QATAR UNIVERSITY

COLLEGE OF ENGINEERING

SELECTION OF LIQUEFIED NATURAL GAS MARITIME TRANSPORT CARRIER: AN INTEGRATED APPROACH OF LIFE CYCLE SUSTAINABILITY ASSESSMENT AND MULTI-CRITERIA DECISION MAKING

BY

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ABSTRACT

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Title: Selection of Liquefied Natural Gas Maritime Transport Carrier: An Integrated Approach of Life Cycle Sustainability Assessment and Multi-Criteria Decision Making

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Incorporating sustainability considerations into the distribution network processes is a major challenge for any maritime shipping operations, particularly in the energy sector. Liquefied natural gas (LNG) is carried worldwide by specialized LNG carriers as a major energy source. Considering that LNG is one of the largest and most important forms of energy, the mode of transportation for LNG products must have a lower environmental impact. While the research has investigated such environmental effects, there has been minimal focus on the social and economic sustainability of natural gas production and supply chains. The primary goal of this work is to build an integrated sustainability assessment model to assess and select the most sustainable LNG carrier option by considering all dimensions of sustainability and stakeholder perspectives. To realize this goal, a life cycle sustainability assessment (LCSA) model is created to determine macro-level sustainability impacts of various LNG maritime carrier types, which are composed of Q-Flex, Q-Max, Conventional type 1, and Conventional type 2. Later, the analytic hierarchy process (AHP) is applied to determine the essential weights of each evaluation criteria, factors, and sub-factors considered in the LCSA model. Finally, integrated AHP-TOPSIS and integrated AHP-PROMETHEE II methods rank the sustainability performance of different carrier sections in order to support the decision-making process. The results show that Conventional type 2 achieves the best sustainability performance among the four types of LNG maritime transport carriers, while Q-Flex presents the lowest performance following both AHP-TOPSIS and AHP-PROMETHEE II methods. We suggest several recommendations to get more precise results in the future, considering the entire LNG process chain under uncertainty.

DEDICATION

I dedicate this dissertation report to those who work in the energy maritime transport industry and logistics, particularly in the transportation and shipping of liquefied natural gas products by sea worldwide towards having more sustainable maritime transport of energy. Let's main the world safe, satisfy people's demands, and *excellently sustain the environment for future generations.*

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NOMENCLATURE

Variables and parameters

Variable/Parameter	Description
A	Maximum loading capacity of LNG
AEF	Air emission footprint
B	Gross calorific value
BO	Boil-off
BOR	Boil-off rate
CC	Conventional capacity
CF	Carbon footprint
C_i	The relative closeness coefficient to the ideal solution
D	Traveling distance
EF	Emission factor
FCR	Fuel consumption rate
FF	Fossil fuel
HH	Human health impact
NOB	Net outbound bunker
p	Parameter value
PP	Passage period of the ship in the canal
Q	Gross fuel consumption
φ^+	Positive outranking flow
φ^-	Negative outranking flow
φ	Net outranking flow
RL	Reliquification process
S	Ship speed
s_i^*	Positive closeness to the ideal solution
s_i^-	Negative closeness to the ideal solution
WT	Waiting time of the ship in the canal
x_i	Loaded capacity
y_1	Load port in days
y_2	Steam process in days
y_3	At anchorage duration in days
y_4	Canal waiting and passing duration of each round trip
y_5	Discharge duration
z_1	Loading at port fuel consumption
z_2	Steam process fuel consumption
z_3	At the anchorage stage fuel consumption
z_4	Canal waiting and passing stage fuel consumption
z_5	Discharge stage fuel consumption

Acronyms

Acronym	Description
AR5	Fifth Assessment Report
BOG	Boil-off Gas
CF	Characterization factors
CH_4	Methane
CO_2	Carbon Dioxide
CO_2-eq	Carbon Dioxide Equivalent
CODAS	Combinative distance-based assessment
DALY	Disability-Adjusted Life Year
DEMATEL	Decision Making Trial and Evaluation Laboratory
EEDI	Energy Efficiency Design Index
EU MRR	European Union Monitoring and Reporting Regulations 2012
FDE	Fuel Diesel Electric
FGSS	Fuel gas supply systems
FTE	Full-time employees
GHG	Greenhouse Gas
GRI	Global Reporting Initiative
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
HPDF	High-pressure dual-fuel
IGU	International Gas Union
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ISO 26000	International Standardization Organization / Guidance on Social Responsibility
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life-Cycle Inventory
LCSA	Life Cycle Sustainability Assessment
LNG	Liquefied Natural Gas
LSFO	Low-sulfur fuel oil
MCDM	Multicriteria decision-making
MGO	Marine Gas Oil
MMBtu	million British Thermal Units
MMTPA	Million Metric Tonnes per Annum
N_2O	Nitrous oxide
NFE	North Field Expansion
NFS	North Field South
NO_x	Nitrogen Oxides
PM	Particulate matter
PMFP	Particulate Matter Formation Potential
POFP	Photochemical Oxidant Formation Potential
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
Q-Flex	LNG carrier
Q-Max	LNG carrier

Acronym	Description
SEEMP	Ship Energy Efficiency Management Plan
SFS	Spherical fuzzy sets
SLCA	Social Life Cycle Assessment
SMAA	Stochastic Multicriteria Acceptability Analysis
SME	Subject matter expert
SO_x	Sulfur Oxides
SSD	Slow-speed diesel
ST	Steam turbine
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
UNEP/SETAC	United Nations Environment Programme / Society for Environmental Toxicology and Chemistry
WHO	World Health Organization
WTW	Well-to-wake

CHAPTER 1: INTRODUCTION

1.1. Background

The energy sector is one of the primary contributors to greenhouse gas (GHG) emissions (Litvinenko, 2020). Natural gas is becoming more critical in worldwide energy usage for both industrial and residential applications. Due to the geographical difference between producer/supplier and consumer countries, the great bulk of natural gas is transported between ports in vessels as liquefied natural gas (LNG). As a result, a critical step in investigating worldwide LNG transportation networks utilizing bulk vessels is essential (Peng, Lu, Cheng, & Yang, 2021). More than two hundred LNG-fueled ships, excluding LNG carriers and inland waterway boats, have been in use or under development globally since the world's first LNG-fueled sea transport. Over the last decade, the fast expansion of LNG-fueled ships has revealed a slew of issues with LNG fuel system management and operation (C. Wang, Ju, & Fu, 2021).

The demand for natural gas increased in many countries, considering its reliability as an energy source (e.g., electricity) and reducing the environment's carbon footprint. The new natural gas consumers found that LNG is a promising and sustainable option to replace coal and meet the required energy demand, including electricity generation until the development of renewable energy substitute exists (EIA, 2010). Over 1.0×10^{10} m^3 of new LNG production is to be commissioned between 2018 and 2023, with the bulk of these additions coming from Australia and the United States (IEA, 2019). Additional electricity demand will create opportunities for LNG to increase worldwide, although the sensitivity to insurance policies applied to ship owners (e.g., product transport, equipment damage or failure, service overseas, etc.) and rate levels continue to be uncertain. LNG trade is increasing from local regions and neighboring countries to global markets. International Gas Union (IGU) (2020) reported the top LNG exporters in the world. Qatar with 22%, Australia with 21%, the USA with 10%, and

Russia with 8% contribution to the overall LNG exports in the world.

Natural gas distribution entirely relies on pipeline and shipment networks between supply and demand regions. Global statistics indicate that the global LNG trade mainly depends on marine vessels for transport (Nations, 2019). LNG producers are currently working on improved liquefaction and regasification processes to tailor an environmentally friendly operation (Oliver, 2015). Suppliers aim to deliver LNG at the right time with highly efficient processes, making the bilateral trade and amount of financial profits more attractive. The effective revolution in processing and delivery services also increases the number of natural gas-consuming countries every year (Msakni & Haouari, 2018).

The maritime transportation operation is strongly reliant on fossil fuels and is one of the greatest consumers of petroleum. In 2019, the universal demand for marine fuel was expected to reach over 400 million metric tons. Furthermore, ocean transportation is a major source of sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM) emissions. For instance, shipping is responsible for 13% of anthropogenic SO_x emissions and 2.6% of carbon dioxide (CO_2) emissions globally. Starting on January 1st, 2020, the international maritime organization (IMO) has set emission targets, known as IMO 2020, to reduce worldwide marine fuel sulfur content from 3.5% m/m (mass by mass) to 0.5% m/m (Sharma, Dimitrios, Olcer, & Nikitakos, 2020). Moreover, the IMO has devised a framework for decreasing shipping's CO_2 output: a 40% decrease by 2030 compared to 2008 levels, and a 70% decrease by 2050. An expected increase in low-sulfur marine fuels and other upcoming emission rules and the additional processing associated with heavy fuel oil (HFO) could open new market opportunities for cleaner options (such as biofuels, cleaner non-renewable alternative fuels, and renewable energy) (E. C. D. Tan et al., 2021).

The principal exhaust emissions from ships significantly affect air quality and climate change, which are fundamentally international problems. The Paris Agreement acknowledges this as an imminent challenge and lays out the stabilization target of controlling the global temperature rise to less than 2 °C. Although GHG emissions have grown exponentially, deep cuts are needed to accomplish this objective, where the shipping sector has gained traction in recent years. In 1997, the Kyoto Protocol handed down the IMO action to mitigate the carbon footprint from worldwide shipping. In 2011, the IMO adopted amendments to MARPOL ANNEX VI, the atmospheric pollution section of its environmental principle, by implementing the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). However, these steps do not entirely resolve air pollution resulting from the shipping trade as fleet numbers keep increasing, and demand continues. The IMO has established a plan to minimize the carbon footprint to identify the policy of the shipping sector and its part in promoting the Paris Agreement. It also aims to evaluate the possibilities for reducing GHG emissions, including renewable fuels (Gilbert et al., 2018).

Many atmospheric carbon dioxide emitting sources in addition to other atmospheric air pollutants, such as the use of traditional energy fuels, energy losses, and the transport sector, are directly impacting health. This observation forms an additional motivation to mitigate the climate change problem. Air pollution causes over seven million deaths per year and is considered one of the most significant contributors to human health impacts. Nearly 90% of the urban population worldwide was vulnerable to pollution and living in environments not meeting the World Health Organization (WHO) standards for ambient air quality (WHO, 2019a). Therefore, a comprehensive approach to address all risks is required for the close connection between climate change and polluting activities and the inclusion of health benefits in climate change and national health plans and strategies (WHO, 2019b).

Following the implementation of the Legislation on the Prevention of Air Pollution from Ships (Annex VI), several renewable maritime energy sources have been identified as encouraging possibilities for reducing atmospheric contamination from carriers. In the meantime, alternative or renewable energy resources that can replace conventional fossil fuels, particularly HFO, has been identified as a favorable approach to achieving environmentally friendly transport. In addition, growing people's attitudes, commitment to environmental conservation, and enhancing air quality are essential to increase awareness of sustainability.

LNG has demonstrated slightly improved efficiency than HFO in the environmental impacts of the life cycle, and LNG emits 92% fewer emissions than HFO (Ren & Liang, 2017). This demonstration has created a substantial shift in natural gas needs globally. Developments push companies to spend extensively on supply chains to accomplish effective global delivery of LNG. LNG is cleaner than oil and coal and provides a chance to diversify electricity supplies. Therefore, the use of LNG in the gas market has gained considerable global attention. Natural gas transportation from multiple parts of the world (carbon supplied to consuming areas) has become more critical. Demand for natural gas increased after numerous critiques of carbon emissions from coal-based power plants (Energy, 2010). The LNG trade and consumption have increased dramatically over the last 40 years. Accordingly, the economic status of the LNG has changed over time. The need for cleaner energy sources has contributed positively to the use and the distribution of LNG manufacturing and economic growth worldwide (Aydin, 2018).

Natural gas has appeared as the highly favored energy source nowadays. It anticipated good cost-effectiveness and better socio-environmental performance. For overseas importing countries, transporting liquefied gas has several advantages over pipeline transport. Natural gas liquefaction offers a cleaner and more efficient transportation option and likewise raises its storage capacity. The liquefaction activity involves cooling the gas by employing numerous cryogenic techniques and depressurizing to atmospheric conditions (Kumar et al., 2011).

LNG carriers are specially constructed ships for transporting cryogenic LNG products. They are equipped with shielded double-hulled tanks meant to hold cargo at a freezing temperature slightly above atmospheric pressure without external refrigeration. The design pressure and temperature are usually around 0.7 barg and -169 °C, respectively. Methane (CH_4) makes up the majority of the mixture, with smaller amounts of ethane (C_2H_6), propane (C_3H_8), butane (C_4H_{10}), and nitrogen (N_2) (Marques, Belchior, & Caprace, 2019). Due to its cryogenic nature, however, ship owners and operators must choose an LNG tank size that links directly to the cost of equipment, installation, and/or conversion, as well as other factors such as space loss and boil-off gas (BOG) control (R. Tan, Duru, & Thepsithar, 2020). Transporting LNG has environmental, economic, and social impacts.

1.2. Environmental, social, and economic impacts

1.2.1. Environmental dimension

Natural gas combustion emits roughly 20% less CO_2 than diesel oil (Schlick, 2014). Natural gas has a lower carbon-to-hydrogen mass ratio than diesel oil, which results in reduced CO_2 emissions (Levander, 2011). Furthermore, a reduction of 79% in NO_x, 100% in SO_x, and 92% in the PM can be obtained due to the switching to natural gas use, as measured in parts per billion energy units (Kumar et al., 2011). On the other hand, methane slip is a concern during the operation of LNG carriers because it will always be present with dual-fuel technology. Methane leakage is included when estimating GHG emissions, resulting in a substantial penalty on future taxation (Papagiannakis, Zannis, Pariotis, & Katsanis, 2019).

A recent study looked at the need to maintain LNG pressure and temperature consistency and insulating cargo tank structures and designs to prevent LNG vaporization and the generation of BOG. Avoiding the BOG phenomena reduces the risk of harmful overpressure and incident and societal effects. Moreover, it minimized fuel consumption and enhanced productivity (Marques et al., 2019). According to HFO, LNG improves PM, SO_x, and NO_x emissions (E. C. D. Tan et al., 2021). Across all of the paths investigated, LNG had the lowest PM emissions. Compared to HFO's 2.7% Sulfur, LNG provides a 26% reduction in NO_x (E. C. D. Tan et al., 2021).

1.2.2. Social dimension

Since the 1960s, there has been a growing understanding that continuing expansion in production and supply within the finite boundaries of the globe is unsustainable for humans and ecosystems. As a result of this insight, a vision for long-term development has emerged. Concerns about the social dimension of sustainability are reflected in today’s modern structural reforms, such as the United Nations' Sustainable Development Goals, numerous international programs aimed at achieving sustainable growth, and social standards development methodologies, such as the ISO 26000's Guidance on Social Responsibility (Valcarcel & Lucena, 2014). In this context, since the turn of the millennium, a development of the life cycle assessment (LCA) framework to include the impacts on social entities (e.g., workers, consumers, and communities) has been underway in order to assess a product's or program's contribution to sustainability more thoroughly (Moltesen, Bonou, Wangel, & Bozhilova-Kisheva, 2018).

Energy cannot be described just as a techno-economic issue because it affects all aspects of society, including culture, beliefs, habits, and power structures. Energy system changes have had a long-term impact on communities, as long-term social and cultural processes fundamentally impact energy systems. As a result, energy systems should be examined from both a social and cultural standpoint. The energy sector's knowledge, skills, connections, and infrastructure can help diversify the economy (Liko, 2019).

Given that switching from one kind of energy to another has resulted in social change in areas such as manufacturing processes, the standard of living, and labor productivity, it is reasonable to argue that there is a link between this social change and the creation of various political systems (J. Lee & Yang, 2019). In whatever shape they take, energy transitions will be complicated socio-technical shifts that will necessitate considerable adjustments in many populations. One of the most critical limiting elements in determining the viability of such a shift between energy forms is societal acceptance. For example, in the case of wind energy, which has become a source of heated dispute in various nations due to its visual impact on landscapes, this is particularly evident (Wüstenhagen, Wolsink, & Bürer, 2007). The study of social relationships, social organization, and group behavior patterns is common from the social perspective. It also entails comprehending individuals' attitudes, feelings, and motives as members of society. The evaluation of the reaction, as well as the benefits, is part of the social standpoint.

The societal human health implications linked with air emissions from LNG maritime transport are explained by three assumptions, according to Aseel, Al-Yafei, Kucukvar, and Onat (2021). The proposed theories describe the relationship between human health impact and energy consumption as a function of journey distance, fuel type, and carrier type in the LNG supply chain. In terms of the three hypotheses, it is expected that using natural gas as a fuel will lessen the influence on human health.

1.2.3. Economic dimension

Exports of worldwide sea trade have risen steadily by 25%, from over 7 billion tons in 2008 to about 11 billion tons in 2017 (H.-J. Lee, Yoo, & Huh, 2020). The shipping and ship construction industries are facing new difficulties as a result of the stiffening of emission rules and are looking for solutions to address them (Hoffmann, Asariotis, Assaf, & Benamara, 2018). In general, there are four ways to deal with IMO requirements like these. The first is to utilize low-sulfur fuel oil on ships (LSFO). Switching to LSFO is the simplest approach because existing technologies may be used without the need for infrastructure upgrades. The cost of LSFO, on the other hand, is more than 25% greater than that of HFO (Greg Knowler, 2019). Additionally, because there aren't enough reactors to produce LSFO, a supply shortage could lead to price rises (Pacific Green Technologies Group, 2019). The second alternative is to utilize HFO with a SO_x scrubber. This method has the advantage of employing HFO, but the initial implementation costs are high. Severe backpressure can also occur, resulting in reduced engine performance and increased energy consumption. Because of the device's features, a large amount of setup area is required in the ship, making installation on small ships difficult (Sargun Sethi, 2019). The third option is to replace HFO with marine gas oil (MGO). MGO can utilize existing systems; therefore, no additional infrastructure is necessary. MGO, on the other hand, may have an impact on marine operations such as pace, engine service, and combustion and emission characteristics (ABS, 2010). Lastly, LNG can be substituted for HFO. LNG has several drawbacks, including a lack of a distribution network and a high upfront cost (Andrea Hayward, 2018; Jonathan Saul, 2018).

Further information related to sustainability assessment indicators is available in Appendix A of this dissertation report.

1.3. Problem statement

At the policy level, the concept of sustainable development is implemented. Still, it needs to be expanded in the commercial context: as a result of the rising demand for sustainable products from more informed consumers, the fuel industries have included sustainability in their goals. In addition, the gas maritime transport operations sector must identify and report the substantial impacts of their various activities on the environment and numerous stakeholders from a sustainable development perspective, according to the Global Reporting

Initiative (GRI) criteria (GRI, 2021). Upgrading the methodologies for analyzing the life cycle and aiming for sustainable shipping is also necessary for progressing towards sustainability. The environment's conservation is critical to accomplishing this objective of sustainable development. Aside from environmental preservation, the approach also includes economic and social safeguards.

Moreover, the LNG maritime transport carrier option selectivity based on its adverse and beneficial integrated environmental, social, and economic assessment was not attempted comprehensively as part of the decision selection criteria before design and operations as per the literature. Considering the complexity of the best LNG maritime carrier evaluation, it is seen as multipart multicriteria decision-making (MCDM) problem. Usually, there is no specific rubric or a dedicated set of criteria while implementing the MCDM method; the criteria vary from one case to another based on practicality and applicability (Yilmaz, Kusakci, Tatoglu, Icten, & Yetgin, 2019). Each decision is influenced by the source of information, how precise the data is, evaluation criteria, and the opinion of decision-makers (Lin, Wang, & Yu, 2008). Similarly, practitioners of LCSA use subjective assessments and oral statements while determining the appropriate weights and evaluating the factors and sub-factors (Erdoğan & Kaya, 2016). To this point, sustainability assessment sets based on AHP appear to be the aid that allows us to appropriately handle several types of uncertainty in decision-making (Abdel-Basset, Mohamed, & Sangaiah, 2018; Bolturk & Kahraman, 2018). After determining criteria’s weights as part of AHP, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Preference Ranking Organization Method for Enrichment Evaluation II (PROMETHEE II) methods are employed to determine the best sustainable LNG maritime transport operations carrier. TOPSIS and PROMETHEE II are commonly applied MCDM approach with some encouraging direction toward the best results (Jiang, Zhang, Asante, & Yang, 2019; Z. Wang et al., 2019).

