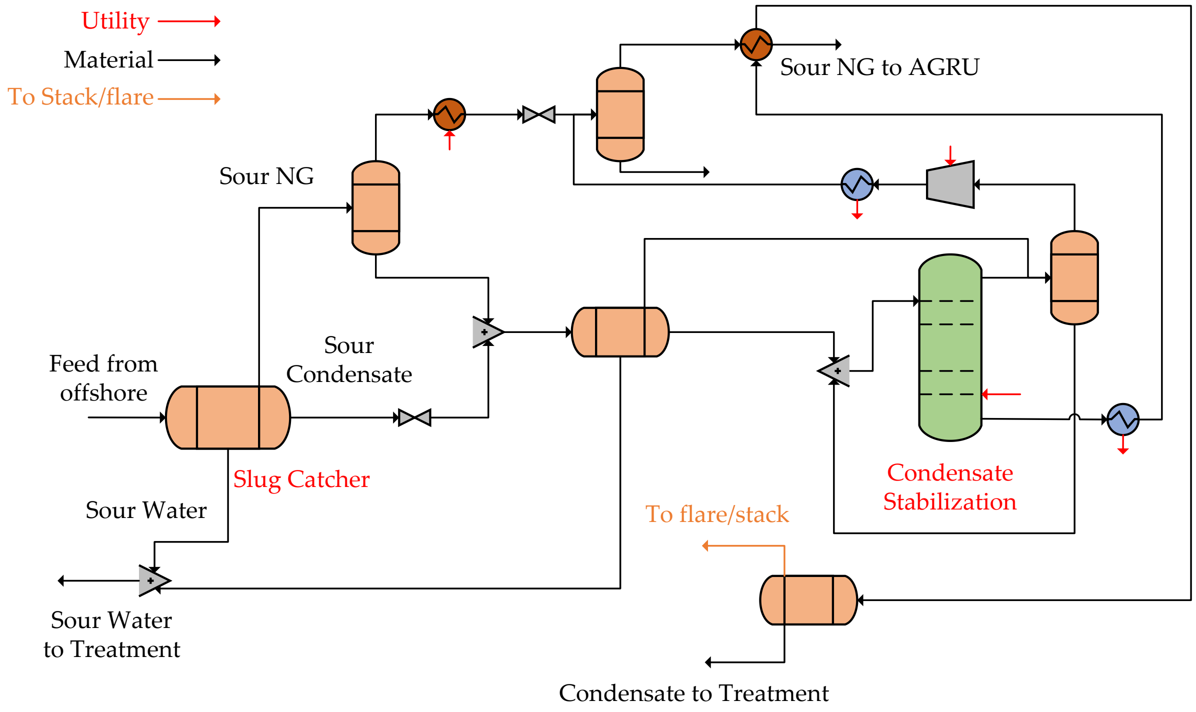

Figure 7. PFD of the simulated pre-separation unit.

After the pre-separation section, the separated sour NG is placed in the sweetening unit to extract undesired acid gases ($CO_2$ and $H_2S$), mercaptans, and BTX and send them to SRU and Tail Gas Treatment (TGT) sections. Figures 8 and 9 demonstrate the flowsheets of the sweetening and SRU/TGT units with the simulation technique. Methyl diethanolamine (MDEA) was utilized in this study to eliminate NG acid gasses on the basis of a reaction separation model. All the reactions, aside from the kinetically constrained $CO_2$, were considered to be in equilibrium. SRUs produce sulfur Allotropes by the acid gas by-product from the sweetening unit. SRUs employ the process Claus consisting of the thermal and the catalytic parts. The first phase consists of the heat recovery system for steam production and the reaction chamber. In this step, the oxidation of a part of the $H_2S$ input produces sulfur allotropes and $SO_2$. The use of a downstream TGT unit is one technique to reduce excess $SO_x$ generation from SRUs. The SRU scheme follows the acid gas removal unit with 2 stage Claus process and TGT unit (Perdu, Normand, Laborie, & Alhatou, 2016). The conditions and specifications illustrated in Tables 5 and 6 demonstrate 99.61% removal of $CO_2$ and 99.97% removal of SRU from the sour NG. The Acid gas from the first regenerator rich in $CO_2$ is sent directly to the TGT unit, where the Acid gas from the first regenerator rich in $H_2S$ is sent to the SRU unit to convert it to elemental Sulfur.

Table 5. Sweeting Unit Conditions and Specifications.

| Specification \ Stream | Sweet gas to dehydration | Acid gas to TGT | Acid gas to SRU | Wastewater |
|---|---|---|---|---|
| Temperature ($^oC$) | 47.00 | 58.91 | 113.80 | 127.60 |
| Pressure (bar) | 68.59 | 5.00 | 1.90 | 2.30 |
| Flowrate (MMSCFD) | 16,994.18 | 237.51 | 428.96 | 1.16 |
| Composition (mol%) | | | | |
| $N_2$ | 4.01 | 0.57 | 0.04 | 0.00 |
| $H_2S$ | 0.00 | 6.50 | 32.89 | 27.56 |
| $CO_2$ | 0.01 | 84.27 | 66.27 | 4.51 |
| C1 | 86.19 | 6.16 | 0.38 | 0.02 |
| C2 | 5.14 | 0.04 | 0.00 | 0.01 |

| Specification \ Stream | Sweet gas to dehydration | Acid gas to TGT | Acid gas to SRU | Wastewater |
|---|---|---|---|---|
| C3 | 1.93 | 0.42 | 0.03 | 0.01 |
| C4 | 0.98 | 0.32 | 0.02 | 0.01 |
| C5+ | 1.50 | 0.94 | 0.05 | 0.01 |
| BTX | 0.09 | 0.48 | 0.26 | 0.05 |
| Mercaptans | 0.04 | 0.31 | 0.06 | 0.03 |
| $H_2O$ | 0.07 | 0.00 | 0.00 | 67.79 |
| He | 0.04 | 0.00 | 0.00 | 0.00 |

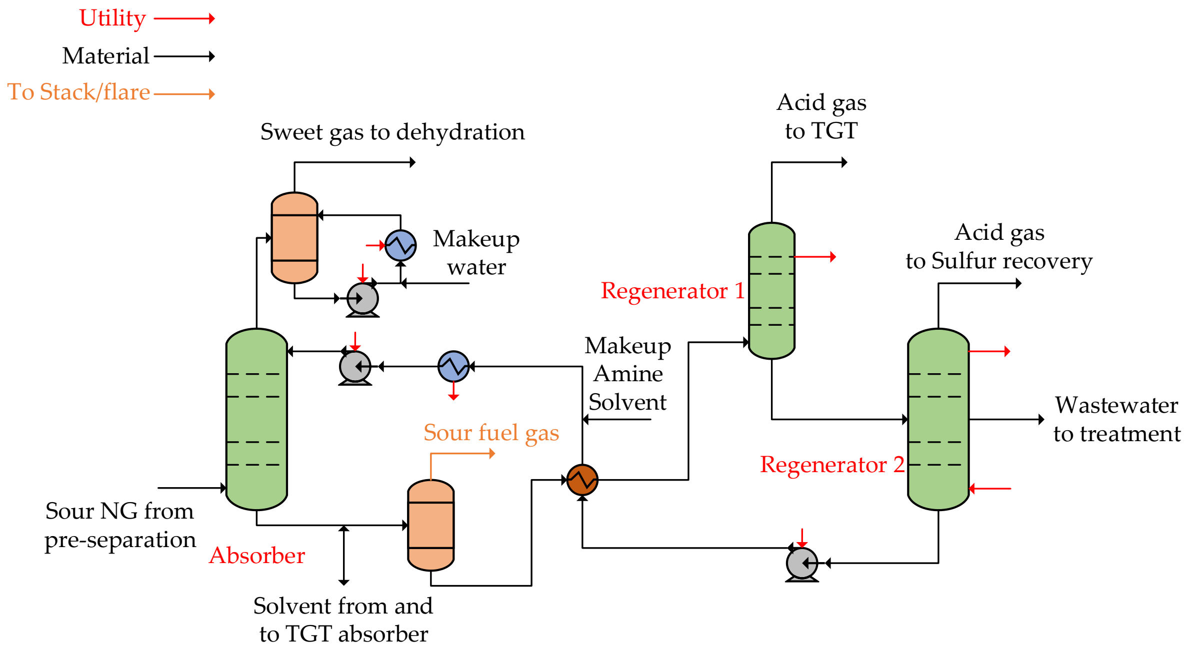

Figure 8. PFD of the simulated sweetening unit.

Table 6. SRU and TGT Conditions and Specifications.

| Specification \ Stream | Steam | Fuel | Air | Sour water | Water out | Absorber top | Sulfur |
|---|---|---|---|---|---|---|---|
| Temperature ($^{o}$C) | 148.04 | 14.95 | 34.99 | 25.00 | 100.01 | 35.00 | 135.00 |
| Pressure (bar) | 4.51 | 3.77 | 1.70 | 1.01 | 1.01 | 1.06 | 1.43 |
| Flowrate (MMSCFD) | 7.53 | 8.04 | 68.14 | 0.58 | 437.34 | 577.56 | 118.43 |
| Composition (mol%) | | | | | | | |
| $O_2$ | | | 20.95 | | | | |
| $N_2$ | | | 79.02 | | | 77.64 | |

| Specification \ Stream | Steam | Fuel | Air | Sour water | Water out | Absorber top | Sulfur |
|---|---|---|---|---|---|---|---|
| $H_2S$ | | | | | | 0.02 | |
| $CO_2$ | | | 0.03 | | | 10.28 | |
| C1 | | 95.00 | | | | | |
| C2 | | 4.00 | | | | | |
| C3 | | 1.00 | | | | | |
| $H_2O$ | 100.00 | | | 100.00 | 100.00 | 5.28 | |
| H2 | | | | | | 6.78 | |
| S | | | | | | | 100.00 |

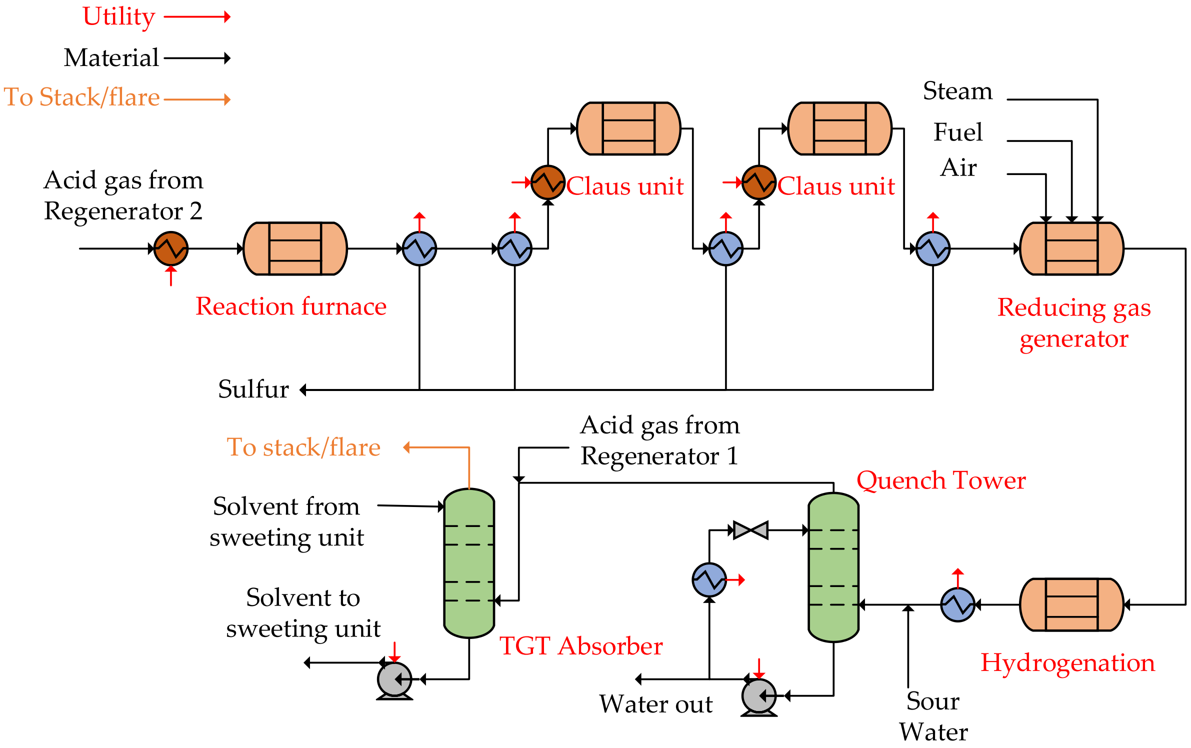

Figure 9. PFD of the simulated SRU/TGT unit.

To avoid downstream corrosion and hydrate creation, which can clog pipes and heat exchanger passes, NG exiting the sweetening unit should be treated to remove water (dehydration). Figure 10 shows the simulated dehydration unit's PFD with three molecular sieve adsorbers. If water has saturated an adsorber, the NG feed must be regenerated to a new adsorber where in principle, two of the beds are in duty, and one is in regenerations mode. The conditions and specifications illustrated in Table 7 demonstrate 100% dehydration of the sweet NG.

Table 7. Dehydration Unit Conditions and Specifications.

| Specification \ Stream | Sour water | Dehydrated NG |
|---|---|---|
| Temperature ($^oC$) | 24.96 | 24.08 |
| Pressure (bar) | 67.54 | 66.81 |
| Flowrate (MMSCFD) | 1.00 | 16,817.03 |
| Composition (mol%) | | |
| $N_2$ | | 4.04 |
| $CO_2$ | | 0.01 |
| C1 | | 86.80 |
| C2 | | 5.12 |
| C3 | | 1.90 |
| C4 | | 0.92 |
| C5+ | | 1.14 |
| BTX | | 0.03 |
| $H_2O$ | 100.00 | |
| He | | 0.04 |

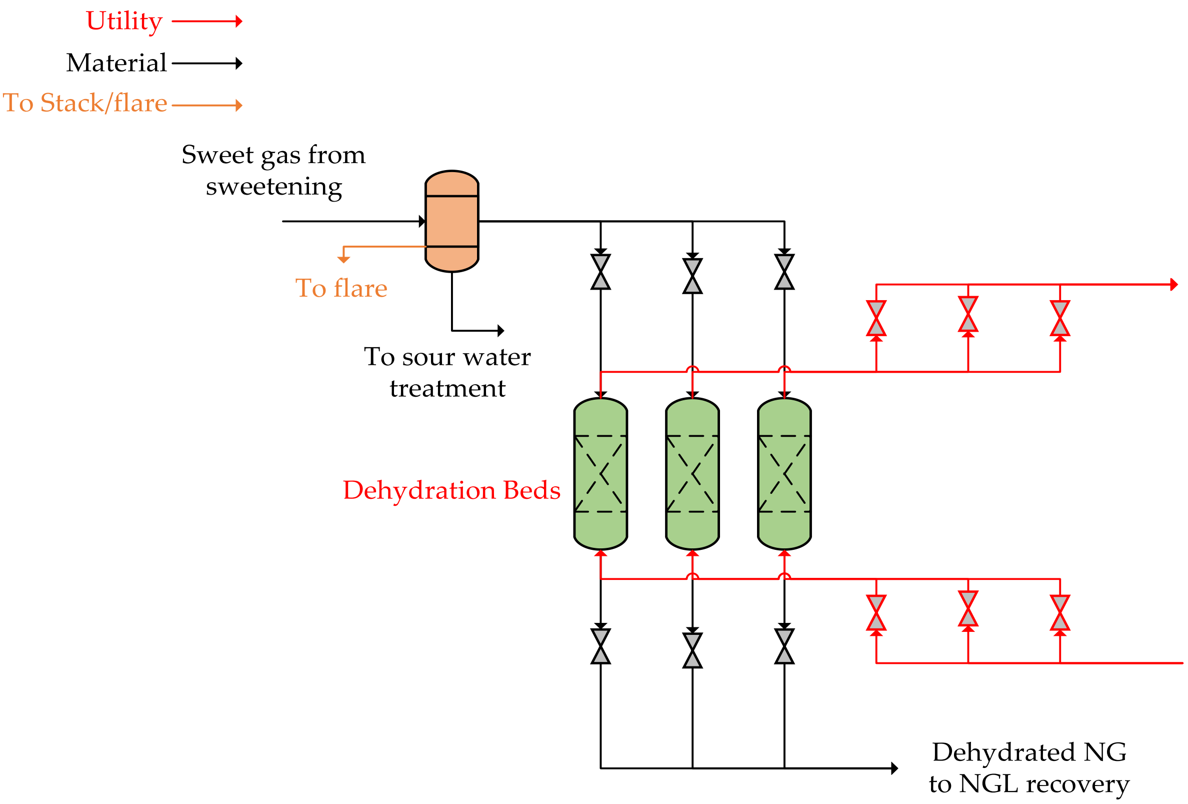

Figure 10. PFD of the simulated dehydration unit.

Dehydrated NG enters the NGL recovery unit after pre-treatment. This unit contributes to the regeneration of the residual condensate of the NG stream, provides the ethane/propane cooling make-up, and the production of necessary LNG specifications for the liquefaction system. As seen in Figure 11, a scrub column for feed Precooling and reflux generation is installed in the NGL recovery unit for the under examination chain. This compresses, condenses, sub-cools, and throbs refrigerant compression over two vapor compression cycles, such that coolers are provided mainly through evaporation. Low-pressure mixed refrigeration (MRs) is given for cooling and liquefaction in the primary cryogenic heat exchanger (MCHE), as indicated in Figure 12. The NG is coming out from the NGL recovery unit at 36 $^{o}$C and 67 bar as illustrated in Table 8 and is being cooled to -148.4 $^{o}$C and 43 bar as illustrated in Table 9.

Table 8. NGL Recovery Unit Conditions and Specifications.

| Specification \ Stream | NG to liquefaction | NGL |
|---|---|---|
| Temperature ($^{o}$C) | 36.42 | 123.60 |
| Pressure (bar) | 66.83 | 32.20 |
| Flowrate (MMSCFD) | 14,640.59 | 723.79 |
| Composition (mol%) | | |
| $N_2$ | 4.20 | |
| $CO_2$ | 0.01 | |
| C1 | 90.39 | |
| C2 | 5.33 | 1.05 |
| C3 | 0.03 | 46.48 |
| C4 | | 23.14 |
| C5+ | | 28.49 |
| BTX | | 0.85 |
| He | 0.04 | |

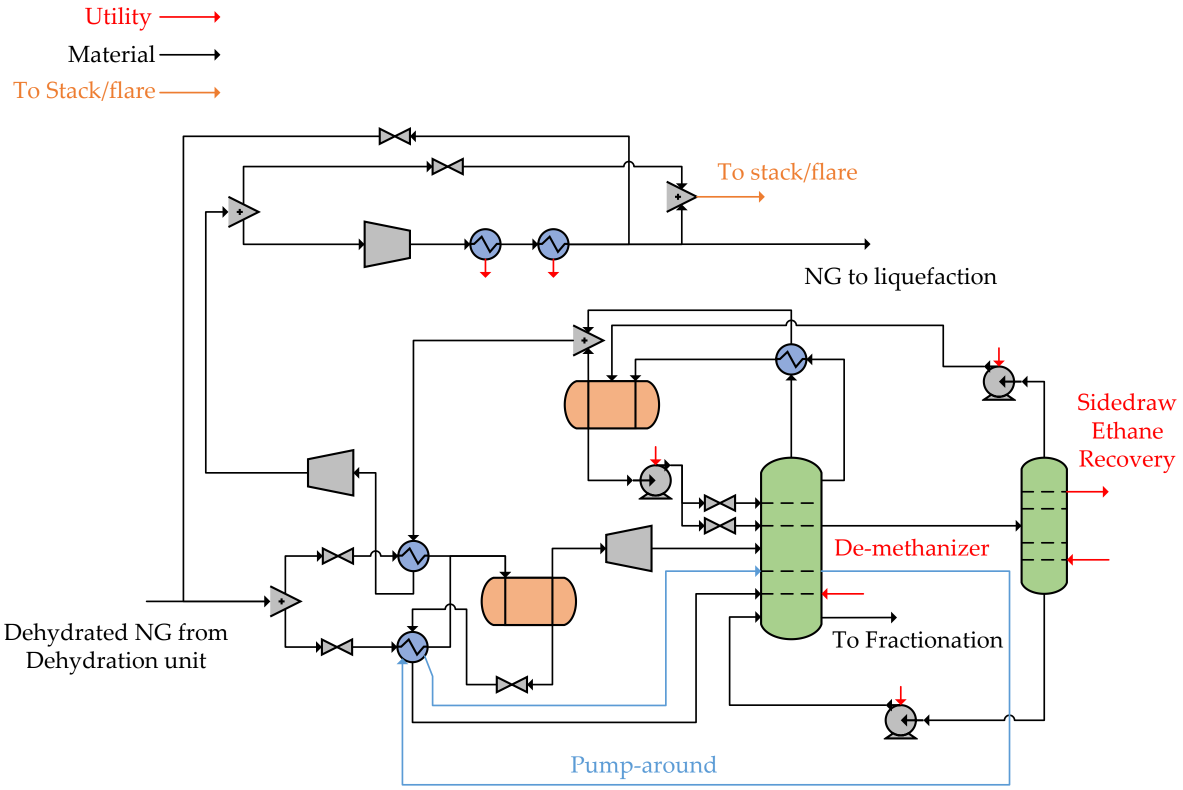

Figure 11. PFD of the simulated NGL recovery unit.

