QATAR UNIVERSITY

COLLEGE OF ENGINEERING

# LIFE CYCLE AIR EMISSIONS AND HUMAN HEALTH IMPACTS OF LNG TRANSPORTATION

BY

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# ABSTRACT

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Title: Life Cycle Air emissions and Human Health Impacts of LNG Transportation

Supervisor of Thesis: Murat Kucukvar

The aim of this thesis is to study the life cycle air emissions and human health impacts of the LNG transportation, by calculating the emissions from the vessels for one trip between Qatar and destination country and back to Qatar. Life Cycle Assessment has been applied as a method to study the impacts on human health due to the emissions by applying the ReCiPe model. Sensitivity analysis is also conducted to investigate the parameters that are affecting the emission results significantly. The proposed method quantifies the environmental impact of LNG transportation using different types of vessels and fuels. The results show that using the conventional vessel type with a fuel type LNG during transportation would have the minimum emission amount among all other fuels and vessels. Consequently, this would lead to having less human health impact among all other vessel and fuel types.

# DEDICATION

*I dedicate this thesis to my beloved husband, Mohammed Al-Ammari,*

*who has supported and stood by me during the past years of my master's degree journey.*

*To my parents and siblings, who believed in me and help me to*

*make this dream come true and for implanted in me the love of learning.*

*I cannot begin to express my gratitude to them for all of the support, love,*

*praise, and prayers they have sent my way along this journey.*

*To all my friends who have been inspiring me, made me stronger, better and more content than I could have ever imagined.*

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Working on this thesis has been an extremely rewarding journey. I would wish to take this opportunity to extend my appreciation to a number of people, who have stood by me, to the completion of my master's thesis, in many different ways.

To begin with, I wish to extend my deepest gratitude to my supervisor Dr. Murat Kucukvar for giving me guidance, encouragement, and support through the many preliminary versions of my text, recommending critical suggestions along the way. Also, for sharing with me, insightful tips on how to highlight the right arguments for my masters' research topic.

I owe my deep sense of gratitude to my colleagues Aisha Yousef and Yahia Mohamed for their kind support and the time they have spent in providing me with the far needed explanation. Their constant encouragement and support did add considerable contribution to my experience during the entire thesis preparation, through to the actual writing of the thesis paper.

Last, but not the least, to my family, for providing me constant and consistent encouragement, support and divine presence throughout this journey. Without them, my master's program would not be a success.

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# Definition of Terms (Acronyms)

BCM – Billion Cubic Meters

BOG – Boil-off Gas

BP – British Petroleum

Btu – British Thermal Unit

CAPEX – Capital Expenditures

$CH_4$ – Methane

$CO_2$ – Carbon Dioxide

ECA – Emission Control Areas

GDP – Gross Domestic Products

GTL – Gas to Liquids

GTT – Gaztransport & Technigaz

HFO – Heavy Fuel Oil

IMO - International Maritime Organization

IOC – International Oil Company

Kb/d – kill barrels (of oil) per Day

LNG – Liquefied Natural Gas

LPG – Liquefied Petroleum Gas

LSFO – Low Sulfur Fuel Oil

MDO – Marine Diesel Oil

MISC – Malaysia International Shipping Corporation

MMBtu – Metric Million British Thermal Unit

MMB/D – Million Barrels per Day

MMTPA – Million Metric Tons per Annum

MT – Metric Tones

nm - Nautical Miles

$NO_x$ – Nitrogen Oxide

OPEC – Organization of Petroleum Exporting Countries

Opex – Operating Expenses

PM – Atmospheric Particulate Matter

QG – Qatargas

QP – Qatar Petroleum

RL – Ras Laffan

$SO_x$ – Sulfur Oxide

SPA – Sales and Purchase Agreement

Tcf – Trillion Cubic Feet

TFDE – Tri-Fuel Diesel Electric

UAE – United Arab Emirates

USA – United States of America

DALYs– Disability Adjusted Life Years

# CHAPTER 1: INTRODUCTION

## 1.1 Background

The physical nature of natural gas makes it complex to ship and store. There are two ways to transport natural gas, either through pipeline or as a liquid using liquefied natural gas (LNG) vessels. Transporting gas through pipeline is technically and economically viable for relatively short distances, but it represents a challenge when the customer is several thousand kilometers away. The state of Qatar is the largest liquefied natural gas supplier in the world with a long history of successful developments in the oil and gas sector since 1971. The liquefied natural gas transportation via customized vessels is the method that is followed by the state of Qatar to deliver its liquefied natural gas to its customers around the globe.

Despite the huge importance that these vessels provide in shipping the LNG, it contributes significantly to global climate change, especially from the greenhouse gas emissions, as mentioned by Kolieb (2008). Not only LNG shipping, it has been found that 90 percent of the global trade is done by marine vessels that are fleeting through international waters. For that reason, international agencies commenced setting rules and regulations for the shipping sector to minimize the harmful effect of shipping emissions. Therefore, almost all those stages of the LNG value chain are regulated, and this is involving shipping to avoid any incidents that may affect shipping safety and security during the LNG transportation journey. According to Shively et al. (2005), all those rules are set by the International Maritime Organization (IMO). IMO is known as a United Nations agency and its main objective is to make sure that vessels are manufactured and operated under safe and secure standards. Additionally, it is working to minimize or eliminate unacceptable effects on the environment and on human health. Consequently, all LNG vessels have to fulfill all rules and regulations defined internationally by IMO.

## 1.2 Problem Statement

As the awareness of the concept of sustainability is increasing, evaluating the logistics activities of oil and gas companies in Qatar with respect to sustainability practices becomes a crucial subject. Shipping the LNG is one of the most important activities during the LNG value chain activities. In spite of how important this step is, it can have a negative impact on the environment, especially on human health. This research involves performing an analysis of the LNG shipping of oil and gas companies in Qatar through measuring and calculating the amount of emissions coming from the vessels in different scenarios and assumptions. Later, using those values to analyze the Environmental Life Cycle Assessment (LCA) which translates those results into the environmental impact that at the midpoint and endpoint levels. In addition, this research aims to identify the critical parameters affecting the emissions results.

## 1.3 Objectives

The main objectives of this research are listed as follows:

1- Develop a model to evaluate the LNG shipping via vessels by analyzing different scenarios and assumptions for LNG transportation in Qatar. This analysis is focusing on calculating the emissions that come out from the vessels during transportation.

2- Evaluate the human health impact of LNG transportation by using the environmental Life Cycle Assessment.

3- Apply sensitivity analysis to identify the main parameters that are significantly affecting the LNG shipping emission results.

4- Analyze the results that LNG shipping emissions are highly sensitive to, and the emission factors that are specified for each vessel/ fuel type, thus the proposed solutions should take this into consideration. These scenarios benefit and challenges have been addressed to facilitate decision making on whether to go with the proposed solutions or not.

5- Define the most beneficial delivery scenarios for Qatar that have less impact on human health based on the emission results. These scenarios will be discussed in detail in the upcoming chapters.