1.4. Research objectives

This dissertation report aims to look into and determine the LNG maritime transportation operations sustainability in connection to LNG trade. In this context, we developed a practical and unique framework for LNG LCA, life cycle costing (LCC), and social life cycle assessment (SLCA) analysis. Due to the ongoing operation of market forces for LNG trading, and the global attractiveness of green energy supplies for sustainable development, it is appropriate to explore this area of concern. The following is a list of the research's main goals:

- Proposing a method of carbon footprint accounting from LNG maritime transportation operations and implementing sensitivity analysis using a Monte Carlo simulation that helps determine the vital parameters that affect LNG shipping's carbon footprints.
- Proposing a method of converting the midpoint air emissions to human health endpoint impacts for various hydrocarbon commodity-shipping disciplines.
- Proposing an economic life cycle assessment method considering the gross operating surplus, operation and equipment costs, and end of life for maritime transportation operations.
- Developing a framework and mechanism for estimating LNG maritime transport operations LCSA. The case of LNG trade is considered.
- Creating and implementing an LCSA model that includes LCA, LCC, and SLCA and data from various sources and domains for the shortlisted LNG maritime transport carrier.
- Creating a long-term impact accounting tool inclusive of a novel LCSA MCDM method that can be used by a wide range of gas and oil industry professionals.

- Analyzing and interpreting the assessment outcomes to estimate the best sustainable selection of the available LNG maritime transport operations carrier.

1.5. Dissertation outline

This dissertation is structured into six chapters. Chapter 1 provides general background on the energy sector, especially LNG trading, product transportation methods, and global demand. Later, more focuses on the environmental, social, and economic impacts related to the LNG maritime transport operations, followed by the problem statement, research objectives, and this dissertation outlines.

Chapter 2 covers the literature review conducted using some recent work performed that is related to this dissertation subject. The review focuses on sustainability pillars and their integration, the MCDM techniques and overview, general information on the LNG process and supply chain, followed by identifying the research gap.

Chapter 3 starts with structuring the flow of this research and the research method. The LCSA goal, scope, life cycle inventory is framed. The model for estimating the air emission, human health impact, and the LCSA, including LCA, LCC, and SLCA, is presented. Qatar is taken as the case study. Finally, AHP, AHP-TOSIS, and AHP-PROMETHEE II are used to interpret and select the best sustainable LNG carrier.

Chapter 4 intends to provide the results of the air emission and human health impact models. Moreover, LCA, LCC, and SLCA results are presented and integrated into MCDM tools. Starting with AHP and followed by well-known selection techniques identifying the positive and negative distancing from the ideal solutions based on sustainability indicators.

Chapter 5 provides a set of recommendations to policy makers for future policy establishment towards more sustainable LNG maritime transport operations that minimize the environment's adverse impacts, improve social satisfaction, and maintain an excellent economy.

Chapter 6 summarizes the key findings of the research and presents the importance of selecting the most sustainably LNG carrier to the decision-makers. The research's limitations and recommendations based on the results are presented, and suggestions for required future research in the same area are offered in the same chapter.

CHAPTER 2: LITERATURE REVIEW

2.1. Integrated sustainability assessment

In this research, integration of LCA, LCC, and SLCA is established to assess the sustainability of LNG maritime transport operations. A new LCSA model-based MCDM is built to help decision-makers investigate the most suitable LNG carriers from a sustainability perspective among four types of LNG maritime carriers. The approach is useful for deciding on the minimum impact on the environment, better social satisfaction, and enhanced profitability.

2.1.1 Environmental life cycle assessment

Environmental laws have long been an important part of the natural gas distribution network, but recent shipping activities have recently received more attention. In their review study, Al-Enazi, Okonkwo, Bicer, and Al-Ansari (2021) examined the obstacles and prospects of replacing HFOs used in marine logistics with cleaner fuels. The evaluation looked at the economic and environmental aspects of various bunker fuels, including LNG, as well as synergies between LNG importers and exporters' supply chains and how to assist maritime operators in complying with recent environmental legislation. With 2008 as a baseline, Ampah, Yusuf, Afrane, Jin, and Liu (2021) conducted a bibliometric analysis for 20 years from well-known database systems, focusing on cleaner options of marine fuels to meet the IMO requirements and CO_2 intensity will be cut by 35% by 2030, and overall Carbon emission will be cut by at least half by 2040. According to the findings, the LNG has been identified as the most investigated alternative transport fuel. Recent developments, however, reveal that researchers are increasingly interested in methanol, ammonia, and hydrogen fuels. Sharafian, Blomerus, and Mérida (2019) analyzed local and imported LNG and maritime oil pollutants using an LCA. According to the study, only high-pressure dual-fuel (HPDF) machines minimize well-to-wake (WTW) carbon footprint by 15% when contrasted to HFO-fueled alternatives. Gas generators have been found to be an effective technique for reducing nitrous oxides, sulfur compounds, and particle pollution in the atmosphere without any additional engine after-treatment.

A "Well-to-Propeller" LCA of marine transportation was undertaken with a spatial concentration on Europe. For four popular types of boats with particular functional profiles, the impact of dual-fuel operated engines with HFO or LNG on energy-related GHG emissions, including the role of natural gas slip on GHG, was investigated by Seithe, Bonou, Giannopoulos, Georgopoulou, and Founti (2020). Several LCA studies that have focused on marine fuels recognized the importance of LCA as supplementary to regulatory measures (Bengtsson, 2011; Blanco-Davis & Zhou, 2016; Corbett & Winebrake, 2008). The vast majority of studies examine various fuel supply networks, including excess oil, normal diesel, low sulfur diesel, LNG, HFO, offshore gas-to-liquid fuel, and biofuels. Furthermore, Lindstad and Rialland (2020) conducted an LCA by transparently developing comparable GHG projections for WTW emissions for LNG and traditional fuels. The findings demonstrate that efforts that reduce broader GHG emissions of shipping, rather than just CO_2, are needed, including well-to-tank emissions of ship fuels. Hansson, Månsson, Brynolf, and Grahn (2019) used an MCDM approach to examine the prospects for seven alternative energy sources for the maritime sector in 2030, including LNG. Cucinotta, Raffaele, Salmeri, and Sfravara (2021) did a comparative LCA for a cruise ferry engine using traditional diesel fuel and LNG. LNG propulsion has been found to be more environmentally friendly, but the results in terms of climate change are particularly intriguing, as they are influenced by decreased CO_2 emissions as well as the phenomena of methane slip, which can enhance the CO_2-equivalent effect. The energy costs of transportation and gas liquefaction must also be considered.

Wada, Yamamura, Hamada, and Wanaka (2021) constructed a model employing system dynamics to assess GHG emission cases in maritime transport, which was then incorporated into a shipping and shipbuilding market tool. By using the suggested tool, simulations were run to assess the impact and effectiveness of GHG emission-reduction initiatives. LNG is one of the fuels evaluated in the model. When compared to other conventional fuels, Al-Douri et al. (2021) found that LNG can cut life cycle emissions by up to 18%. Furthermore, they stated that adding renewable energy generation into liquefaction can lower emissions by a further 5% to 10%. Aseel, Al-Yafei, et al. (2021a) created an innovative and realistic approach for calculating the carbon footprint of LNG maritime transportation. An uncertainty-based carbon footprint accounting paradigm is constructed using the MATLAB application. The type of fuel has a significant impact on pollution values due to the carbon content of the product. When the two typical boats are compared, the one that runs only on LNG generates fewer carbon emissions than the one that runs on dual-mode. A review by Deng et al. (2021) outlined the numerous pollution reduction techniques for marine engines. The usage of LNG as a naval engine fuel is assessed holistically, considering three factors: environmental preservation, energy structure, and economic benefits.

2.1.2 Social life cycle assessment

Only a few published studies in the literature highlight the social impact of maritime transportation fuels. As a result, research has been launched by H.-J. Lee et al. (2020) to determine customer acceptance and the social benefits of replacing HFO with more environmentally friendly alternatives. Contini and Merico (2021) analyzed some recent studies on air pollutants and the relative health implications of maritime emissions and future forecasts on the benefits of the new IMO-2020 regulation's adoption. Zhou and Yuen (2021) developed a model for Low Sulfur Fuel and High Sulfur Fuel under a government subsidy incentive scheme, taking into account monopoly and duopoly market structures. The findings suggest that a government subsidy could induce more people to buy Low Sulfur Fuels. However, when the market's entire demand grows, there will be a greater effect on the environment. The ideal subsidy amount can be determined to maximize total welfare program. Furthermore, market structure might have an impact on social welfare. Chen and Kim (2020) released a study in 2020 that examined the power, business, and social implications of Delaware's clean, renewable energy economic policies. This article suggests that public approval should be considered when a government offers financial initiatives to promote new technical innovation, especially when the policy involves long-term expectations and repercussions. Al-Yafei, Kucukvar, AlNouss, Aseel, and Onat (2021) built a comprehensive LCA framework to investigate the overall health impacts of LNG production and maritime transport atmospheric air pollution generation. The everyday loss of life linked with the LNG process chain was examined using ReCiPe 2016 characterization criteria to compute the social and health impact outcomes. Aseel, Al-Yafei, Kucukvar, and Onat (2021) also created an LCA system for air pollutants and social and community health implications connected with LNG sea transportation in order to study the impact of each type of fuel utilized by the numerous maritime carriers. The findings highlight the significance of utilizing a greener fuel option, such as Conventional type 2, to reduce the health impact of LNG maritime transportation.

2.1.3 Economic life cycle assessment

LNG-fueled ships must be evaluated economically to guarantee that LNG is a more sustainable and economically feasible fossil energy alternative. As a result, many studies to establish the commercial feasibility of LNG as a ship fuel have been done. Adachi, Kosaka, Fukuda, Ohashi, and Harumi (2014) assessed the financial potential of using LNG as a fuel in several scenarios based on the architecture of modern container ships. Eise Fokkema, Buijs, and Vis (2017) evaluated the scenarios in which LNG-fueled ships are comparable to conventional vessels regarding utilization expenses. Yoo (2017) investigated if using LNG energy would be more cost-effective if oil prices were around 30–50 USD/bbl or higher and whether LNG fuel's appeal would be reinforced if LNG fuel innovation and infrastructure were built. The economic analysis of LNG-fueled ships is easy to discover in terms of national and linked sectors. In the case of variable fuel costs, Oh and Karimi (2010) presented mathematical models to maximize fuel purchases and trip speeds for multiparcel vessels. In identifying the optimal ship speed, bunkering ports, and amount of bunker fuel for a given ship's route, H.-J. Kim, Chang, Kim, and Kim (2012) took into account the fixed ordering, purchase, and inventory carrying costs associated with bunker fuel, as well as daily fixed costs and environmental costs (carbon tax).

R. Tan et al. (2020) explored liner bunkering with dual fuel operation in a subset of the important shipping channels east of Suez to provide fuel variety in the face of limited LNG-fueled facilities. Many aspects were stressed by the authors, including the economic aspect. The research was prompted by the major construction of new LNG bunkering facilities in recent years and a growth in global fuel consumption. Al-Haidous, Govindan, and Al-Ansari (2020) created a multi-objective computational formula for shipping fleet scheduling, navigation, and delivery for sustainable LNG supply chains. The model considers flexibility in delivery time, inventory management and berth availability, and fuel usage and CO_2 emissions. The solutions for planning, transportation, and delivery produced thus far show that the average total expenses associated with a single cargo are roughly 1.6 million USD over the relevant planning horizon. To reduce the cost of the LNG supply chain, Utku and Soyöz (2020) presented a new model. The model factored in the expenses of liquefaction, transportation, and regasification. The proposed model considers sea, road, and pipeline transportation modalities.

The financial viability and CO_2 emission reduction of deploying LNG-fueled container ships to travel over the Northern Sea Route were investigated in research by Xu and Yang (2020). A profit model for shipping and a CO_2 emission model was developed. Dai, Jing, Hu, and Wang (2021) created an environmental and techno-economic model that quantifies emissions and total expenses. The data also suggest that HFO is still the most cost-effective alternative for ships in the short run, regardless of environmental costs. Compared to other fuel types, LNG offers a better economic and environmental performance. Jurkovič, Kalina, Stopka, Gorzelanczyk, and Abramović (2021) conducted a cost-benefit analysis of LNG carriages. The techniques employed were MCDM and TOPSIS. The manuscript compares carriage using regular MGO fuels with alternative LNG fuels and a technological evaluation.

An LCC analysis of low-pressure fuel gas supply systems (FGSS) for LNG-fueled ships was undertaken by C. Wang et al. (2021). According to the study, ship dimensions, LNG fuel cost, and ship management all significantly impact the LCC of FGSS. BOG reliquefaction aboard is reliable when the sailing time gauge is low, and the LNG cost is high, particularly for big ships. When the sailing time gauge is high, and LNG's price is low, sending the BOG to supplemental engines after contraction is more cost-effective. Al-Breiki and Bicer (2020) investigated the economic implications of BOG in the manufacturing and transportation phases of potential energy carriers. A mathematical approach is applied to determine various energy carriers' production and transportation costs and account for BOG as a unit cost within the total cost.

2.2. Multi-criteria decision making

MCDM methods applications are widely used because of their beneficial outcomes for selecting different alternatives based on users’ judgment and criteria. Many life cycle studies followed MCDM methods as part of the sustainability assessment-based decision-making. It also helps address multiple variables towards the best sustainable option, not considering the different opinions of judgment and other constraints that may apply due to the nature of the applications (J.-J. Wang, Jing, Zhang, & Zhao, 2009). AHP and several decision-making methods are followed in many energy and non-energy application.

For instance, in the energy sector, AHP was deployed to prioritize the supply chain strategies to their economic impacts on the LNG networks that guide the decision-makers on the strategic planning for the LNG network sector (Zubairu, Dinwoodie, Govindan, Hunter, & Roh, 2021). Aspen and Sparrevik (2020) studied comparative indicators that focus mainly on the environmental, economic, and safety impacts and how they could reflect on the decisions of the ship owners and regulators to transport operations. To achieve the main goal, the MCDM method was followed. A Stochastic Multicriteria Acceptability Analysis (SMAA) was integrated with TOPSIS to evaluate the use of several energy sources, including natural gas, for the impact assessment and decision-making guidance. For the non-energy sector, for example, the selection of alternative fuel vehicles was studied in detail by Cihat Onat (2022). MRIO-based LCSA and MCDM method has been considered under the research methodology to help decision-makers at national and international levels journey towards sustainability. Spherical fuzzy sets analytic hierarchy process (SFS-AHP) method for weights determination is followed and then incorporated with combinative distance-based assessment (CODAS). Moreover, James et al. (2021) initiated the discussion and the current issue of India’s focus on switching from automobile usage to electric vehicles. The challenges of implementing electric vehicles have been studied following a proposed structural model. This model is built as a combined AHP and Decision-Making Trial and Evaluation Laboratory (DEMATEL) to evaluate those challenges.

2.3. LNG process and supply chain

The natural gas from the source well is transported to the natural gas treatment and liquefaction process as soon as possible. After that, the main product is separated from the byproducts, and LNG is piped to the storage tanks at a temperature of -162 °C. After that, the LNG will be loaded onto LNG carriers and sent to customers in other countries. LNG shipping is a cost-effective means to move huge amounts of natural gas over great distances. LNG can be carried via LNG carriers, which are specifically constructed cryogenic sea boats (Al-Yafei, Aseel, et al., 2021). The flammability range refers to the range of LNG vapor concentrations in air that can ignite and burn into an explosive combination. The flammability range for methane, the major component of LNG vapor, is around 5 to 15% by volume. It cannot burn when the vapor levels exceed the higher flammability limit because there is insufficient oxygen present, and it cannot burn when the concentration is below the lower flammability limit because there is insufficient methane present. Its flammability, the freezing of its lower temperatures, and suffocation from its fumes are all concerns. When the LNG carrier arrives at its location, the LNG will be unpacked and held in insulated tanks designed to withstand the extreme cold. When there is a demand, the LNG will be cooked in a 1:600 ratio to transform it back into gas. Steel mills, businesses, power plants, and residences are among the places where it is delivered (Kader, Oladokun, & Shamsuri, 2015).

2.4. Research gap

According to a comprehensive literature review, the sustainability assessment of LNG carriers has not been studied sufficiently. While there are some applications of LCA and LCC of LNG carriers, there is a significant gap in the social impact assessment. Careful consideration of all these dimensions together is crucial. Furthermore, there has been no stakeholder involvement and consideration of multiple criteria in the sustainability assessment of LNG carriers. Hence, this study proposes a novel integrated sustainability assessment approach that involves all dimensions of sustainability and stakeholder perspective with a comprehensive MCDM approach. In this study, we analyzed Qatar, the largest exporter of LNG globally, as a case study. The outcomes of the proposed model are scalable and can be applied to a wide range of carrier selection problems within the oil and gas industry and beyond.

CHAPTER 3: MATERIAL AND METHODS

3.1. Research flow chart

The process for studying the LNG maritime transport operations LCSA, according to UNEP/SETAC standards, (contains four steps: LCSA objective and scope, evaluation methodologies, impact assessment, and LCSA-MCDM interpretation) (see Figure 1) (Benoît-Norris et al., 2011). LCSA is the consequence of merging LCA, LCC, and SLCA life cycle characteristics. LCA is the only one of these that has been certified to ISO-14040-44. The MCDM consists of some well-known selective techniques. The steps involved in LCSA are presented in the following subsections.

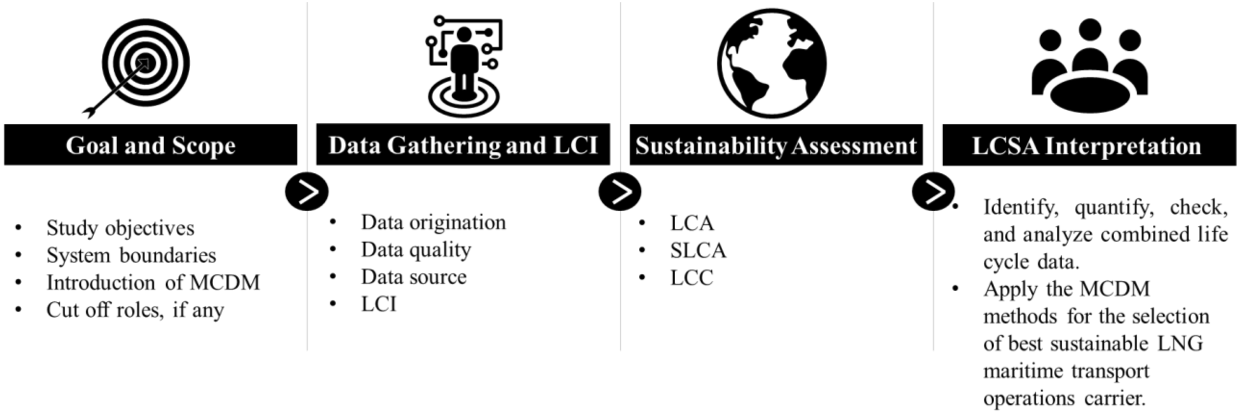


Figure 1. Research method.