Table 9. NG Liquefaction Unit Conditions and Specifications.

| Specification \ Stream | From He | From $N_2$ | LNG |
|---|---|---|---|
| Temperature (°C) | -155.30 | -161.90 | -148.40 |
| Pressure (bar) | 3.18 | 1.20 | 43.35 |
| Flowrate (MMSCFD) | 13.51 | 1,547.55 | 16,487.81 |
| Composition (mol%) | | | |
| $N_2$ | 49.94 | 37.61 | 4.20 |
| $CO_2$ | | | 0.01 |
| C1 | 2.00 | 62.35 | 90.39 |
| C2 | | 0.01 | 5.33 |
| C3 | | | 0.03 |
| He | 48.06 | 0.03 | 0.04 |

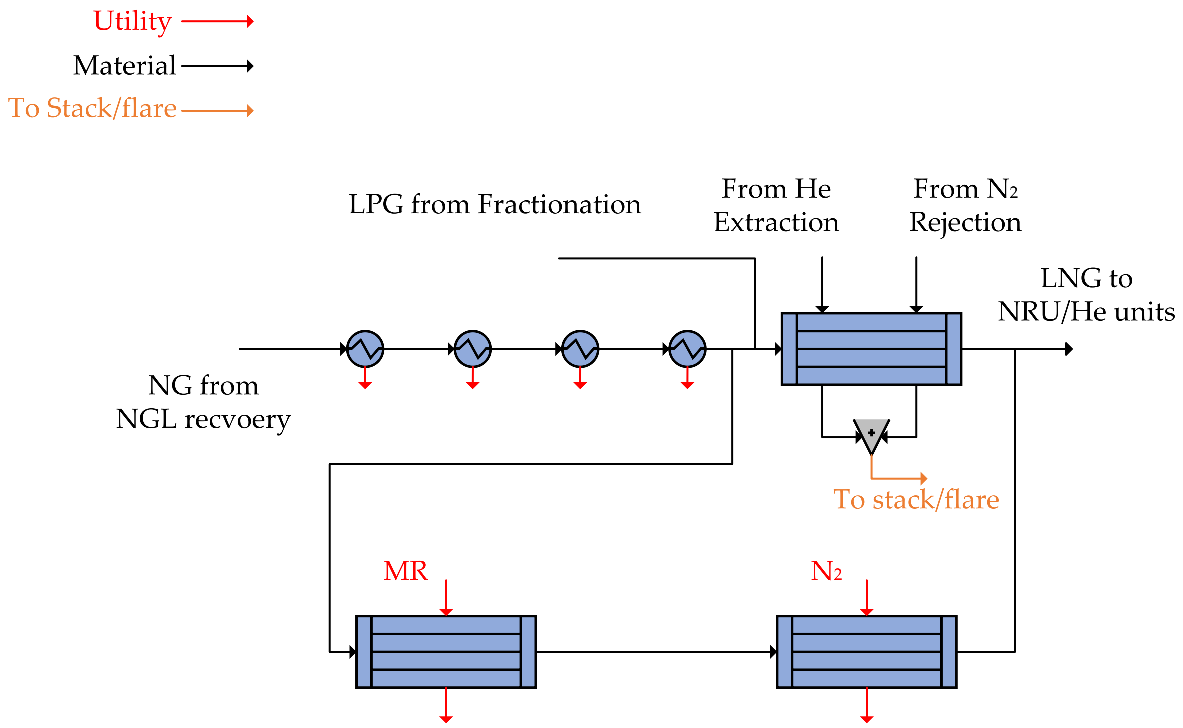

Figure 12. PFD of the simulated Liquefaction unit.

After the liquefaction process, the LNG transfers to the helium and nitrogen recovery through the integrated HeX and NR units. As illustrated in Figure 13, a self-refrigeration flash mechanism separates helium from the chain. On the other hand, nitrogen is rejected using a column with a stripper produced by a cold built-in reboiler. Some light hydrocarbons are found in the rejected nitrogen; thus, they are used as fuel. The final LNG project is stored at -161.6 °C and 1.2 bar, as indicated in the unit conditions and specifications in Table 10.

Table 10. HeX and NR Unit Conditions and Specifications.

| Specification \ Stream | Crude He | LNG product |
|---|---|---|
| Temperature (°C) | -155.30 | -161.60 |
| Pressure (bar) | 3.18 | 1.20 |
| Flowrate (MMSCFD) | 13.51 | 14,931.41 |
| Composition (mol%) | | |
| $N_2$ | 49.94 | 0.70 |
| $H_2S$ (ppm) | | ≤4 |
| $CO_2$ (ppm) | | ≤59.2 |
| C1 | 2.00 | 93.38 |
| C2 | | 5.88 |

| Specification \ Stream | Crude He | LNG product |
|---|---|---|
| C3 | | 0.03 |
| He | 48.06 | |

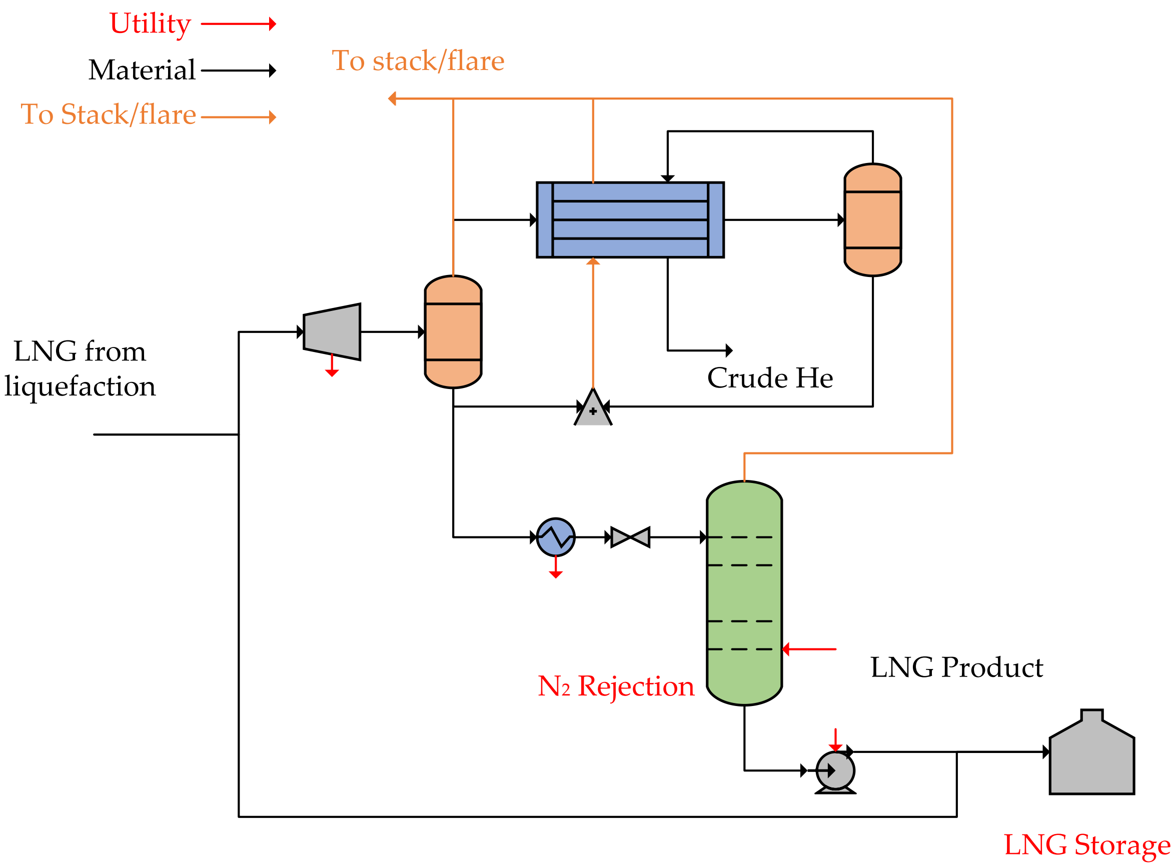

Figure 13. PFD of the simulated HeX and NR unit.

The fractionating unit consists mainly of three conventional distilling columns. One of them is the de-ethanizing (C-21), one is the de-propanizer (C-22), and the other is the de-butanizer (C-23), as indicated in Figure 14. The conditions and specifications of this unit are illustrated in Table 11. The liquefied petroleum gas (LPG) is sent back to liquefaction to be mixed with LNG.

Table 11. Fractionation Unit Conditions and Specifications.

| Specification \ Stream | LPG | Ethane | Propane | Pentane plus |
|---|---|---|---|---|
| Temperature (°C) | 16.40 | 35 | 45 | 130.63 |
| Pressure (bar) | 32.00 | 27.5 | 30.09 | 8.30 |
| Flowrate (MMSCFD) | 1,847.23 | 7.09 | 4.61 | 170.27 |
| Composition (mol%) | | | | |
| C2 | 67.21 | 98.02 | 1.61 | |
| C3 | 20.36 | 1.98 | 96.44 | |
| C4 | 12.35 | | 1.95 | 0.34 |
| C5+ | 0.08 | | | 97.49 |
| BTX | | | | 2.17 |

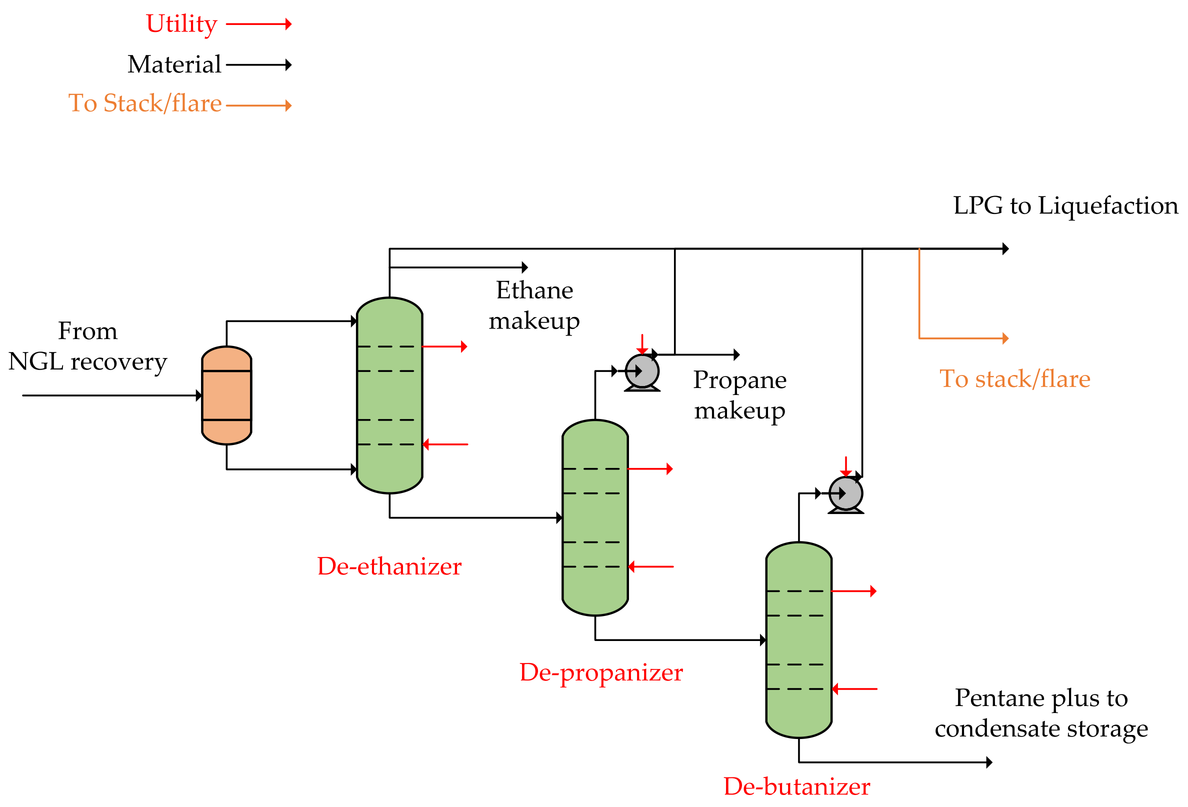

Figure 14. PFD of the simulated fractionation unit.

As indicated in Figure 15, LNG pressure is lowered in the tank entry around the -161°C storage temperature. The LNG high-pressure at the storage tank, heat leaks, cooling of pipes via part of the LNG, and displacing of steam filling the vapor space were detected as a source of BOG. The terminal in the receipt is mainly the LNG storage, regasification, and support utilities. The conditions specific to the simulated regasification plant are illustrated in Table 12.

Table 12. Regasification Plant Conditions and Specifications.

| Specification \ Stream | LNG out from the tank | LNG to customers |
|---|---|---|
| Temperature ($^{o}$C) | -160.6 | 25 |
| Pressure (bar) | 3.0 | 81 |
| Flowrate (MMSCFD) | 14,931.41 | 14,931.41 |
| Composition (mol%) | | |
| $N_2$ | 0.70 | 0.70 |
| $H_2S$ (ppm) | $\leq 4$ | $\leq 4$ |
| $CO_2$ (ppm) | $\leq 59.2$ | $\leq 59.2$ |
| C1 | 93.38 | 93.38 |
| C2 | 5.88 | 5.88 |
| C3 | 0.03 | 0.03 |

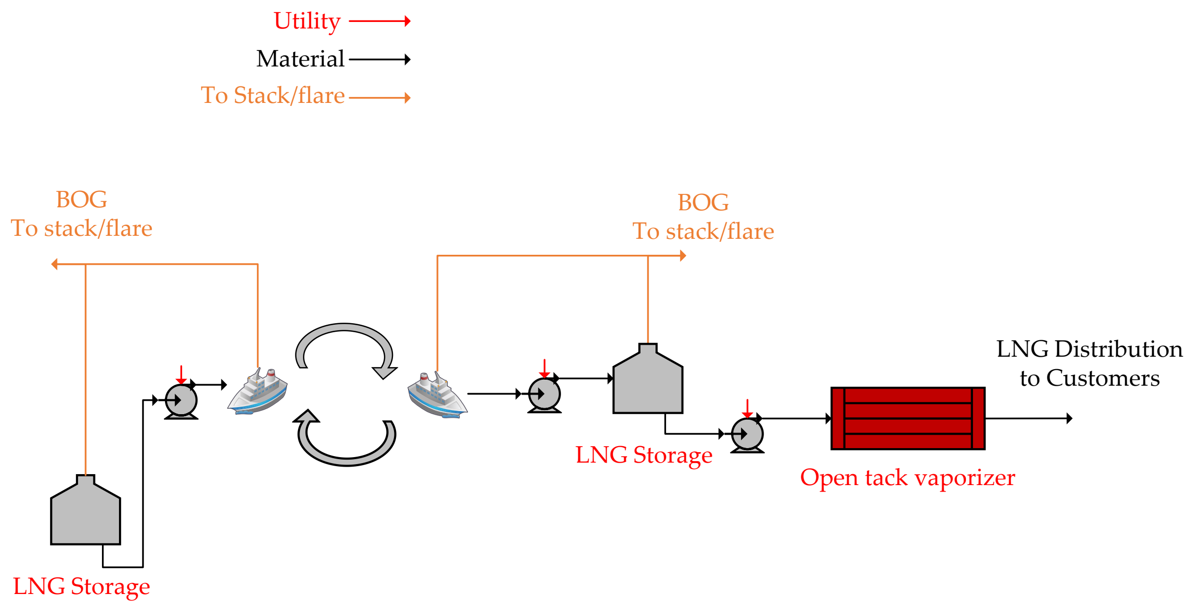

Figure 15. PFD of the export LNG loading, import terminal, and regasification plant.

The integrated LNG production with hot and cold sections that have been simulated using the Aspen HYSYS program employed certain assumptions while conducting the steadystate simulation and the economic and environmental analysis that are listed here in addition to Table 1:

- Investment and operating costs of the exporting terminal are approximated at 26.7 billion USD and annually 504.0 million USD, while for the import regasification terminal are approximated at 1.3 billion USD and annually 28.8 million USD based on literature studies (ERIA, 2017, 2018)
- Total annualized cost is approximated using the following Equation (4):

$$\begin{aligned} &Total\ annualized\ cost \\ &\quad = Capital\ cost \frac{i(1+i)^n}{(1+i)^n - 1} + Operating\ cost + Raw\ material\ cost \\ &\quad + Emissions\ tax \end{aligned} \tag{4}$$

- Net profit is approximated using the following Equation (5):

$$Net\ profit = \frac{Revenue\ (Gross\ operating\ surplus)\ - Total\ annualized\ cost}{Annual\ LNG\ production} \tag{5}$$

- The land use for the different sections of the LNG process is approximated using the built-in sizing tool in Aspen HYSYS of the equipment and following the heuristic of process synthesis and plant layout configuration (ERIA, 2017, 2018)
- Energy consumption is approximated based on the electricity usage of each plant section.
- Employment is approximated considering three shifts per day and the requirement of shift operators, shift supervisors, maintenance technicians, discipline engineers, human resource coordinators, health, safety, and environment specials, managers, and chief operating officer.

- Man-hours are approximated considering 8 hours per shift and 22 days per month in addition to the required period for engineering, procurement, and commissioning stages specific for each plant section.
- The compensation of employees is approximated to be on the average of 11,000 USD per employee monthly.

### *3.4.3. LNG maritime transport operations sustainability assessment tool*

The transportation of LNG products is an integral part of the LNG trading supply chain and plays a role in the LNG industry's whole life cycle. Aseel, Al-Yafei, et al. (2021a) created the LNG maritime transport emission quantification tool and followed it with the human health effect calculation method (Aseel, Al-Yafei, Kucukvar, & Onat, 2021). The data gathering process, assumptions, tools to estimate the energy utilized, emissions calculations as a midway impact, and human health impact as an endpoint estimation were all included in the tool. In this research, the proposed mechanism is utilized to qualify Qatar's LNG supply's midpoint and endpoint implications to the United Kingdom as a case study. The tool's method is to compute GHG, other emissions, and human health based on an estimate of the fuel burned and calculate principal pollutants using emission factors.