## 1.4 Scope

The scope is focusing on calculating the emissions that are related to the transportation process of the LNG value chain, so all other stages like liquefaction and regasification are excluded. We targeted 4 group of gases as follows: 1- Greenhouse gases (GHG) including $CO_2$, $CH_4$, $N_2O$, 2- Priority metals including Pb, Cd, Hg, 3- Particular Matter including $PM_{2.5}$, $PM_{10}$, TSP, 4- Main Pollutants including $NO_x$, CO, NMVOC, and $NH_3$. Consequently, we aim to use this calculated air emission results to develop a generalized Life Cycle Assessment based model. In the model, the focus will be to evaluate the environmental impact, specifically on human health. The model for evaluating the environmental impact is implemented in the midpoint and endpoint level. The midpoint impact category includes many factors like climate change, resource depletion, land use, water use, human toxic effects, ozone depletion, photochemical ozone depletion, ecotoxic effects, eutrophication, acidification, and biodiversity. For the endpoint (damage categories), as mentioned earlier the focus will be only on human health impact. This research is applied to the LNG companies inside Qatar only.

## 1.5 Outline of the Thesis

This research started with inspecting published research about LCA and sustainable development of LNG transportation in Chapter 2. In addition, it tackled the LNG subject and the Hydrocarbon sector in Qatar. Chapter 3 explained the LNG shipping by providing an overview of the LNG shipping and types of vessels used in Qatar. Chapter 4 describes the methodology embraced and the various approaches used to develop this research. It includes information about finding the emission results from different types of vessels and fuels, as well as applying the Environmental- LCA ReCiPe approach to evaluate the Human health impact coming from each type. While in Chapter 5, findings and results are discussed in detail including emission calculation results, LCA results, and sensitivity analysis findings. Finally, Chapter 6 provide research summary, conclusion and recommendations well as limitation and future work related to this research.

# CHAPTER 2: LITERATURE REVIEW

## 2.1 LCA and its Applications on LNG Transportation

According to WCED (1987), Sustainable development is the development that satisfies the requirements of the current time without cooperating with the ability of the coming generations to satisfy their own requirements (Shaikh et al. 2017; Onat et al. 2017a, b; Kucukvar et al. 2016; 2014). Sustainable development is mainly focusing on 3 main points of sustainability as follow: Economic, Environmental, and social (Kucukvar and Tatari, 2012). For Ciroth et al. (2011), Life cycle sustainability assessment (LCSA) is very important as it is addressing the assessment of all environmental, social and economic in terms of positive and negative effects in decision-making processes in order to have products that are sustainable during their life cycle (Onat et al. 2016 a, b; Onat et al. 2014a, b; Gumus et al. 2016; Kucukvar et al. 2014; Kucukvar and Tatari, 2013). A lot of reasons are behind the desire in following LCSA.

LCSA helped in increasing the global consciousness of the necessity to save and protect the environment; raising the acknowledgment of the dangers of trade-offs between possible effects related to the goods for both manufactured and consumed. This highlights the need of considering and paying attention to the issues related to climate change and biodiversity from a holistic perspective. Because of that, the interest increases, specifically in terms of evolving approaches to realize and address the effects of products along their life cycle in a better way. By following the LCSA approach, many benefits have been obtained; it allows experts to organize complex environmental, economic and social information and data in a structured form as well as affords a full picture of the good and bad effect of the product along the life cycle (Tatari and Kucukvar, 2012; Kucukvar et al. 2015; Kucukvar et al. 2014;  LCSA also increases the awareness in value chain actors on sustainability subjects and it helps enterprises in finding weaknesses and enables additional enhancements of the life cycle of the product (Onat et al. 2014). Finally, it supports decision-makers in ordering resources and investing them where there are more chances of optimistic effects, supports them also to select sustainable technologies and goods, helps customers to select the best products especially in terms of cost-efficient, and stimulates innovation in enterprises and value chain actors. There are three stand-alone techniques that adapt to ISO 14040 2006 and ISO 14044 2006 as follows: Environmental LCA, Social LCA, and Economic LCA as addresses by (Alirezaei et al. 2017; Onat et al. 2017; Onat et al. 2016; Onat et al. 2014).

Huijbregts et al. (2016) addressed the Environmental Life Cycle Assessment (E-LCA) as an operational tool that is used to analyze the life cycle of products or activities within the framework of environmental influence. To align with this goal, definite calculation tools are being implemented. In LCA, the product or activities total life cycle is measured starting from the phase of extraction of resource materials until the phase of the waste and waste treatment (Onat et al. 2019a, b; Onat et. al. 2018; Kucukvar et al. 2019; Onat et al. 2018a, Sen et al. 2019). As mentioned earlier, this can be referred to as "from cradle to grave".

There are many studies that applied the LCA method in the LNG sector. Barnett et al. (2010) represent in his study an assessment on the impact of LNG from the environmental perspective especially in the stage of liquefaction, shipping, and re-gasification. Barnett et al. (2010) focused on implementing the LCA tactic. In this study, the focus was on the emitted Greenhouse Gases (GHG) that are measured in the form of carbon dioxide ($CO_2$) equivalent emissions and he provided some endorsements for enhancing the technology and process. Arteconi et al. (2009) conducted an important life cycle comparison of LNG as well as diesel where both are used as fuels for heavy-duty automobiles in the European market. This comparison is done using the emissions of greenhouse gas (GHG). The main concentration was on the European situation and on heavy-duty street transport automobiles, and the reason behind that is given their significant incidence on the global emissions of greenhouse gas. Tamura et al. (2001), conducted a life cycle analysis for $CO_2$ emissions of LNG production and city gases. The study was performed mainly on greenhouse gas emissions that are coming out from the LNG chain. Adding to that it also performed on the life cycle of City Gas 13A that is formed from LNG. The study was constructed by analyzing consistent data. Therefore, in terms of representativeness and source, data proved to be reliable. This analysis used the field studies to obtain data for the latest emissions of $CO_2$ and $CH_4$ that are coming from the natural gas field and liquefaction plant. Furthermore, it covers the emissions of $CO_2$ while delivering the LNG to Japan from exporting countries, as well as the production and distribution of the city gas in Japan.  It also covers the manufacturing of facilities that are related to natural gas production abroad to final domestic consumption. Kameyama et al. (2005), concentrated on the expansion of the software of LCA for ships as well as the analysis of LCI, which is based on certain operations and shipbuilding. He proceeds with his study by developing database and software made especially for ship analysis by using

LCI that is built on an exhaustive investigation of real procedures of shipbuilding and ship-operation. This important database contains data that are processed with respect to material processing in typical shipbuilding processes. It affords average data of real operational conditions of typical ocean-going cargo ships which contains the data of two tankers, two bulk carriers and two container ships with different sizes, and an LNG carrier and a pure car carrier. Ryste (2012) applied the screening in her study which is a simplified LCA that meant to detect the significant parts of a life cycle. So, the main objective is viewing the LCA of LNG as fuel by performing a life cycle study of the procedure of LNG Bunkering. The reason behind selecting the area of the LNG bunkering and the facility bunkering is the uniqueness of this area as the processes associated with the bunkering area are not tackled or analyzed at a detailed level in any of the published literature. This study used GaBi Educational to execute the bunkering model and to analyze the life cycle inventory results. Basically, GaBi Educational is a software related to LCA and used for this purpose. Shi, et al. (2015) focused on evaluating the effect of the recently produced diesel engine and reproduced LNG Engine from Life Cycle Environmental point of view. In this analysis, he used a life cycle assessment for the sack of measuring the energy that has been saved. LCA also used to find out the emissions to the environment that come out from the reproduced engines which are consuming the LNG and the ones that are newly manufactured engine using diesel. Comparison has been applied for both engines in terms of the used material, amount of emissions to the environment during its lifetime and the required amount of energy by time. As said by Korre et al. (2012), the study applied the analysis of LCA on the supply chain of natural gas as well as the generating of the alternative shapes of power by taking into consideration the storage and the capturing of $CO_2$.  In this study, the area of LCA was tackled, and the phrase “cradle-to-grave” was mentioned to the implementation of a dynamic LCA framework as the assessment of different CCS technologies in the generating of the fossil fuel power. It demonstrated the mechanism of the LCA model that is created by using natural gas formed in the state of Qatar sent to the United Kingdom (UK) by using LNG in power plants with other conformations and $CO_2$ roads. The created LCI models are very effective in helping to measure the materials flow, natural resources flow, energy consumption, and so on. S. Finnegan1 addressed LCA of different types of energy sources in the area of transport operation. A comparison made between conventional and other types of vehicle fuels on the basis of LCA. The results demonstrated that, on the basis of a life cycle, the vehicles which run by LFG compare favorably with the ones that are powered with gas as they proved to produce less amount of pollution compared to those that are that the powered with liquid-fuel. On top of all of those, the electric vehicles become the best as it generally creates the least amount of pollution among all types.