3.2. LCSA goal and scope

This research aims to conduct an LNG maritime transport operation LCSA and compare its effectiveness from post product loading until delivery to the intended location using numerous types of carriers. The functional unit for the LCA and LCC analyses was one metric ton (MT) of LNG shipped. There is no requirement for a fundamental structure in SLCA because subjective data is captured and then transformed into quantitative data for assessment. Nonetheless, UNEP/SETAC advises that the main structure be chosen for performing the SLCA factor used was 1 MT of LNG shipped.

Some premises and limits in LNG sea transport operations were analyzed in this research in order to ensure compliance with ecological safety requirements, limit environmental harm, and apply the optimum operational strategies:

1. The shipping overseas is expected to cause minimal flaring.
2. Emissions from point sources stacks must not exceed the authorities' restrictions.
3. BOG flaring must be kept to a bare minimum in accordance with the design and best operational procedures.
4. There is no outflow of untreated wastewater into the sea.
5. As per design and best operational methods, methane slip should be kept to a bare minimum.
6. The unitary cost of air pollution and global warming are not considered for GHG emissions.

3.3. Inventory analysis

A life cycle inventory (LCI) for the maritime transport operation phase was created for evaluation. The Ras Laffan port in Qatar is used as the exporting port, and the case study looks at the top 11 LNG buyers of Qatar’s LNG. To understand this purpose, take the LNG marine transport operations domain, which was earlier constructed by (Aseel, Al-Yafei, Kucukvar, & Onat, 2021), including the boundary system. Second, the must-recognize sustainability indicators, including socio-environmental and economic elements, are briefly discussed in Table 1.

Table 1. Life Cycle Inventory of the Study.

Impact area	Impact/Indicator	Unit	Description
Environmental	Global warming potential (GWP)	kTon CO_2-eq.	GHG emissions are determined on IPCC GWP100 parameters AR5
	Particulate matter formation potential (PMFP)	kTon $PM_{2.5}$-eq.	Emissions of all air pollutants that meet the criteria
	Photochemical oxidant formation potential (POFP)	kTon NO_x-eq.	The number of airborne chemicals capable of forming oxidants in the atmosphere.
	Energy consumption	PJ	The entire amount of energy is derived from natural resources.
	Land used	Mm^2	The approximate area used to park the carrier in for loading and unloading
	The use of water	km^3	The volume of water is permanently withdrawn from its source for use.
	Removal of water	km^3	The amount of water that has been taken from a source of water for private use and subsequently returned to the source.
Social	Employment	person	The number of employees in each industry in Qatar and worldwide,
	Compensation of employment	MUSD	The monetary value assigned to a service, loss, accident, debt, or other events.
	Total tax	MUSD	The entire tax income is generated by each industry, both within and outside Qatar.
	Man-hours	1000 hrs	Number of working hours
	Human health	DALY	The number of years of life lost as a result of infirmity, illness, or death at a young age.
Economic	Gross operating surplus	MUSD	Corporations' available capital allows them to pay taxes, reimburse creditors, and support their investments.
	Operational cost	MUSD	The expenses a business incurs in its normal day-to-day operations (such as utilities, maintenance, other resources, etc.)
	Equipment cost	MUSD	The purchase price therefore paid by the Owner to install the equipment
	Salvage value (End of life)	MUSD	The book value of an asset after all depreciation has been fully expensed

Finally, the associated data of life cycle sustainability with each type of carrier will be compiled from several sources and domains.

3.4. Model for estimating air emissions and human health impact

This section focuses on the research structure for air emissions and human health impact. It starts with data obtained from public domains and earlier research by Aseel, Al-Yafei, et al. (2021b). Then, the total fuel consumption from the exporting terminal to the distribution terminals and the return trip are calculated. This part of the research is essential as the emission factors are applied to measure the overall amount of gases released by different vessels during a single roundtrip. Finally, characterization factors (CF) are used to convert the midpoint environmental emissions into endpoint human health impacts representing the disability-adjusted life year (DALY). Figure 2 demonstrates the step-by-step research method.

The first step starts with data collection, including these items: the annual LNG demand for Qatar’s main customers, carrier’s design details and capacities, traveling distances and ports details, laden and ballast traveling details, and their relevant fuel consumption during each operation process, and the ballast water loading and unloading details. This research selected four specific types of ships by considering actual ship transits from departure port to 11 destinations. The model reflects the nature of the carriers and their suitable fuel type. Mixing such ships to a destination was not deemed for the per roundtrip and per year emissions. The second step contains developing a modeling tool to measure the carrier's fuel consumed for multiple situations involving 11 different destinations worldwide. In the third step, the average CO_2-eq, NO_x-eq, and $PM_{2.5}$-eq pollutants are then calculated utilizing the total fuel consumed and the relevant emission factors. The fourth step presents CFs from ReCiPe 2016 to convert the environmental emissions to endpoint human health impact. CO_2-eq, NO_x-eq, and $PM_{2.5}$-eq represent the critical pollutants related to human health impact as per ReCiPe 2016 that are expected to occur during maritime LNG transportation. The rest of the emissions defined in ReCiPe 2016 can be neglected, as they don’t have a critical contribution towards human health impact in maritime LNG transport.

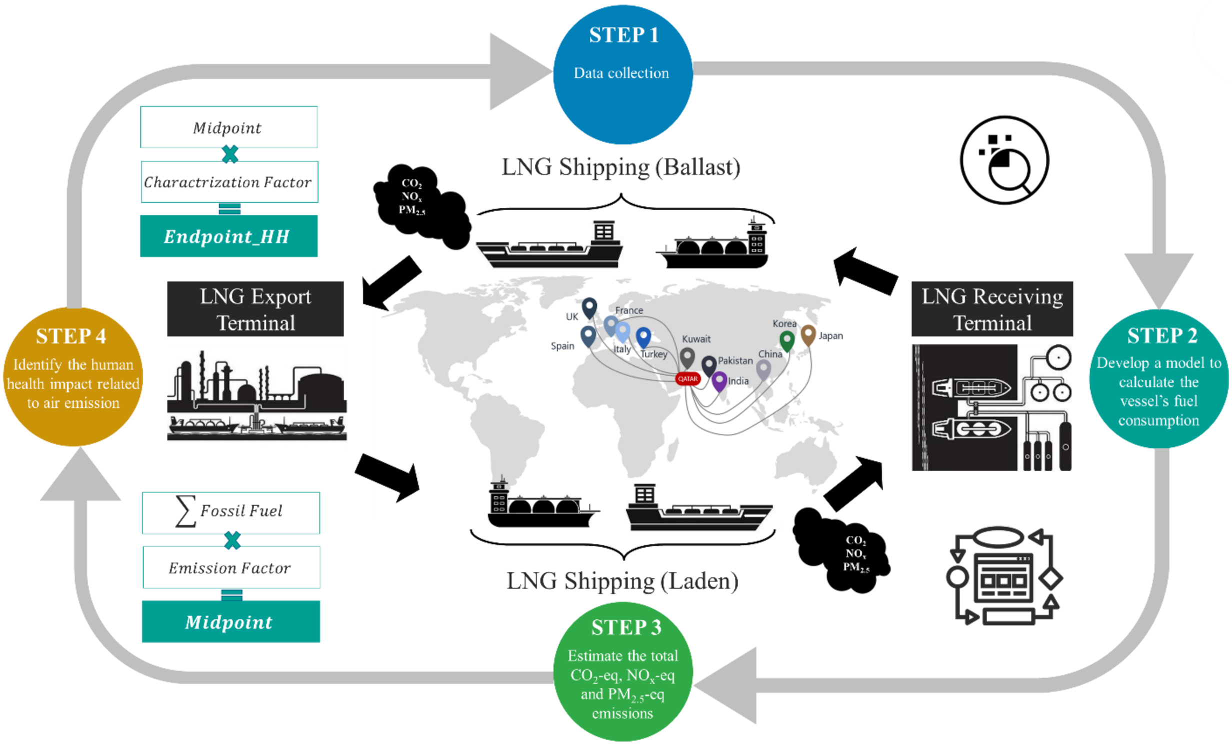


Figure 2. The main four steps of the research methodology.

3.4.1 Data gathering and assumptions

As shown in Figure 3, the proposed tool for air pollution footprint accounting was used for LNG trade between 11 different destinations of Qatar's LNG key customers. Qatar was chosen because of its high LNG production rate and ability to export LNG to other countries through maritime transport. Furthermore, QatarEnergy (named earlier as Qatar Petroleum, QP) declared the North Field Expansion (NFE) mission in November 2019, which will raise Qatar's LNG output capability to slightly more than 100 million metric tons per annum (MMTPA) as the first expansion phase. The second phase is to increase 126 MMTPA, known as the North

Field South (NFS) mission, reflecting around a 63% increase compared with the current capacity (QatarEnergy, 2020). Asian countries represented by China, Korea, India, and Japan are the highest beneficiary of Qatar’s LNG export at 17, 14, 12, and 11%, respectively (IGU, 2020).

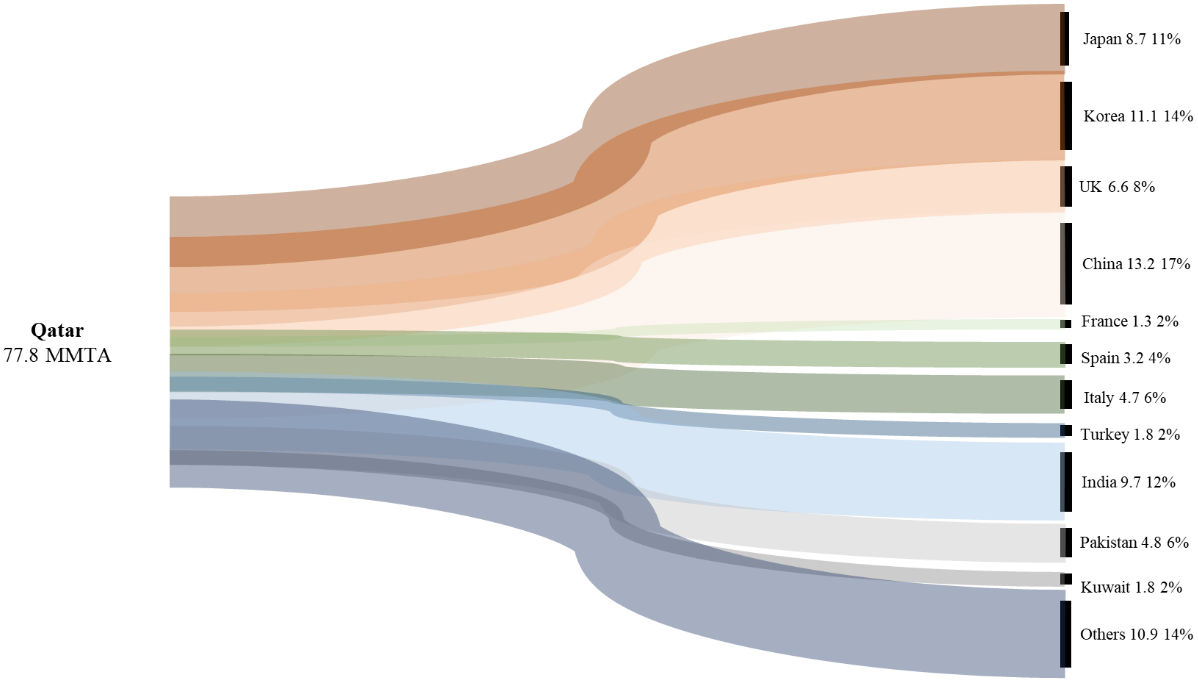


Figure 3. Qatar LNG's current production and the demand of the main 11 destinations.

Several air emissions accounting methods determine the current fuel consumption systems for LNG carrier operators. In this research, gathering the required data and specifying the assumptions are the first steps in calculating the emissions value for each vessel as follows:

1. The maritime path distance between Ras Laffan Port (Qatar) and other destinations is found from (Ports, 2020).
2. Emission evaluation for different fuel types is also available per vessel type: HFO and LNG.

The traditional vessels have two modes of operation. The first mode operates on a dual-mode system. The dual system is able to operate using HFO and LNG. Besides, the ship uses the boiled gases from the storage as fuel and other forms of fuel oil. Cargo BOG is an unavoidable phenomenon resulting in more vessels' internal pressure. The second mode is when the vessel is solely powered by LNG, with natural and enforced BOG depending on the carrier's requirements.

Each LNG fleet's capacity used in the research is displayed in Table 2:

Table 2. Q-Flex, Q-Max, and Conventional Carriers' Loading Capacity.

Carrier type	Unit	Maximum capacity
Q-Flex	m^3	212,660
Q-Max		260,680
Conventional type 1 & type 2		166,600

3.4.2 Total fuel used for Q-Flex and Q-Max carriers

Since LNG is not currently applicable for this type of vessel as a fuel, Q-Flex and Q-Max just utilize HFO fossil fuel forms. Equation (1) below gives the total LNG loading capacity estimate, A:

$$A = x_i\ (\mathrm{m}^3) \times \mathrm{B}\left(\frac{\mathrm{kJ}}{\mathrm{m}^3}\right) \text{ (K. Kim, Park, Roh, \& Chun, 2019)} \qquad (1)$$

where x_i denotes total LNG loaded and B denotes gross calorific value. This formula is used to determine the A. The BOG is assumed reliquefied for Q-Flex and Q-Max. Unit conversion is required for each type of vessel to have consistency and correct calculation. The computations in this research are established on a set of assumptions. The first is the count of days while loading the ship ($\boldsymbol{y_1}$) is considered as one day. Second, the steam process time ($\boldsymbol{y_2}$) is estimated using the following Equation (2):

$$y_2 = \frac{\text{Traveling distance, D}}{\text{Carrier speed}, S} \tag{2}$$

Third, anchorage duration (**y_3**) is assumed to be 1.5 days on average. Fourth, the overall canal period and passing time (**y_4**) is the total waiting (*WT*), and the passage period (*PP*) during each roundtrip is estimated to be around 1.8 days on average. Fifth and finally, the discharge duration (**y_5**) is assumed 2 days on average.

Several parameters have been assumed and considered to measure the quantity of fuel consumed for each point of the voyage days, as shown in Equations (3) and (4):

$$z_2 = \text{FCR}_{\text{steam process}} \times \text{RL} \tag{3}$$

$$z_4 = \text{FCR}_{\text{At Anchorage stage}} \times \text{RL} \tag{4}$$

RL represents the reliquification level, and *FCR* is the rate of fuel consumed during the steaming phase. The sum of days at each point is multiplied by the corresponding consumed quantity. Equation (5) below determined the total fuel consumed, *Q*, for the roundtrip scenario:

$$Q = \sum_{i=1,j=1}^{5} y_{i,j} z_{i,j} \tag{5}$$

where *i* denotes the laden path and *j* denotes the ballast path. z_1 denotes fuel consumed during vessel loading, z_2 denotes fuel consumed due to the steaming operation, z_3 denotes fuel consumed during the anchorage stage, z_4 denotes fuel consumption during the canal passing, and z_5 denotes fuel consumed during the discharging phase.

3.4.3 Total fuel used for Conventional type 1 & type 2 carriers

The similar computations from the prior section will be replicated for the vessel styles Conventional type 1 and type 2, with the addition of the gas boiled-off estimates, *BO*, that occur in these kinds of carriers. BOG is an unavoidable portion of *A* mentioned in Equation (1) earlier. Conventional type 1 could use both HFO and LNG as fuel. However, Conventional type 2 can use LNG as a fuel option only. Equations (6)-(8) are used to calculate it.

$$\mathrm{BO_{Natural}}\ (\mathrm{m}^3) = \text{Actual CC}\ (\mathrm{m}^3) \times \text{Conventional BOR}\ \left(\frac{\%}{\mathrm{day}}\right) \times [z_2 + z_3 + z_4] \tag{6}$$

$$\mathrm{BO_{Natural}}\ (\mathrm{t}) = \mathrm{BO}\ (\mathrm{m}^3) \times \text{conversion factor} \tag{7}$$

$$\mathrm{NOB_{Conventional\ mode\ 1}}(\mathrm{t}) = \mathrm{Q} - \mathrm{BO} \tag{8}$$

CC stands for conventional loading capability, *BOR* stands for boil-off rate, and *NOB* stands for the total net outbound bunker.

Turning towards the conventional carrier that can only use LNG for bunkering, both natural boil-off and forced boil-off are considered here. Equations (9) and (10) are used to measure the quantity:

$$\mathrm{BO}_{\mathrm{Forced}}(\mathrm{t}) = \mathrm{Q} - \mathrm{BO} \tag{9}$$

$$\mathrm{NOB_{Conventional\ mode\ 2}}\ (\mathrm{t}) = \mathrm{BO_{Total}} = \mathrm{BO_{Natural}} + \mathrm{BO}_{\mathrm{Forced}} \tag{10}$$

Using Equation (11), the total LNG boil-off, BO_{Total}, will be needed to measure the emissions. LNG density is multiplied by the summation of both $BO_{Natural}$ and BO_{Forced}.

$$\mathrm{BO}_{\mathrm{Total}}\ (\mathrm{t}) = [(\mathrm{BO_{Natural}}(\mathrm{m}^3) + \mathrm{BO}_{\mathrm{Forced}}\ (\mathrm{m}^3)] \times \text{LNG Density} \tag{11}$$

For every ship type, the air emissions calculation methodology is assessed in the model following Figure 4. Emission factors for global warming emissions equivalent (CO_2, CH_4, and N_2O), photochemical ozone formation equivalent (NO_x and NMVOC), and fine particulate matter formation equivalent (NH_3, NO_x, SO_2, and $PM_{2.5}$) are considered.

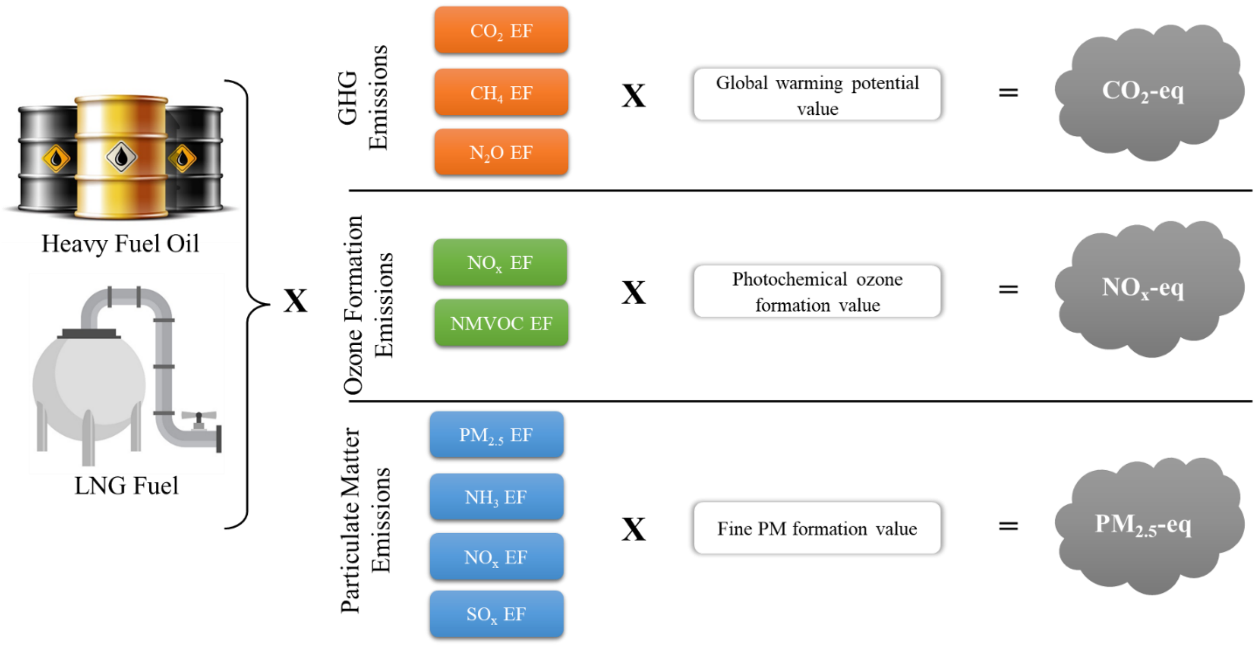


Figure 4. The calculation methodology for CO_2-eq, NO_x-eq, and $PM_{2.5}$-eq.