Calculating emissions begins with gathering the necessary data and laying out the assumptions that are used to compute the emission value for each vessel. Many data points were collected during the data gathering stage, including but not limited to marine route distance between exporter and importer, days of operation duration, types of carriers, carrier maximum loading capacity in accordance with IMO requirements, fuel types per carrier, carrier's engine, and BOG operations during the Laden and Ballast operations. The next phase employs the required emissions parameters to convert the total energy combusted into midway emissions after estimating fuel consumption per carrier and selecting the fuel category. D.

Cooper and Gustafsson (2004) reported the emission factors that are employed in the suggested tool. Equation (6) shows the methods of calculation that have been considered:

$$LNG\ transport\ emission_{midpoint} = \sum Fuel\ consumption \times Emission\ factor \qquad (6)$$

Figure 16 explains the four steps followed using the LNG maritime transport operations LCSA tool to identify the adverse and beneficial indicators.

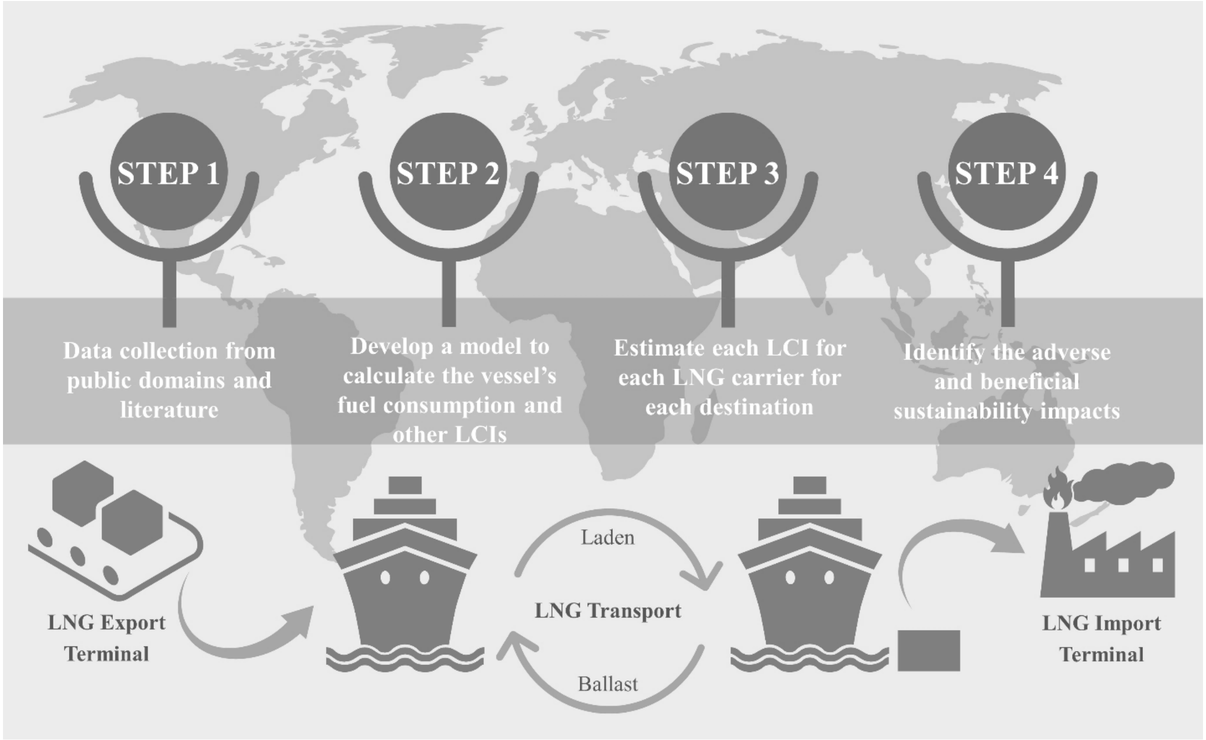

Figure 16. Steps of LNG maritime transport operations LCSA tool.

The energy consumption in the LNG maritime transport operations is mainly from the fuel consumption due to transport purposes or usage of BOG. The land used for the LNG carrier is assumed to be the length multiplied by the width of each carrier and then multiplied by the annual number of roundtrips of Qatar-United Kingdom trade. The size of the carriers is found from (Huan, Hongjun, Wei, & Guoqiang, 2019). The utility water used in the LNG carrier for domestic use, boiler feed water, fire incident response, etc is assumed as 5% of the voyage capacity, and the removal of ocean seawater and return back for the ballast trip balancing is assumed as 15% of voyage capacity multiplied by the annual number of roundtrips for each parameter.

For the social part, the approximate consequence of a substance on human health is calculated by multiplying the ReCiPe 2016 characterization factor with the amount of substance emitted to the atmosphere following Equation (7):

$$Endpoint\ HH_{Hierarchic} = Midpoint\ _{Hierarchic} \times CF_{Hierarchic} \tag{7}$$

Where Endpoint $HH_{Hierarchic}$ is the human health impact and $CF_{Hierarchic}$ is the characterization factor as defined in Table 13. A hierarchical perspective is being applied for all midpoint and endpoint level analyses, representing the impacts for a 100-year time horizon. The conversion of Global Warming ($CO_2$-eq) to human health equivalence is achieved following Equation (7), where the GWP100 is calculated first for GHG emissions. Then the human health impact is calculated based on the characterization factor. Similarly, the conversion of fine particulate matter formation ($PM_{2.5}$-eq) and Photochemical ozone formation ($NO_x$-eq) to human health equivalence is achieved.

Table 13. Midpoint to Endpoint Characterization Factors.

| Midpoint to the endpoint CF human health | Midpoint emission considered | Midpoint unit | Midpoint impact CF (Hierarchic) | Endpoint unit | Endpoint impact CF (Hierarchic) |
|---|---|---|---|---|---|
| Global Warming Potential (GWP) | $CO_2$<br>$CH_4$<br>$N_2O$ | kg $CO_2$-eq./ kg midpoint emission | 1.00<br>28.00<br>265.00 | DALY/kg $CO_2$-eq. | 9.28E-07 |
| Photochemical ozone formation | $NO_x$ | kg $NO_x$-eq./ kg midpoint emission | 1.00 | DALY/kg $NO_x$-eq. | 9.10E-07 |
| Fine particulate matter formation | $SO_2$<br>$NH_3$<br>NO<br>$NO_2$<br>$SO_3$<br>$PM_{2.5}$ | kg $PM_{2.5}$-eq./ kg midpoint emission | 0.29<br>0.24<br>0.17<br>0.11<br>0.23<br>1.00 | DALY/kg $PM_{2.5}$-eq. | 6.29E-04 |

The approximate number of full-time employments, compensation for employees, and total man-hours information are provided by subject matter experts in LNG maritime transport. The total taxes are assumed as 15% of the total revenue of LNG trade between Qatar and the United Kingdom based on the annual LNG supply agreement contract.

For the economic part, the capital cost is the cost associated with the equipment construction, installation, and commissioning of the LNG carrier used. In this research, LNG Conventional type 2 carrier is assumed. Moreover, the fuel cost associated with the roundtrip along the calendar year based on United Kingdom demand is considered and counted. The LNG BOG is assumed to be 0.15% of the total loaded quantity, and the boil-off cost is calculated. Below Equations (8) has been followed to quantify the operational, revenue, and salvage value (end of life) (Rogers, 2018):

$$LNG\ boil-off\ cost = LNG\ loaded\ quantity\ (MMBTU) \times LNG\ cost\ (USD/MMBTU) \times 0.15\% \tag{8}$$

The charter rates for Qatar-United Kingdom trade are assumed for Steam Turbine (ST) and Slow Speed Diesel (SSD) (in USD/day) equal to 47,125 and 79,342, respectively. The charter cost calculation as per Equation (9):

$$Charter\ cost = Roundtrip\ voyage\ days\ (days) \times Charter\ rate\ (USD/days) \tag{9}$$

Port cost is counted following the below Equation (10):

$$Port\ cost = Port\ days \times 100{,}000\ USD/day \tag{10}$$

The Suez Canal is the only canal considered in this research, and the fee is assumed to be 400,000 USD/LNG ship. Agents and broker fees, and insurance can be assumed as per the following Equation (11):

$$Agent, broker, and\ insurance\ cost = 2\%\ of\ Charter\ cost + 2{,}600\ USD/day\ for\ inusratnce \tag{11}$$

The total operational cost is calculated following the below Equation (12):

$$Total\ cost = Charter\ cost + Fuel\ cost + Canal\ cost + Port\ cost + Agent, broker, and\ insurance\ cost \tag{12}$$

Salvage Value (end of life) is calculated using the formula given in Equation (13) below:

$$\begin{aligned} Salvage\ value \\ &= Purchase\ price\ of\ the\ engineering\ machinery \\ &- (Depreciation \times Useful\ life) \end{aligned} \tag{13}$$

The annual revenue (gross operating surplus) is counted following Equation (14):

$$Revenue\ (Gross\ operating\ surplus) = Annual\ supply\ of\ LNG\ \times LNG\ price \tag{14}$$

The gross operating surplus of each stage is calculated separately by multiplying the LNG price annually with each stage's annualized cost and then divided by the overall annualized cost of all LNG stages in the value chain.

### 3.5. Interpretation of hybrid LCSA model

At this stage, the data gathered from the impact analysis results must be recognized, quantified, validated, and assessed. The evaluation is based on our research findings, which were collected using the methods described earlier. The findings are also discussed, highlighting the most serious concerns for LNG's long-term viability. The areas that need to be improved are also included.

Without specific weighting, LCSA is a blend of LCA, LCC, and SLCA. LCSA necessitates a multi-criteria review to handle the markers' balance as well as their grading. The metrics chosen for this research have varying percentages of contributors to the overall sustainability of the systems analyzed to tie various indicators and their influence to the system component and keep the number of social indicators presented to a tolerable and comparative number. Based on their contribution to sustainable development in connection to the properties of the systems studied, beneficial and adverse indicators have been established. Bad indicators have high values and have a negative impact on sustainability, whilst positive indicators have a positive impact on sustainability.

In order to perform the sustainability assessment, the variables used in LCA, LCC, and SLCA have been combined into three sustainability factors (SF) in this study: $SF_{environmental}$, $SF_{economic}$, and $SF_{social}$. The following are the phases of SF calculation:

1. Following the acquisition of the LCA, LCC, and SLCA outcomes, the data for all indicators are transformed into contribution proportions. These proportions are analyzed by comparing the values collected by each collecting system for the same marker, with the greatest marker value providing 100% and the rest systems receiving a comparable amount.
2. Based on the percentage of contribution attributed to each indication, a score of 1 to 5 is assigned. Bad signals (higher percentages of involvement indicate a lower contribution to sustainability) and good indicators (higher percentages of contribution suggest a higher contribution to sustainable development) have been distinguished (greater percentage of contribution means a greater contribution to sustainability). For negative signs, the scoring scale is as follows: 1 point for the participation of 100–81%, 2 points for 80–61%, 3 points for 60–41%, 4 points for 40–21%, and 5 points for 20–1%. On the other side, positive metrics are graded as follows: 1 point for a percentage contribution between 1 and 20%, 2 points for a percentage contribution between 21 and 40%, 3 points for relative proportions between 41 and 60%, 4 points for a percentage contribution between 61 and 80%, and 5 points for a percentage contribution between 81 and 100%. To be more random across economic variables, the overall cost in the LCC scoring system has been obtained instead of examining individual indicators independently.

3. After assessing all indicators, a total score is obtained for each evaluation (LCA, LCA, and SLCA). To compare the three collection systems and the three dimensions studied: environmental, economic, and social, total scores were recalculated into indicator proportions to get the same magnitude (between 0 and 1) and to compare the three collection systems and the three dimensions studied: environmental, economic, and social. The relative values found were given the acronym SF, which stands for three sustainability factors: $SF_{environmental}$, $SF_{economic,}$ and $SF_{social}$. Because SF values range from 0 to 1, those around 1 contribute significantly to sustainability assessments, while those near 0 contribute less.

# CHAPTER 4: RESULTS AND DISCUSSION

## 4.1. Sources and LCI clustering in the LNG supply chain

The life cycle sustainability indicators for each operation stage are identified and analyzed using a heat map diagram for LNG production and supply chain, as shown in Figure 17. As a result, the highest environmental, social and economic impact was the NGL recovery and fractionation unit, without differentiating between the adverse and beneficial effects followed by LNG loading and MDEA sweetening unit. However, the lowest in terms of the sustainability pillars is the pre-separation unit. There is a clear correlation between employment, the compensation of the employment, and the total man-hour results. Moreover, most processing units' social and economic impacts are slightly the same. It is recommended to further research and enhance technology to reduce or capture the particulate matters in higher efficiency to minimize the environmental and human health impacts associated with the LNG midstream process.

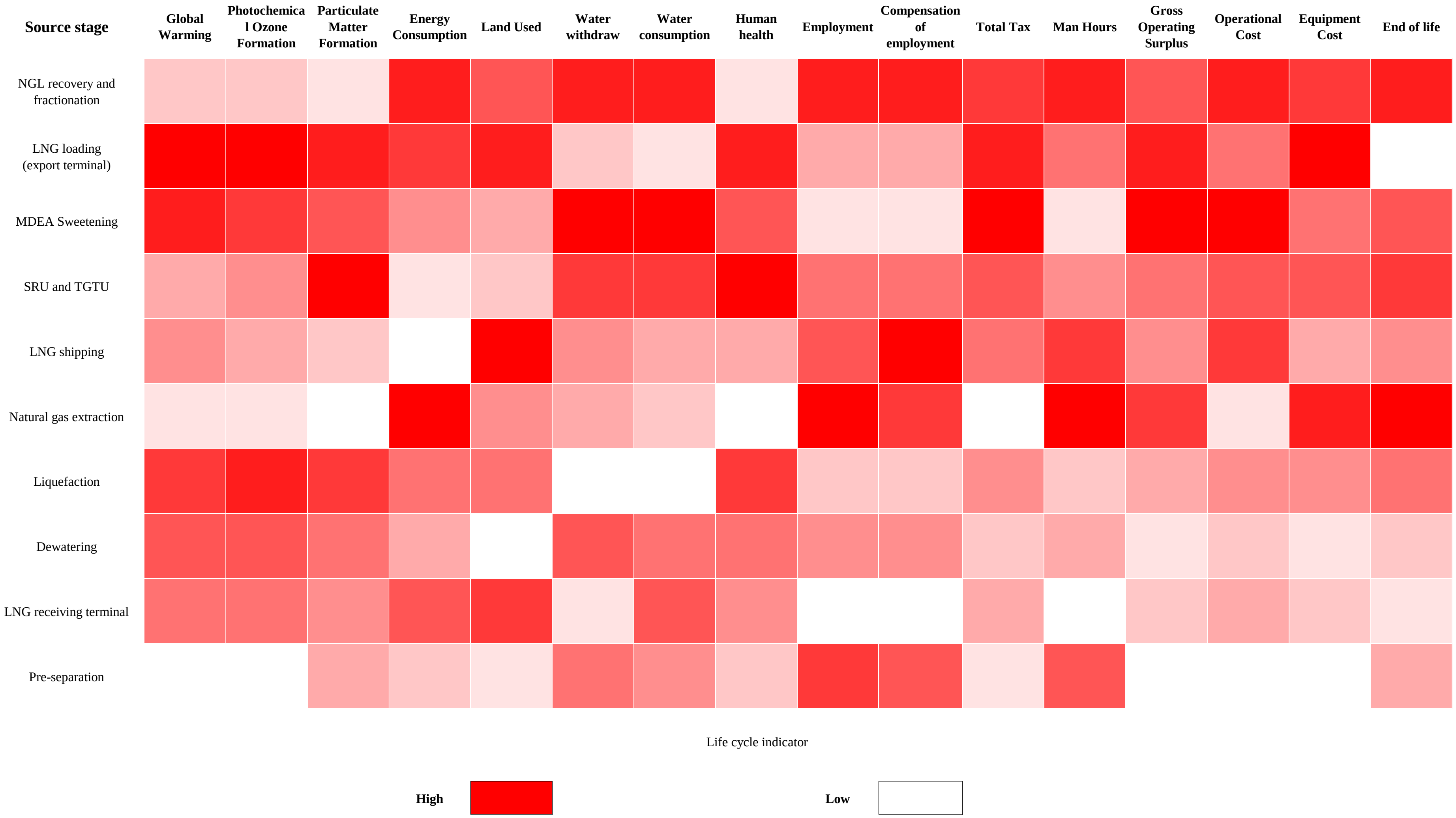

Figure 17. Heat map diagram for LCIs of LNG process chain.

## 4.2. LCA, LCC, and SLCA analysis

LNG process chain provides various quantities and quality of sustainability indicators. The sustainability results from various tools were normalized in ratios for each stage throughout the process chain to make the analysis easier and more beneficial for decision-makers. After, the highest value was considered for all the stages. The results of every single stage were divided by the highest value considered in the previous stage to perform the deemed normalization. Post normalizing, results shall be unitless and dimensionless and within a range from zero to one. The LCI results are provided for each value chain stage in Appendix C.

### *4.2.1. LCA results*

Figure 18 indicates the normalized environmental indicators comparison of the LNG supply chain. As for the normalized $CO_2$-eq emission, LNG loading (export terminal) found the highest source of contribution throughout the process chain with 40%, followed by the MDEA sweetening unit, which represents 24%, and liquefaction unit with 20%. The highest contribution is found again for the normalized $NO_x$-eq emission from LNG loading (export terminal), Liquefaction unit, and MDEA Sweetening unit with 46%, 21%, and 16%, respectively. The lowest normalized $CO_2$-eq and $NO_x$-eq emission were found from the pre-separation unit. The highest contribution is found for the normalized $PM_{2.5}$-eq emission from SRU and TGTU units, LNG loading (export terminal), and Liquefaction unit with 79%, 9.5%, and 4%, respectively. The lowest normalized $PM_{2.5}$-eq emission was found from the natural gas extraction. It is essential to treat the LNG loading unit as a hot spot where further process improvement and emission caption are required. The emissions are generated mainly from product storage, utility consumption, loading to carriers, and BOG flaring. A reliquification unit shall exist to maximize the gas recovery, avoid losses and abate ecological degradation. The depreciation of the environmental releases to the atmosphere is definitely helping to save human lives.

From the normalized energy consumption perspective, the most contribution is from the natural gas extraction stage with 96%. The raw data was taken from MRIO, which is expected to cover the direct and indirect emissions associated with natural gas extraction and processing. It is recommended to furtherly have deep research to validate the MRIO current factors. On the other hand, normalized land used found the highest with 97% for LNG shipping as LNG carriers and taking massive space in the loading and unloading ports throughout the year. The MDEA Sweetening unit found the highest with 74.6% and 73.5%, respectively, regarding the normalized water withdrawal and water consumption. The environmental impact results related to the LNG process chain are provided for each value chain stage in Appendix C Table C.1.