Biswas et al. (2013) assessed the Carbon footprint of Western Australian of the production and delivering of the LNG to their customers in Asia specifically China. In this study, LCA is used to confirm the fact that the emission of Green House Gases (GHG) is created as a maximum during the phase of producing and liquefaction stage with a percentage of 45.4%. Then the next big amount comes out from the phase of exploring and separating the natural gas with GHG percentage of 39%. The least amount comes out during the phase of delivering the LNG with an emission amount of a maximum of 15.7%. On the other hand, Song et al. (2017) addressed the emissions of LNG and diesel used to operate the heavy-duty vessels as well as the consuming of energy in China. In this research, the investigation LCA is showed with a mixture of real-time energy consumption rate data for diesel and LNG used for automobiles in China that are heavy-duty, real provincial diesel and LNG heavy-duty vehicles population data, and a database of life-cycle inventory for the Tsinghua-LCA Model (TLCAM) stated for the context of China. Jaramillo (2007) aimed to distinguish between the electricity emissions of greenhouse gas (GHG), $SO_x$, and $NO_x$ life-cycle that are created with an energy source like natural gas (NG), LNG and coal. From the study point of view, the approach of comparing life-cycle air emissions from different energy sources can support to realize the pros and cons of utilizing coal versus globally sourced NG for generating the electricity.

### *2.1.2 The ReCiPe model*

According to Huijbregts et al. (2016), ReCiPe is considered as a technique for measuring the impact in LCA. Life cycle impact assessment (LCIA) interprets emissions and resource extractions into a definite and specified number of environmental impact scores by means of so-called characterization factors (Park et al. 2016; Onat et al. 2019). There are two mainstream ways to derive characterization factors, firstly at the mid-point level and secondly at the end-point level. ReCiPe measures 18 mid-point indicators and 3 endpoint indicators. For the mid-point level this covers the following: ozone depletion (OD); climate change (CC); freshwater eutrophication (FE); terrestrial acidification (TA);

marine eutrophication (ME); photochemical oxidant formation (POF); human toxicity (HT); particulate matter formation (PMF); freshwater ecotoxicity (FET); terrestrial ecotoxicity (TET); marine ecotoxicity (MET); agricultural land occupation (ALO); ionizing radiation (IR); urban land occupation (ULO); water depletion (WD); natural land transformation (NLT); mineral resource depletion (MRD) and fossil fuel depletion (FD). At the level of end-point, most of the listed mid-point impact groups are more transformed and collected into the following three end-point groups: damage to human health (HH); damage to ecosystem diversity (ED) and damage to resource availability (RA). So, the Midpoint indicators emphasis on single environmental issue, like climate change or acidification while Endpoint indicators illustrate the environmental effect on three higher aggregation levels. The process of changing midpoints to endpoints makes it easier to understand the results of LCIA. Nevertheless, with each aggregation step, uncertainty in the results can increase. Figure 1 below demonstrates and provides an overview of the structure of the ReCiPe.

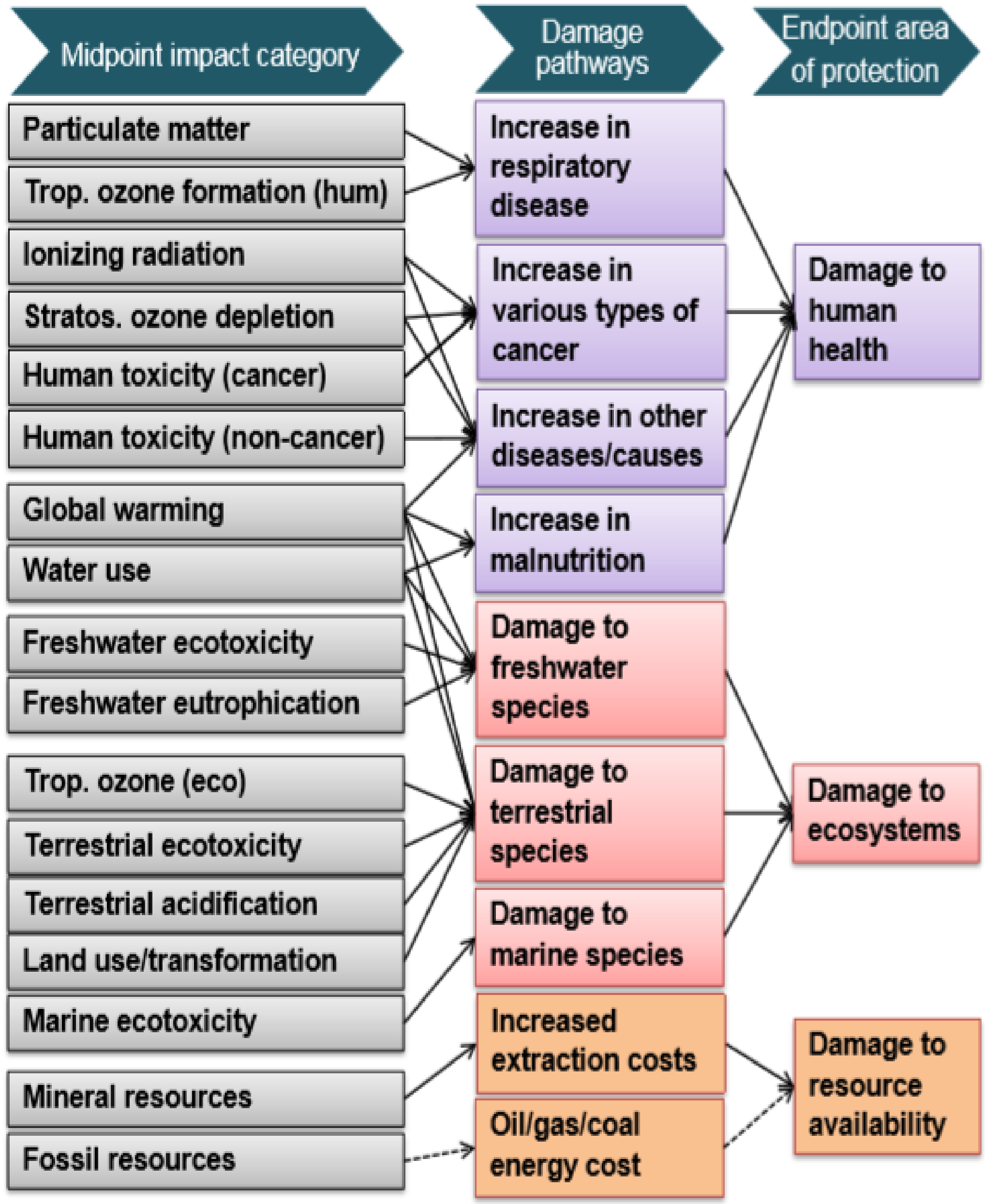



Figure 1: Overview of the impact categories that are covered in the ReCiPe2016 methodology and their relation to the areas of protection