3.4.4 Emission factors

The amount of fuel and air emissions vary based on the fuel's nature and content. According to Cooper and Gustafsson (2004b), researchers determined emission factors for a category of pollutants released from various carriers. Table 3 illustrate the carrier type, engine type, and fuel type used by Cooper and Gustafsson to establish the emissions factors:

Table 3. Carrier Type, Engine Type, and Fuel Type.

Carrier type	Carrier type	Propulsion type	Fuel type
Q-Flex	Membrane	Slow-speed diesel (SSD)	HFO
Q-Max	Membrane	Two-stroke SSD	
Conventional type 1	Moss	Dual Fuel Diesel Electric (FDE) and Triple FDE	HFO/ LNG
Conventional type 2	Moss	Steam turbines	LNG

The emissions generated from the shipping division are determined by the amount and composition of a specific component in the fuel, such as sulfur, nitrogen, etc., during the combustion procedure through the transportation of LNG products. Accordingly, precise emissions calculations must be made by considering the sum of fuel burned and the latest emission factors to estimate the midpoint and endpoint impacts. Equation (12) presents the calculation way considered:

$$AEF = \sum EF \times FF \tag{12}$$

where *AEF* is the air emission footprint determined, *EF* is the emission factor of the air pollutant, and *FF* is the fossil fuel consumed trip-wise. The fuel's compositions and their emissions factors assumed constants according to the published research by Cooper and Gustafsson (2004b).

3.4.5 Annual air emissions footprint

The annual air emissions footprint is calculated based on each destination's annual LNG demand. First, the yearly LNG product is shipped to be converted into volume units per Equation (13).

$$Annual\ Volume\ (m^3\ LNG) = \frac{Annual\ Demand\ (Ton\ LNG)}{\frac{1\ (Ton\ LNG)}{1.293\ (m^3 LNG)}} \tag{13}$$

Second, the annual volume is divided into each carrier's safe loading volume to estimate the annual number of roundtrips. See Equation (13):

$$Annual\ Number\ of\ Roundtrips = \frac{Annual\ LNG\ Demand\ (m^3)}{Carrier\ Capcity\ (m^3)} \tag{14}$$

Third and finally, Equation (15) explains the annual air emission footprint estimation by multiplying the yearly number of roundtrips by the total air emissions per roundtrip.

$$\begin{aligned} &Annual\ Air\ Emissions\ Footprint \\ &\qquad = Annual\ Number\ of\ Roundtrips \times AEF \end{aligned} \tag{15}$$

3.4.6 Midpoint to endpoint

Midpoint and endpoint LCA approaches look at different stages in the cause-effect chain to measure the effects. The endpoint analysis examines the environmental effects down the road as the final impact. On the other hand, a midpoint approach considers the impact earlier in the cause-and-effect chain before the endpoint is extended. The effect on human wellness, ecology quality, and resources reduction are typically seen as endpoint outcomes.

In this research, the calculated air emissions footprints of LNG trade between 11 different destinations of Qatar's LNG main customers have been used to estimate the emission equivalence of CO_2, NO_x, and $PM_{2.5}$ global potential in human health. The conversion of Global Warming CO_2-eq, Ozone Formation NO_x-eq, and Particulate Matter $PM_{2.5}$-eq to endpoint human health equivalence is achieved following Equation (16), where the midpoint hierarchic is calculated first.

The hierarchic scenario uses a 100-year time horizon to estimate the impacts using the ReCiPe database. Then the Human Health impact is calculated based on the CFs. The ReCiPe 2016 model is utilized in this study to measure the human health equivalence. The ReCiPe model can estimate the midpoint and endpoint values meaning to detect the impact on human health and provide the decision-maker with more detailed knowledge in the intervention to minimize human health effects (Huijbregts et al., 2017).

$$Endpoint\_HH_{Hierarchic} = Midpoint_{Hierarchic} \times CF_{Hierarchic} \tag{16}$$

Where $Endpoint\_HH_{Hierarchic}$ is the human health impact, $Midpoint_{Hierarchic}$ are the CO_2-eq, $PM_{2.5}$, and NO_x-eq values of the emitted substances and $CF_{Hierarchic}$ are the characterization factors defined in Table 4. The conversion of global warming potential (CO_2-eq), fine particulate matter formation ($PM_{2.5}$-eq), and Photochemical ozone formation (NO_x-eq) to human health equivalence are achieved following Equation (16), where the CO_2-eq,

$PM_{2.5}$-eq, and NO_x-eq are calculated first for emitted substances. Then the Human Health impact is determined based on constant factors developed by ReCiPe 2016. These factors are named characterization factors and are defined in Table 4. The calculation is done based on the annual cumulative emissions estimated following Aseel, Al-Yafei, et al. (2021b) approach while accounting for the yearly demand and delivery by LNG fleets, distance, type of vessel, vessel engine design and performance, and finally on the fuel type.

Table 4. Midpoint to Endpoint Human Health CFs.

Midpoint to endpoint human health	Unit	CF (Hierarchic)
Global worming	DALY/kg CO_2-eq.	9.28E-07
Fine particulate matter formation	DALY/kg $PM_{2.5}$-eq.	6.29E-04
Photochemical ozone formation	DALY/kg NO_x-eq.	9.10E-07

From the above table, it is clear that the Hierarchic CF for the $PM_{2.5}$-eq is more than the rest by a factor of 1,000 difference which indicates a more serious impact when particulate matter exists in the atmosphere and can cause much more serious human health problems.

3.5. Sustainability impact assessment tool

Following the air emissions and human health impact assessment, more LCI has been added in addition to the economic indicators to achieve the LCSA evaluation of LNG maritime transport and select the best alternative among LNG carriers from a sustainability perspective. Gathering data and laying out the assumptions that will be used is the first step. After estimating fuel consumption per carrier and selecting a fuel category, the next process uses the relevant emissions characteristics to convert the total energy combusted into halfway emissions. The emission factors used in the recommended technique were reported by Cooper and Gustafsson (2004a) (see Figure 4). The majority of the energy used in LNG maritime transport operations comes from fuel consumption for transportation purposes or the use of BOG. The land used for the LNG carrier is assumed to be the length multiplied by the width of the carrier and then multiplied by the annual number of roundtrips from Qatar to the 11 destinations to estimate the occupied area through the year. The size of the carriers is found from (Huan, Hongjun, Wei, & Guoqiang, 2019). The expulsion of ocean seawater and return for ballast trip balancing is assumed to be 15% of the voyage volume multiplied by the annual number of roundtrips for each measurement, and the utility water used in the LNG carrier for domestic use, boiler feed water, fire incident response, and so on is assumed to be 40 m^3 daily.

For the social part, the approximate consequence of a substance on human health is calculated by multiplying the ReCiPe 2016 CFs with the amount of substance emitted to the atmosphere following Equation (16). A subject matter expert (SME) in LNG maritime transport provides information on the estimated number of full-time jobs, remuneration, and total man-hours. Based on annual LNG demand, total taxes are expected to equal 15% of total profit from LNG trade between Qatar and its main customers.

In terms of economics, the capital cost is the cost of the LNG carrier's equipment building, installation, and commissioning and is provided with approximate values by an LNG shipping expert. Furthermore, the cost of gasoline for the roundtrip throughout the course of the calendar year, based on customer’s demand, is examined and counted. The LNG boil-off is considered 0.15% of the total loaded quantity. The cost of the boil-off is computed as per the following Equation (17):

$$LNG\ boil-off\ cost = LNG\ loaded\ quantity\ (MMBtu) \times 0.15\% \times LNG\ price\ (USD\ /MMBtu) \tag{17}$$

The charter rate and cost were calculated using (Rogers, 2018). The charter rates are expected to be 47,125 and 79,342 dollars per day for steam turbine driven and slow speed diesel driven, respectively. The following Equations (18) and (19) are used to calculate the charter cost and port cost:

$$Charter\ cost = Roundtrip\ voyage\ days\ (days) \times Charter\ rate\ (USD/days) \tag{18}$$

$$Port\ cost = Port\ days \times 100{,}000\ USD/day \tag{19}$$

The Suez Canal is the sole canal evaluated in this study, with a cost of 400,000 USD per LNG ship anticipated. Fees for agents and brokers, as well as insurance, can be assumed to be as per the following Equations (20):

$$\begin{aligned} &Agent, broker, amd\ insurance\ cost \\ &\qquad = 2\%\ of\ Charter\ cost + 2{,}600\ USD/day\ for\ inusratnce \end{aligned} \tag{20}$$

The total cost is calculated following Equations (21):

$$\begin{aligned} Total\ cost = {} & Charter\ cost + Fuel\ cost + Canal\ cost + Port\ cost \\ & + Agent, broker, amd\ insurance\ cost \end{aligned} \tag{21}$$

Salvage value (end of life) is calculated using the formula given below in Equation (22):

$$\begin{aligned} &Salvage\ value \\ &\qquad = Purchase\ price\ of\ the\ engineering\ machinery \\ &\qquad - (Depreciation \times Useful\ life) \end{aligned} \tag{22}$$

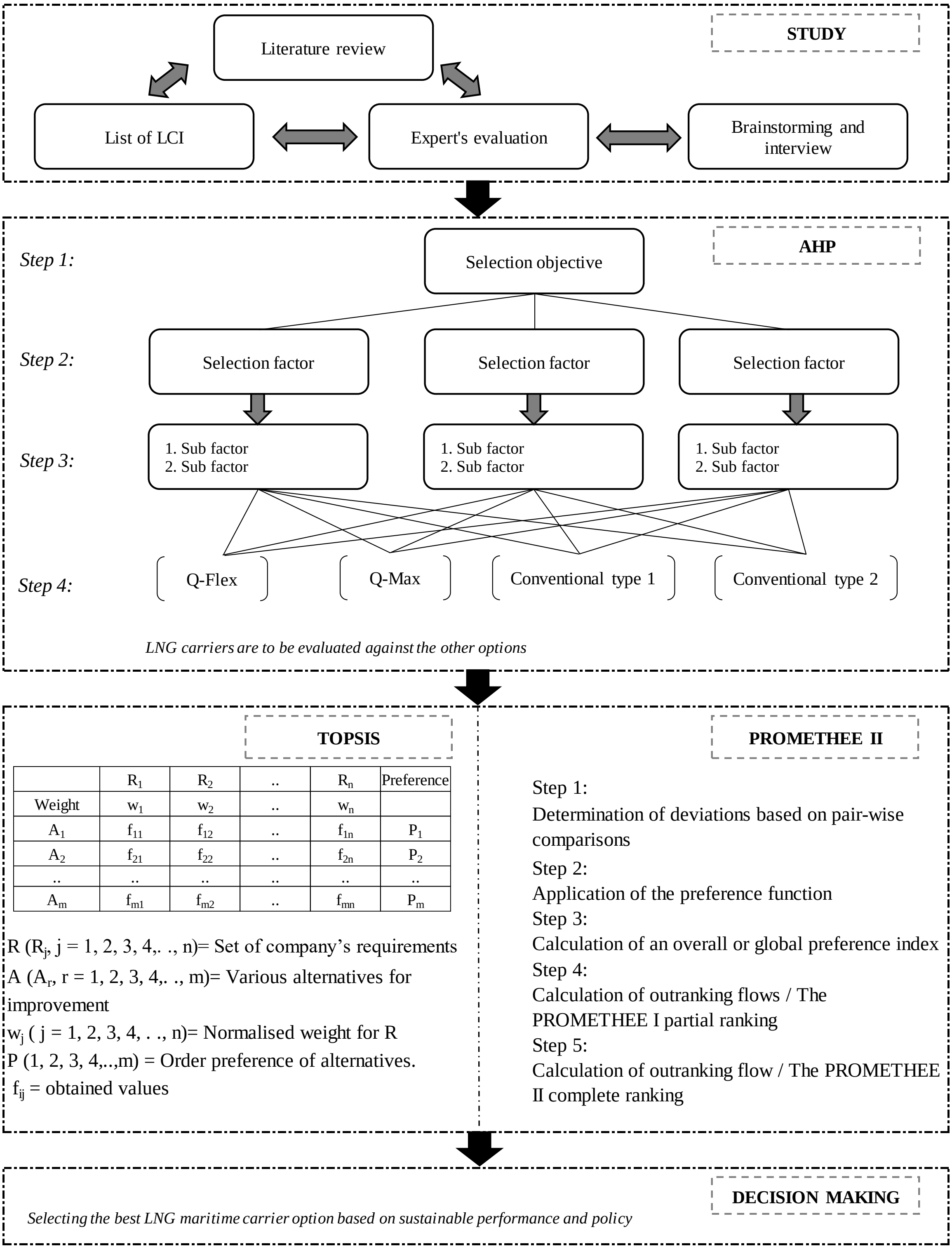
The profit (gross operating surplus) is counted as per Equation (23):

$$\begin{aligned} &Profit\ (Gross\ operating\ surplus) \\ &\quad = (LNG\ price \times Cutomer\ annual\ demand) - Total\ cost \end{aligned} \tag{23}$$

3.6. Interpretation: Selecting the most sustainable option

Two main approaches, LCSA and MCDM, are used to introduce an integrated sustainability assessment framework. This proposed framework is mainly established for selecting the best alternative LNG maritime transport carrier. Sixteen macro-level indicators related to environment, economy, and society have been incorporated into the model. The proposed model is designed to compare four-LNG carriers of maritime transport operations worldwide using two types of fuels. The proposed LCSA model addresses the sustainability assessment from a decision-making perspective using AHP, TOPSIS, and PROMETHEE II methods. The AHP method is applied to focus on uncertainties, specialist assessments, and the determination of weights. After determining the weights, the alternative LNG maritime transport carrier options are ranked using the TOPSIS and PROMETHEE II methods separately, considering the quantified micro-level sustainability impacts.

The research has included integrating AHP-TOPSIS and AHP-PROMETHEE II methodologies to assist the benchmarking process, as illustrated in Figure 5. Step 1 is preparing the main information for the preliminary study, including the literature review, data gathering, and meeting the experts. Step 2 is to perform the AHP technique as part of the performance evaluation and judgment. Step 3 is to adopt the TOPSIS and PROMETHEE II separately to select the best alternative. Step 4 is choosing the best and most sustainable option based on the obtained results.



LNG carriers are to be evaluated against the other options

	R_1	R_2	..	R_n	Preference
Weight	w_1	w_2	..	w_n	
A_1	f_{11}	f_{12}	..	f_{1n}	P_1
A_2	f_{21}	f_{22}	..	f_{2n}	P_2
..	..	..	..	..	..
A_m	f_{m1}	f_{m2}	..	f_{mn}	P_m

R (R_j, j = 1, 2, 3, 4,. ., n)= Set of company’s requirements
A (A_r, r = 1, 2, 3, 4,. ., m)= Various alternatives for improvement
w_j (j = 1, 2, 3, 4, . ., n)= Normalised weight for R
P (1, 2, 3, 4,..,m) = Order preference of alternatives.
f_{ij} = obtained values

Step 1:
Determination of deviations based on pair-wise comparisons
Step 2:
Application of the preference function
Step 3:
Calculation of an overall or global preference index
Step 4:
Calculation of outranking flows / The PROMETHEE I partial ranking
Step 5:
Calculation of outranking flow / The PROMETHEE II complete ranking

Selecting the best LNG maritime carrier option based on sustainable performance and policy

Figure 5. A general structure for evaluating alternatives through AHP, TOPSIS, and PROMETHEE II methods.

3.6.1 AHP

The AHP is a technique towards achieving the best alternative in the decision-making process (Saaty, 1994). In this case, AHP evaluates the LNG maritime transport carrier performance level from a sustainability perspective in this phase. The hierarchy of AHP is shown in Figure 6 for this research case. The weights are applied to all the factors inter and intra hierarchy. The AHP method is organized in such a way that it sets the priority but hierarchy level. As per the AHP process, a matrix is to be developed to determine the weights and relative comparison and estimate the consistency for comparing the alternatives.

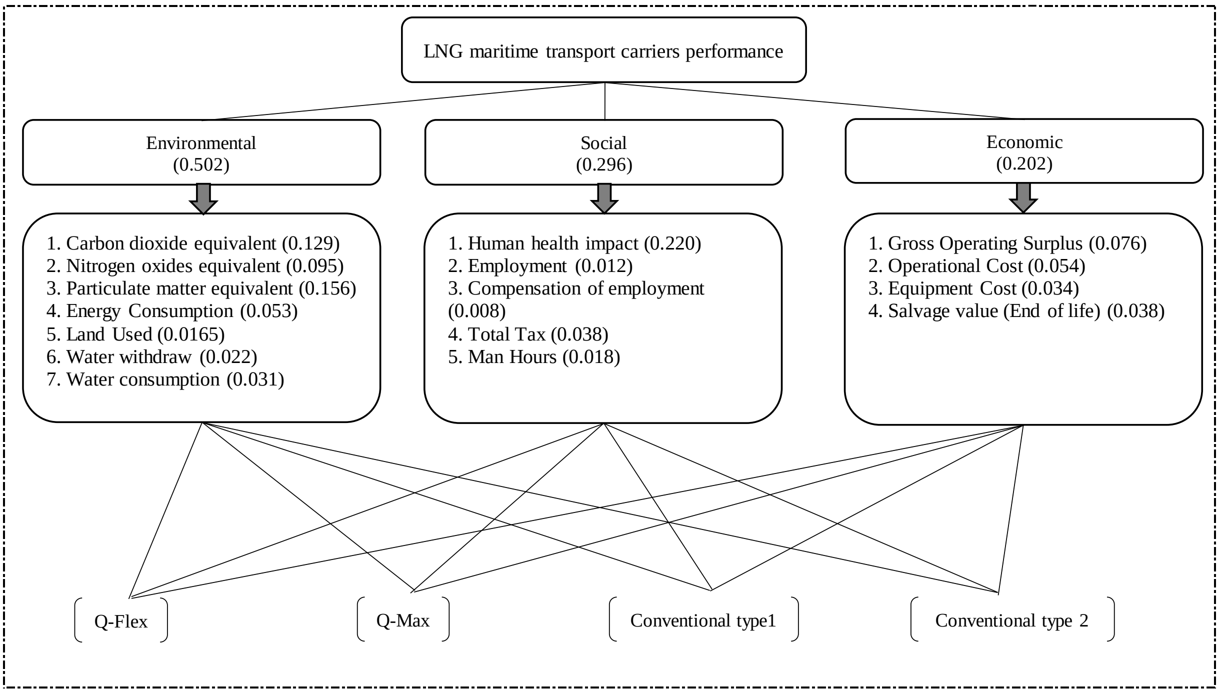


Figure 6. Factors and sub-factors to evaluate the alternatives following the AHP method.

3.6.2 Integrated AHP and TOPSIS method

The integrated AHP-TOPSIS method has been used in the literature for several cases as part of the decision-making practice (Joshi, Banwet, & Shankar, 2011). Hsieh, Chin, and

Wu (2006) followed the integrated method in their research as it was more precise than others and considered the weights of desirable and non-desirable criteria in the ranking. The detailed method of AHP and TOPSIS with the relative equations are aligned with Aboushaqrah et al. (2021) and its supplementary information file.

3.6.3 Integrated AHP and PROMETHEE II method

PROMETHEE is an outranking method for a finite set of alternatives (Mareschal, Brans, & Vincke, 1984). It is another well know decision-making tool. It simply defines how each alternative is relative to the other based on the evaluation in a unique way. The PROMETHEE method is based on the calculation of positive flow (φ^+) and negative flow (φ^-) for each alternative according to the given weight for each criterion. The higher the positive flow (φ^+), the better the alternative. The PROMETHEE II complete ranking is based on a net outranking flow value (φ) calculation that represents the balance between the positive and negative outranking flows. Bogdanovic, Nikolic, and Ilic (2012) illustrated a detailed explanation of the research method.