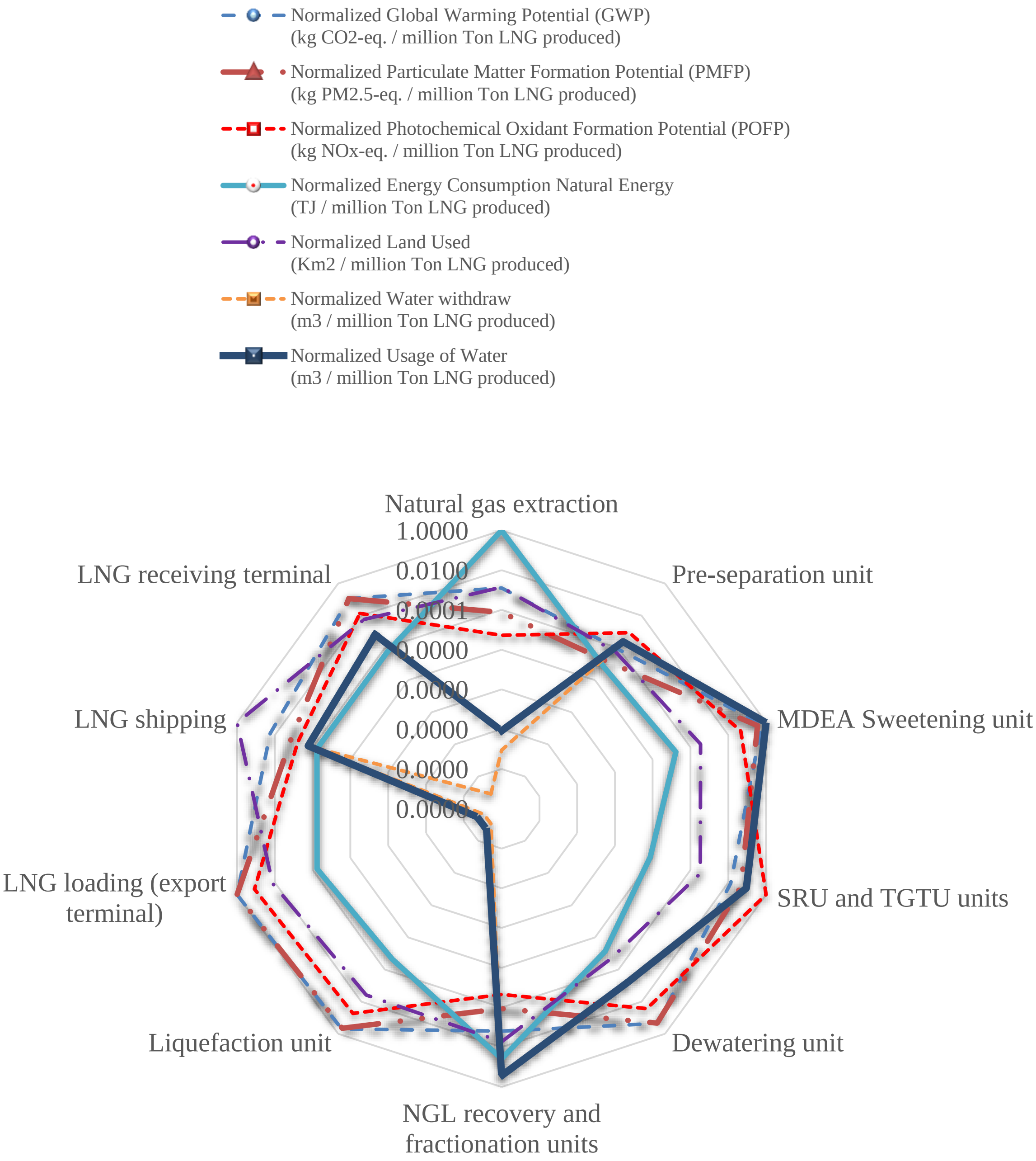

Figure 18. Normalized LCA results of the LNG supply chain.

### *4.2.2. LCC results*

Figure 19 shows the normalized economic impacts directly related to the LNG process chain. MDEA Sweetening unit presents the maximum gross operating surplus, followed by LNG loading (export terminal) and Natural gas extraction stage with 26%, 20%, and 18%, respectively. The minimum gross operating surplus is found in the Pre-separation unit. Moreover, the MDEA Sweetening unit found the highest operational cost with 44% contribution, followed by NGL recovery and fractionation units with 22%, and the lowest in the Pre-separation unit. Furthermore, LNG loading (export terminal) followed by Natural gas extraction stages presented most of the total equipment cost, and the Natural gas extraction stage introduced more than half of the end of life throughout the process chain. The economic impact results related to the LNG process chain are provided for each value chain stage in Appendix C Table C.2.

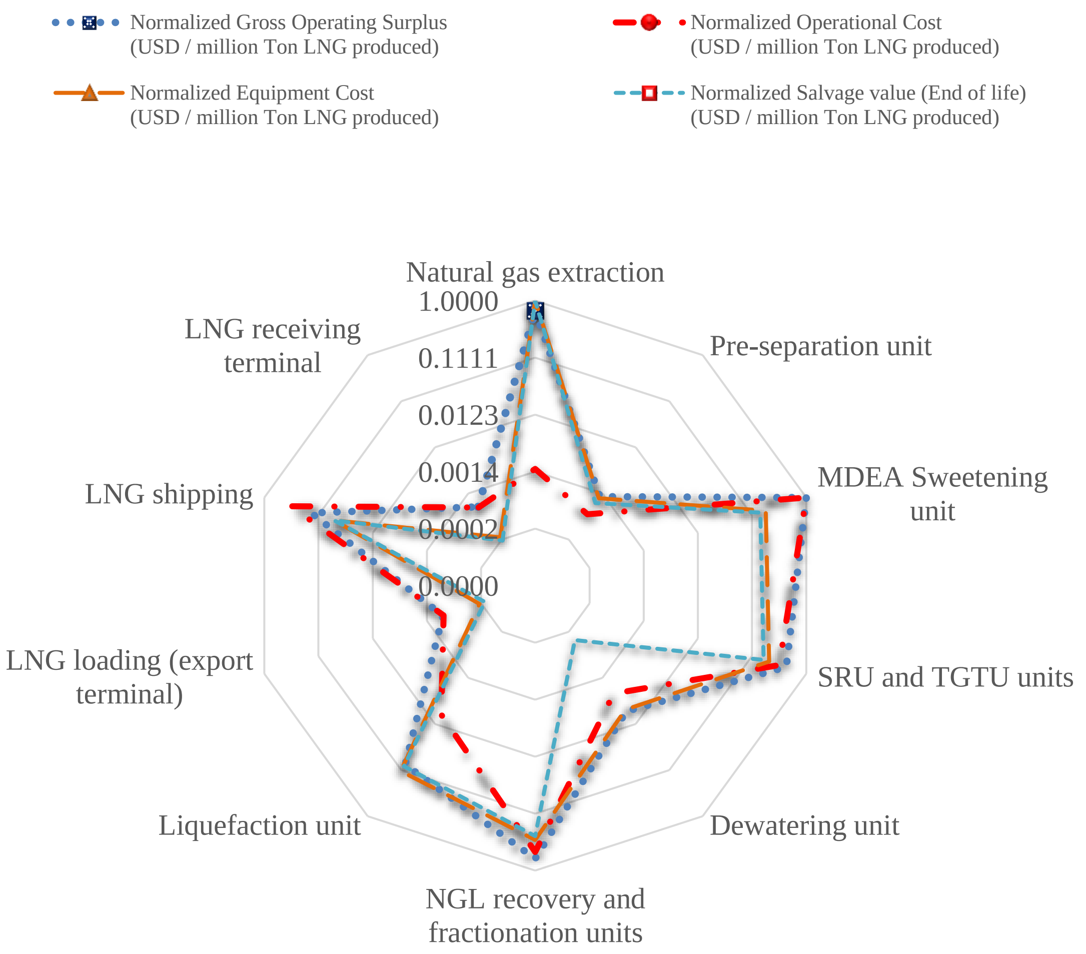

Figure 19. Normalized LCC results of the LNG supply chain.

### 4.2.3. SLCA results

Figure 20 shows the social impacts directly related to the LNG process chain. It was found that more than 73% of human health impact comes from SRU and TGTU units which are the most contributors to $PM_{2.5}$-eq, as illustrated earlier. The second highest contributor to human health impact is the LNG loading (export terminal) stage with approximately 12%. On the other hand, Natural gas extraction and NGL recovery and fractionation units found the highest full-time employment with 58% and 13%, respectively. Also, the same stages have the highest man-hours estimated in this research.

The employment compensation is investigated and found that the highest compensation comes from LNG shipping, followed by NGL recovery and fractionation units. Regarding the tax impact on the social, the MDEA Sweetening unit and NGL recovery and fractionation units present the highest impact with 43% and 27%, respectively. The social impact results related to the LNG process chain are provided for each value chain stage in Appendix C Table C.3.

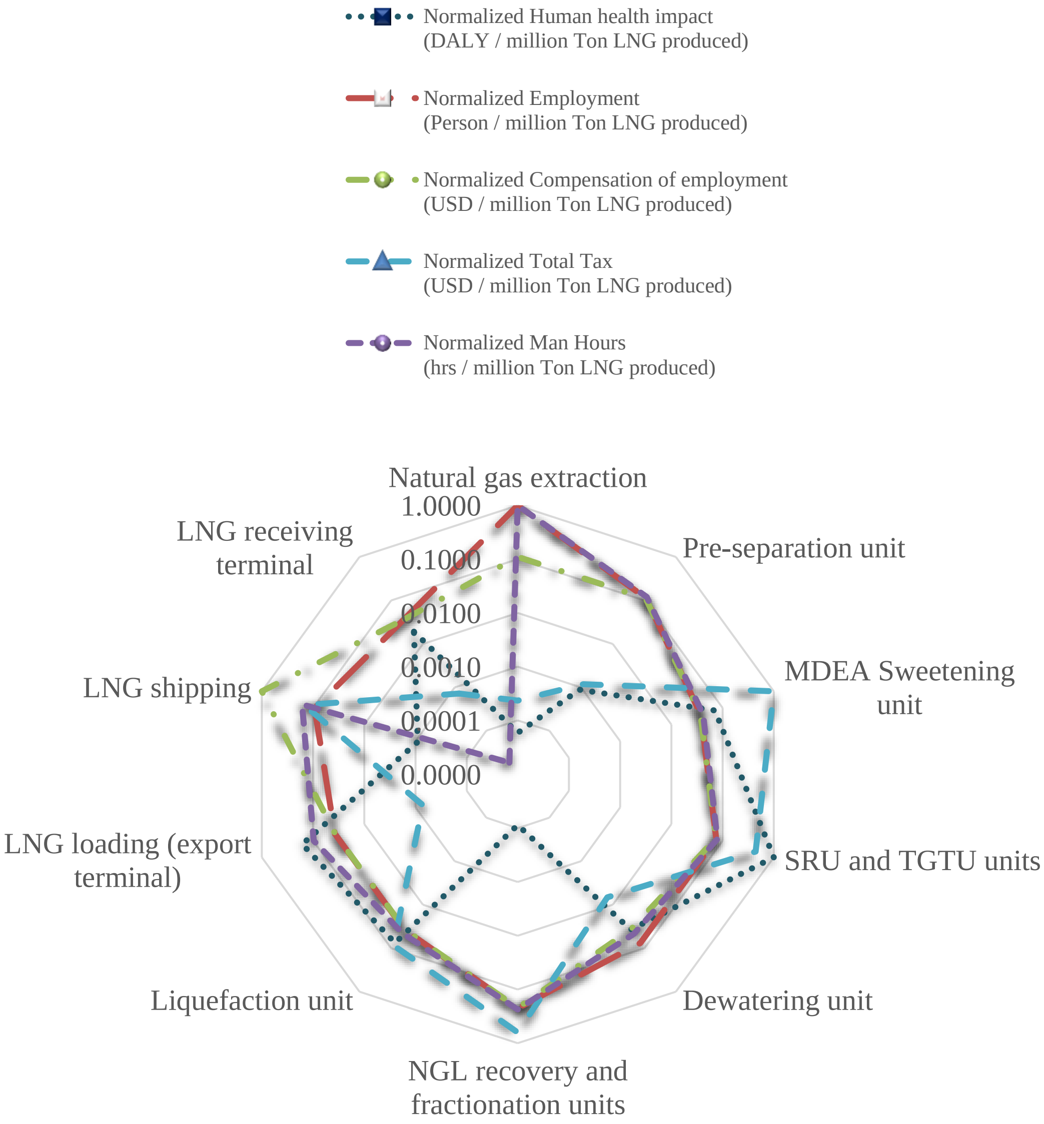

Figure 20. Normalized SLCA results of the LNG supply chain.

### 4.3. Cumulative triangle chart and sustainability assessment results

Table 14 and Figure 21 shows the results of the LCSA and the different values obtained for the SF defined. According to the results obtained, the Pre-separation unit and LNG receiving terminal have the best environmental performance by having the lowest environmental impact, with SF equal to 1. The environmental impact still exists, although the performance is the best among other units. On the other hand, the MDEA Sweetening unit has the worst environmental performance and the lowest SF, equal to 0.66. Note that MDEA Sweetening unit is removing the undesired components such as $H_2S$, $CO_2$, and BTX, which are then released into the environment. The MDEA unit is expected to be the worse from an environmental perspective among the other units.

In terms of social and economic impacts, the Natural gas extraction stage system presents the best performance among all other stages, with SF equal to 1. However, SRU and TGTU units illustrate the lowest performance in the social perspective, with SF equal to 0.41. Moreover, LNG loading (export terminal) and LNG shipping are both showing the minimum performance in terms of economic impact, with SF equal to 0.73 for each stage. Overall, the natural gas extraction stage shows the best performance among other stages in the LNG value chain from the sustainability perspective.

Note that transportation is only considering the United Kingdom demand of 6.6 MMTA, and accordingly, all sustainability impacts are considered per the current demand. The sustainability assessment results, contribution percentage, and scoring results are provided for each LNG value chain stage in Appendix C Tables C.4, C.5, and C.6.

Table 14. LCSA Results Summary.

| Total scores | Natural gas extraction | Pre-separation unit | MDEA Sweetening unit | SRU and TGTU units | Dewatering unit | NGL recovery & fractionation units | Liquefaction unit | LNG loading (export terminal) | LNG shipping | LNG receiving terminal |
|---|---|---|---|---|---|---|---|---|---|---|
| LCA | 31 | 35 | 23 | 31 | 33 | 33 | 31 | 27 | 31 | 35 |
| SLCA | 17 | 9 | 13 | 7 | 9 | 15 | 9 | 12 | 13 | 9 |
| LCC | 15 | 12 | 12 | 12 | 12 | 13 | 12 | 11 | 11 | 12 |
| Sustainability factors (Relative values) | Natural gas extraction | Pre-separation unit | MDEA Sweetening unit | SRU and TGTU units | Dewatering unit | NGL recovery and fractionation units | Liquefaction unit | LNG loading (export terminal) | LNG shipping | LNG receiving terminal |
| $SF_{environmental}$ | 0.89 | 1.00 | 0.66 | 0.89 | 0.94 | 0.94 | 0.89 | 0.77 | 0.89 | 1.00 |
| $Sf_{social}$ | 1.00 | 0.53 | 0.76 | 0.41 | 0.53 | 0.88 | 0.53 | 0.71 | 0.76 | 0.53 |
| $Sf_{economic}$ | 1.00 | 0.80 | 0.80 | 0.80 | 0.80 | 0.87 | 0.80 | 0.73 | 0.73 | 0.80 |

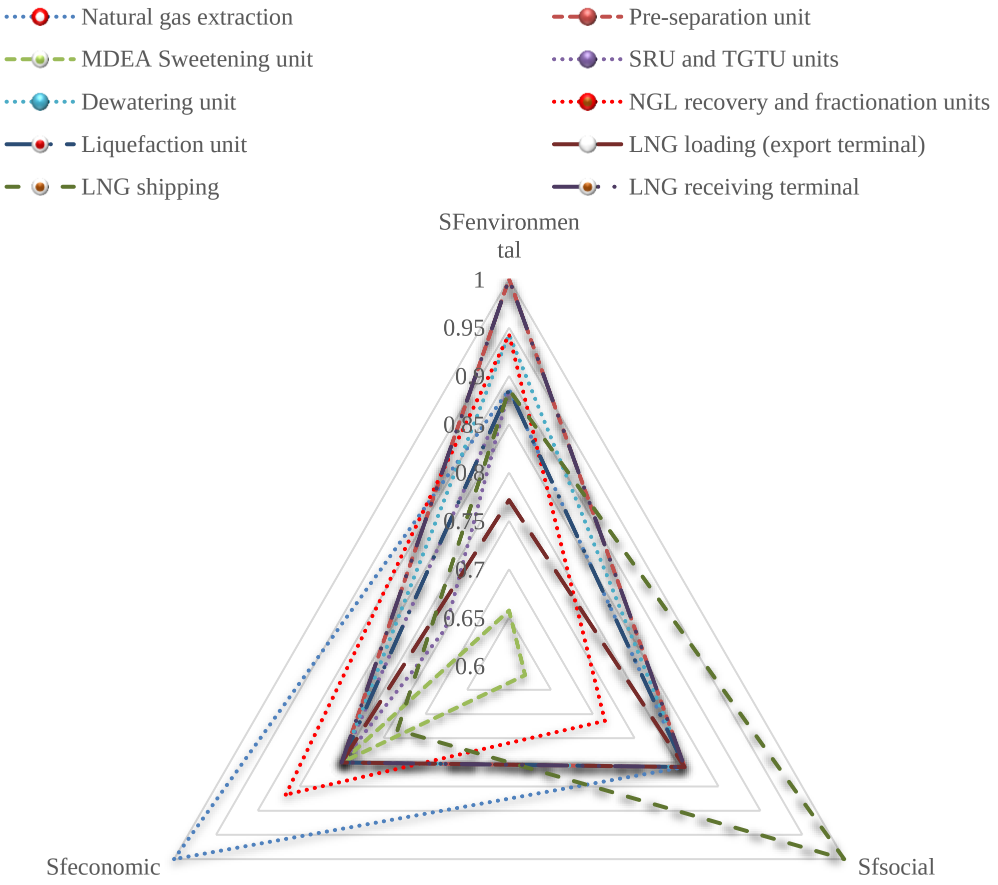

Figure 21. Interpretation of LCSA results.

## 4.4. Social human health implications

This research is considered eye-opening for the social human health impact of the most attractive and promising energy source in the 21st century. According to the results demonstrated in previous sections, many necessary actions need to be considered in the LNG supply chain to ensure social human satisfaction and wellbeing. The proposed implications are divided into administrative and engineering controls. A continuous stack emission monitoring system shall be installed in all individual point source combustion units for the administrative controls to measure the emissions during different operational scenarios. Furthermore, modeling the releases shall be considered for all point sources emission, and simulating the impact for the critical primary receptors is required. The primary sensitive receptors could be but are not limited to crowded areas such as hospitals, schools, stadiums, etc. Moreover, further research is necessary to revalidate the environmental limits set by governments to ensure better air quality and minimum human health impact according to the United States Environmental Protection Agency (US EPA) laws and regulations.

For the engineering controls, industries shall implement the best available control technologies (BACT) to eliminate the air pollutants associated with human health impact. LNG producers shall have the social responsibility against the society to build the evidence on the community and worldwide customers. LNG industries and shipping companies shall implement the possible solutions toward safe, healthy, and efficient processes to have such a sustainable LNG production and supply chain for long-term trading.

Besides, World Health Organization (WHO) shall continue to monitor the air quality conditions and the impact on human health. Industrial evolution must include operation within WHO's standard for air quality to avoid further human treatment and community unsatisfaction costs. Finally, energy policies must also be implemented in order to improve global human health and mitigate the significant contributors to health deterioration in a sustainable manner.

### 4.5. Policymaking implications

The establishment and implementation of sustainability policy in the energy sector, including the LNG supply chain, is crucial and promotes business development, social acceptance, and a green environment. Rare studies are focusing on the LNG supply chain strategies and policymaking. Recent research by Al-Yafei, Aseel, et al. (2021) highlighted critical areas of potential improvement from an energy policy perspective toward sustainability. Generally, representative sustainability performance data shall exist to adopt any new policy. However, it was challenging to get accurate data from the specialized sector during this research, especially natural gas extraction and processing. Towards valid policymaking, precise data is needed. Further policy focus can be provided on the below subjects:

1. LNG loading and MDEA sweetening units need more focus to minimize the adverse environmental impacts. The process of LNG loading requires more optimization and improvement by process engineers and designers to reduce the pollution and human health impacts. For the MDEA sweetening and SRU units, applying recent engineering controls (such as scrubbers and absorbers) are recommended from the early stage of future projects. Authorities could set compliance action plans on non-compliance or excess emission sources for the existing projects to achieve the minimum impact and meet the local and international standards.
2. As $CO_2$ emissions are produced throughout the LNG process, maximization of $CO_2$ use as a by-product for syngas production or enhancement gas for oil recovery is recommended to policymakers and industry owners with specifications that meet the requirement.