## 2.2 Liquefied Natural Gas (LNG)

Liquefied Natural Gas has been defined as a natural gas that has been cooled to 161°C below zero until it turns into a condensed liquid state. The main components of liquefied Natural Gas are methane (90%), smaller amounts of ethane, propane, and butane (Qatargas - Homepage). Sakmar (2013) described the liquefaction as the process where the gas is transformed into a liquid, which was initially experimented in the 19th century by the British chemist and physicist Michael Faraday. Michael transformed several kinds of gasses into a liquid state in a successful way including methane which is natural gas. As a result of this successful liquefaction approach, it ended up having a liquid that is clear, colorless, non–toxic, and non–flammable. Along with Qatargas (Qatargas - Homepage), the liquefaction approach can minimize the volume of gas by approximately 600 times, which is similar to shrinking the size of a beach ball into a golf ball size (Figure 2). Ultimately, this approach resulted in the storage and transportation stages becoming easier and more efficient.

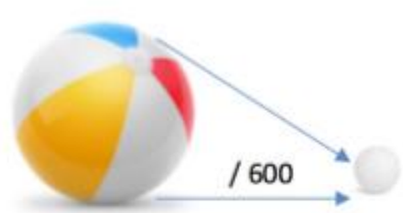



Figure 2: Demonstration of the changing on the size of Gas after liquefaction

Moving to the transportation and referring to the study done by Donev, J. (2015), he described the way of transporting the LNG as any movement or shipping of natural gas while in its liquid form. For natural gas, there are two ways to transport, either through a pipeline or by using vessels to ship it as LNG. Transporting gas through a pipeline is technically and economically feasible for short distances, in contrast, it turns to be a real struggle if the customer is thousands of kilometers away.

### *2.2.1 Liquefied natural gas pipelines*

As said by Donev, J. (2015), liquefied natural gas flows efficiently through pipelines so it is considered an ideal way of transferring natural gas. The set-up of the LNG pipeline takes the LNG between liquefaction facilities and storage facilities, from facilities of storage to trucks, and from trucks to facilities of re-gasification. The density of the LNG is more than the density of the compressed natural gas (CNG). This leads to the fact that it is possible to deliver higher amounts of gas for the same volume flow. The main disadvantage of the pipelines of the LNG is that it is difficult to build plus their cost is high.

As per Donev, J. (2015), liquefied natural gas needs a temperature of -260°F (-160°C) to keep it in liquid formula. Important insulation should be combined into LNG pipelines in order to maintain this low temperature and ensure no re-gasification occurs. Usually, this contains a mixture of mechanical insulation, for instance, glass foam and a vacuum layer. In the end, this complicated system makes LNG pipelines manufacturing harder and much costly compared to the standard natural gas pipelines.

### *2.2.2 Value Chain of the Liquefied Natural Gas (LNG)*

According to SLNG (Singapore LNG Corporation Pte Ltd.), natural gas goes through many steps and technologies before it finally ends up to the clients. Those steps are called the value chain of the Liquefied Natural Gas. This LNG value chain consists mainly of 7 steps: exploration, production (hydrocarbon reservoir) and gas treatment, liquefaction (processing plant), shipping (LNG carriers), receiving and distribution (storage and regasification). Firstly, is extracting and producing natural gas from the field as the extracted natural gas is not pure and it involves other components such as water, other non-hydrocarbons such as sulfur and condensates. As a result, natural gas must go through the treatment process in specialized factories to isolate liquids of natural gas (such as condensate and LPG) from solids and other impurities so that mainly methane is remaining. After that and as explained in the Qatargas, the methane is transferred into a liquefaction train where it gets cooled to -161°C. The liquefaction step is essential in order to decrease the volume of gas by transforming it into a liquid, which leads to having an easy and more efficient transportation to clients. Thereafter, the LNG is stored in insulated metal tanks whenever liquefaction is done to maintain it at -161°C until it gets loaded into a specially created LNG vessel. Later, the LNG is moved to be transported by the LNG vessels which also has chambers that are insulated especially to maintain it at -161°C during the voyage (Qatargas- Home Page). Subsequently, when the LNG ship reaches its endpoint, the LNG is converted to a regasification plant to be changed again to its gaseous state. Finally, the last stage in the value chain is transporting the gas through a pipeline to end-users to provide energy to different purposes. Figure 3 illustrates, in brief, the main LNG value chain phases as well as the gas volume variation in each stage.


Figure 3: shows the main steps in the LNG value chain and gas volume variation in each stage

### *2.2.3 The Supply and Demand of the Natural Gas*

As stated by BP Energy Outlook- Energy Economics (2017), the global landscape of energy is kept moving and varying, as the demand for energy is continuing to increase along with the prosperity growth in emerging markets like China and India. Both the environmental concerns of the world and the continuous improvement of the efficiency of energy are the main drivers of the transition in the energy mix. Nevertheless, oil, gas, and coal will continue to be the major source in the energy mix with having natural gas to be the fastest-growing fuel from all with an increased rate of 1.6% per annum and is expected to be the second-largest source of energy by 2035. As it is clear in Figure 4 there is a continuous growing share of gas in the world primary energy which proves the importance of natural gas to be chosen as a preferable source of clean energy.

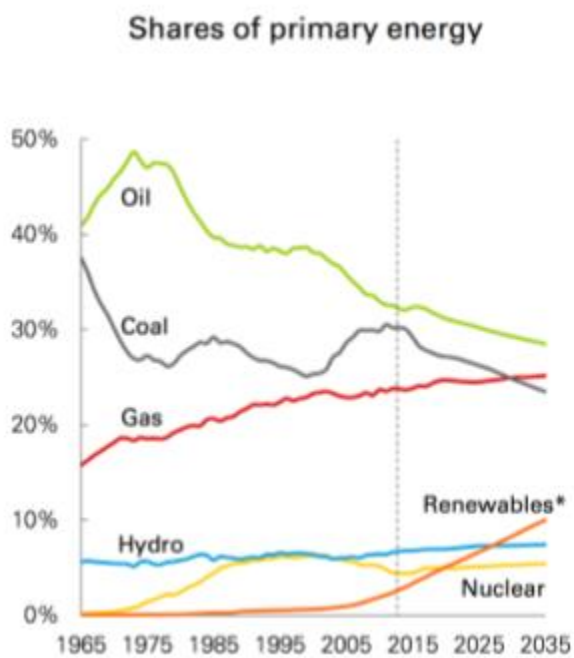
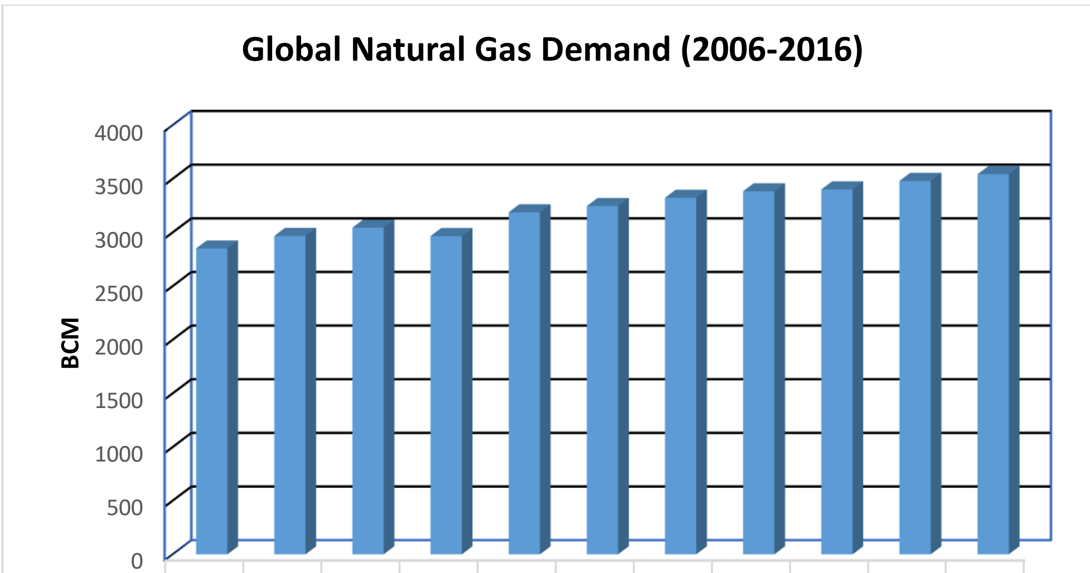