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Air emissions and human health impact results

Following the defined methodology, the entire quantity of CO_2-eq, NO_x-eq, and $PM_{2.5}$-eq for each carrier type is calculated using Excel. The equivalent footprint values vary from one vessel/ fuel to another. The results are discussed on two scales; the midpoint and endpoint values and the overall human health impact.

4.1.1. GHG emissions

The results of the GHG emissions correlated with the type of fuel used and the supply destination are summarized in Figure 7 for both the annual and per roundtrip emissions. Kuwait has demonstrated the lowest CO_2-eq emissions for both the yearly and per roundtrip values, given the short destination from the origin (Qatar). Whereas Japan has been shown the highest per roundtrip CO_2-eq emissions, China has indicated the highest annual CO_2-eq emissions. Conventional type 2 showed the lowest per roundtrip CO_2-eq emissions in terms of fuel type, followed by Q-Max, Q-Flex, and finally Conventional type 1. However, the annual CO_2-eq emissions demonstrated different results, with Q-Max having the lowest CO_2-eq yearly emissions, followed by Q-Flex, Conventional type 2, and Conventional type 1. These results indicated the general trend with some exceptions for the case of Kuwait. Hence, the results can be proposed to use Q-Max or Q-Flex fuel types for short distances trips. Whereas, for long distances, it is better to use Q-Max or Conventional type 2.

Moreover, the annual results are strongly influenced by the number of trips per year. As future alternatives, using larger fleet capacities for Conventional type 1 and type 2 fuel types can reduce the required number of roundtrips and the associated CO_2 emissions when compared with the existing Q-Flex and Q-Max carriers. For the old carriers, further technical solutions with cost-benefit analysis could be taken to enhance the existing fleet to meet the environmental limits by IMO and promote the overall emission reduction.

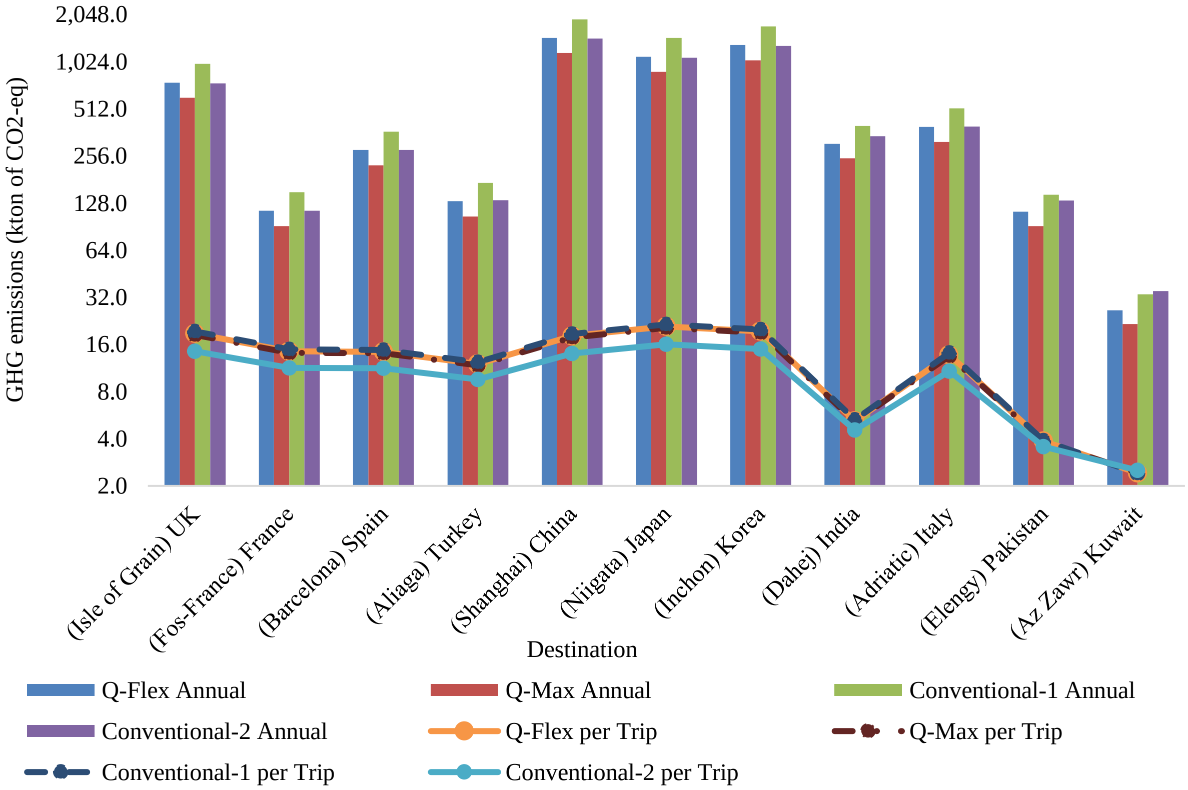


Figure 7. CO_2-eq emission results for the roundtrip and annual.

4.1.2. Ozone formation emissions

Similarly, the ozone formation emissions results have revealed differences based on the type of fuel used and the supply destination, as summarized in Figure 8. Kuwait has demonstrated the lowest NO_x-eq emissions for both the annual and per roundtrip values, given the short destination from the origin (Qatar). On the other hand, Japan has demonstrated the highest per roundtrip NO_x-eq emissions, and China has indicated the highest annual NO_x-eq emissions. Conventional type 2 indicated the lowest per roundtrip NO_x-eq emissions in terms of fuel type, followed by Conventional type 1, Q-Max, and finally Q-Flex. However, the annual NO_x-eq emissions which are influenced by the number of trips yearly, demonstrated different results, with Conventional type 2 having the lowest NO_x-eq yearly emissions, followed by Conventional type 1, Q-Max, and Q-Flex. These results indicated the general trend with some exceptions for the case of Kuwait as it has the shortest traveling distance. Hence, it can be advised to use Conventional type 1 fuel types for short-distance trips from the findings. Whereas, for long distances, it is better to use Conventional type 2.

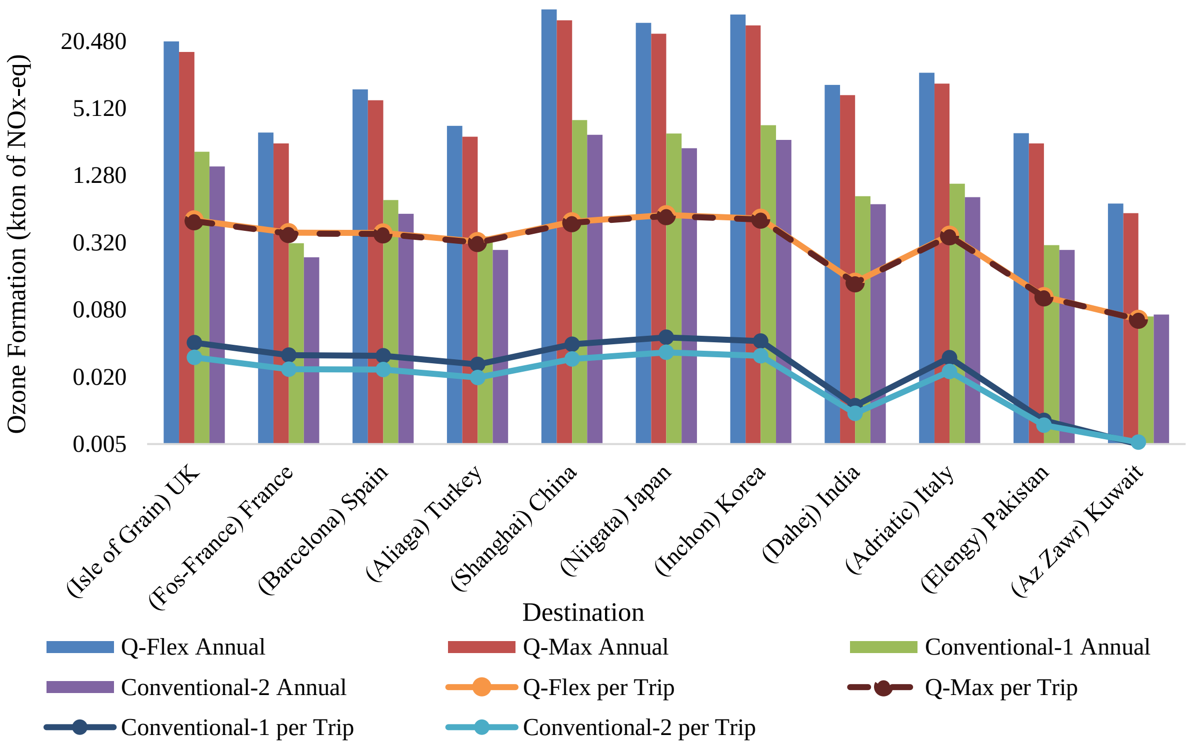


Figure 8. NO_x-eq emission results for the roundtrip and annual.

4.1.3. Particulate matter emissions

The third type of emissions results, particulate matter, as illustrated in Figure 9, have revealed more distinguishable observations as per the type of fuels used and the supply destination. Kuwait has demonstrated the lowest $PM_{2.5}$-eq emissions for both the annual and per roundtrip values, given the short destination from the origin (Qatar). On the other hand, Japan has demonstrated the highest per roundtrip $PM_{2.5}$-eq emissions, and China has indicated the highest annual $PM_{2.5}$-eq emissions. Conventional type 2 indicated the lowest per roundtrip $PM_{2.5}$-eq emissions in terms of fuel type, followed by Conventional type 1, Q-Max, and finally Q-Flex. However, the annual $PM_{2.5}$-eq emissions demonstrated different results, with Conventional type 2 having the lowest $PM_{2.5}$-eq yearly emissions, followed by Conventional type 1, Q-Max, and Q-Flex. These results indicated the general trend for all the destinations, and the distance plays a significant factor in the variation of emissions. Hence, from the results, it can be suggested to use Conventional type 2 fuel types for short and long distances associated with lower $PM_{2.5}$-eq emissions.

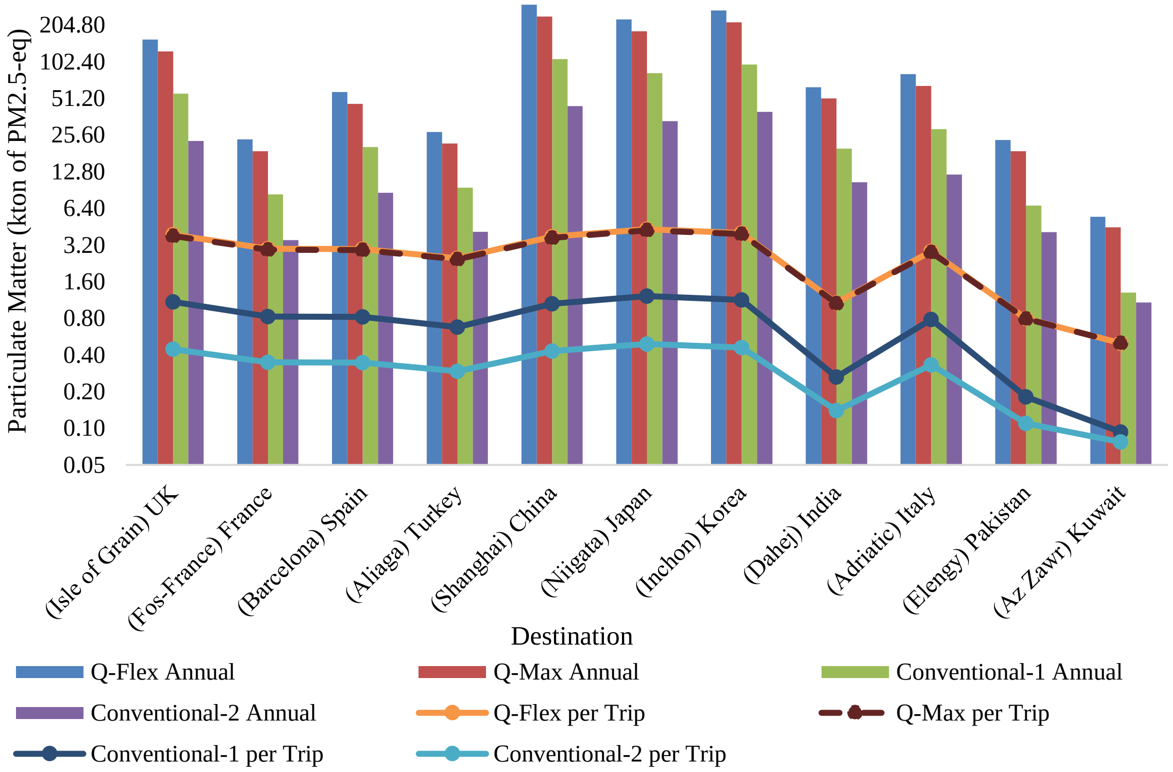


Figure 9. PM$_{2.5}$-eq emission results for the roundtrip and annual.

4.1.4. *Overall social human health impact*

The midpoint and endpoint emissions results have been converted to the human health impact potential associated with the type of fuels used and the supply destination, as illustrated in Figure 10. Figure 10 represents the annual social human health impact per the unit of LNG shipped by each type of carrier. The figure provides the calculated factor that can be used to measure the daily effects on human health related to LNG shipping through the sea. The factors consider the distance and number of trips annually and the annual demand per location. Moreover, these factors can help researchers estimate the annual social human health impact of air emissions related to LNG shipping to these 11 destinations. Also, it provides guidance on the carrier type that can be utilized for shipping to each destination and transportation planning to satisfy customer needs and reduce the possible air emissions and perhaps the social human health impact.

The results indicate Kuwait as the lowest destination associated with human health impact for annual calculation mode given the short destination from the origin (Qatar). Japan has demonstrated the highest yearly human health impact. In terms of fuel type, Conventional type 2 indicated the lowest human health impact for the annual mode of calculations, followed by Conventional type 1, Q-Max, and finally Q-Flex. The analysis method for the yearly mode demonstrated discrepancies in the relative human health impact due to the variation of the annual LNG demand by each destination and not only per the trip needs. The results show the importance of using a relatively cleaner fuel type like Conventional type 2 to reduce LNG maritime transportation's human health impact.

This research faced several limitations that are directly proportional to the final estimated results for the air emissions quantification and human health daily losses of life. Emission factors published by (Cooper & Gustafsson) in 2004 may require a reassessment to verify the applicability for the current time and technology development. Moreover, there is a slight uncertainty associated with the assumed numbers of LNG loading and unloading time, carrier’s steam process time, canal waiting time, and other related parameters affecting the final air emission and human health impact estimation. This uncertainty is non-avoided due to the facts of dynamic changes in the shipping process, such as the delivery and traveling process, canal passing, and waiting time.

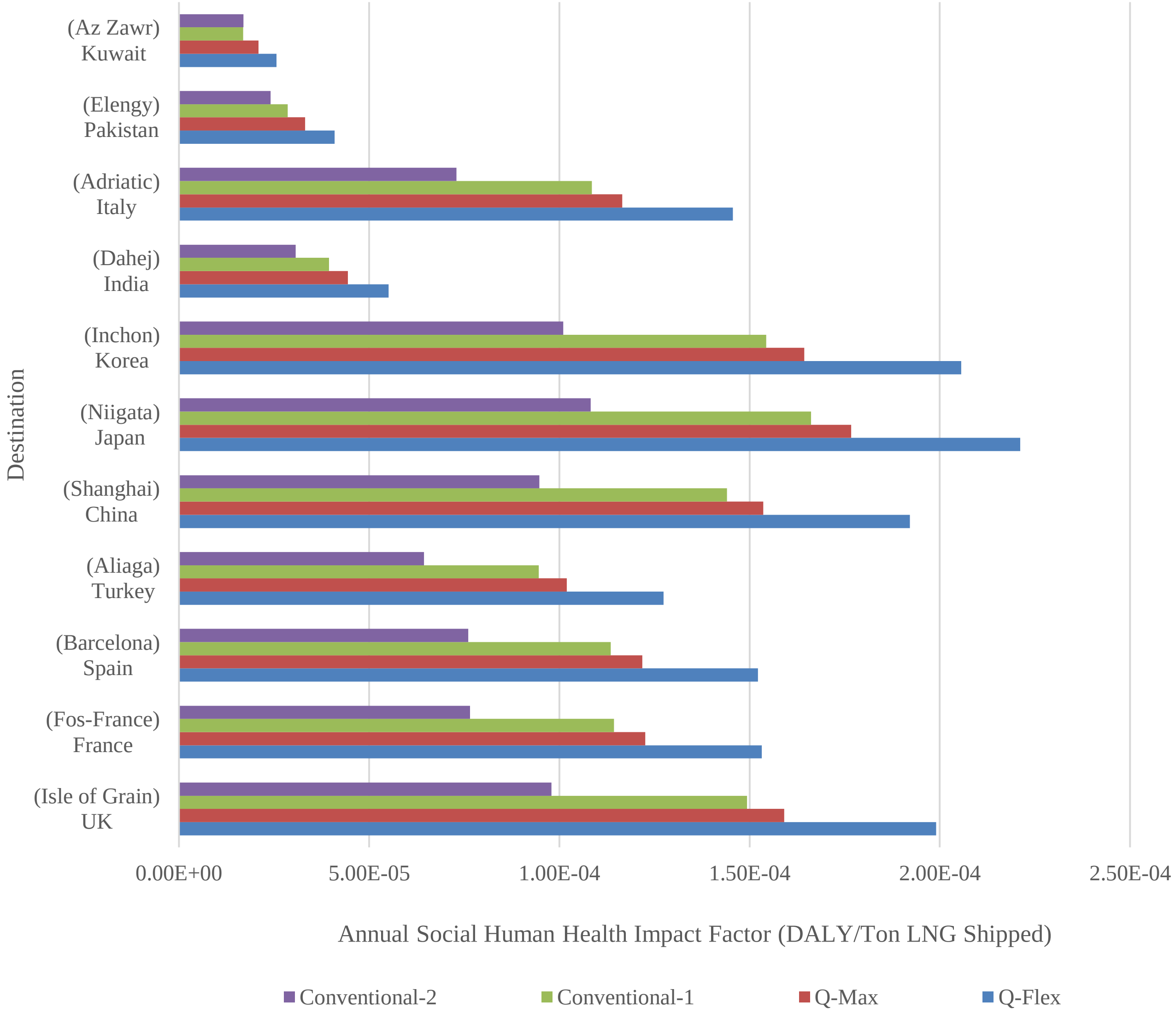


Figure 10. Overall social human health impact factors while accounting for annual emissions.

Understandably, there is a significant need for LNG in most countries to maintain the development, energy needs, and human needs worldwide. However, this need is expected to continue due to the absolute requirement for clean energy sources. Therefore, it is more feasible to explore the engineering controls such as electrical carriers, engine overhauling, and LNG pipeline transport for closer countries with a long-term agreement. Moreover, the administrative controls such as improving the shipping route planning, synergies in LNG pipeline networks, etc., to reduce the overall emissions and human health impact are essential to be discussed, planned, and executed by management.

As the model used in this research was established based on actual ship transits from departure port to 11 destinations, it is recommended for future researchers to use these research results for further comparison and validation. It would be worth validating this research with other locations in the region and worldwide, investigating the impact of atmospheric pollution and human health while using a mix of carrier types, and studying the most impactful ports and cities due to the LNG loading and unloading activities.