3. The construction material is expensive for the process equipment that handles sour gases. Further study and research can focus on other alternatives supported by LNG industries for further investigation. Moreover, LNG maritime carrier design, process, and traveling routes require further optimization. Energy shipping security is an essential factor in the shipping part in which reduces pollution, satisfies customers, and promotes more business globally. As the LNG demand forecast increases, the governments shall focus more on energy security policy.
4. From a worldwide geopolitics risk perspective, any rise in the risk due to countries' relationship shocks, political issues, wars, attacks, etc., has a high potential to increase the spot charter cost rates of the LNG. Geopolitics plays a significant role and could have negatively affected the exporting and importing countries due to the lack of energy security (Michail & Melas, 2021). Accordingly, the price of LNG and its delivery are expected to be affected by a noticeable increase. International unions must consider the geopolitical risk of energy trading to ensure the minimum sudden adverse impact on economic development, social satisfaction, and environmental releases.
5. Governments and unions to set objectives, targets, and action plans towards utilizing renewable energy. The achievement and success stories can get benefits such as tax exemption, governmental support, and free marketing. Parallelly, help can be provided to the LNG manufacturers who are producing carbon-neutral LNG.

6. The integrity of old wellhead platforms, pipelines, process units, maritime carriers, etc., should meet the minimum requirements of potential concerns for process safety, personal safety, and environmental impacts.
7. Most LNG exporting companies focus on environmental, social, and economic studies before establishing any plant for the compliance requirement. After the industry production starts, the focus is on economic development and business growth worldwide. However, policymakers have the authority to insist on revalidating their supply chain sustainability impact study on the surroundings, such as the air quality, wastewater discharges, waste management, human health impact, etc., in such a frequency. The frequency of the reoccurring studies can be decided by the authority to verify the sustainability consistency.
8. Implement the best available technology for any new process unit considering its high reliability and integrity. The new units shall be designed to be environmentally friendly, not cause the community complaint, and be cost-effective.
9. Include the carbon footprint reporting as one of the Tender Criteria of LNG trade to insist on the importance of customer and supplier awareness and derive the sellers ensuring the best sustainability performance. Not to limit the monitoring and reporting to the production unit only, but to cover the maritime transport as well.
10. Organizations are encouraged to come up with systems and procedures for slowly improving their energy efficiency by following the ISO 50001 energy management system standards (Lam, Ko, Sim, & Tee, 2017).

11. Studies can look into more details on the research gaps, especially energy efficiency (Korkmaz, Gardumi, Avgerinopoulos, Blesl, & Fahl, 2020). Technology and innovation processes are among the hottest research topics concerning energy efficiency (Balcombe et al., 2019).
12. The provision of financial incentives for those who buy LNG-powered vehicles is an alternative discussed. This is an approach necessitated by the greater fee of LNG-powered automobiles than those powered by diesel (Charabi, Al Nasiri, Al Awadhi, Choudri, & Al Bimani, 2020). Most commercial users of HDVs have been sensitive to the acquisition cost of vehicles because they are considered assets whose value depreciates. Therefore, financial incentives can promote the purchase of LNG-powered vehicles (Brooks & Jedele, 2018).
13. There should be an application of the emission prices control approach. In this approach, there are various strategies used, including (Langshaw, Ainalis, Acha, Shah, & Stettler, 2020):

    - Charges “en route”. This is a cost-effective program that has been implemented in many sectors to influence the route option for energy optimization and lower emissions.
    - Environmental taxes and fees. This program is enforced by environmental authorities to apply penalties for excess pollution, natural resource misusing, and any environmental damage which can degrade the baseline environment
    - Environmentally enhanced fairway or port dues. This concept is cost-related to the environmental impact, such as air emissions caused by idle ships (e.g., waiting, parking, etc.).

14. The emission quantity control approach involves using limits, and the rights to emit, which can be traded, can also be applied. This approach includes (Elvidge et al., 2018; Langshaw et al., 2020):

    - Credit programs. This program will provide an allowable limit for each company on the total amount of GHG emissions that must not be exceeded.
    - Cap-and-trade programs. If the company has consumed its credit, it can purchase other companies' credit under a secured trading system.
    - Benchmarking programs. In this case, the company is benchmarking its system and performance with other similar sectors. This evaluation focuses on energy efficiency, energy optimization, pollution reduction, and continual improvement.

15. Subsidies can also motivate entities that have invested in decarbonization research toward implementation (Langshaw et al., 2020).
16. Providing enough refueling stations that can be easily accessed is important for increasing the use of LNG for transportation. New regulations for controlling and mitigating risks such as fugitive emission and BOGs are strongly encouraged. Most importantly, overall vehicle efficiency needs to be improved for the benefits that are linked to the use of LNG to be fully realized. Suppose the efficiency is not improved by the year 2024; in that case, policymakers should opt for fixing the fuel duty gap and raising the duty on NG as a way of reflecting the expenses related to technology (Khan, Karimi, & Wood, 2017).

17. Research needs to be undertaken to reduce the quantity of methane released into the air because of the expected lifecycle of the LNG industry. Most methane is released during the transportation of LNG through pipeline systems. Other impacts that LNG-powered vehicles have, such as the release of $NO_x$ and PM require further investigation. More focus should be on the impact and probable solution of the impacts in densely populated areas (Khan et al., 2017).

# CHAPTER 5: LESSONS LEARNED AND RECOMMENDATIONS

From the literature review and research results, there are many lessons learned. This dissertation highlights and combines the most relevant lessons about LNG as sustainable fuel to allow readers, researchers, and interested parties in the LNG sector to understand how suitable LNG is as an energy source. Furthermore, recommendations are based on this dissertation report and other gaps and areas of concern. The following are the main lesson learned from several perspectives and disciplines.

## 5.1. Challenges for using LNG as a transportation fuel

Despite the increase in the use of LNG for powering automobiles, several numbers of challenges that hinder the utilization of LNG in NGVs globally. These challenges include (S. Kumar, Kwon, Choi, Lim, et al., 2011):

1. The relatively low number of worldwide regulations for NGV leads to various gaps in global standards. The lack of global regulations and standards is an obstacle to the production and use of LNG equipment.
2. Countries have non-uniform policies and national interests about energy for transportation and the legal passage of either pipeline or sea routes within each country’s boundaries. This is a factor that limits the improvement of different types of NGVs in countries where the LNG markets would be strong.
3. Producers of HDVs and machines are yet to adapt their products to use LNG. The LNG-powered HDVs and machines that are available in the market are few. This is a factor that limits the increase in reliance on LNG fuel.

4. The systems installed in HDVs, and machines operate differently, especially with the need for LNG to be availed in varying pressures. This is an implication that the development of LNG fueling stations is a complex endeavor.
5. The inconsistency of the quality of LNG and biogas fuels is a concern that needs to be addressed. Different importers would request various product specifications and purities of the final LNG product and biogas that may impact the process's consistency and maximize the production rate.

For LNG to be normalized as fuel for automobiles, there is a need to establish global regulations for NGV and the development of more infrastructure (S. Kumar, Kwon, Choi, Lim, et al., 2011).

Aseel, Al-Yafei, et al. (2021b) discovered that, although traveling the same distance and utilizing the same fuel type, the Q-Max vessel emits more carbon emissions than the Q-Flex. Because of the relevant carbon content in the fuel, the kind of fuel has a major impact on emission values. When comparing the two conventional fleets, the one running on LNG only emits fewer emissions than the one running on dual-mode. Also, the associated human health impact is relatively linked with air emissions. Accordingly, a decrease in air emissions leads to less human health impact (Aseel, Al-Yafei, Kucukvar, & Onat, 2021).

## 5.2. Selecting the LNG supply option

One of the primary obstacles that are associated with the use of LNG is the determination of the most appropriate exploration terminals in different countries. It is appropriate for the most accurate decision support model to be used as far as this type of decision-making is concerned. The options that involve the optimization of green logistics should always be considered. A. Kumar et al. (2017) researched various multi-criteria decision-making (MCDM) techniques. The work focused on renewable energy applications and prospects in this area. Promethee II, Weighted Sum Model, Weighted Product Model, ELECTRE, TOPSIS, MAUT, and AHP are the main methods that can be used for the evaluation of all the options available. The methods could be different from one potential supplier to another based on various factors such as supply economics, the sustainability of the supply and demand network, and the possibility of supplies being available in the future. The process of evaluating the available alternatives should entail ranking the preferred scenarios. This approach assesses future consortiums possible (Strantzali, Aravossis, Livanos, & Nikoloudis, 2019; L. Yao, Shi, & Andrews-Speed, 2018).

### 5.3. Designs of LNG refueling stations

There is a possibility that LNG can be used in the place of diesel in HDVs, trains, and ships. However, the release of methane into the atmosphere due to LNG usage is a major environmental concern. Methane is a greater threat to the environment than $CO_2$ as far as climate change is concerned. Storage, transportation, and distribution of LNG contributed to methane emission. Some of the constraints that shall be highlighted and considered while designing LNG fueling stations include the management of BOG, vehicle fueling flexibility, and the minimization of the heat transfer between dispensers and the storage tanks. Most of the existing LNG fueling stations lack BOG management systems (Griffiths, 2017; Sharafian, Talebian, Blomerus, Herrera, & Mérida, 2017; Siu, Herring, Cadwallader, Reece, & Byers, 1998; Ventura, Kweon, Hwang, Tormay, & Li, 2017). Thousands of LNG barrels are delivered by road in the US for different clients to meet the demand for public cars. The delivery is made via small-scale LNG filling stations, which allow better flexibility and reliability (NGV Global, 2018).

## 5.4. Energy security of LNG

The difference between the pursuit of stability and stability of energy supply does not affect the energy security that is associated with the use of LNG. Research over the past 20 years has furtherly provided a new provision to the issue of energy security. The added dimensions include environmental and technological dimensions. Therefore, the inclusion of new dimensions is a sign of national interest in ensuring energy security (Holley & Lecavalier, 2017; Nawaz, Linke, & Koç, 2019; Zou et al., 2018).

Energy security management is essential as energy trading worldwide is increasing across countries and regions. For that, long-term agreements and measures shall exist in addition to reliable and accurate strategic and business planning.

## 5.5. Sustainability and safety

Sustainability has three primary pillars: financial stability, social protection, and environmental responsibility. Therefore, safety is an important starting point when it comes to the operationalization of sustainability (D. Lee & Cheng, 2016). Experts and industries often acknowledge the link between sustainability and safety. However, this link has also been disregarded at operational and strategic levels. The major reason for the link being disregarded is that there is a lack of safety culture. There seems to be a void in terms of safety culture globally. It has not developed to the levels that it is expected to have grown by now. Safety is only considered to be necessary after an accident has taken place. Risk management and minimization can have many benefits for the organization. The absence of safety culture has led to a situation where the benefits associated with sustainability and safety can hardly be realized. There is a need for highly structured empirical research to be undertaken to strengthen the link between sustainability and safety at operational and strategic levels (D. Lee & Cheng, 2016).

### 5.6. Sustainable development strategy of LNG

There are new factors that are of influence the production, demand, and importation of NG globally. Some of the suggestions on strategic actions that can be taken to encourage the usage of NG in the future include:

1. The expedition of the production, storing capability, and pipeline carriage volume. This is a way to improve the domestic production of LNG. Furthermore, there should be an enhanced focus on growing unconventional gas production. An excellent example of unconventional gas is marine shale gas. This strategy should take into consideration factors such as storage and environmental circumstances to provide a guarantee for the LNG demand (Gerlitz, Philipp, & Beifert, 2017).
2. The analysis of gas and oil consumption traits should be undertaken to set up a timely warming system for the safety of gas and oil consumption based on historical data and predictions due to any changes in the claim for both NG and oil in the future. The stability of both demand and supply is important to the degree of extending that the maintenance of business accomplishments in the country is apprehensive (Debra Mary Stokes, 2017).
3. There is a need for breakthroughs in industrial technologies for cleaning coal to be advanced, especially in countries with large supplies of coal and scarcity of NG. As far as the historical law of energy development is

concerned, NG can be considered the “bridge” for changing from fossil fuels to renewable energy sources. The LCA of the various energy sources should be part of any perspective used for strategic development (Debra Mary Stokes, 2017).

4. Set the strategy towards the reduction of GHG emissions, $CO_2$ capture and storage, minimum flaring, process optimization, waste heat recovery, restriction on fugitive methane emissions, and the treated industrial water reuse and recovery (Nair, 2021).

### 5.7. Natural gas liquefaction design and optimization of future research directions

The process that requires the most volume of energy in the life cycle of NG is the liquefaction process. This is the reason why there has been an increase in the interest in the scheme and optimization of liquefaction industries. The minimization of costs and energy used for liquefaction has been of interest to researchers. The LNG market's growth and technological advancement have increased the extent to which designers are focused on small-scale markets. The anticipated trend is likely to come with an increase in the optimization of the liquefaction process. Optimization goals can be met by (Leal, Rego, & de Oliveira Ribeiro, 2019):

- Consideration of the process optimization, design of natural gas liquefaction, and integration before starting any project.
- Natural Gas Liquid (NGL) and LNG plants should be integrated to avoid duplication and provide a synergy of equipment. This is an implication that trends relating to optimization are likely to include revenue streams associated with processing plants.

- The design and optimization of NG should consider the environmental impact and other factors such as operational and capital costs.
- Optimization should be carried out with the intent of responding to ambient and feed fluctuations.

# CHAPTER 6: CONCLUSION AND FUTURE WORK

## 6.1. Summary of research and key findings

There are two sides to using LNG. One side is that it leads to a substantial reduction in the total of GHGs that are released into the air. This is among the primary goals of sustainable development. Additionally, the availability of LNG and the increase in the interest in its production are factors that can be considered. However, before LNG can reach its developmental potential, some concerns have to be addressed. Among the concerns that need to be addressed is the excessive release of methane into the atmosphere. Methane is considered more harmful to the environment than $CO_2$ and $NO_x$. Therefore, it is appropriate to put measures in place to ensure that the risks of environmental pollution are mitigated. There is also a question of the cost of using LNG equipment compared to the costs of equipment that run on diesel. Notably, economic sustainability is another dimension of sustainable development. Governments need to level the groups for LNG if in any case, it is to be used as the lowest environmental impact among non-renewable energy sources in the course of seeking sustainable development. In the absence of government intervention, there is likely to be a failure in the use of LNG because the diesel equipment and vehicles are more affordable as compared to the LNG ones. LNG vehicles and equipment need to be financially viable for the people using them on a large scale.

To better understand the above, this dissertation accompanied a comprehensive universal literature overview concentrating on the sustainability development study of the LNG industry. It emphasized the key gaps in the literature. The review focused on 168 studies that have been studied, and the bibliometric analysis outcomes are the number of publications per year, country, scope margin, and analysis theory of each study. Upon further analysis, the TBL impacts on the world's LNG commerce and associated services require close attention to understand the TBL sustainability impacts considering all the stages of the LNG sector. The literature review outcome ignites the motivation to conduct a global multiregional hybrid LCSA which can also ensure safe, healthy, secured energy use and marketing worldwide throughout the LNG value chain.

The integration of sustainability pillars in the LNG sector is crucial and has not been discussed earlier in the literature; however, the demand for the product is increasing. Regarding the methodology of this research, it included the multi-regional input-output tool, Aspect HYSYS, and LNG maritime transport operations LCSA tool. This dissertation has successfully designed and simulated an LNG plant with up to 126 MMTA production, considering many constraints, assumptions, and limitations. After gathering the data, sustainability interpretation is adopted to verify each stage's sustainability impact and factor throughout the LNG value chain, considering the negative and positive impacts.

According to the results obtained, the $CO_2$-eq and $NO_x$-eq emission found the highest normalized found from LNG loading (export terminal) with around 40% contribution in both. SRU and TGTU units have the highest contribution of $PM_{2.5}$-eq emission, 79%, among other stages. Midpoint air emission impacts are highly dependent on the nature of the process equipment and the design purpose of the unit. Also, it depends on the fuel used and the characteristics of the fired stream. From the normalized energy consumption and the land used perspective, the majority contributors are the natural gas extraction stage with 96% and LNG shipping with 97%, respectively. The MDEA Sweetening unit found the highest with approximately 73% in normalized water withdrawal and water consumption. Gross operating surplus and salvage value indicators for the economic impact are considered positive, and operational and equipment costs are negative. The results concluded that the MDEA Sweetening unit presents the maximum gross operating surplus and operational cost with 26% and 44%, respectively. LNG loading (export terminal) showed most of the total equipment cost, and the natural gas extraction stage introduced more than half of the end of life throughout the process chain. From the social perspective, all indicators are considered positive except for the human health impact. The natural gas extraction stage found the highest full-time employment and man-hours. On the other hand, human health impact is mainly affected by SRU and TGTU units. The employment compensation is investigated, and it found that the highest compensation comes from LNG shipping and the maximum total tax from MDEA Sweetening unit.

The sustainability assessment is then converted to sustainability factors following this research method. According to the results obtained, the Pre-separation unit and LNG receiving terminal have the best environmental performance by having the lowest environmental impact, with SF equal to 1. The MDEA Sweetening unit is considered the worst environmental performance, with the most inferior SF equal to 0.66. In terms of social and economic impacts, the natural gas extraction stage system presents the best performance among all other stages, with SF equal to 1. However, SRU and TGTU units illustrate the lowest performance from the social perspective, with SF equal to 0.41. On the economic side, LNG loading (export terminal) and LNG shipping are both showing the minimum performance in terms of economic impact, with SF equal to 0.73 for each stage. This research discussed several policymaking recommendations, and the importance of geopolitics risk factors and concerns is highlighted. Moreover, provide some essential suggestions that are expected to improve the sustainability of LNG as the current cleanest fossil fuel option worldwide.

## 6.2. Limitations of the current research

There is a lack in the literature getting information on drilling and extraction of natural gas to validate the accuracy. The MRIO sector is called natural gas extraction and processing, but there are no further details about the type of process. It would appear much more informative if further MRIO data splitting between natural gas extraction and natural gas processing. Uncertainty could also be presented in the Aspen HYSYS due to the design of the equipment and estimation of equipment cost social and environmental impacts. It is expected that the HYSYS is not deciding the maximum equipment capacity by the equipment's manufacturer or adding standby units that are available by design in real applications. It requires a manual entry for each additional tank, vessel, pump, valve, etc.

Moreover, LNG maritime transport operation is assumed as one type of carrier from Qatar to the United Kingdom throughout the calendar year. However, several types of carriers are currently in use for this trade. Finally, there was a limited number of social indicators in this research; however, more social indicators provide a comprehensive overview of the impact on people, communities, forests, oceans, and the whole world. SLCA and LCSA studies are of late, and more research is required to provide enough evidence on the sector's sustainability performance.

## 6.3. Recommendations and future work

Future work aims to study the TBL for world LNG production sustainability assessment with a larger set of indicators, including import and export. Moreover, it is recommended to cover the gaps in the following areas which were not fully covered in LNG production and supply chain literature and research:

- LCA of the carbon footprint for major LNG importers and exporters. As LNG's future demand increases, importers must keep evaluating the LNG option, monitor the improvement of $CO_2$ reduction, and optimize energy usage. On the other hand, the exporters shall utilize the best available control technologies during the LNG production operations and shipping to target the lowest emissions throughout LNG manufacturing.
- The LCSA method proposed and followed in this dissertation is helpful and clear for each step. It is recommended to apply the tool to other industrial systems and identify any gap that can improve the method. As much as indicators provided and accurate data, the results are expected to be more representative. Furthermore, an uncertainty-embedded hybrid LCSA framework is needed to assess the uncertainty of LNG supply chains.