Figure 4: Shares of primary energy (Source: BP Energy Outlook – 2017)

As per BP Statistical Review of World Energy (2017), during the period between 2006 and 2016, there was an obvious demand increase in the global natural gas in annual basis by almost 2.2%, as the global energy demand during 2006 was 2851 bcm (billion cubic meters) and it increased during 2016 to become 3543 bcm as it is shown in Figure 5. Excluding the year of the financial crisis in 2009, where the sector of oil and gas affected due to the fall in demand level.




| | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| BCM | 2850.6 | 2967.3 | 3044.9 | 2965.9 | 3187.6 | 3245.9 | 3323.1 | 3383.8 | 3400.8 | 3480.1 | 3542.9 |

Figure 5:Global natural gas demand (source: BP statistical Review)

IHS Markit, IGU World LNG Report. (2017) explained that natural gas proved to become a preferred source of energy as its demand represents almost a quarter of the energy worldwide, of which 9.8% is LNG. As per the Wood Mackenzie – LNG Tool (2017), the total demand for LNG is around 350.63 bcm/yr during 2016, and it is expected to continue growing to reach 535.32 bcm/yr in 2023. Japan ranks the first as one of the most important customers with the share of 32.2%, followed by South Korea and China which account for 13.1% and 10.4% consecutively, for that reason, the demand of LNG in Asia-Pacific becomes the highest as shown in Figure 6

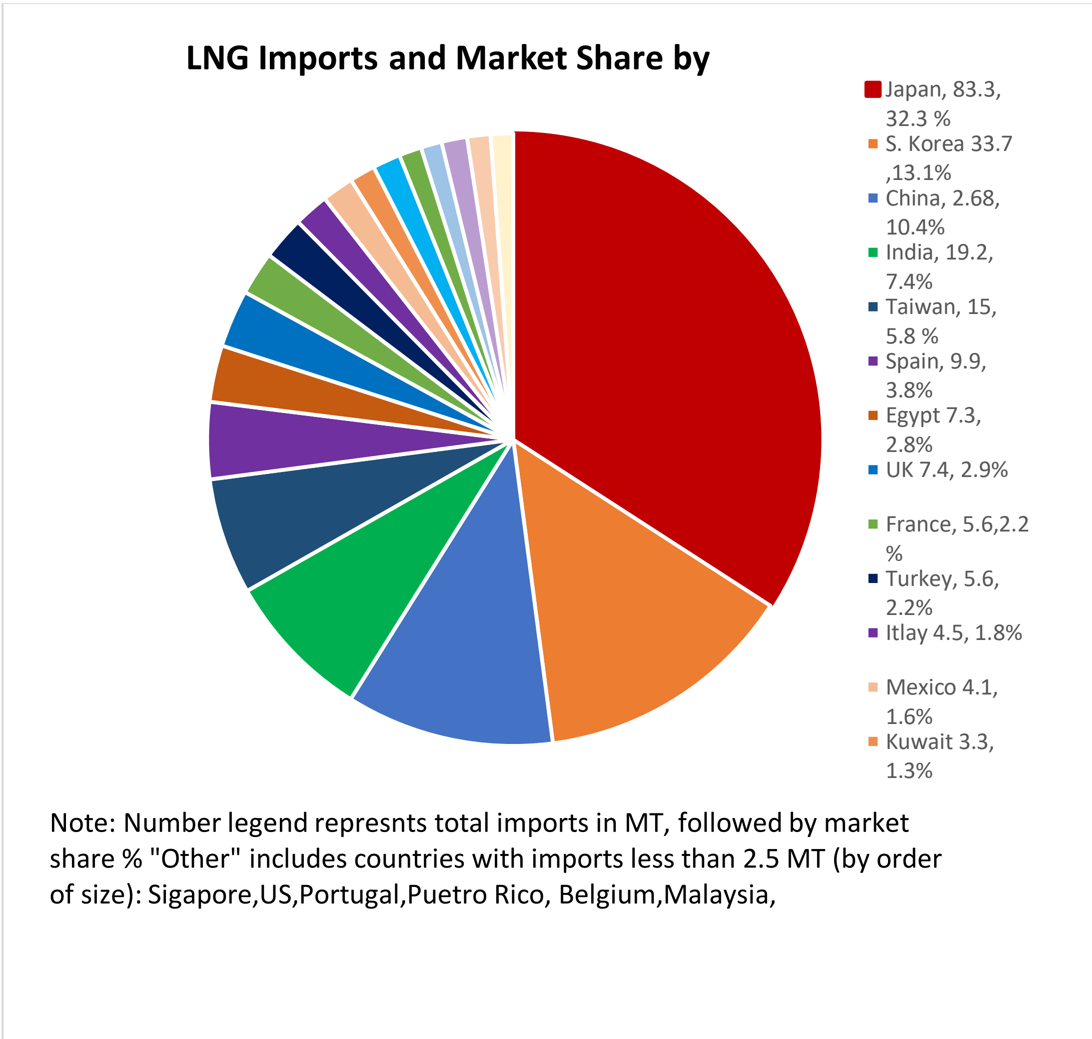



Figure 6: LNG Imports and Market Share by country (Source: IHS Markit, IGU – 2017)

According to the BP Statistical Review of World Energy (2017), the global supply of natural gas is led by the demand as both of them are increasing in parallel with each other with annual increases of almost 2.13% from the period 2006 to 2016. The study found that the global energy supply was 2876.7 billion cubic meters where it amounted to 3551.6 billion cubic meters in 2016 as it is shown in Figure 7.