4.2. LCSA results

4.2.1. LCA results

The environmental results from the comparative assessment can be seen in Table 5. The GHG emissions are proportional to the fuel type used in each carrier and how far each destination is from the export location (in this case, Qatar is the exporter). Kuwait has proved the lowest GHG (as CO_2-eq) emissions throughout the year using Q-Max carrier while China has been demonstrated the highest using Conventional type 1 carrier with 0.02 and 2 million Ton CO_2-eq, respectively. For the ozone formation emissions (as NO_x-eq), Kuwait has shown the lowest NO_x-eq emissions throughout the year using the Conventional type 1 carrier by emitting 70 Ton NO_x-eq. On the other hand, China has demonstrated the highest using Q-Flex carrier with approximately 39 thousand Ton NO_x-eq emission annually. Regarding the particulate matter emissions (as $PM_{2.5}$-eq), Kuwait has been the lowest $PM_{2.5}$-eq emissions throughout the year using Conventional type 2 carriers, while again, China has been demonstrated the highest using Q-Flex carrier with 11 and 3,008 Ton of $PM_{2.5}$-eq emission, respectively.

Energy consumption was selected as an environmental indicator for the best LNG carrier performance. Kuwait has shown the lowest energy consumption using Q-Max carrier with 281 TJ per year. At the same time, China has demonstrated the highest using Conventional type 1 carrier with 24 thousand TJ per year. For the land used and water consumption, China represents the highest land used with 2,780 Km^2 using Conventional type 1 carrier and around 176 Km^3 of water consumption using Conventional type 1 and Conventional type 2 carriers. On the other hand, the lowest impact for both indicators was found in France and Kuwait using Q-Max carriers with 245 Km^2 and 5.20 Km^3, respectively. Finally, the water withdrawal (which is mainly seawater) is found to be the highest for China and lowest for France. The results of all carriers' water withdrawal usage were found to be the same due to the annual number of trips which are based on the yearly demand for LNG products.

4.2.2. SLCA results

The four LNG maritime carriers' social assessment results for 11 different destinations have been considered. The results of human health impact, employment, compensation of employment, total tax, and total man-hours are available in Table 6. The lowest human health impact was found while using the Conventional type 1 carrier for Qatar-Kuwait trade with 39 DALY, and Qatar-China trade found the highest impact with 3,279 DALY using the Q-Flex carrier. However, China has shown outstanding employment and employment compensation performance with 301 full-time employees (FTE) and 65 MUSD using Conventional type 1 and Conventional type 2 carriers, respectively. On the other hand, Kuwait has proven the lowest by having 14 FTE and 3 MUSD using the same carriers yearly.

The total tax is determined as part of the assessment for all carriers. However, it was considered 15% of the gross operating surplus. China significantly contributes to the total tax due to the high demand for LNG products with 3,534 MUSD. On the other hand, France found the lowest total tax with 348 MUSD. For the total man-hours, China represents the highest number of working hours with 1.3 million hrs operating the Q-Flex carrier, and Kuwait shows the lowest man-hours with 50 thousand man-hours yearly using both Conventional type 1 and Conventional type 2 LNG maritime carriers.

4.2.3. LCC results

The life cycle costing results for gross operating surplus, operational cost, equipment cost, and salvage value can be seen in Table 7 for each destination. The LNG carriers' highest gross operating surplus and operational cost are from the Qatar-China trade, with 23,560 MUSD and 660 MUSD for Conventional type 1 carriers, respectively. The lowest among the above indicators are found in the Qatar-France trade for the gross operating surplus with 2,320 MUSD and Kuwait with 19 MUSD for Conventional type 1 carrier. Furthermore, the highest equipment cost and salvage value are also for the Qatar-China case with 2,531 MUSD and 633 MUSD for Conventional type 1, respectively. Nevertheless, the lowest among the above indicators are found in Qatar-Kuwait for both Conventional type 1 and type 2 carriers with 117 MUSD and 30 MUSD, respectively.

Table 5. Environmental LCA Results of the Study.

Destination	Carrier type	CO$_2$-eq. (kTon)	NO$_x$-eq. (kTon)	PM$_{2.5}$-eq. (kTon)	Energy (PJ)	Land used (Mm^2)	Water withdraw (km^3)	Water consumption (km^3)
(Isle of Grain) UK	Q-Flex	754.29	20.43	1.56	9.82	1.26	1,306.19	70.82
	Q-Max	602.90	16.33	1.25	7.85	1.24	1,306.19	57.77
	Conv-1	991.88	2.08	0.56	12.24	1.39	1,306.19	90.40
	Conv-2	744.22	1.54	0.23	8.75	1.39	1,306.19	90.40
(Fos-France) France	Q-Flex	114.38	3.10	0.24	1.49	0.25	257.28	11.48
	Q-Max	91.51	2.48	0.19	1.19	0.24	257.28	9.36
	Conv-1	150.15	0.32	0.08	1.85	0.27	257.28	14.65
	Conv-2	114.56	0.24	0.04	1.35	0.27	257.28	14.65
(Barcelona) Spain	Q-Flex	279.61	7.57	0.58	3.64	0.61	633.31	28.11
	Q-Max	223.71	6.06	0.46	2.91	0.60	633.31	22.93
	Conv-1	367.05	0.77	0.20	4.52	0.67	633.31	35.89
	Conv-2	280.17	0.58	0.09	3.29	0.67	633.31	35.89
(Aliaga) Turkey	Q-Flex	131.62	3.56	0.27	1.71	0.34	356.23	13.96
	Q-Max	105.39	2.85	0.22	1.37	0.34	356.23	11.39
	Conv-1	172.53	0.36	0.09	2.12	0.38	356.23	17.82
	Conv-2	133.55	0.28	0.04	1.57	0.38	356.23	17.82
(Shanghai) China	Q-Flex	1,456.17	39.44	3.01	18.95	2.53	2,612.39	137.85
	Q-Max	1,164.04	31.53	2.40	15.15	2.48	2,612.39	112.45
	Conv-1	1,914.45	4.02	1.08	23.62	2.78	2,612.39	175.96
	Conv-2	1,439.34	2.97	0.44	16.92	2.78	2,612.39	175.96
(Niigata) Japan	Q-Flex	1,104.48	29.91	2.28	14.37	1.67	1,721.80	101.31
	Q-Max	882.52	23.90	1.82	11.48	1.64	1,721.80	82.65
	Conv-1	1,453.17	3.05	0.82	17.94	1.83	1,721.80	129.32
	Conv-2	1,084.23	2.24	0.33	12.74	1.83	1,721.80	129.32

Destination	Carrier type	CO_2-eq. (kTon)	NO_x-eq. (kTon)	$PM_{2.5}$-eq. (kTon)	Energy (PJ)	Land used (Mm^2)	Water withdraw (km^3)	Water consumption (km^3)
(Inchon) Korea	Q-Flex	1,310.53	35.49	2.71	17.05	2.13	2,196.78	122.13
	Q-Max	1,047.39	28.37	2.16	13.63	2.09	2,196.78	99.63
	Conv-1	1,723.62	3.62	0.97	21.28	2.34	2,196.78	155.90
	Conv-2	1,290.93	2.66	0.40	15.17	2.34	2,196.78	155.90
(Dahej) India	Q-Flex	306.94	8.31	0.63	3.99	1.86	1,919.71	46.15
	Q-Max	247.36	6.70	0.51	3.22	1.83	1,919.71	37.65
	Conv-1	397.71	0.83	0.20	4.85	2.04	1,919.71	58.91
	Conv-2	342.81	0.71	0.11	4.03	2.04	1,919.71	58.91
(Adriatic) Italy	Q-Flex	392.92	10.64	0.81	5.11	0.90	930.17	40.01
	Q-Max	314.42	8.52	0.65	4.09	0.88	930.17	32.64
	Conv-1	515.62	1.08	0.29	6.35	0.99	930.17	51.07
	Conv-2	394.86	0.82	0.12	4.64	0.99	930.17	51.07
(Elengy) Pakistan	Q-Flex	112.85	3.06	0.23	1.47	0.92	949.96	20.01
	Q-Max	91.30	2.47	0.19	1.19	0.90	949.96	16.33
	Conv-1	145.18	0.30	0.07	1.76	1.01	949.96	25.55
	Conv-2	133.07	0.27	0.04	1.56	1.01	949.96	25.55
(Az Zawr) Kuwait	Q-Flex	26.48	0.72	0.05	0.34	0.34	356.23	6.36
	Q-Max	21.62	0.59	0.04	0.28	0.34	356.23	5.19
	Conv-1	33.50	0.07	0.01	0.40	0.38	356.23	8.12
	Conv-2	35.07	0.07	0.01	0.41	0.38	356.23	8.12

Table 6. SLCA Results of the Study.

Destination	Carrier type	Human health impact (DALY)	Employment (Person)	Compensation of employment (MUSD)	Total tax (MUSD)	Man-hours (1000 hrs)
(Isle of Grain) UK	Q-Flex	1,698.66	146	26.19	1,767.06	668.68
	Q-Max	1,357.73	119	21.37	1,767.06	427.35
	Conv-1	1,274.16	155	33.43	1,767.06	557.23
	Conv-2	835.68	155	33.43	1,767.06	557.23
(Fos-France) France	Q-Flex	257.58	24	4.25	348.06	108.38
	Q-Max	206.08	19	3.46	348.06	69.26
	Conv-1	192.18	25	5.42	348.06	90.31
	Conv-2	128.63	25	5.42	348.06	90.31
(Barcelona) Spain	Q-Flex	629.68	58	10.40	856.76	265.45
	Q-Max	503.79	47	8.48	856.76	169.65
	Conv-1	469.74	61	13.27	856.76	221.21
	Conv-2	314.60	61	13.27	856.76	221.21
(Aliaga) Turkey	Q-Flex	296.40	29	5.16	481.93	131.80
	Q-Max	237.33	23	4.21	481.93	84.24
	Conv-1	220.10	31	6.59	481.93	109.84
	Conv-2	149.97	31	6.59	481.93	109.84
(Shanghai) China	Q-Flex	3,279.29	283	50.98	3,534.13	1,301.60
	Q-Max	2,621.42	231	41.59	3,534.13	831.85
	Conv-1	2,458.21	301	65.08	3,534.13	1,084.66
	Conv-2	1,616.22	301	65.08	3,534.13	1,084.66
(Niigata) Japan	Q-Flex	2,487.27	208	37.47	2,329.31	956.63
	Q-Max	1,987.43	170	30.57	2,329.31	611.38
	Conv-1	1,869.00	221	47.83	2,329.31	797.19
	Conv-2	1,217.47	221	47.83	2,329.31	797.19
(Inchon) Korea	Q-Flex	2,951.29	251	45.17	2,971.88	1,153.22
	Q-Max	2,358.71	205	36.85	2,971.88	737.02

Destination	Carrier type	Human health impact (DALY)	Employment (Person)	Compensation of employment (MUSD)	Total tax (MUSD)	Man-hours (1000 hrs)
	Conv-1	2,215.02	267	57.66	2,971.88	961.02
	Conv-2	1,449.58	267	57.66	2,971.88	961.02
(Dahej) India	Q-Flex	691.22	95	17.07	2,597.05	435.74
	Q-Max	557.06	77	13.92	2,597.05	278.48
	Conv-1	494.42	101	21.79	2,597.05	363.12
	Conv-2	384.94	101	21.79	2,597.05	363.12
(Adriatic) Italy	Q-Flex	884.85	82	14.80	1,258.36	377.76
	Q-Max	708.08	67	12.07	1,258.36	241.43
	Conv-1	659.40	87	18.89	1,258.36	314.80
	Conv-2	443.39	87	18.89	1,258.36	314.80
(Elengy) Pakistan	Q-Flex	254.13	41	7.40	1,285.14	188.98
	Q-Max	205.61	34	6.04	1,285.14	120.78
	Conv-1	177.55	44	9.45	1,285.14	157.49
	Conv-2	149.42	44	9.45	1,285.14	157.49
(Az Zawr) Kuwait	Q-Flex	59.64	30	5.40	481.93	60.06
	Q-Max	48.69	30	5.40	481.93	108.00
	Conv-1	39.36	14	3.00	481.93	50.05
	Conv-2	39.38	14	3.00	481.93	50.05

Table 7. LCC Results of the Study.

Destination	Carrier type	Gross operating surplus (MUSD)	Operational cost (MUSD)	Equipment cost (MUSD)	Salvage value (MUSD)
(Isle of Grain) UK	Q-Flex	11,780.43	345.48	1,115.61	278.90
	Q-Max	11,780.43	281.22	949.67	237.42
	Conv-1	11,780.43	279.41	1,300.21	325.05
	Conv-2	11,780.43	380.52	1,300.21	325.05
(Fos-France) France	Q-Flex	2,320.39	50.21	180.81	45.20
	Q-Max	2,320.39	40.96	153.92	38.48
	Conv-1	2,320.39	38.26	210.73	52.68
	Conv-2	2,320.39	54.59	210.73	52.68
(Barcelona) Spain	Q-Flex	5,711.72	138.50	442.87	110.72
	Q-Max	5,711.72	113.00	377.00	94.25
	Conv-1	5,711.72	113.55	516.16	129.04
	Conv-2	5,711.72	153.55	516.16	129.04
(Aliaga) Turkey	Q-Flex	3,212.84	69.26	219.90	54.97
	Q-Max	3,212.84	56.60	187.19	46.80
	Conv-1	3,212.84	57.34	256.28	64.07
	Conv-2	3,212.84	77.15	256.28	64.07
(Shanghai) China	Q-Flex	23,560.85	609.10	2,171.55	542.89
	Q-Max	23,560.85	495.85	1,848.55	462.14
	Conv-1	23,560.85	463.51	2,530.88	632.72
	Conv-2	23,560.85	660.24	2,530.88	632.72
(Niigata) Japan	Q-Flex	15,528.74	450.20	1,596.01	399.00
	Q-Max	15,528.74	366.07	1,358.62	339.65
	Conv-1	15,528.74	342.33	1,860.11	465.03
	Conv-2	15,528.74	487.17	1,860.11	465.03
(Inchon) Korea	Q-Flex	19,812.53	541.17	1,924.00	481.00
	Q-Max	19,812.53	440.30	1,637.82	409.46

Destination	Carrier type	Gross operating surplus (MUSD)	Operational cost (MUSD)	Equipment cost (MUSD)	Salvage value (MUSD)
	Conv-1	19,812.53	411.67	2,242.37	560.59
	Conv-2	19,812.53	586.11	2,242.37	560.59
(Dahej) India	Q-Flex	17,313.66	190.56	726.97	181.74
	Q-Max	17,313.66	157.39	618.84	154.71
	Conv-1	17,313.66	146.38	847.27	211.82
	Conv-2	17,313.66	210.92	847.27	211.82
(Adriatic) Italy	Q-Flex	8,389.09	174.58	630.25	157.56
	Q-Max	8,389.09	142.50	536.51	134.13
	Conv-1	8,389.09	133.08	734.54	183.64
	Conv-2	8,389.09	189.96	734.54	183.64
(Elengy) Pakistan	Q-Flex	8,567.58	81.15	315.30	78.82
	Q-Max	8,567.58	67.30	268.40	67.10
	Conv-1	8,567.58	62.50	367.47	91.87
	Conv-2	8,567.58	90.34	367.47	91.87
(Az Zawr) Kuwait	Q-Flex	3,212.84	25.10	230.00	57.50
	Q-Max	3,212.84	20.94	240.00	60.00
	Conv-1	3,212.84	19.41	116.79	29.20
	Conv-2	3,212.84	28.19	116.79	29.20

4.3. A systematic ranking of alternative LNG maritime transport carrier

4.3.1. Performance evaluation using AHP

In the AHP performance evaluation, it is expected that the LNG maritime carriers to be evaluated are Q-Flex against the other options mentioned earlier. Rating the performance level must be entered by the evaluator for all factors and sub-factors. An LNG SME determines the overall performance level for the LNG carriers with the priority derived in Table 8. For example, when CO_2 equivalent and Operational Cost are pair-wise compared, CO_2 equivalent is judged as eight times more important than Operational Cost. Table 8 shows the results of the pair-wise comparison of factors in step 2 for the first phase of AHP in Figure 6.

Similarly, pair-wise comparisons for sub-factors are also performed, and the final priority vector is indicated against each sub-factor (column 3 of Table 9). The final rating of the AHP is presented (last row of Table 9). The ranking indicates that Q-Max is the best alternative among others, followed by Q-Flex, Conventional type 1, and Conventional type 2. The below Equation (10) is used to rank each alternative.

$$AHP\ ranking = \sum Performance \times Weight \tag{10}$$

Note that AHP is not considering whether the indicator has a positive or negative impact. The deliverables of this AHP-based stage are recognition of preferable options to transport LNG through sea shipment and identification of strengths and weaknesses of alternatives when compared to the rating of each sub-criterion against the four options. Generally, in the benchmark process, the analysis is terminated here. There are a variety of good practices that can be used as different options for enhancing performance. There can be many issues (current operational conditions or adverse impacts) that may influence the efficiency and effectiveness of a particular alternative, favorably or adversely, towards continuous improvement and sustainability. Hence, the following step integrates the AHP and TOPSIS methods to assess and improve the decision. TOPSIS is used to provide the decision-maker with preferable order. It helps in ranking based on desirable and non-desirable needs.

Table 8. Relative Priority of Factors in AHP.

	CO_2-eq	NO_x-eq	$PM_{2.5}$-eq	Energy consumption	Land used	Water withdraws	Water consumption	Human health impact	Employment	Compensation of	Total tax	Man-hours	Gross operating surplus	Operational cost	Equipment cost	Salvage value
CO_2-eq	1	4	1/5	7	8	9	9	1/8	9	9	9	9	7	8	8	9
NO_x-eq	1/4	1	1/8	5	6	7	7	1/7	7	7	7	7	6	7	7	7
$PM_{2.5}$-eq	5	8	1	6	7	8	8	1/9	8	8	8	8	8	9	9	8
Energy Consumption	1/7	1/5	1/6	1	6	6	6	1/6	4	4	8	8	1/6	1/3	5	1/5
Land Used	1/8	1/6	1/7	1/6	1	1/6	1/8	1/4	3	3	1/3	2	1/9	1	1	1/6
Water withdraws	1/9	1/7	1/8	1/6	6	1	1/7	1/3	2	2	1/5	3	1/5	1/4	1/4	1/5
Water consumption	1/9	1/7	1/8	1/6	8	7	1	1/5	5	5	1/4	1/4	1/4	1/3	1/3	1/4
Human health impact	8	7	9	6	4	3	5	1	9	9	9	9	9	9	9	9
Employment	1/9	1/7	1/8	1/4	1/3	1	1/5	1/9	1	6	1/6	1/5	1/6	1/5	1/6	1/5
Compensation of employment	1/9	1/7	1/8	1/4	1/3	1	1/5	1/9	1/6	1	1	1/4	1/3	1/5	1/5	1/3
Total Tax	1/9	1/7	1/8	1/8	3	5	4	1/9	6	2	1	6	1	1/6	4	4
Man Hours	1/9	1/7	1/8	1/8	1	1/3	4	1/9	5	4	1/6	1	1/4	1/5	1/5	1/4
Gross Operating Surplus	1/7	1/6	1/8	6	9	5	4	1/9	6	3	2	4	1	9	9	9

	CO_2-eq	NO_x-eq	$PM_{2.5}$-eq	Energy consumption	Land used	Water withdraws	Water consumption	Human health impact	Employment	Compensation of	Total tax	Man-hours	Gross operating surplus	Operational cost	Equipment cost	Salvage value
Operational Cost	1/8	1/7	1/9	3	2	4	3	1/9	5	5	6	5	1/9	1	8	8
Equipment Cost	1/8	1/7	1/9	1/5	2	4	3	1/9	6	5	1/4	5	1/9	1/8	1	6
Salvage value	1/9	1/7	1/8	5	6	5	4	1/9	5	3	1/4	4	1/9	1/8	1/6	1

Table 9. AHP Performance Evaluation.