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# APPENDICES

## Appendix A: Bibliometric analysis

Table A.1 Bibliometric Analysis of the LNG Industry and Sustainability Studies in between 2010 and 2020.

| ID | Authors and year | Year | Country | Method | Analyzed system | Scope | Period |
|---|---|---|---|---|---|---|---|
| 1 | Koilo (2021) | 2020 | Norway | The twofold model was proposed, Sustainable Development Index (SDI), and mathematical modeling | LNG Fueled Ship | National, Global | Multi Years |
| 2 | Ji and El-Halwagi (2020) | 2020 | US, China | A bottom-up emission inventory model and shipboard Automatic Identification System (AIS) | LNG Fueled Ship | National, Global | Single Year |
| 3 | Yuanqi, Yang, Mingpeng, and Shen (2020) | 2020 | China | National energy network | LNG Sector | National, Global | Multi Years |
| 4 | Luo, Hu, Xu, Gao, and Li (2020) | 2020 | China | A hydrogen energy cost model | Energy Sector | National | Multi Years |
| 5 | Rao, Yin, and Werij (2020) | 2020 | Netherlands | Various options f<br>or energy carriers in aviation | Aircraft | Global | Multi Years |
| 6 | J. Li et al. (2020) | 2020 | China | Global natural gas resources status, trade pattern, and development trend | LNG Sector | National | Multi Years |
| 7 | Jiao, Huang, and Liao (2020) | 2020 | China | Quantitative analysis model based on the Long-range Energy Alternatives Planning (LEAP) framework | Energy Sector | City | Multi Years |

| ID | Authors and year | Year | Country | Method | Analyzed system | Scope | Period |
|---|---|---|---|---|---|---|---|
| 8 | Maksakova and Popov (2020) | 2020 | Russian Federation | A model of national gas infrastructure creation | Energy Sector | National, Regional, Global | Multi Years |
| 9 | Lachkov (2020) | 2020 | Russian Federation | The efficiency of gasification evaluation | Energy Sector | National | Multi Years |
| 10 | Arefin, Nabi, Akram, Islam, and Chowdhury (2020) | 2020 | Bangladesh, Australia | Overview of the LNG as a potential fuel for diesel engines | Energy Sector | Global | Single Year |
| 11 | Laribi and Guy (2020) | 2020 | Canada | Niche analysis approaches such as the multilevel perspective model (MLP) | LNG Fueled Ship | National | Multi Years |
| 12 | Al-Breiki and Bicer (2020a) | 2020 | Qatar | Examine the effects of BOG economically in production and transportation phases | LNG Transportation | Global | Single Year |
| 13 | Allahyarzadeh-Bidgoli, Dezan, and Yanagihara (2020) | 2020 | Brazil | An automated optimization procedure is performed for commonly used MPFHE | LNG Industry | Global | Single Year |
| 14 | Kharlamova, Kharlamov, and Gavrilova (2020) | 2020 | Russian Federation | Sustainability of the world market the Fourth Industrial Revolution brings. | LNG Sector | Regional | Multi Years |
| 15 | Najm and Matsumoto (2020) | 2020 | Saudi Arabia, UK, Japan | Examining the impact of renewable policies on international trade in LNG among 1359 trading partners during the period 1988–2017 | LNG Sector | Global | Multi Years |
| 16 | V. V. Kumar, Shastri, and Hoadley (2020) | 2020 | India, Australia | A modeling approach to quantify the economic and | LNG Sector | National, Global | Multi Years |

| ID | Authors and year | Year | Country | Method | Analyzed system | Scope | Period |
|---|---|---|---|---|---|---|---|
| | | | | environmental impacts of natural gas utilization | | | |
| 17 | Barone, Buonomano, Forzano, Palombo, and Vicidomini (2020) | 2020 | Italy, Canada | TRNSYS software is adopted for analyzing the the energy system of a moving ship | LNG Fueled Ship | National, Global | Single Year |
| 18 | Lasemi, Assili, and Hajizadeh (2020) | 2020 | Iran, Denmark | Integrated scheduling for fuel dispatching and the generation planning of the power system comprising multi-fuel-fired thermal power plants and hydro units | Energy Sector | Global | Single Year |
| 19 | B. Yao et al. (2020) | 2020 | UK, Saudi Arabia | Emerge is in hydrogen energy as a sustainable vector for our future energy needs | Ecosystem Impact | Global | Single Year |
| 20 | Kusuma, Artana, and Dinariyana (2020) | 2020 | Indonesia | Two scopes of research, first determining the supply and demand of natural gas in Java Island, and then market analysis | LNG Sector | National | Single Year |
| 21 | Maulana and Kurniawan (2020) | 2020 | Indonesia | Ship to Ship (STS) LNG transfer activity | LNG Terminal and Ship | Global | Single Year |
| 22 | Sherry and Thompson (2020) | 2020 | US | Physics of AIC formation and RF | Aircraft | Global | Single Year |
| 23 | Vaferi, Pazouki, and Klink (2020) | 2020 | Belgium, UK, Netherlands | Analytical model for conversion from HFO to LNG dual-fuel engine in a fleet with three sizes of vessels | LNG Fueled Ship | Global | Single Year |

| ID | Authors and year | Year | Country | Method | Analyzed system | Scope | Period |
|---|---|---|---|---|---|---|---|
| 24 | Ayou and Eveloy (2020b) | 2020 | United Arab Emirates | Multi-generation concepts combining low-to-medium grade environmental or waste heat utilization, and waste cryogenic cold recovery, are investigated | LNG Industry | Global | Single Year |
| 25 | Malik, Qasim, Saeed, Chang, and Taghizadeh-Hesary (2020) | 2020 | United Arab Emirates, US, Singapore, Japan | The 4-As methodology attempts to measure and illustrate the change in energy security graphically | Energy Sector | National | Multi Years |
| 26 | X. Zhang, Wang, Wang, Bai, and Xie (2020) | 2020 | China | Driving Cycle and Establishment of Emission Inventory | Ecosystem Impact | City | Single Year |
| 27 | Al Marzooqi and Ahmad (2020) | 2020 | United Arab Emirates | Gas Project | Energy Sector | National | Multi Years |
| 28 | Budiyanto, Riadi, Buana, and Kurnia (2020) | 2020 | Indonesia | Optimize LNG distribution using small-scale LNG carriers and carry out an economic analysis | LNG Transportation | National | Single Year |
| 29 | L. Zhang and Bai (2020) | 2020 | China | Risk Assessment and use of Fuzzy AHP-TOPSIS | LNG Sector | National | Multi Years |
| 30 | Seithe, Bonou, Giannopoulos, Georgopoulou, and Founti (2020) | 2020 | Norway Greece | A “Well-to-Propeller” Life Cycle Assessment of maritime transport | LNG Fueled Ship | Regional | Single Year |
| 31 | Ayou and Eveloy (2020a) | 2020 | United Arab Emirates | Sustainable district cooling | LNG Regasification | Global | Single Year |

| ID | Authors and year | Year | Country | Method | Analyzed system | Scope | Period |
|---|---|---|---|---|---|---|---|
| 32 | Litvinenko (2020) | 2020 | Russian Federation | Analyze the consistency of criticism towards HCR | LNG Sector | National, Regional, Global | Multi Years |
| 33 | Thao, Phu, and Truyen (2020) | 2020 | Viet Nam | Aspen HYSYS-based performance simulations for LNG-fired power plants | LNG Regasification | Global | Single Year |
| 34 | Smajla, Crneković, Sedlar, and Božić (2020) | 2020 | Croatia | Analyses the possibility of establishing a regional gas hub. | LNG Terminal | Regional | Multi Years |
| 35 | AlNouss and Al-Sobhi (2020) | 2020 | Qatar | Aspen HYSYS | LNG Industry | Global | Single Year |
| 36 | Meenakshi Sundaram and Karimi (2020) | 2020 | Singapore | A comprehensive evaluation of the existing LNG bunkering protocol using a Unisim Dynamic Simulation (DS) model | LNG Transportation | Global | Single Year |
| 37 | Al-Haidous, Govindan, and Al-Ansari (2020) | 2020 | Qatar | A multi-objective mathematical model for shipping fleet scheduling, routing, and delivery for sustainable LNG supply chains. | LNG Transportation | Global | Single Year |
| 38 | Boahen and Oppong (2020) | 2020 | Ghana | Assessment of Natural Gas Infrastructure Development | LNG Sector | National | Multi Years |
| 39 | Köhler (2020) | 2020 | Germany | MATISSE-SHIP model for illustrative long term scenarios of technical change in shipping | LNG Fueled Ship | Global | Multi Years |
| 40 | Al-Breiki and Bicer (2020b) | 2020 | Qatar | Mathematical calculation of BOG | Energy Sector | Global | Single Year |

| ID | Authors and year | Year | Country | Method | Analyzed system | Scope | Period |
|---|---|---|---|---|---|---|---|
| 41 | Al-Haidous and Al-Ansari (2020) | 2020 | Qatar | Life cycle assessment | Energy Sector | Global | Single Year |
| 42 | S. Yoon, Oh, and Kim (2020) | 2020 | South Korea | Process simulation | LNG Sector | Global | Single Year |
| 43 | Iannaccone, Landucci, Tugnoli, Salzano, and Cozzani (2020) | 2020 | Italy | Overview and sustainability assessment | LNG Fueled Ship | National | Single Year |
| 44 | Debra M. Stokes, Marshall, and Veiga (2019) | 2019 | Canada | socio-economic analysis | LNG Industry | City | Multi Years |
| 45 | Wu et al. (2019) | 2019 | China | “cradle to grave” life cycle assessment (LCA) | Energy Sector | Global | Single Year |
| 46 | Jovanović, Rudan, Žuškin, and Sumner (2019) | 2019 | Croatia | Overview | LNG Terminal and Ship | Global | Single Year |
| 47 | Łaciak, Sztekler, Szurlej, and Włodek (2019) | 2019 | Poland | Review and analysis | LNG Industry | Global | Single Year |
| 48 | Włodek (2019) | 2019 | Poland | Review and analysis | LNG Industry | Global | Single Year |
| 49 | Qyyum, Chaniago, Ali, Qadeer, and Lee (2019) | 2019 | South Korea, Saudi Arabia | Review and analysis | Energy Sector | Global | Single Year |
| 50 | Baldi, Brynolf, and Maréchal (2019) | 2019 | Switzerland, Sweden, Italy | Review and analysis | LNG Fueled Ship | Global | Single Year |
| 51 | Pizzol (2019) | 2019 | Denmark | LCA and Monte Carlo simulation | LNG Transportation | National | Single Year |
| 52 | Viertl and Guccione (2019) | 2019 | Germany | Review and analysis | Energy Sector | National | Single Year |

| ID | Authors and year | Year | Country | Method | Analyzed system | Scope | Period |
|---|---|---|---|---|---|---|---|
| 53 | Karnauskaitė, Schernewski, Støttrup, and Kataržytė (2019) | 2019 | Lithuania, Denmark, Germany | Setting Indicators and Indicator-Based Sustainability Assessment | Energy Sector | National | Single Year |
| 54 | Gounni, Rais, and Idrissi (2019) | 2019 | Morocco | Simulation of Urban Mobility | LNG Fueled Vehicles | National | Single Year |
| 55 | Al Salmi and Khan (2019) | 2019 | Oman, Malaysia | Survey | LNG Sector | National | Multi Years |
| 56 | Deja, Harasym, Kaup, and Łozowicka (2019) | 2019 | Poland | Review and analysis | LNG Fueled Vehicles | National | Single Year |
| 57 | Kanbur, Xiang, Dubey, Choo, and Duan (2019) | 2019 | Singapore | Life-cycle-based enviroeconomic and life-cycle-integrated thermoeconomic assessment (LCiTA) models | LNG Sector | National | Single Year |
| 58 | Choi et al. (2019) | 2019 | South Korea | Emission calculation | Energy Sector | National | Multi Years |
| 59 | Navas-Anguita, García-Gusano, and Iribarren (2019) | 2019 | Spain | Review and analysis | LNG Fueled Vehicles | National | Multi Years |
| 60 | Hansson, Månsson, Brynolf, and Grahn (2019) | 2019 | Sweden | MCDM | LNG Fueled Ship | National | Single Year |
| 61 | Iannaccone, Landucci, and Cozzani (2018) | 2018 | Netherlands, Italy | Review and analysis | LNG Fueled Ship | Global | Single Year |
| 62 | Saad A. Al-Sobhi, Elkamel, Erenay, and Shaik (2018) | 2018 | Qatar, India, United Arab Emirates, Canada | Aspen Plus simulation | Energy Sector | Global | Single Year |

| ID | Authors and year | Year | Country | Method | Analyzed system | Scope | Period |
|---|---|---|---|---|---|---|---|
| 63 | Bicer and Dincer (2018) | 2018 | Qatar, Turkey, Canada | Life cycle environmental impact assessments | LNG Fueled Vehicles | Global | Single Year |
| 64 | B. Yoon, Shin, and Lee (2018) | 2018 | South Korea | K-TOL for strategic technology planning | LNG Terminal and Ship | Global | Single Year |
| 65 | S. Lee, Seo, and Chang (2018) | 2018 | South Korea | Aspen HYSYS | LNG Sector | Global | Single Year |
| 66 | Azad, Rasul, Islam, and Ahmed (2018) | 2018 | Australia, Bangladesh | Environmental review | Energy Sector | National | Single Year |
| 67 | Pope, Bond, Cameron, Retief, and Morrison-Saunders (2018) | 2018 | Australia, South Africa, UK | Environmental Impact Assessment | LNG Industry | National | Single Year |
| 68 | L. Li, Wang, Liu, Li, and Zhang (2018) | 2018 | China | Review and analysis | Energy Sector | National | Multi Years |
| 69 | J. Yang (2018) | 2018 | China | Macro-economic and environmental review | Energy Sector | National | Multi Years |
| 70 | Strantzali, Aravossis, Livanos, and Chrysanthopoulos (2018) | 2018 | Greece | Multicriteria evaluation model, PROMETHEE and Simos approach | LNG Sector | National | Single Year |
| 71 | Matsuzaka (2018) | 2018 | Japan | Review and analysis | LNG Transportation | National | Single Year |
| 72 | Ullah, Hamid, Mirza, and Shakoor (2018) | 2018 | Pakistan | MCDM | LNG Fueled Vehicles | National | Single Year |
| 73 | Son et al. (2018) | 2018 | South Korea | Environmental review | LNG Industry | National | Single Year |
| 74 | J. Cooper, Stamford, and Azapagic (2018b) | 2018 | UK | LCA, LCC, MCDM | Energy Sector | National | Single Year |

| ID | Authors and year | Year | Country | Method | Analyzed system | Scope | Period |
|---|---|---|---|---|---|---|---|
| 75 | Castán Broto (2018) | 2018 | UK | Review and analysis | Energy Sector | National | Single Year |
| 76 | Kurle, Xu, and Palanki (2018) | 2018 | US | Process simulation using Aspen Plus | LNG Terminal | National | Single Year |
| 77 | Pfoser, Schauer, and Costa (2018) | 2018 | Colombia, Austria | Technology acceptance model (TAM) | Energy Sector | Regional | Multi Years |
| 78 | Ren and Lützen (2017) | 2017 | Hong Kong, Denmark | Novel multi-criteria decision-making method with Dempster-Shafer theory and a trapezoidal fuzzy analytic hierarchy process | LNG Fueled Ship | Global | Single Year |
| 79 | Raghoo et al. (2017) | 2017 | Mauritius, Germany | Techno-economic analysis | Energy Sector | Global | Single Year |
| 80 | Gao and You (2017) | 2017 | US | A novel mixed-integer nonlinear fractional programming model | Energy Sector | Global | Single Year |
| 81 | Benham (2017) | 2017 | Australia | Environmental impact review | LNG Sector | National | Single Year |
| 82 | Sharma and Strezov (2017) | 2017 | Australia | LCA | LNG Fueled Ship | National | Single Year |
| 83 | Yan et al. (2017) | 2017 | China, Sweden, Singapore, Italy | Review and analysis | Energy Sector | National | Single Year |
| 84 | Köppel (2017) | 2017 | Germany | Review and analysis | LNG Fueled Vehicles | National | Single Year |
| 85 | Strantzali, Aravossis, and Livanos (2017) | 2017 | Greece | Multicriteria decision making model, PROMETHEE II, to | Energy Sector | National | Single Year |

| ID | Authors and year | Year | Country | Method | Analyzed system | Scope | Period |
|---|---|---|---|---|---|---|---|
| 86 | To and Lee (2017) | 2017 | Macao, Hong Kong | LCA GHG | Energy Sector | National | Single Year |
| 87 | Osorio-Tejada, Llera-Sastresa, and Scarpellini (2017) | 2017 | Spain | MCDM | LNG Fueled Ship | National | Single Year |
| 88 | Hua, Wu, and Chen (2017) | 2017 | Taiwan | LCA | LNG Fueled Ship | National | Single Year |
| 89 | Brooks and Jedele (2018) | 2017 | US | Academic analysis | Ecosystem Impact | National | Single Year |
| 90 | Ren and Liang (2017) | 2017 | China, Hong Kong | Fuzzy TOPSIS (Technique for Order Performance by Similarity to Ideal Solution). | LNG Fueled Ship | Regional | Single Year |
| 91 | Hao, Liu, Zhao, and Li (2016) | 2016 | China | Review and analysis | LNG Fueled Vehicles | Global | Single Year |
| 92 | Cerf (2016) | 2016 | France | Review and analysis | LNG Sector | Global | Single Year |
| 93 | Jiang, Wang, Duan, and Zhou (2016) | 2016 | China | Review and analysis | LNG Sector | National | Single Year |
| 94 | Chen, Li, and Huang (2016) | 2016 | China, Canada | Interval-fuzzy municipal-scale energy model | Energy Sector | National | Multi Years |
| 95 | van Bets, van Tatenhove, and Mol (2016) | 2016 | Netherlands | Socio-economic and political dynamics | LNG Sector | National | Single Year |
| 96 | Acomi and Acomi (2016) | 2016 | Romania | Overview | Energy Sector | National | Multi Years |
| 97 | Osorio-Tejada, Llera-Sastresa, and Scarpellini (2016) | 2016 | Spain | MCDM | LNG Fueled Ship | National | Single Year |

| ID | Authors and year | Year | Country | Method | Analyzed system | Scope | Period |
|---|---|---|---|---|---|---|---|
| 98 | X. Liu and Schlake (2016) | 2016 | US | Event chain | Energy Sector | National | Single Year |
| 99 | Poyraz and Keskin (2016) | 2016 | US | Review | Energy Sector | National | Multi Years |
| 100 | Schönsteiner, Massier, and Hamacher (2016) | 2016 | Singapore, Germany | LCA | LNG Fueled Ship | National | Single Year |
| 101 | Agbonifo (2016) | 2016 | UK | Review and analysis | LNG Sector | National | Single Year |
| 102 | Sanavandi and Ziabasharhagh (2016) | 2016 | Iran | Optimization | LNG Industry | National, Global | Single Year |
| 103 | Elgohary, Seddiek, and Salem (2015) | 2015 | Egypt, Saudi Arabia | Review and analysis | LNG Fueled Ship | Global | Single Year |
| 104 | Dato' Wee (2015) | 2015 | Malaysia | Overview | LNG Sector | Global | Multi Years |
| 105 | Thunnissen, Bunt, and Vis (2016) | 2015 | Netherlands | Review and analysis (BOOK) | Energy Sector | Global | Multi Years |
| 106 | Vleugel and Bal (2015) | 2015 | Netherlands | Alternative fuels selection | LNG Fueled Ship | Global | Single Year |
| 107 | Mering et al. (2015) | 2015 | Qatar, India, Netherlands, South Korea, Iran, Russian Federation, Thailand Japan, Malaysia, | Review and analysis | Energy Sector | Global | Multi Years |