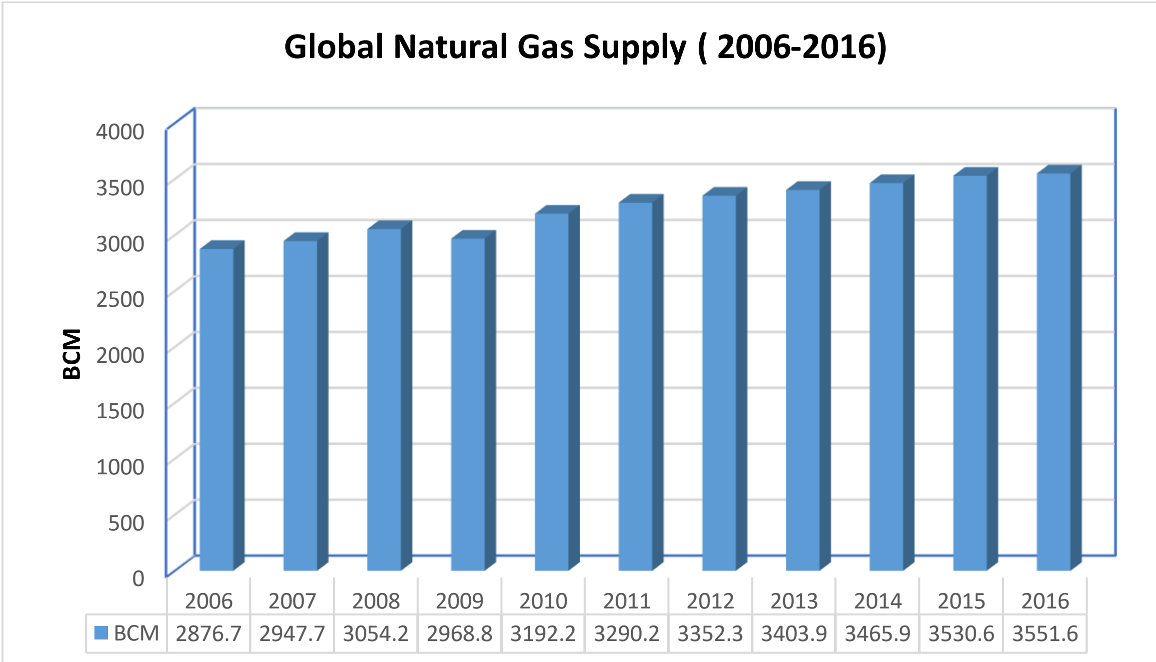



Figure 7:Global natural gas supply (source: BP Statistical Review)

IHS Markit, IGU World LNG Report. (2017), detected that LNG grew quicker as a source of supply much more than other types of gas, and it will continue its growth in the future. As is clear in Figure 8, the number of LNG exporting countries in 2016 becomes even more and reaches 18, as Egypt and Angola resumed their LNG production. In spite of that, the state of Qatar continues to be the largest LNG supplier among them all with the amount of 77 MT and a global market share of 30%.

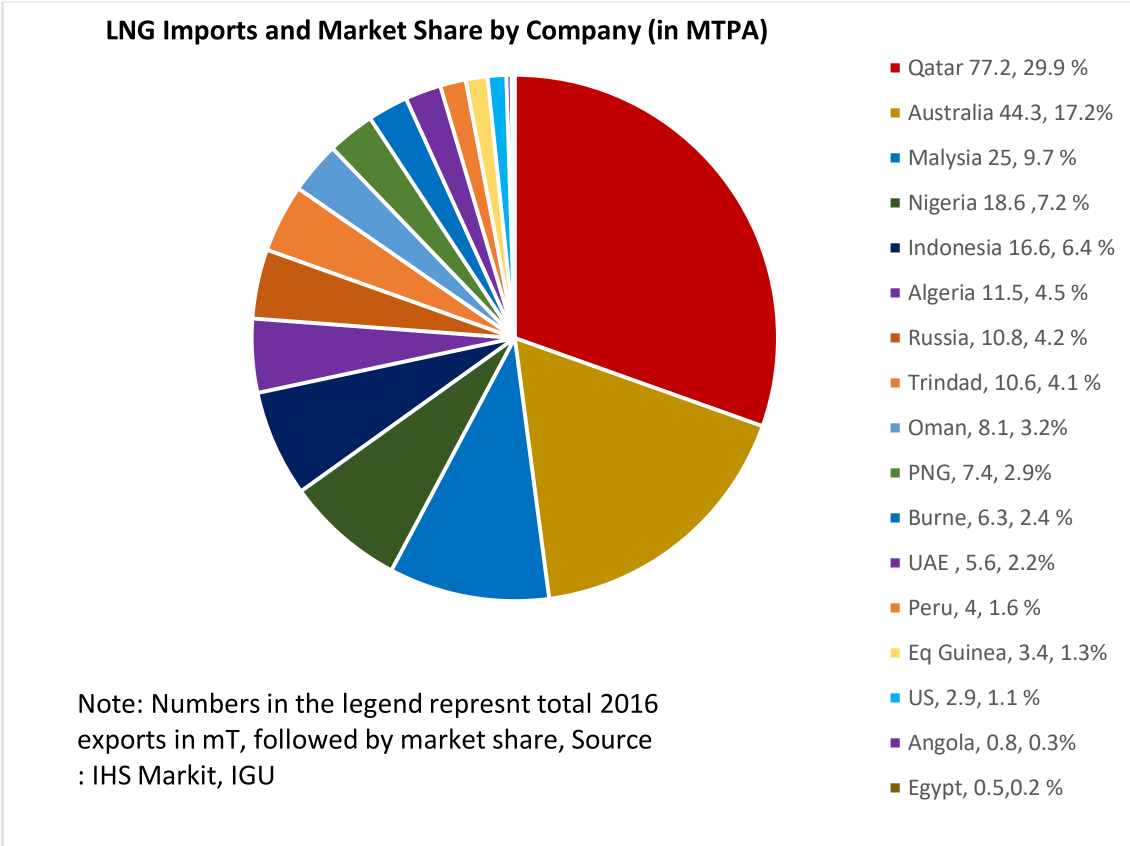



Figure 8: LNG exports and market share by country (Source: IHS Markit, IGU – 2017)

## 2.3 Qatar and its Hydrocarbon Sector

Consistent with the U.S. Energy Information Administration. (2015), Qatar is identified as the largest liquefied natural gas exporting country in the world. Similar to other countries in the region, Qatar’s economy is highly dependent on oil and gas extraction. During 2015, about 85% of Qatar’s exports were from the hydrocarbon sector. Figure 9 shows Qatar's export percentage by commodity.

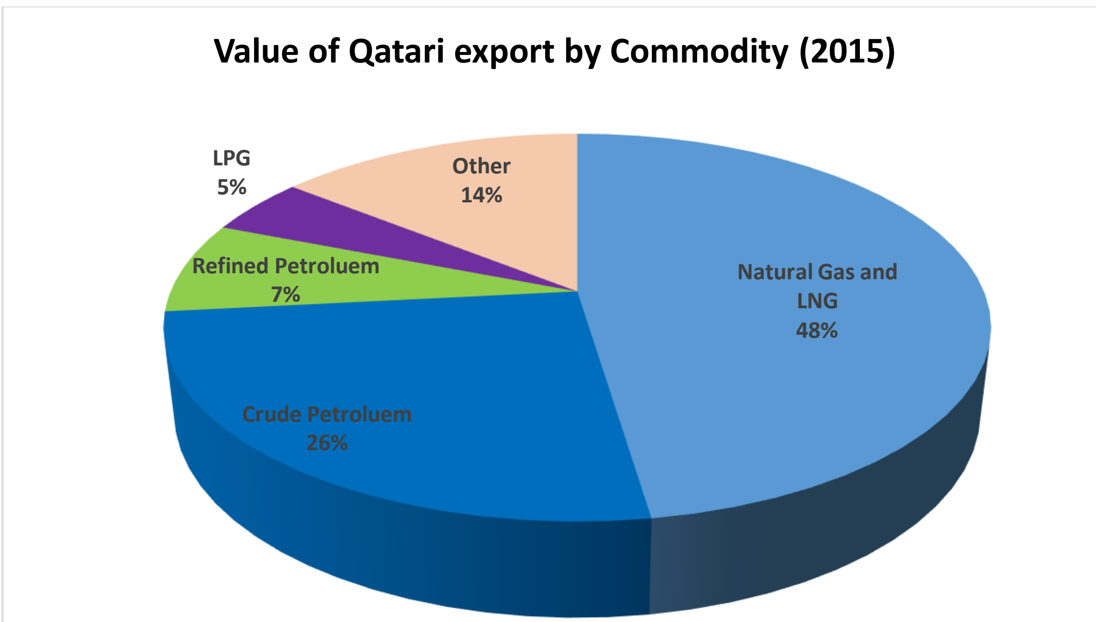



Figure 9:Value of Qatari exports by commodity- 2015 (Source: Wood Mackenzie)