Factors	Sub-factors	Weights	Q-Flex	Q-Max	Conventional type 1	Conventional type 2
Environmental (0.502)	Carbon dioxide equivalent	0.129	0.034	0.072	0.015	0.008
	Nitrogen oxides equivalent	0.095	0.040	0.034	0.008	0.005
	Particulate matter equivalent	0.156	0.039	0.092	0.016	0.009
	Energy consumption	0.053	0.012	0.034	0.005	0.003
	Land used	0.017	0.004	0.009	0.002	0.002
	Water withdraws	0.022	0.005	0.005	0.005	0.005
	Water consumption	0.031	0.008	0.017	0.003	0.003
Social (0.296)	Human health impact	0.220	0.054	0.136	0.010	0.020
	Employment	0.012	0.003	0.007	0.001	0.001
	Compensation of employment	0.008	0.002	0.005	0.001	0.001
	Total tax	0.038	0.010	0.022	0.002	0.002
	Man-hours	0.018	0.005	0.010	0.002	0.002
Economic (0.202)	Gross operating surplus	0.076	0.012	0.034	0.022	0.007
	Operational cost	0.054	0.017	0.007	0.006	0.024
	Equipment cost	0.034	0.008	0.003	0.011	0.011
	Salvage value	0.037	0.008	0.004	0.013	0.013
Ranking			0.030	0.064	0.011	0.011
			2	1	3	4

4.3.2. Performance evaluation using integrated AHP-TOPSIS

This sub-section summarizes the details of the application of TOPSIS, which employs the weights obtained from the AHP. Later, two artificial solutions were built, as mentioned in Figure 5, namely, the positive Ideal (s_i^*) and Negative Ideal (s_i^-) solutions are obtained. The relative closeness coefficients to the ideal solutions are shown in Table 10. The higher C_i, the closer it is to the positive ideal solution and the farther distance it is from the negative ideal solution. Finally, alternatives are ranked in descending order by their respective closeness coefficients, where the highest value indicates the preferable alternative.

Table 10. Positive–Negative Closeness Coefficients Values.

Carrier type	s_i^*	s_i^-	C_i
Q-Flex	0.140	0.022	0.133
Q-Max	0.102	0.053	0.342
Conventional type 1	0.055	0.107	0.661
Conventional type 2	0.018	0.141	0.888

From Figure 11, when all sustainability impact categories are considered for LNG maritime transport operations carrier selection, the Conventional type 2 achieves the best performance as it has the highest closeness coefficient value. As can be seen, the Conventional type 2 has the most distance from the positive solution (carrier selection) and the least distance from the negative ideal solution. At the same time, Conventional type 1, Q-Max, and Q-Flex demonstrate lower performance. Q-Flex carrier has the least interval from positive solution and the most from negative solution. The Q-Flex carrier is the most distance from the negative solution, and Conventional type 2 is the least distance.

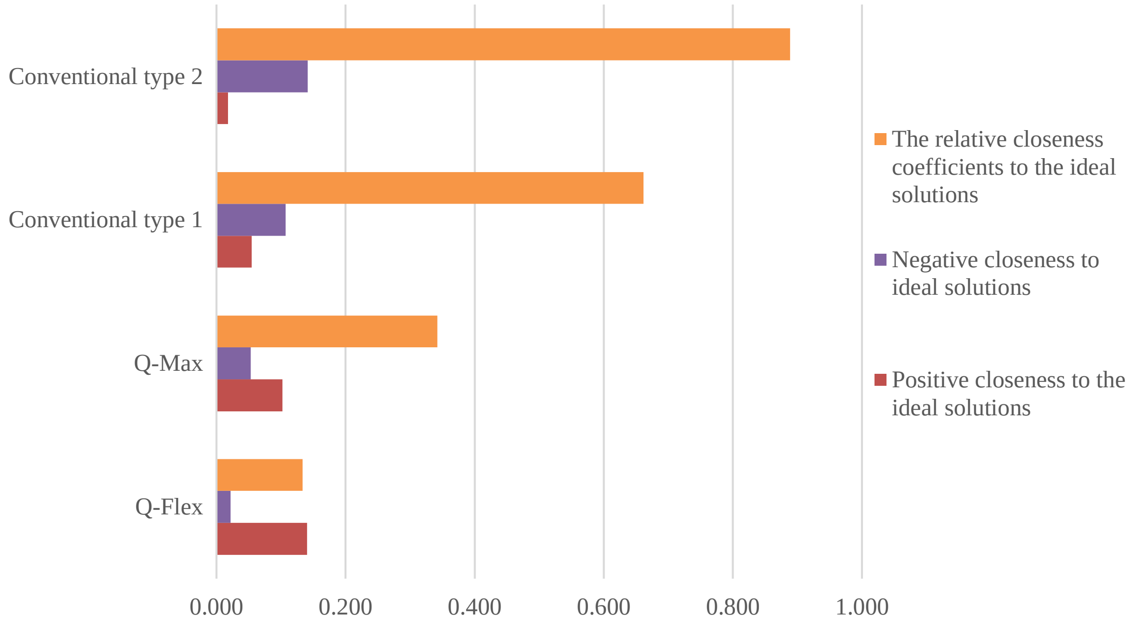


Figure 11. The relative and positive-negative closeness coefficients values.

4.3.3. Performance evaluation using integrated AHP-PROMETHEE II

After finding the weights of each criterion with the help of AHP, the PROMETHEE II method was conducted. A rigorous analysis was undertaken with a panel of experts to define each criterion's most relevant preference function. The validity of all preference functions was carried out concerning adequate conditions of the criteria. Following this collaborative evaluation work, the Linear function is preferred to be used for the criteria. The parameter value "*p*" of the Linear function is defined to be 2 for criteria depending on the outcomes of our analyzes. Table 11 shows the specified preference functions as well as the values of the corresponding parameters.

The application of the PROMETHEE method is performed with Visual Promethee software, and the steps are explained precisely in the method part. Table 12 demonstrates the results of positive, negative, and net outranking flows. The positive preference flow indicates what proportion of one alternative outperforms the others, and the negative preference flow shows what proportion of the other alternatives outperform the alternative.

Table 11. Preference Function and Parameter Values for the Criteria.

No.	Criterion	Preference function	Parameter value
1	Carbon dioxide equivalent	Linear	p=2
2	Nitrogen oxides equivalent	Linear	p=2
3	Particulate matter equivalent	Linear	p=2
4	Energy consumption	Linear	p=2
5	Land used	Linear	p=2
6	Water withdraws	Linear	p=2
7	Water consumption	Linear	p=2
8	Human health impact	Linear	p=2
9	Employment	Linear	p=2
10	Compensation of employment	Linear	p=2
11	Total tax	Linear	p=2
12	Man-hours	Linear	p=2
13	Gross operating surplus	Linear	p=2
14	Operational cost	Linear	p=2
15	Equipment cost	Linear	p=2
16	Salvage value	Linear	p=2

Table 12. Outranking Flows of the LNG Carriers.

Carrier type	φ^+	φ^-	φ (net)
Q-Flex	0.2143	0.6575	-0.4432
Q-Max	0.4592	0.4126	0.0466
Conventional type 1	0.4172	0.4024	0.0148
Conventional type 2	0.6007	0.2189	0.3818

Based on the net values, the ranking of the different carriers is found to be Conventional type 2, Q-Max, Conventional type 1, and Q-Flex, as illustrated in Figure 12. Conventional type 2 carrier comes out with the highest net outranking flow value, 0.3818, which enables it to occupy the first rank. Similarly, the Q-Flex carrier is coming out with the lowest net outranking flow value, that is, -0.4432, occupying the last place, which concludes that it is the unpreferable carrier among these groups of carriers. Although 16 different indicators belonging to 3 criteria are considered for this analysis, other technical and non-technical specifications can also be included. For example, engine type, travel path availability, maintenance cycle, dynamic demand of LNG by customers, etc., helps make the decision-making more precise and accurate in solving problems and system enhancement. Generally, the PROMETHEE findings are another confirmation that Conventional type 2 achieves the best sustainability performance among the four types of LNG maritime transport. Moreover, Q-Flex shows the lowest performance in both methods used; TOPSIS and PROMETHEE II.

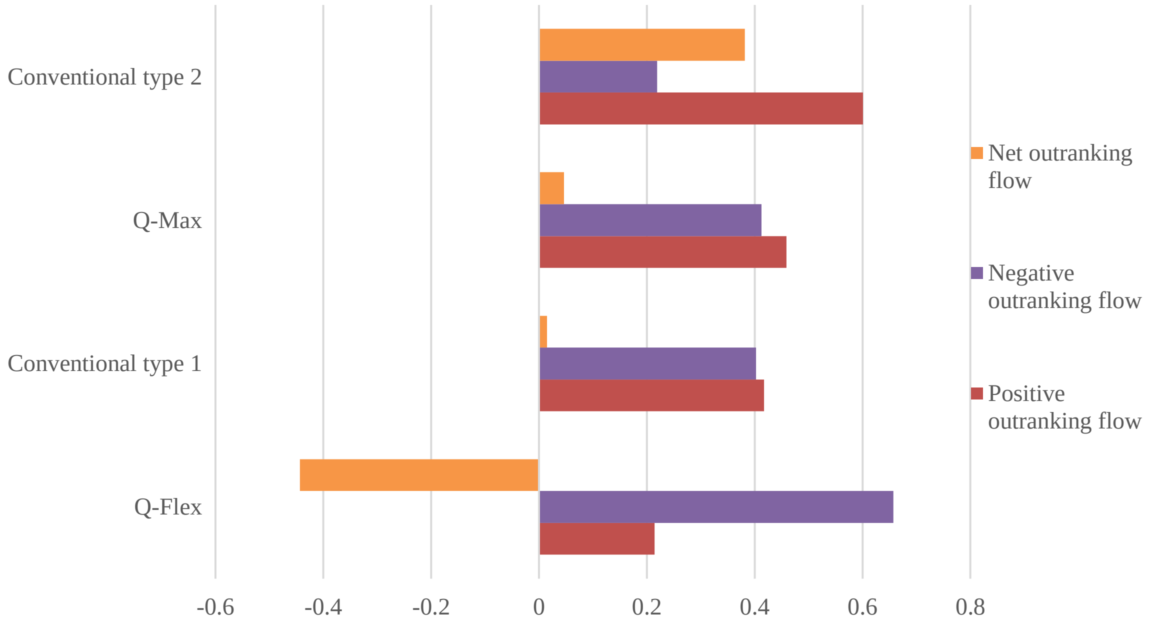


Figure 12. The net and positive-negative outranking flows.

CHAPTER 5: POLICYMAKING OPPORTUNITIES

This research provides a set of recommendations for further policy analysis toward improving the environmental, social, and economic performance of LNG carriers. For environmental, process design and operations improvement are required to minimize the air emissions footprint, which is directly proportional to the human health impact. However Conventional type 2 performs well in the NO_x-eq and $PM_{2.5}$-eq, CO_2-eq reduction remains an area of improvement, especially for future fleet manufacturing. LNG maritime carrier manufacturers must insist buyers on the latest best available control technologies with minimal environmental impacts and report the compliance status to the dedicated authorities based on the latest local and international standards. In addition, it is recommended from a policy perspective to include the carbon footprint reporting as one of the Tender Criteria of LNG maritime shipping to insist on the importance of customer and supplier awareness and derive the sellers ensuring the best sustainability performance. From a social perspective, as Conventional type 2 carriers found the best performer in the social standpoint, it is advised to provide fair and well-distributed job opportunities and hire the most experienced and trained staff to perform the job safely. Ensure adequate technical training to the operations and maintenance teams on the best safety procedures and target incident-free LNG maritime carriers' manufacturing and operations. From an economic perspective, the construction material and operational costs are slightly more expensive for Conventional type 1 and Conventional type 2 compared to other LNG carriers. Further research is required to analyze alternative construction materials, operational planning, and best operating procedures by the manufacturers and operating companies during the operational phase. Moreover, LNG maritime carrier design, process (including BOG management), and traveling routes require further optimization.

Carbon emissions accounting and reporting should be made in high accuracy calculation tools and verified by a competent external party to ensure the implementation of the right solutions to reduce the carbon footprint to the possible extent. The verification audit can be in line with the European Union Monitoring and Reporting Regulations (EU MRR) 601/2012 and 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Governments and policymakers shall enforce and manage the verification process to ensure compliance and consistency with carbon emission monitoring. Furthermore, the followings present some important policies for reducing the carbon footprint of LNG carriers:

- Optimize the route plan for LNG carriers considering the political barriers: Governments shall be aligned to IMO requirements and support the optimization of route maps of LNG carriers to maximize shipload, minimize fuel consumption, cargo loss, and reduce the environmental footprint.
- Investigate the slow streaming operation mode and its effectiveness in the LNG ships: There are considerable benefits of slow steaming, such as higher fuel savings, reduction in carbon emissions, improved reliability, and efficiency.
- Evaluate the installation of an electric power option in the carrier: Replacing fossil fuel with electricity is expected to have greater efficiencies, better environmental sustainability, and enhanced safety for ship-owners.
- Reduce the flaring of BOG, either naturally occurring or the enforced one to a maximum extent: Flaring is one of the major sources of GHG emissions, and preventive actions, as well as continual improvement journeys, shall be encouraged.
- Timely repair and maintenance: It is highly critical to control leakages, especially from the hydrocarbon storage tanks and fugitive emission sources, to avoid such environmental releases to the sea and/or atmosphere.

Natural gas demand is expected to increase due to rising energy crises in the post-COVID19 era and geopolitical instabilities in eastern Europe. LNG transportation proposes an alternative way of meeting the rising energy demand and can contribute diversification of energy suppliers toward improving energy security in the world. Furthermore, energy shipping security is an essential factor in the shipping part in which reduces pollution, satisfies customers, and promotes more business globally. International unions must consider the geopolitical risk of energy trading and maritime shipping to ensure the minimum sudden adverse impact on economic development, social satisfaction, and environmental releases

CHAPTER 6: CONCLUSION AND FUTURE WORK

6.1. Summary of research and key findings

Consumption of a cleaner fossil fuel option such as natural gas has paved the road to providing more attention to maritime transport worldwide. Global indicators show the continuation of LNG needs that require assurance of this product's sustainability, including supply chains. Obviously, along with the LNG transportation by maritime carriers, several adverse and beneficial environmental, social, and economic impacts are essential to be assessed for long-term LNG trading, which ignites the motivation of this research. This research established the first LCSA model based on MCDM by integrated LCA, LCC, and SLCA results. Four types of LNG carriers using two different fuel types have been considered.

The ranking results show that the Conventional type 2 has the best performance as it has the highest closeness coefficient value, followed by Conventional type 1, Q-Max, and Q-Flex. On the other hand, following the AHP-PROMETHEE II method, the ranking of the different carriers based on the net values is found to be Conventional type 2, Q-Max, Conventional type 1, and Q-Flex. In short, the Conventional type 2 is found to be the most sustainable carrier among others to be used for the LNG maritime transport operations considered in this research. Two different ranking methods provide a consistent result for the first and last ranking of LNG carrier options from a sustainability perspective.

6.2. Limitations of the current research

The limitations addressed in this research are mainly related to the uncertainty of emission factors used from the literature published in 2004 and the assumption of LNG maritime transport time for each shipping stage. Therefore, it is recommended to study both areas further to reduce the associated uncertainty and have more accurate results. Moreover, the sources of information related to water consumption, water withdrawal, and some other numerous information were very limited to the point of assuming those data as performed and illustrated throughout the research; finding those data from the literature and carrier's design documents was challenging.

6.3. Recommendations and future work

Although sixteen different indicators belonging to three criteria are considered for this analysis, it is recommended to include a wider range of indicators to get more precise results for each LNG carrier selection option. Moreover, uncertainty embedded LCSA for the LNG production and supply chain is suggested to further understand the sustainability performance of the LNG process chain.

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APPENDICES

Appendix A: Further details on the sustainability pillars, LNG shipping, and Qatar-UK trade and Carbon Emission Calculation

— *Sustainability Assessment Indicators*

A definition based on research defines sustainable development as one which suits the present requirements without cooperating with the ability of future generations to meet their expectations (Kucukvar, Cansev, Egilmez, Onat, & Samadi, 2016; Shaikh, Kucukvar, Onat, & Kirkil, 2017). There are three main determinants of sustainability. Sustainable development focuses on economic, environmental, and social welfare. LCSA is critical because it addresses these three elements of sustainable development. It addresses both sides of decision-making, positive and negative, to produce more sustainable products in their life cycle. Environmental, social, and economic factors determine the sustainability of development (Gumus, Kucukvar, & Tatari, 2016). Any knowledgeable and quality assessment presentation must address those three-bottom lines of sustainability assessment.

- *Economic Impact*

There is a relationship between LNG carriage and delivery expenses and natural gas value margins. Statisticians utilize information from the price of natural gas along with LNG freight rates to determine the distribution-related effects of endogenous distribution expenses on the trade profits of LNG. Statistical evidence illustrates that the average net spread growth translates to a relative increase in the shipping cost for specific routes. After the process of liquefaction, LNG is stored in large tanks or transported in customized cryogenic tankers (Nikhalat-Jahromi, Bell, Fontes, Cochrane, & Angeloudis, 2016). From the 2015 international gas union annual report, the global LNG transportation sector had 373 carriers that account for

55 million cubic meters. This capability is 10% of the total amount of LNG in the market for that year, which is slightly higher than the 2014 global LNG storage capacity, 50 million cubic meters. The trade market for LNG freight appears very much competitive (Oglend, Kleppe, & Osmundsen, 2016).

- *Environment Impact*

The primary method of delivering LNG is the use of many big ships that load at the same point. There are three groups of LNG tankers that group according to their carriage capacities. Conventional tankers have a size ranging from 138,200 to 151,900 cubic meters. Q-Flex tankers have carrying capacity ranging from 210,000 to 217,000 cubic meters. Q-Max tankers have the largest carrying capacity of 266,000 cubic meters. This family comprises the biggest LNG carriers around the globe. They are 345 m long and 53 m wide. Taking the carrying capacities of the above three families into consideration, it is evident that Q-Flex and Q-Max cannot dock at some ports while conventional vessels dock at any regasification terminal. Part of the LNG that has been carried is emitted into the atmosphere through evaporation during the voyage. Voyage is the boil-off effect that is of two distinct types. Laden voyage takes place at a rate of 0.12% per day, while ballast voyage occurs at a rate of 0.1%. This gas works as a complementary energy source throughout a voyage in complementary vessels.

The BOG has the potential to power to a vessel when it is waiting in call ports or going across the Suez Canal. The BOG from Q-Flex and Q-Max gets liquefied again and then stored for delivery. Extensive adoption of LNG propulsion technology will reduce the emission of air pollutants and carbon dioxide gas into the atmosphere. However, this might cause an increase in the number of methane emissions into the atmosphere and translate to net climatic change of an estimated carbon dioxide amount range of 0.8 to 6.0 million tons in the chosen range of time. Statistical evaluations indicate that methane emissions from engines imply an additional climatic change of approximately 2.3 - 6.9 million tons of carbon dioxide equivalent. This report is a result of the analysis done on the use of LNG propulsion technologies (Åström, Yaramenka, Winnes, Fridell, & Holland, 2018). The methane sleep causes the most extensive effects on climate. However, these are bare perceptions of the facts of advancements in technology that may cause a significant increase in emissions from engines (Åström et al., 2018; Burel, Taccani, & Zuliani, 2013).

Holzer et al. (2017) surveyed to analyze the ability for export of natural gas in America towards two subjects. The first one is its potential to drive a substantial increment in ballast water flux to the United States. The second subject is its potential to change the channels of global ports buying relative to selling LNG. The adjustments in the amount, origin, and channels of the LNG market may cause adverse results in the exchange of non-native organisms. This effect is because of the amount and biotic composition of resultant ballast released to parts. The alteration of the trade regime of LNG is common to the United States. These changes have the potential to alter the current global ecosystem. The use of LNG as an option over all other sources of fuel has environmental benefits. The use of LNG involves pure burning of natural gas, which produces 99% fewer particles, and Sulphur oxide emissions. It accounts for 80% less emission of nitrous oxides and 20% less emissions compared to the use of diesel as a fuel (Pfoser, Schauer, & Costa, 2018). Research by Tamura et al. (2001) reports that LNG is pure green fuel for future analysis of GHG production from various types of fuel. The relationship between LNG and sustainability depends on the environmental importance of the gas and depends on multiple factors. The link considers the excellent chronological record from safety and environmental impact analysis. The relationship also assesses the essential solutions that provide shallow distribution and the uses of inexhaustible sources of energy.