| ID | Authors and year | Year | Country | Method | Analyzed system | Scope | Period |
|---|---|---|---|---|---|---|---|
| | | | France, Spain, UK, Germany | | | | |
| 108 | Han and Shin (2015) | 2015 | South Korea | Description | LNG Sector | Global | Single Year |
| 109 | Williams et al. (2015) | 2015 | US, Qatar, Iran, Croatia, Algeria, Russian Federation<br>Finland, France, UK, Germany | Review and policy implication | LNG Sector | Global | Single Year |
| 110 | Lammons et al. (2015) | 2015 | US, Qatar, India, Netherland, Iran Algeria, Portugal, Thailand, Denmark, Austria, Sweden<br>Japan, Norway, France, Spain, Singapore, UK | Review and policy implication | LNG Sector | Global | Single Year |
| 111 | S. A. Al-Sobhi and Elkamel (2015) | 2015 | Canada | Process simulation using Aspen Plus | Energy Sector | National | Single Year |

| ID | Authors and year | Year | Country | Method | Analyzed system | Scope | Period |
|---|---|---|---|---|---|---|---|
| 112 | Jinjing, Lixia, Li, Xinpeng, and Kaihua (2015) | 2015 | China | Review standards and regulations | LNG Transportation | National | Single Year |
| 113 | Q. Wang et al. (2015) | 2015 | China, Australia | Information Entropy Model and LMDI Model | Energy Sector | National | Multi Years |
| 114 | Ernestos Tzannatos, Papadimitriou, and Koliousis (2015) | 2015 | Greece | Review and analysis | LNG Fueled Ship | National | Single Year |
| 115 | King (2015) | 2015 | Australia | Review and analysis | LNG Sector | National, Global | Multi Years |
| 116 | Ren and Lützen (2015) | 2015 | Denmark | MCDM combining Fuzzy Analytic Hierarchy Process (AHP) and VIKOR | LNG Fueled Ship | National, Regional | Single Year |
| 117 | Mozgovoy, Burmeister, and Albus (2015) | 2015 | Germany | Review and analysis | Energy Sector | Regional | Single Year |
| 118 | Yannoulis (2015) | 2015 | Greece | Review and analysis | LNG Fueled Ship | Regional | Single Year |
| 119 | Alahmad, Bacani, and Deb (2014) | 2014 | Qatar | Review and analysis | LNG Industry | City | Multi Years |
| 120 | Mirza (2014) | 2014 | Qatar | Review and analysis | LNG Industry | City | Multi Years |
| 121 | Al-Sulaiti and Subedar (2014) | 2014 | Qatar | GHG accounting and reporting EU standards | LNG Industry | City | Multi Years |
| 122 | Deb et al. (2014) | 2014 | US, China, Qatar | CALPUFF modeling for air quality | Energy Sector | City | Multi Years |
| 123 | Conroy and Bil (2014) | 2014 | Australia | LCC | Aircraft | Global | Single Year |

| ID | Authors and year | Year | Country | Method | Analyzed system | Scope | Period |
|---|---|---|---|---|---|---|---|
| 124 | Ikealumba and Wu (2014) | 2014 | Australia | Review and analysis | LNG Sector | Global | Multi Years |
| 125 | Xu, Luo, Mao, Gong, and Huang (2014) | 2014 | China | Cascade recycling strategy | LNG Regasification | Global | Single Year |
| 126 | Gangoli Rao, Yin, and P. van Buijtenen (2014) | 2014 | Netherlands | Hybrid engine | Aircraft | Global | Single Year |
| 127 | Gudmestad (2014) | 2014 | Norway | Review and analysis | LNG Extraction and Processing | Global | Single Year |
| 128 | Mozgovoy, Burmeister, and Albus (2014) | 2014 | Germany | Review and analysis | Energy Sector | National | Single Year |
| 129 | Ahmad (2014) | 2014 | India | Review and analysis | LNG Fueled Ship | National | Multi Years |
| 130 | Pereira, Fontes, and Coelho (2014) | 2014 | Portugal | LCA | Aircraft | National | Single Year |
| 131 | Nwaoha and Wood (2014) | 2014 | Thailand, UK | Review and analysis | Energy Sector | National | Multi Years |
| 132 | Turaga (2014) | 2014 | US | Review | Energy Sector | National | Single Year |
| 133 | Conroy, Lim Ee Wei, Bil, and Dorrington (2014) | 2014 | Australia | Review and analysis | Aircraft | National | Multi Years |
| 134 | Robinson (2014) | 2014 | US | GHG review and reduction | LNG Industry | Regional | Single Year |
| 135 | Albacete (2013) | 2013 | Belgium | Overview | LNG Industry | Global | Single Year |
| 136 | Hubert and Ragetly (2013) | 2013 | France | Overview | LNG Industry | Global | Single Year |

| ID | Authors and year | Year | Country | Method | Analyzed system | Scope | Period |
|---|---|---|---|---|---|---|---|
| 137 | Hoagie, Amorer, Wang, and Economides (2013) | 2013 | US, Australia | Prediction of withdrawal rates and time | LNG Extraction and Processing | Global | Single Year |
| 138 | Osborne et al. (2013) | 2013 | US, Australia, Germany | Academic analysis | Ecosystem Impact | Global | Single Year |
| 139 | Burston et al. (2013) | 2013 | Australia | Review and analysis | Aircraft | National | Single Year |
| 140 | Senthamaraikkannan, Chakrabarti, and Prasad (2014) | 2013 | Canada | Overview | LNG Fueled Ship | National | Single Year |
| 141 | D. Z. Yang, Peng, and Xu (2013) | 2013 | China | Review and analysis | LNG Sector | National | Single Year |
| 142 | E. Tzannatos and Nikitakos (2013) | 2013 | Greece | Review and analysis | LNG Transportation | National | Single Year |
| 143 | Balyan (2013) | 2013 | India | Review and analysis | Energy Sector | National | Multi Years |
| 144 | Burel et al. (2013) | 2013 | Italy | Statistical analysis | LNG Terminal | National | Single Year |
| 145 | Goncalves (2013) | 2013 | US | Analysis of current natural gas in the US | LNG Industry | National | Multi Years |
| 146 | Attanasi and Freeman (2013) | 2013 | US | Review analysis | LNG Sector | Regional | Multi Years |
| 147 | X. Wang and Economides (2012) | 2012 | US | Calculations and estimations applied to an underground natural gas | LNG Industry | Global | Single Year |
| 148 | Kini, Van Duker, and Hayes (2012) | 2012 | US | Community Development Support Plan | LNG Industry | Global | Single Year |

| ID | Authors and year | Year | Country | Method | Analyzed system | Scope | Period |
|---|---|---|---|---|---|---|---|
| 149 | Hamdani (2012) | 2012 | Venezuela | Review and analysis | LNG Sector | Global | Single Year |
| 150 | Zihang, Kun, and Tongwen (2012) | 2012 | China | Review and analysis | LNG Terminal | National | Single Year |
| 151 | C. M. Zhang and Peng (2012) | 2012 | China | Energy comparison | Energy Sector | National | Multi Years |
| 152 | Beckwith (2012) | 2012 | Australia | Strategic environmental assessment and decision-making | LNG Sector | National, Global | |
| 153 | True (2012) | 2012 | US | Review and policy implication | LNG Industry | National, Global | Single Year |
| 154 | Nicotra (2012) | 2012 | Germany | Review and analysis | Energy Sector | Regional | Multi Years |
| 155 | S. Liu, Huang, Zhang, and Li (2011) | 2011 | China | Pipeline engineering | LNG Transportation | Global | Multi Years |
| 156 | Lydia Stougie and Van der Kooi (2011) | 2011 | Netherlands | LNG evaporation Techniques selection. Environmental, economic, and social aspects of its sustainability. | LNG Regasification | Global | Single Year |
| 157 | Kortenaar, Walraven, Hart, and Vergoossen (2011) | 2011 | Netherlands | LCC | LNG Terminal | Global | Single Year |
| 158 | S. Kumar, Kwon, Choi, Hyun Cho, et al. (2011) | 2011 | South Korea | Review and analysis | LNG Sector | Global | Multi Years |
| 159 | S. Kumar, Kwon, Choi, Lim, et al. (2011) | 2011 | South Korea | Overview | LNG Sector | Global | Multi Years |

| ID | Authors and year | Year | Country | Method | Analyzed system | Scope | Period |
|---|---|---|---|---|---|---|---|
| 160 | Barclay, Oseen-Senda, and Skrzypkowski (2011) | 2011 | US | Magnetic liquefaction technology | LNG Industry | Global | Single Year |
| 161 | Hardisty, Sivapalan, and Brooks (2011) | 2011 | US, Australia, UK | Method and analysis | Energy Sector | National | Multi Years |
| 162 | Gangadharan, Zanwar, and Lou (2011) | 2011 | US | Aspen Plus software, comprehensive sustainability assessment, and Enhanced Inherent Safety methods | LNG Sector | National, City | Single Year |
| 163 | Haselip, Al-Shafai, and Morse (2010) | 2010 | Qatar, UK | Review and analysis | LNG Industry | City | Multi Years |
| 164 | L. Stougie and Van der Kooi (2010) | 2010 | Netherlands | Review and analysis | Energy Sector | Global | Single Year |
| 165 | Shi, Jing, Wang, and Zhang (2010) | 2010 | China | Overview on LNG | Energy Sector | National | Single Year |
| 166 | Wei (2010) | 2010 | China | Decision-making method | Energy Sector | National | Single Year |
| 167 | Tkalčič and Špendl (2010) | 2010 | Slovenia | Socio-economic impact assessment | LNG Terminal and Ship | National | Single Year |
| 168 | Boodoo (2010) | 2010 | Trinidad and Tobago | Overview | Energy Sector | National | Single Year |

## Appendix B: Further literature review

### – *Transportation of LNG product*

Transportation of LNG starting from the manufacturing facility to the end-user location has been a challenge because of the possibility of changing the LNG back to the gas phase. For this purpose, pipelines are the most preferred mode of transporting liquid gas from one point to another. The demand for LNG in remote places in the 1960s necessitated the design of a suitable and safe way of transporting LNG. However, using pipelines to transport LNG to remote areas was considered either economically infeasible or technologically impractical (Khalilpour & Karimi, 2011). The use of pipelines in the transportation of LNG is recommendable for a distance of approximately 2,000km. When the distance exceeds 2,000km, there is a significant increase in the costs involved (Dobrota, Lalić, & Komar, 2013). However, the benefits associated with the use of LNG mean that there is a need for effective ways of transporting it from one place to another. Among the benefits that are related to the use of LNG is less emission of sulfur oxide ($SO_x$), nitrogen oxides ($NO_x$), and carbon oxides (COx) in comparison with other alternatives (e.g., diesel) (Pascoli, Femia, & Luzzati, 2001; Pfoser et al., 2018).

LNG is known as a green source of energy for the future. The life cycle analysis of GHG emissions of LNG illustrates much better improvement than other fuels. There is a clear and positive relationship between LNG and sustainable development referred to the advantages in reducing the environmental footprint, promising future in safety and social respects, and the flexible and available solutions for many uses globally along with renewable energy sources.

Unlike pipelines, LNG cargoes have the benefit of flexibility. They can be used to access any part of the nation, thus enabling the supply of the commodity to respond to changes in demand (Dudley, 2018). However, the supply of LNG has often been hindered by the difficulty of selecting the most appropriate supplier. There are various models for determining the suitable suppliers that have been used in multiple sectors. There is one approach that involves four steps. The first step of this model consists in defining the objectives that need to be met by the supplier. The second step consists of developing selection criteria, which entails the identification of the traits that an organization will be seeking in a supplier. The third step involves the qualification of suitable alternatives with reference to the criteria developed in step two. The final stage is the selection of suppliers. The criteria commonly used in selecting an appropriate supplier are delivery cost, quality, and flexibility (International Gas Union, 2017; Thanaraksakul & Phruksaphanrat, 2009). The risks that are supposed to be taken into consideration include availability and stability. Furthermore, commercial, political, and geographical risks should be considered (Smith Stegen & Palovic, 2014; Strantzali et al., 2019).

### – *Emissions of LNG against coal and oil*

The energy industry has often been under scrutiny for its impact on the environment. Industries' influence on the surrounding environment is not entirely attributed to the nature of combusting the fuels. Other processes such as production, exploitation, and transportation of energy sources have been confirmed to have an effect on the ecosystems and the environment. The mainstream of the energy that is consumed globally comes from sources that are not environmentally sustainable. Fossil fuel, which is the most demanded of the available sources of energy, has the highest level of threat to the environment (Our energy, 2015). The $CO_2$ produced after the combustion of fossil fuels causes harm to the environment by causing global warming (Weisser, 2007). However, the carbon monoxide (CO) produced after the combustion of fossil fuels should be of more significant concern. CO is a colorless, scentless, and tasteless gas that is poisonous. A slightly above 0.5% CO concentration can kill a person after just 15 minutes of breathing (Anthea M, 1993).

In addition to CO and $CO_2$, oil and coal combustion releases particles of dangerous $SO_x$ and $NO_x$ into the environment. When NG is compared to both coal and oil, it is noted that the production of $SO_x$ is reduced to almost zero. The production of $NO_x$ is reduced with a percentage of around 75-80, particulate matter reduction close to the percentage of 99, reduction of $SO_x$ emissions relatively close to 100 percent, and last but not least, 70 percent less in GHG emissions (Tamura et al., 2001) as mentioned in Table 1.

Table B.1 Comparison of LNG, Oil, and Coal Emissions[1] (García Rellán, Vázquez Brea, & Bello Bugallo, 2018).

| Pollutant | LNG | Oil | Coal |
|---|---|---|---|
| $CO_2$ | 117,000 | 164,000 | 208,000 |
| CO | 40 | 33 | 208 |
| $NO_x$ | 92 | 448 | 457 |
| $SO_x$ | 1 | 1112 | 2591 |
| PM | 7 | 84 | 2774 |
| Mercury | 0.000 | 0.007 | 0.016 |

When LNG goes through combustion, the production of $SO_2$ and its elimination seizes to be a cause of concern. There is also a significant decrease in the quantity of

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[1] (in PPB BTU of Energy Input)

$CO_2$ that is emitted into the air. Therefore, it is advisable consuming the LNG instead of other fossil fuels (e.g., oil and coal) to be encouraged. Evidence can prove that LNG is an eco-friendly energy source based on the significant decrease of the GHGs produced when used instead of oil and coal (N. Zhang & Lior, 2006).

Concerns regarding the environmental effects of the development and operation of ports have been on the increase, especially because of the emergence of energy conservation and climate conservation as global agendas. As far as sustainable development is concerned, ports' existence should be anchored on the management of three bottom lines: economic progress, environmental sustainability, and wellbeing of the society. Therefore, the development of suitable ports marketing plans that fulfill the three bottom lines should be used in guiding ports towards the type of development that can be categorized as sustainable (Lam & Li, 2019).

- *LNG as an alternative for transportation*

The road transport network has been acknowledged as a unique contributor to air pollution worldwide because of the level of energy intensity associated with road transport. This is a factor that should be taken into consideration by governments and other stakeholders when formulating strategies and programs that are aimed at making transport more sustainable. Therefore, the use of alternative greener energy sources should be one of the approaches used in making road transportation greener. The alternatives that can be considered include using electric cars or cars that run on more sustainable fuels (e.g., NG, biofuel, and liquefied petroleum gas). The lack of sufficient details on the techno-economic viability of these alternatives is a foremost stumbling block in the pursuit of a higher level of sustainability in road transportation (Navas-Anguita et al., 2019).

Because of the sustainable nature of the combustion of NG, heavy-duty vehicles powered by LNG can effectively reduce the amount of carbon footprint that results from road transportation. It will also reduce the number of resources that will have to be channeled towards emission control. Furthermore, ships that use LNG have also been observed to have higher efficiency levels than the alternatives available in the market because of the dependence on NG. LNG represents 7% of the demand for NG globally.

LNG definitively can show a considerable role in the reduction of GHG emissions into the atmosphere. Its comparison with commonly used alternatives, such as oil and coal, tells a lot about what will occur when NG completely replaces oil and coal (Hekkert, Hendriks, Faaij, & Neelis, 2005; Hondo, 2005; Kannan, Leong, Osman, & Ho, 2007). Using HDVs that LNG powers as an alternative to diesel-powered ones can lead to a 10% reduction in the resultant carbon emission (Arteconi, Brandoni, Evangelista, & Polonara, 2010).

A research that was undertaken on the lifecycle of a system using LNG and one using coal reveals that the system that depends on coal has a rate of emission that is 161% higher than the system that uses LNG. The study also reveals that the cleanest that a system using coal can be will still lead to an emission rate that will be 73% higher than the emission rate that is observed in a system using LNG. Notably, some costs are associated with making a system that is powered by coal as clean as possible (Graham, Rideout, Rosenblatt, & Hendren, 2008).

The LCA conducted in China considers a combination of data on the real-time consumption rate for diesel and LNG. There was also the consideration: HDV population data for both diesel and LNG and the database for Tsinghua-LCA Model (TLCAM) precisely for the situation in the country. From such an analysis, it was observed that diesel use resulted in a significantly high carbon emission rate. Given the fact that the use of LNG has been on the increase in China, the increase in the LNG HDV population is an indication that there is a likelihood of a significant decline in the contribution of road transport to carbon emission in the future (Andress, Nguyen, & Das, 2011; Song, Ou, Yuan, Yu, & Wang, 2017).

Among the studies that have been undertaken in China in relation to energy efficiency and suitability is the availability of technological resources that would support the use of NG for powering automobiles. Such analysis focused on the comparison of six possibilities: electricity, methanol, hydrogen, Compressed Natural Gas (CNG), Gas to Liquid (GTL), and LNG using various dimensions (Hao et al., 2016).

- *LNG storage*

To achieve the appropriate storage of LNG, many aspects shall be determined. One such factor is whether the storage intends to serve the gas shortage experienced during winter. The other factor is the vessel's baseload gas supply that is used for long-distance shipment. In addition to the needed installations that are aimed at reducing possible losses from vaporization, it is advisable for the cargo that carries the LNG not to be in contact with the structure of the ship. This is because mild steel is vulnerable to brittleness when the temperatures get below 223K. Therefore, allowing the contact can lead to disastrous occurrences. There is a possibility of the evaporation kept to levels as low as 0.1% daily as long as there is sufficient installation of the tank, especially considering all the safety measures. 0.3% boil-off can result from re-liquefaction facilities that are installed in sea-going vessels (S. Kumar, Kwon, Choi, Lim, et al., 2011).

At the on-shore, the storage of LNG can be done using double-walled metal tanks. Such tanks are not similar to the tanks that are used while LNG is in ships. The inner wall should be made of either nickel steel or aluminum. Additionally, concrete tanks that are attached to the ground can be contracted for the same purpose. Underground spaces that are specifically designed for the storage of LNG can be an alternative. The main advantage that is associated with the use of in-ground tanks is that there is no need for containment dikes. Such an advantage stands regardless of whether the tank is built from concrete or natural substances. The use of above-ground tanks can be recommendable because there is an ease in controlling heat leakage. Above-ground tanks are also easier to repair as compared to underground ones (S. Kumar, Kwon, Choi, Lim, et al., 2011).