Today, Qatar’s economy has shown a remarkable transformation in a short phase of time as the revenues of hydrocarbon increased dramatically especially with the development of oil and gas production.

As stated by Wood Mackenzie-LNG Tool (2017), Qatar's natural gas production is increasing year by year (excluding the time during 2016 where a slight reduction appears in Qatari LNG output), as it is clear in Figure 10. This amount will be even more especially with the additional production coming from the North Field expansion project, so the natural gas production is anticipated to keep increasing.

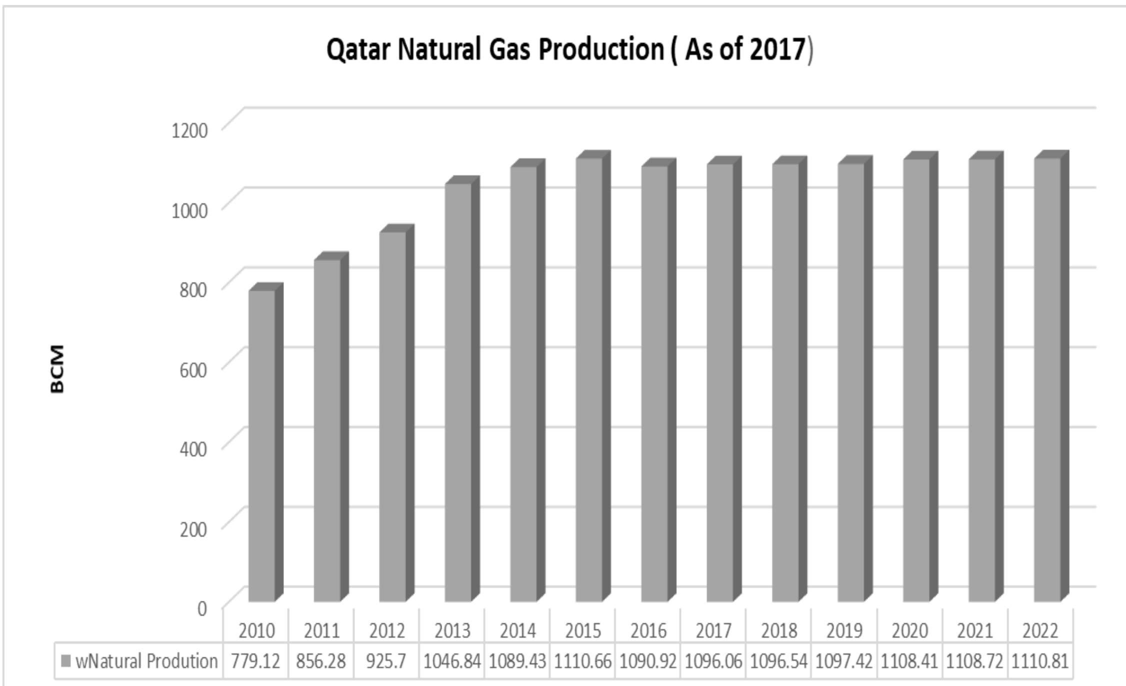



Figure 10:Qatar Natural Gas production-2017 (Source: Wood Mackenzie – LNG Tool (2017))

As per the study The Richest Countries in The World. (2018) it has been found that the state of Qatar is classified as one of the richest countries not only in its region but in the whole world, and the reason behind that is its high GDP (gross domestic product) per capita. As stated by The Peninsula Qatar, it tickled the subject of North Field development to boost Qatar's GDP (2017) and it came up with the fact that this high increase in GDP is due to the country’s huge growth in the area of hydrocarbon, with emphasizing on the production of the natural gas that represents a major driver for Qatar’s economic development.

Along with Wood Mackenzie- LNG Tool (2017), it becomes clear that the GDP is continuously growing year by year. For example, in 2015 the state revenue was 141 US$ billion and in 2016 it continues to grow to 147 US$ billion. Data projection shows that GDP evolution will continue after 2022, especially with the North Field project expansion which will boost the GDP growth.  Figures 11 and 12 show the values of real GDP on a yearly basis and the annual GDP growth rate yearly.

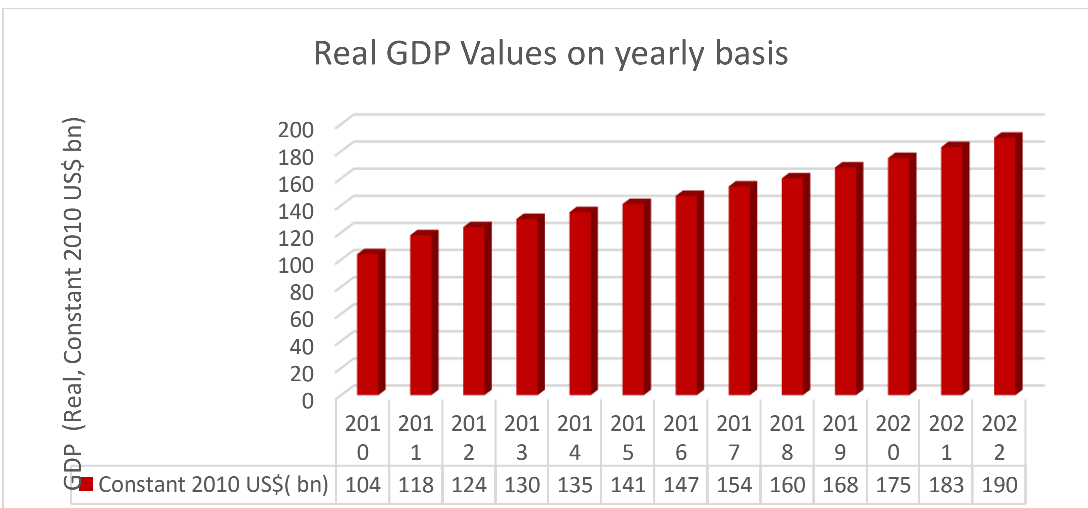



Figure 11:GDP values on a yearly basis (Source: Wood Mackenzie – LNG Tool (2017))


Figure 12:Annual GDP growth rate (Source: Wood Mackenzie – LNG Tool (2017))

This started in 1971, when the State of Qatar discovered the world's largest non-associated natural gas field. As said by Ibrahim and Harrigan (2012), the North field reservoir gas reserves were estimated to be over 900 trillion cubic feet (Tcf), accounting for 14.3% of the world's proven reserves.