- *Social Impact*

The key component of LNG is methane, and it is usually in the form of a cryogenic liquid at a low temperature. It has a combustion range of approximately 5 to 15% in vapor form. During this condition, its mixture of air is highly flammable. LNG spills are associated with possible damages due to its temperatures in its cryogenic state as well as various hazards like pool fires and ignition of drifting vapor clouds. LNG is not explosive in its liquid state. Furthermore, LNG vapor explodes only in the condition that it ignites in the air within the flammability range and in a fully or partially closed space. Some sources also claim that natural gas presents an asphyxiation hazard. LNG is not a toxic substance and is not persistent if spilled in water. It floats on water because it is lighter than water (Planas-Cuchi, Gasulla, Ventosa, & Casal, 2004).

When workers ignore the necessary precaution and fail to apply protective measures during loading operations of tankers used to transport hazardous cargoes, there is a high probability of occurrence of fire and explosion risks (Paltrinieri, Tugnoli, & Cozzani, 2015). Carelessness in daily work routines around these tankers also exposes the area to a risk of experiencing fire and explosion accidents (Shichuan, Liang, Yuhong, & Xiang, 2012). The intensity and how prone ship fires get depends on the presence and quantity of hazardous materials and, most importantly, the control precautions that prevail. Ship fires can get destructive, especially where the responsible teams take longer to control the outbreak (Uğurlu, Köse, Yıldırım, & Yüksekyıldız, 2015). The flames can lead to loss of cargo, lives, and the entire ship without leaving out environmental pollution. Ship fires are proof to happen intrusively. Any small mistake or mishandling of the tankers translates to significant accidents whose effects are very destructive. Knowing the risks associated with this field and observing the necessary precautions is the only way to prevent these accidents. The information available about the risks associated with transporting hazardous cargo depends on history by accessing the previous fire accidents related to interactions with tankers (Burel et al., 2013).

Many scholars conduct vast research on risks for LNG shipping and studies about LNG fueled ships, intending to end the hazards associated with these particular areas (Fu, Yan, Zhang, Li, & Zio, 2016; Martins, Pestana, Souza, & Schleder, 2016). The explanation behind reducing the link is that the whole process revolving around LNG remains friendly to the environment and ensures social safety in a community by reducing the risk of fire and explosion accidents. An increase in LNG production services means that many workers and many property investments suffer exposure to many social, health, economic, and environmental risks (Baalisampang, Abbassi, Garaniya, Khan, & Dadashzadeh, 2018). For this reason, the responsible authorities must go the extra mile to install the safety of LNG facilities. They can achieve this by implementing quality safety measures in the production, distribution, usage, and storage of LNG. The stakeholders must review the pipes that transport gasses, toxic or flammable substances, especially those that pass near residential sites. They should evaluate the risks they pose to the lives of the people. They should determine how much threat the people around are exposed to by considering past accident scenarios. Populated areas account for major hazard scenarios where outcomes. The introduction of LNG as a clean fuel has some social benefits like creating employment and a significant source of revenue for the government through foreign exchange. This income enables the government to provide essential services to its citizens. Employments would allow people to have better living standards.

— *LNG shipping fleet and vessel types*

- *LNG shipping fleet*

A recent report by the International Gas Union (IGU) (2020) World LNG research team indicates that the active LNG shipping fleet in the world comprised 525 ships in 2018. There is a relative increase in the overall storing volume of the carriers, considering the past few years. The push and thirst by authorities to start enjoying the benefits that come with massive economies of scale made them build enormous vessels in the early months of 2010. By the end of the year 2018, more than half of the order book contained a specific project or charterer. At this time, there were only 56 carriers left available for the spot market for chartering out in the name of a business—more details in Figure 13.

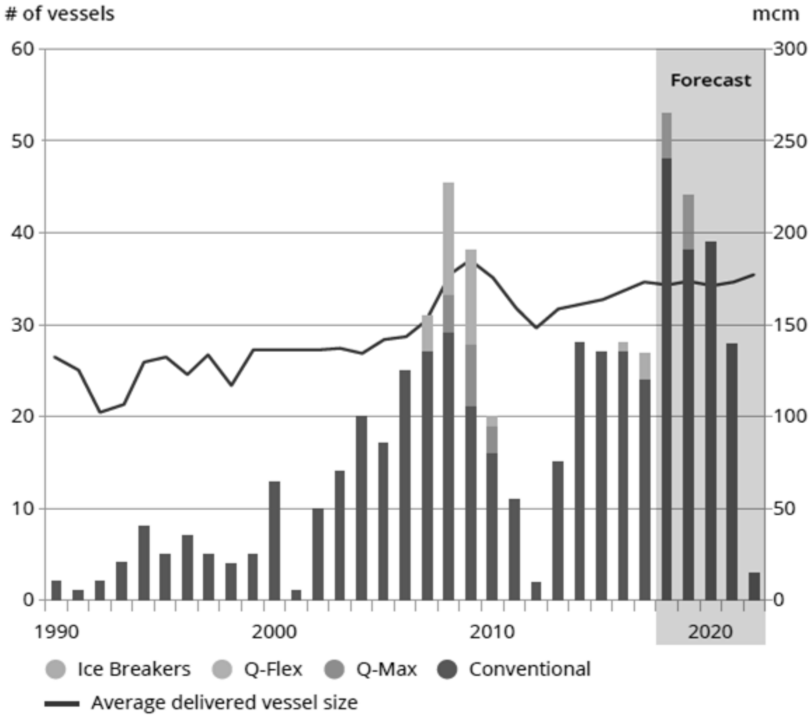

Figure 13. International LNG fleet delivery per year against their average vessel size.

Workers must first take BOG out of the tanks to maintain the pressure of the container close to the prevailing environmental conditions as per the design specifications for Moss and membrane systems. BOG applies in the processes for fueling the ship’s steam-turbine operating systems, which appear to be reliable, although not the best source of propulsion. From the year 2000, the world has experienced major innovations and upgrades of these systems of LNG carriers to help reduce fuel costs during the transportation of LNG.

The issue of the cost of fuel became even more critical after the year 2000, following a rise in bunker cost. Delivery costs depend on the particular transport system, such as volume, specific vessels' speed, time taken for subsequent deliveries, and other operational factors. Any new approach to the propulsion of LNG and the entire energy industry must consider all sides of the LNG transport process.

There are several systems available today for LNG carrier operators. The steam turbines are the oldest propulsion systems of LNG carriers. This process comprises of two boilers that generate sufficient steam to move the turbines and auxiliary engines. Heavy fuel oil is an essential requirement for full or partial fueling of the furnaces. The significant advantage of this particular system is that the burning of gas is not required since the boilers use the entire amount of BOG.

The dual-fuel diesel-electric systems (DFDE) improve the efficiency of vessels by around 25% over the traditional steam turbines because they function by burning both diesel oil and BOG. These propulsion systems have an electric version operating on dual fuel, medium-speed diesel engines. They work on low-pressure natural gas with a minimal volume of diesel used as a spark in gas mode. Moreover, the engine operators have the power to change to the early marine diesel at any given moment. A few years after implementing the DFDE systems, a new version of these vessels known as the tri-fuel diesel-electric vessels (TFDE) came. These newer versions can burn massive amounts of fossil fuel, diesel, and gas. They provided a better innovation to operating flexibility that is now able to increase efficiency at different speeds. There is a separate system invented for transport purposes in 2000. It developed in tandem with the Qatari mega train projects.

The vessels use conventional SSD engines consuming HFO generator assets for propulsion instead of using the BOG or electric energy. The BOG, in this case, entirely undergoes liquefaction and is then stored in the designated tanks. This system creates room for the transport of LNG without losing cargo, which is better if HFO or MDO is relatively cheaper compared to the process of combustion of BOG for fuel. By the end of the year 2018, more than 27% of machines in the order book were tailored to accommodate the latest invention of engine designs. The designs transitioned from the M-type, Electronically Controlled, Gas Injection (ME-GI) engine, which uses powerful low-speed gas injection engines, to the newest innovation. The Q-Class are different in that they do not accommodate BOG. Still, ME-GI engines optimize the capability of slower drivers by running directly off BOG, or fuel oil were essential, other than only re-liquefying the gas. This unique flexibility translates to important economic optimization.

The substitute to DFDE powering systems can offer a cost minimization of approximately 15 to 20%. This economic benefit arises due to the LNG and gas operating system's reduced cost. The system usually achieves more gains through the process of removing the high-pressure gas compression system. Moreover, the nitrous oxide abatement systems are now useless. Another method is the steam reheat design that basis on a reheat cycle, where they reheat all the steam used in the turbine to boost output. The STaGE system unites steam turbines and gas engines that enable waste heat recovery. This enhancement in the usability of steam maintains advantages that come with a simple steam turbine during the process of improving overall efficiency.

- *LNG vessel types*

Earlier in the industry, there were rarely large vessels, but of late, there are vessels as large as a capacity of 180,000 cubic meters. The Q-Class ships are the newest and largest vessels ever in the history of existing fleets. Following Shively and Ferrare (2005) research, there are two significant groups of LNG containment systems. Two types are Moss sphere tanks and membrane tanks. These containment systems play a vital role in storing the LNG and keeping it in its liquid state through temperature maintenance. Sources indicate that the Moss designs originated from the Japanese shipyards, whereas the membrane vessel designs originated from Chinese and Korean shipyards. The moss design, which began in 1971, is more popular due to its independent spherical tanks. The engineers designed the separate tanks to be on the deck of the ship. This design leaves half of the tank above the deck and the other half below the deck. The membrane originates from the vessel hull. Its container consists of a design with double-walled storage since it appears to cover most of the space below the deck with only a small part of left bare to the wind. Membrane design has an extensive storage capacity compared to the Moss design with less contact with wind drag. Figure 14 illustrates both types (Vanem, Antão, Østvik, & de Comas, 2008).

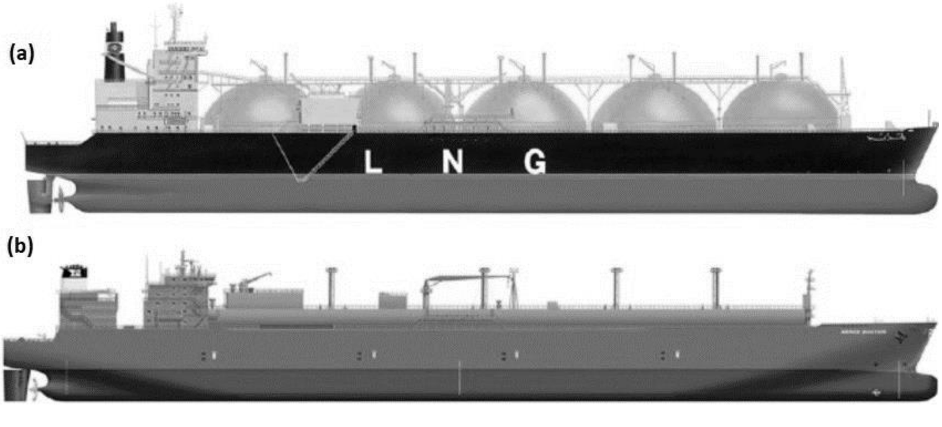

Figure 14. Type of containment a) moss type containment and b) membrane type containment.

— *Further Information on Qatar-UK Case Study*

- *LNG transport between Qatar and the UK*

The success of Qatar in LNG supply dates back to 1971. The state of Qatar transports LNG via customized vessels to its customers around the globe. The method of transportation is cheaper and more efficient as there are minimum chances of occurrence of an incident.

Authorities in Qatar are evaluating the gas companies for sustainability and efficiency using a logistical approach. Shipping is an essential activity in LNG marketing. However, its importance cannot surpass the need to protect the environment, which affects human health and climatic change. This evaluation involves analyzing the company's activities by measuring and calculating the total amount of emissions from the vessels in various stages. The process aims at identifying the root causes of emissions and potential solutions for this problem.

The usual value chain consists of natural gas that goes through several stages before reaching the customer. These stages are production, treatment, and liquefaction in a unique and customized plant, then temporary storage before loading it into the designated vessels. According to recent global statistics, Qatar is the world's largest exporter of natural gas, with an extensive market in countries like Japan, South Korea, and the United Kingdom (Medlock, Jaffe, & O'Sullivan, 2014). Qatar values the need for developing an LNG shipping fleet that helps create a connection between Qatar, the supplier, and its customers around the globe, including the UK. Qatar, therefore, took the responsibility to unite with various shipbuilders and owners to develop customized ships that can facilitate the transportation of enormous LNG volumes to satisfy the ever-increasing market demand. Nakilat, a Qatar gas transport company, is the primary transporter and shipping agency. Its mandate is to ensure the customization of LNG tankers for the successful delivery of LNG through laden and ballast transportation.

- *Qatar LNG fleet, vessel type, capacities, and fuel types*

Nakilat is the most prominent known owner of LNG carriers globally, with a fleet of 69 LNG carriers with more than 59 million MT of LNG shipped by the end of 2019. Nakilat uses vessels that meet the standards of modern and sustainable technology. The Q-Max and Q-Flex carry 50 to 80% more cargo volume than conventional LNG carriers' carrying capacity.

The LNG fleet constitutes the following; 24 conventional carriers with a capacity of between 145 and 170 thousand cubic meters, 31 Q-Flex carriers with a total volume of between 210 to 217 thousand cubic meters, and 14 Q-Max carriers whose amount ranges between 263 to 266 thousand cubic meters (Burel et al., 2013).

Nakilat has advanced monitoring systems that improve vessel performance to ensure efficient operations. The vessels have the latest satellite technology that enables remote troubleshooting allowing efficient connectivity and enhanced communication channels all the time. Nakilat unites with its partners in the initiative to ensure the highest international safety, security, and shipping standards in the whole fleet. These collaborations aim to achieve the safest, most reliable, and most efficient shipping services.

The entire Nakilat fleet has a collective carrying capacity of more than 9 million cubic meters. This value accounts for about 12% of the total global fleet carrying capacity. Long-term chartering is the most common method of employing the more significant part of these vessels. Nakilat utilizes the remaining ships in other worldwide shipping markets. Nakilat either wholly owns these vessels or jointly owns them with other large international shipping companies. Nakilat jointly owns one floating storage and regasification unit vessel as well as four extra-large carriers; this brings the entire fleet strength to 74 boats.

Nakilat considers the evaluation of an innovative approach of retrofitting all the low-speed diesel engines into an M-type, electronically operated gas injection set-up system. Currently, the application of LNG as a bunker fuel generator in shipping works in conventional steam-driven carriers. From the latest innovation, Dual or Tri-Fuel Diesel Electric LNG ships also use LNG as a bunker fuel with the application of low pressure and medium-speed four-stroke diesel (NAKILAT; QGN Bureau Staff, 2014). QatarEnergy (named earlier as Qatar Petroleum, QP) has the biggest LNG shipbuilding assertions in history to secure more than 100 ships esteemed in an overabundance of QR 70 billion to cater to its LNG development plans. QP entered three understandings in June 2020 to save LNG dispatch development capacity within the Republic of Korea to be utilized for QP’s future LNG carrier armada necessities, counting those for the ongoing extension ventures within the North Field and in the United States.

— *Parameters for LNG Carriers Carbon Emission Calculation*

In the monitoring plan, the ship's owner must indicate the monitoring approach applied during the evaluation of fuel consumed for particular types of a boat under its responsibility and also approval whether that chosen methodology works. The accurate advancements must balance with the additional costs when deciding on the most appropriate monitoring strategy. The actual fuel consumption for each voyage counts. The following methods in Figure 15 determine the actual fuel consumption:

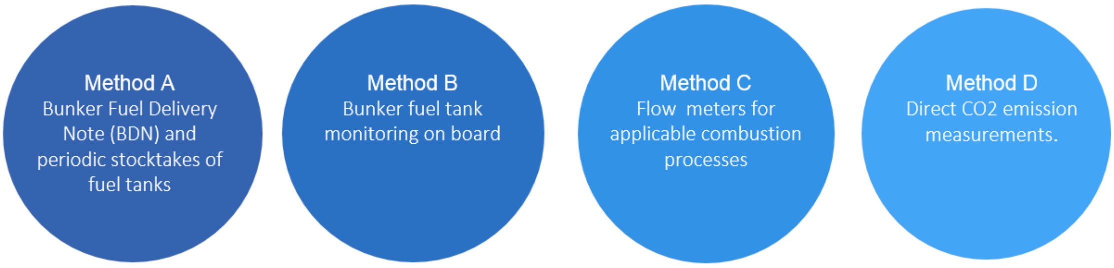

Figure 15. Four methods in CO_2 monitoring methodologies.

- *Calculation of carbon emissions*

Equation (24) below applies when calculating carbon emissions:

$$\mathrm{CO_2\ emissions} = \mathrm{Fuel\ consumption} \times \mathrm{emission\ factor} \tag{24}$$

First, fuel consumption must include all fuel the ship equipment consumes. Secondly, the total fuel consumed at the berth should count separately during evaluation. Third, use the initial data for mission factors. The fourth and last step is that emission factors rely on information from research institutions.

- *Methods for determining carbon emissions*

There are four distinctive methods used in the determination of carbon emissions. *Method A is the BDN and periodic stock takes of fuel tanks*. This method basis on the volume and type of fuel, regarding the definition in the BDN. It also considers the periodic stock-tales of fuel tanks based on various readings. The initial amount of fuel plus the deliveries less than the final amount of fuel remaining and the de-bunkered fuel thought the period add up together to determine the total fuel consumption of the particular fuel. A period refers to the time spent between two ports or the whole time spent within a port. The type of fuel and Sulphur content must be specified for the fuel used during a specific period (Burel et al., 2013). This method is not applicable when BDN is unavailable onboard ships, mainly where cargo is the fuel.

Method B addresses bunker fuel tank monitoring on board, and basis on the accurate tank readings. These readings happen every day if a ship is at sea and when it bunkers or de-bunkers. The collective range of fuel tank volume for different recordings determines the periodical fuel consumption. Period refers to the duration between two docking ports or time spent within a port. When calculating the periodical fuel consumption, specify the fuel type and Sulphur content. Carry out fuel tank readings using appropriate methods like automated systems, soundings, or dip tapes. The monitoring plan specifies the way for tank sounding and the associated uncertainties. The company should convert the amount of fuel uplift or the fuel remaining in the tanks from volume to mass by considering the actual density values. This condition happens when the amount of volume appears in liters.

Method C addresses flow meters for the most appropriate burning processes—this particular method basis on quantified fuel distributions onboard. The values obtained from all flow meters connected to relevant carbon dioxide producers combine to indicate all fuel used for the particular period. A period is a time between two port calls or the time within a port. Again, it is crucial to determine the fuel type and Sulphur content. The monitoring plan indicates the method of calibration used and the uncertainties associated with flow meters. The company should use the actual density values to convert the amounts from volume to mass. The last *method D addresses the measurement of direct carbon dioxide production and release into the air*. The direct carbon dioxide emissions measurements are used for voyages and for CO_2 emissions in ports that lie within a Member State's judgment. When determining the fuel consumption for ships, emissions from major and auxiliary operation units account for the total carbon dioxide emissions. The reporting basis on this method and the quantified CO_2

production and the associated emission factor of the applicable fuel determine the calculation. This method basis on an evaluation of the CO_2 output and tracks in flue gas stacks, and multiplying the CO_2 concentration of the flue gas with the flue gas flow gives the total amount.