### – *LNG Sustainability*

The effect of the LNG usage on the environment in relation to diesel's impact can be determined by applying a Well-to-Wheel (WTW) assessment. The WTW is relaying on real-world HGVs drive cycles for it to be effective in such an analysis. The analysis is supposed to be complemented by the determination of the costs associated with ownership in both cases. The methods can be validated using practical case studies that have been undertaken in further portions of the world, such as the United Kingdom. According to the findings from the United Kingdom, LNG vehicles recorded a lower energy efficiency compared to diesel ones. As a result, around a 7% rise in cumulative GHG emissions. Nevertheless, there is a possibility that the emission will be reduced by 13% as soon as the LNG comes level with the diesel ones in relation to energy efficiency. The findings from this study lead to the conclusion that there would need to be a noteworthy rise in the efficiency of vehicles based on LNG for them to have the impact that the usage of LNG is supposed to have on the environment from a theoretical point of view (Langshaw et al., 2020).

Most of the studies on LNG that have been undertaken have focused on economic and environmental impacts. Very few studies have reviewed the social impact of LNG. The main issues that are associated with the social sustainability of LNG are health, safety, employment, local communities, public participation, resources, and infrastructure. A LCA can be used in the evaluation of the social impacts of LNG. The LCA results can be used in affirming the assumption that the production and use of LNG can lead to various social benefits such as the provision of employment opportunities and financial gain by local governments through the collection of revenue (J. Cooper, Stamford, & Azapagic, 2018a).

Notably, some social barriers need to be overcome in producing and using LNG. The obstacles include the lack of public support, traffic, noise, conflict in relation to land use, a strain of infrastructure, and the accessibility of regulatory resources. Furthermore, there is no sufficient evidence to link the use of LNG with energy security. LNG can only enhance energy efficiency if its production volume significantly increases. Such information is relevant to various stakeholders, including policymakers, scholars, and other LNG stakeholders (J. Cooper et al., 2018a).

Appendix C: Further results and discussion

- *LCA, LCC, and SLCA detailed results:*
    - *LCA results:*

Table C.1 shows the environmental impacts directly related to the LNG process chain. As for the $CO_2$-eq emission, LNG loading (export terminal) was found as the highest source of contribution throughout the process chain with 40%, followed by the MDEA sweetening unit, which represents 24% and liquefaction unit with 20%. For the $NO_x$-eq emission, the highest contribution is found again from LNG loading (export terminal), Liquefaction unit, and MDEA Sweetening unit with 46%, 21%, and 16%, respectively. The lowest $CO_2$-eq and $NO_x$-eq emissions were found from the pre-separation unit. For the $PM_{2.5}$-eq emission, the highest contribution is found from SRU and TGTU units, LNG loading (export terminal), and Liquefaction unit with 79%, 9.5%, and 4%, respectively. The lowest $PM_{2.5}$-eq emission was found from the natural gas extraction. It is essential to treat the LNG loading unit as a hot spot where further process improvement and emission caption are required. The emissions are generated mainly from product storage, utility consumption, loading to carriers, and BOG flaring. Relquification unit shall exist to maximize the gas recovery, avoid losses and abate ecological degradation. Minimizing the environmental releases to the atmosphere will help to save human lives.

The majority contributor is the natural gas extraction stage, with 96% from the energy consumption perspective. The raw data was taken from MRIO, which is expected to cover the direct and indirect emissions associated with natural gas extraction and processing. It is recommended to furtherly have deep research to validate the MRIO current factors. On the other hand, land used found the highest with 97% for LNG shipping as LNG carriers and taking massive space in the loading and unloading ports throughout the year. Regarding the water withdrawal and water consumption, the MDEA Sweetening unit found the highest with 73.6% and 73.5%, respectively.

Table C.1 Environmental Impact Results Related to LNG Process Chain.

| Process Stage | Global warming (kg CO$_2$-eq) | Photochemical ozone formation (kg NO$_x$-eq) | Fine particulate matter formation (kg PM$_{2.5}$-eq) | Energy consumption (TJ) | Land used (Km$^2$) | Water withdraw (m$^3$) | Water consumption (m$^3$) |
|---|---|---|---|---|---|---|---|
| Natural gas extraction | 53,648,395.34 | 78,932.64 | 7,740.91 | 2,838.52 | 1.93 | 0.10 | 0.42 |
| Pre-separation unit | 3,630,834.41 | 14,129.75 | 1,308,947.10 | 0.02 | 0.08 | 2,933,491.53 | 1,257,210.66 |
| MDEA Sweetening unit | 25,414,306,084.39 | 367,511,207.61 | 67,015,269.55 | 0.05 | 0.47 | 11,842,116,930.54 | 5,075,192,970.23 |
| SRU and TGTU units | 569,820,482.48 | 50,239,730.24 | 1,483,250,846.87 | 0.00 | 0.46 | 1,046,177,060.68 | 448,361,597.43 |
| Dewatering unit | 9,591,964,940.34 | 226,246,569.61 | 40,551,701.60 | 0.02 | 0.03 | 7,489,438.16 | 3,209,759.21 |
| NGL recovery and fractionation units | 65,316,380.97 | 118,701.79 | 33,094.41 | 107.49 | 7.37 | 3,195,927,235.24 | 1,369,683,100.82 |
| Liquefaction unit | 21,012,275,442.69 | 469,812,499.27 | 79,849,788.70 | 0.06 | 5.38 | 0.00 | 0.00 |
| LNG loading (export terminal) | 42,201,635,518.84 | 1,043,728,533.51 | 177,395,647.88 | 0.17 | 18.50 | 0.00 | 0.00 |
| LNG shipping | 742,164,478.68 | 1,522,491.68 | 925,655.30 | 0.17 | 1,390.20 | 1,306,193.88 | 870,795.92 |
| LNG receiving terminal | 4,933,090,400.29 | 122,400,674.00 | 20,803,647.24 | 0.17 | 8.20 | 0.00 | 3,354,545.97 |

- *LCC results:*

Table C.2 shows the economic impacts directly related to the LNG process chain. MDEA Sweetening unit presents the maximum gross operating surplus followed by LNG loading (export terminal) and Natural gas extraction stage with 26%, 19.7%, and 17.7%, respectively. The minimum gross operating surplus is found from the Pre-separation unit. Moreover, the MDEA Sweetening unit found the highest operational cost with 44% contribution, followed by NGL recovery and fractionation units with 22% and lowest in the Pre-separation unit. Furthermore, LNG loading (export terminal) followed by Natural gas extraction stages presented most of the total equipment cost. The natural gas extraction stage introduced more than half of the end of life throughout the process chain.

Table C.2 Economic Impact Results Related to LNG Process Chain.

| Process stage | Gross operating surplus (USD/y) | Operational cost (USD/y) | Equipment cost (USD) | Salvage value (End of life) (USD) |
|---|---|---|---|---|
| Natural gas extraction | 53,450,199,668.87 | 10,584,000.00 | 26,224,254,197.58 | 6,556,063,549.40 |
| Pre-separation unit | 93,163,622.08 | 3,546,411.99 | 28,529,135.36 | 5,705,827.07 |
| MDEA Sweetening unit | 79,068,030,658.23 | 6,937,933,632.82 | 5,084,543,088.13 | 1,016,908,617.63 |
| SRU and TGTU units | 34,873,299,933.33 | 2,325,693,306.95 | 5,818,353,647.50 | 1,163,670,729.50 |
| Dewatering unit | 530,124,670.54 | 20,020,317.22 | 163,115,540.32 | 1,483,983.39 |
| NGL recovery and fractionation units | 50,009,767,755.67 | 3,394,922,207.94 | 8,052,653,996.44 | 1,734,728,535.17 |
| Liquefaction unit | 6,760,701,129.21 | 55,597,005.62 | 3,052,785,600.38 | 610,557,120.08 |
| LNG loading (export terminal) | 56,680,321.45 | 4,846,930.00 | 4,261,190.00 | 852,238.00 |
| LNG shipping | 11,780,425,564.78 | 2,355,957,653.32 | 1,547,870,305.30 | 386,967,576.32 |
| LNG receiving terminal | 57,065,750.03 | 4,847,280.00 | 4,448,960.00 | 949,242.00 |

- *SLCA results:*

Table C.3 shows the social impacts directly linked to the LNG process chain. It was found that more than 73% of human health impact is coming from SRU and TGTU units which are the most contributors of $PM_{2.5}$-eq, as illustrated earlier. The second highest contributor to human health impact is the LNG loading (export terminal) stage with approximately 12%. On the other hand, Natural gas extraction and NGL recovery and fractionation units found the highest full-time employment with 57.7% and 13%, respectively. Also, the same stages have the highest man-hours estimated in this research.

The employment compensation is investigated and found that the highest compensation comes from LNG shipping followed by NGL recovery and fractionation units. Regarding the tax impact on the social, MDEA Sweetening unit and NGL recovery and fractionation units present the highest impact with 43% and 27%, respectively.

Table C.3 Social Impact Results Related to LNG Process Chain.

| Process stage | Human health impact (DALY) | Employment (Person) | Compensation of employment (USD) | Total tax (USD) | Man-hours (hrs) |
|---|---|---|---|---|---|
| Natural gas extraction | 54.73 | 2,329.48 | 2,875,972.32 | 1,859,175.01 | 4,774,176.64 |
| Pre-separation unit | 826.71 | 262.00 | 2,871,232.88 | 9,316,362.21 | 568,632.00 |
| MDEA Sweetening unit | 66,071.52 | 88.00 | 964,383.56 | 7,906,803,065.82 | 198,120.00 |
| SRU and TGTU units | 933,539.29 | 175.00 | 1,917,808.22 | 3,487,329,993.33 | 377,496.00 |
| Dewatering unit | 34,614.25 | 175.00 | 964,383.56 | 53,012,467.05 | 222,144.00 |
| NGL recovery and fractionation units | 81.54 | 524.00 | 5,742,465.75 | 5,000,976,775.57 | 1,130,040.00 |
| Liquefaction unit | 70,152.44 | 88.00 | 964,383.56 | 676,070,112.92 | 212,568.00 |
| LNG loading (export terminal) | 151,694.77 | 88.00 | 964,383.56 | 5,668,032.15 | 464,400.00 |
| LNG shipping | 835.68 | 216.70 | 26,004,221.13 | 1,178,042,556.48 | 780,126.63 |
| LNG receiving terminal | 17,774.79 | 88.00 | 964,383.56 | 5,706,575.00 | 88.00 |

- *Cumulative sustainability assessment detailed results:*

The results in Tables C.4, C.5, and C.6 show each stage's negative and positive impacts in the LNG process chain, the contribution of each stage, and the final scoring. The cumulative sustainability assessment methodology was followed, and the following are the main results.

Table C.4 Negative and Positive LCA, LCC, and SLCA Results Related to LNG Process Chain.

| | Units | Natural gas extraction | Pre-separation | MDEA Sweetening | SRU and TGTU | Dewatering unit | NGL recovery and fractionation | Liquefaction | LNG loading (export terminal) | LNG shipping | LNG receiving terminal |
|---|---|---|---|---|---|---|---|---|---|---|---|
| *Environmental indicators (negative indicators)* | | | | | | | | | | | |
| GWP | kg $CO_2$-eq. | 53,648,395 | 3,630,834 | 25,414,306,084 | 569,820,482 | 9,591,964,940 | 65,316,381 | 21,012,275,443 | 42,201,635,519 | 742,164,479 | 4,933,090,400 |
| PMFP | kg $PM_{2.5}$-eq. | 7,741 | 1,308,947 | 67,015,270 | 1,483,250,847 | 40,551,702 | 33,094 | 79,849,789 | 177,395,648 | 925,655 | 20,803,647 |
| POFP | kg $NO_x$-eq. | 78,933 | 14,130 | 367,511,208 | 50,239,730 | 226,246,570 | 118,702 | 469,812,499 | 1,043,728,534 | 1,522,492 | 122,400,674 |
| Energy | TJ | 2,839 | 0.02 | 0.05 | 0.00 | 0.02 | 107 | 0.06 | 0.17 | 0.17 | 0.17 |
| Land used | $Km^2$ | 1.93 | 0.08 | 0.47 | 0.46 | 0.03 | 7.37 | 5.38 | 18.50 | 1,390 | 8.20 |
| Use of water | $m^3$ | 0.10 | 2,933,492 | 11,842,116,931 | 1,046,177,061 | 7,489,438 | 3,195,927,235 | 0.00 | 0.00 | 1,306,194 | 0.00 |
| Removal of water | $m^3$ | 0.42 | 1,257,211 | 5,075,192,970 | 448,361,597 | 3,209,759 | 1,369,683,101 | 0.00 | 0.00 | 870,796 | 3,354,546 |
| *Social indicators (positive indicators)* | | | | | | | | | | | |
| Employment | person | 2,329 | 262 | 88 | 175 | 175 | 524 | 88 | 88 | 217 | 88 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Compensation of employment | USD | 2,875,972 | 2,871,233 | 964,384 | 1,917,808 | 964,384 | 5,742,466 | 964,384 | 964,384 | 26,004,221 | 964,384 |
| Total tax | USD | 1,859,175 | 7,297,074 | 6,193,032,165 | 2,731,463,860 | 41,522,207 | 3,917,033,189 | 529,534,367 | 4,649,571,343 | 1,178,042,556 | 233,942,880 |
| Man-hours | hrs | 4,774,177 | 568,632 | 198,120 | 377,496 | 222,144 | 1,130,040 | 212,568 | 464,400 | 780,127 | 88 |
| *Social indicators (negative indicators)* | | | | | | | | | | | |
| Human health | DALY | 54.7 | 826 | 66,072 | 933,539 | 34,614 | 81.5 | 70,152 | 151,695 | 836 | 17,775 |
| *Economic indicators (positive indicators)* | | | | | | | | | | | |
| Gross operating surplus | USD | 41,865,062,658 | 72,970,745 | 61,930,321,650 | 27,314,638,595 | 415,222,070 | 39,170,331,890 | 5,295,343,668 | 46,495,713,428 | 11,780,425,565 | 2,339,428,805 |
| Salvage value | USD | 6,556,063,550 | 5,705,827 | 1,016,908,618 | 1,163,670,730 | 1,483,983.39 | 1,734,728,535 | 610,557,120 | 852,238 | 386,967,576 | 949,242 |
| *Economic indicators (negative indicators)* | | | | | | | | | | | |
| Operational cost | USD | 10,584,000 | 3,546,412 | 6,937,933,633 | 2,325,693,307 | 20,020,318 | 3,394,922,208 | 55,597,006 | 508,846,930 | 2,355,957,653 | 33,647,280 |
| Equipment cost | USD | 26,224,254,198 | 28,529,135 | 5,084,543,088 | 5,818,353,648 | 163,115,540 | 8,052,653,996 | 3,052,785,600 | 26,704,261,190 | 1,547,870,305 | 1,304,448,960 |

Table C.5 Contribution (%) of Each LCI Among the Others Throughout the LNG Process Chain.

| | Natural gas extraction | Pre-separation unit | MDEA Sweetening unit | SRU and TGTU units | Dewatering unit | NGL recovery and fractionation units | Liquefaction unit | LNG loading (export terminal) | LNG shipping | LNG receiving terminal |
|---|---|---|---|---|---|---|---|---|---|---|
| *Environmental indicators (negative indicators)* | | | | | | | | | | |
| GWP | 0% | 0% | 60% | 1% | 23% | 0% | 50% | 100% | 2% | 12% |
| PMFP | 0% | 0% | 5% | 100% | 3% | 0% | 5% | 12% | 0% | 1% |
| POFP | 0% | 0% | 35% | 5% | 22% | 0% | 45% | 100% | 0% | 12% |
| Energy | 100% | 0% | 0% | 0% | 0% | 4% | 0% | 0% | 0% | 0% |
| Land used | 0% | 0% | 0% | 0% | 0% | 1% | 0% | 1% | 100% | 1% |
| Use of water | 0% | 0% | 100% | 9% | 0% | 27% | 0% | 0% | 0% | 0% |
| Removal of water | 0% | 0% | 100% | 9% | 0% | 27% | 0% | 0% | 0% | 0% |
| *Social indicators (positive indicators)* | | | | | | | | | | |
| Employment | 100% | 11% | 4% | 8% | 8% | 22% | 4% | 4% | 9% | 4% |
| Compensation of employment | 11% | 11% | 4% | 7% | 4% | 22% | 4% | 4% | 100% | 4% |

|  |  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|---|
| Total tax | 0% | 0% | 100% | 44% | 1% | 63% | 9% | 75% | 19% | 4% |
| Man-hours | 100% | 12% | 4% | 8% | 5% | 24% | 4% | 10% | 16% | 0% |
| *Social indicators (negative indicators)* |  |  |  |  |  |  |  |  |  |  |
| Human health | 0% | 0% | 7% | 100% | 4% | 0% | 8% | 16% | 0% | 2% |
| *Economic indicators (positive indicators)* |  |  |  |  |  |  |  |  |  |  |
| Gross operating surplus | 68% | 0% | 100% | 44% | 1% | 63% | 9% | 75% | 19% | 4% |
| Salvage value (End of life) | 100% | 0% | 16% | 18% | 0% | 26% | 9% | 0% | 6% | 0% |
| *Economic indicators (negative indicators)* |  |  |  |  |  |  |  |  |  |  |
| Operational cost | 0% | 0% | 100% | 34% | 0% | 49% | 1% | 7% | 34% | 0% |
| Equipment cost | 98% | 0% | 19% | 22% | 1% | 30% | 11% | 100% | 6% | 5% |

Table C.6 Scoring of Each LCI.

| | Natural gas extraction | Pre-separation unit | MDEA Sweetening unit | SRU and TGTU units | Dewatering unit | NGL recovery and fractionation units | Liquefaction unit | LNG loading (export terminal) | LNG shipping | LNG receiving terminal |
|---|---|---|---|---|---|---|---|---|---|---|
| *Environmental indicators (negative indicators)* | | | | | | | | | | |
| GWP | 5 | 5 | 2 | 5 | 4 | 5 | 3 | 1 | 5 | 5 |
| PMFP | 5 | 5 | 5 | 1 | 5 | 5 | 5 | 5 | 5 | 5 |
| POFP | 5 | 5 | 4 | 5 | 4 | 5 | 3 | 1 | 5 | 5 |
| Energy consumption | 1 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| Land used | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 1 | 5 |
| Use of water | 5 | 5 | 1 | 5 | 5 | 4 | 5 | 5 | 5 | 5 |
| Removal of water | 5 | 5 | 1 | 5 | 5 | 4 | 5 | 5 | 5 | 5 |
| Total score | 31 | 35 | 23 | 31 | 33 | 33 | 31 | 27 | 31 | 35 |
| *Social indicators (positive indicators)* | | | | | | | | | | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Employment | 5 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 |
| Compensation of employment | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 5 | 1 |
| Total tax | 1 | 1 | 5 | 3 | 1 | 4 | 1 | 4 | 1 | 1 |
| Man-hours | 5 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 |
| *Social indicators (negative indicators)* | | | | | | | | | | |
| Human health | 5 | 5 | 5 | 1 | 5 | 5 | 5 | 5 | 5 | 5 |
| Total score | 17 | 9 | 13 | 7 | 9 | 15 | 9 | 12 | 13 | 9 |
| *Economic indicators (positive indicators)* | | | | | | | | | | |
| Gross operating surplus | 4 | 1 | 5 | 3 | 1 | 4 | 1 | 4 | 1 | 1 |
| Salvage value (End of life) | 5 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 1 | 1 |
| *Economic indicators (negative indicators)* | | | | | | | | | | |
| Operational cost | 5 | 5 | 1 | 4 | 5 | 3 | 5 | 5 | 4 | 5 |
| Equipment cost | 1 | 5 | 5 | 4 | 5 | 4 | 5 | 1 | 5 | 5 |
| Total score | 15 | 12 | 12 | 12 | 12 | 13 | 12 | 11 | 11 | 12 |