At that point, the associated gas from oil fields was misused and flared because it had neither the commercial nor usage value worldwide it has today. However, according to Ibrahim and Harrigan (2012), this situation has been changed in the early 1980s, where the world has begun to look at natural gas as a useful and important resource. As a result, the natural gas demand has been increased in a huge way and considered as an important source of energy. Therefore, Qatar had to overcome the challenges of logistics and distance to reach the main markets prior to utilize the huge potential of the North field. Once the country's leadership gave permission to start building a gas hub at Ras Laffan in 1992, the state of Qatar works hard toward improving the supply process of the LNG.

As discussed by Ibrahim and Harrigan (2012) the hub was accomplished by 1996 with a budget of around 2$ billion US dollars. The funding of the North Field development was partly provided by Qatar’s crude oil foreword sales as a self-sponsorship system aimed at upgrading the North field oil and gas sector in the country.

The successful approaches followed in Qatar’s hydrocarbon sector explains the country’s recognized achievement in overcoming most of the constraints that are related to the development of the LNG infrastructure from its early stages of extraction to its end of delivery to the customer. This great success has impacted positively to the country’s position as one of the wealthiest in the world. On the word of Ibrahim and Harrigan (2012), all of that was no coincidence, but a consequence of successful monetization of its hydrocarbon resources, a committed leadership, and visionary and ambitious strategies. Figure 13 shows a timeline view of the major developments of the hydrocarbon sector in Qatar starting from 1970 when the North Field has been discovered until 2015 where the Barzan project was accomplished.

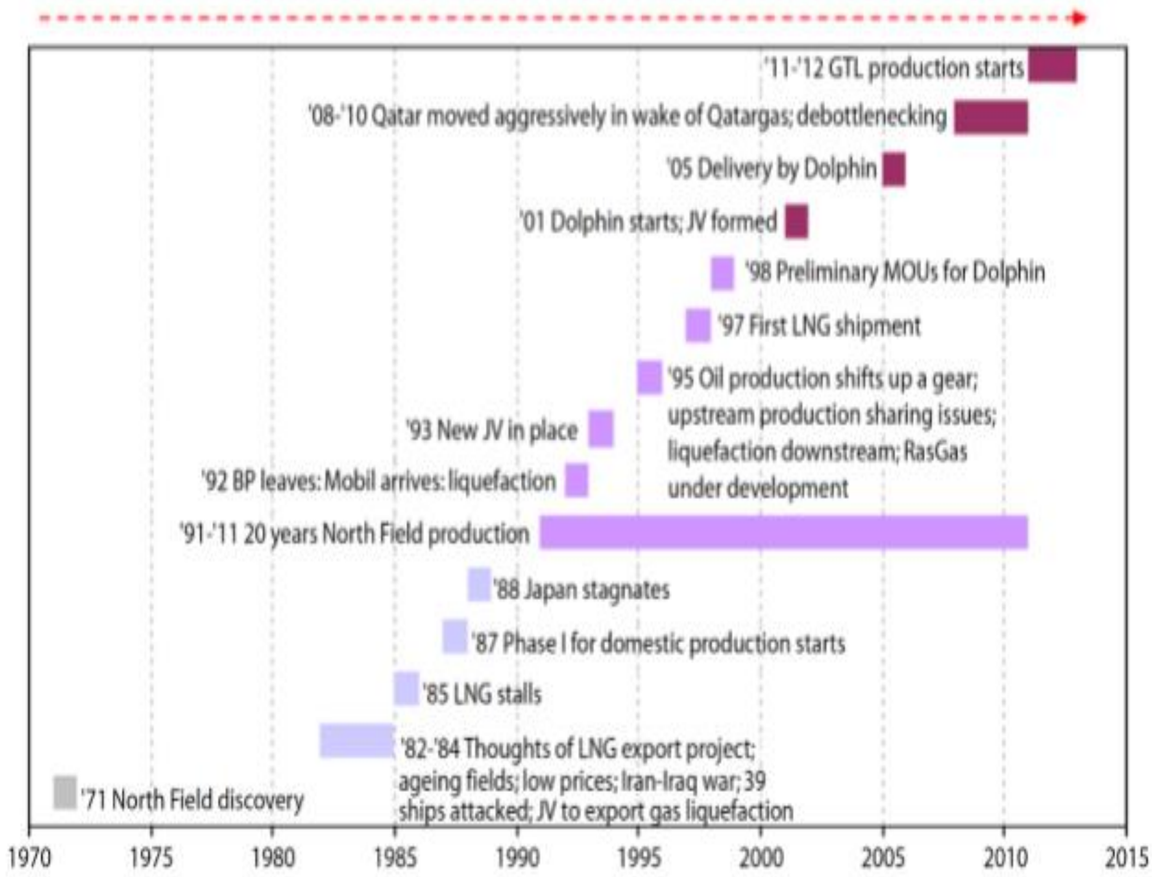



Figure 13: Timeline view of the major developments of the hydrocarbon sector in Qatar (Source: Qatar Petroleum)

### *2.3.1. Qatar's Natural Gas Proved Reserves and Production Capacity*

According to Wood Mackenzie-Qatar energy update (2017), the world's largest LNG provider is the state of Qatar with a production capacity of 78 Mt as of 2016 accounting for 29% of the global LNG supply. Adding to that its crude oil production capacity is 660 kb/d accounting for only 2% of OPEC oil production, as it is clear in Figures 14 and 15.

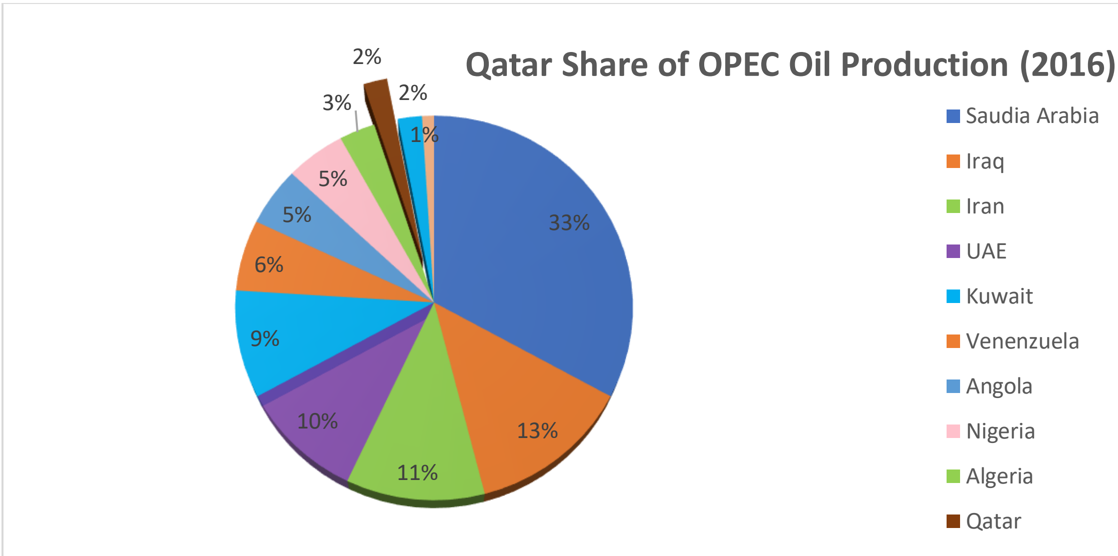



Figure 14: Qatar's Share of OPEC Oil Production- 2016 (Source: Wood Mackenzie)

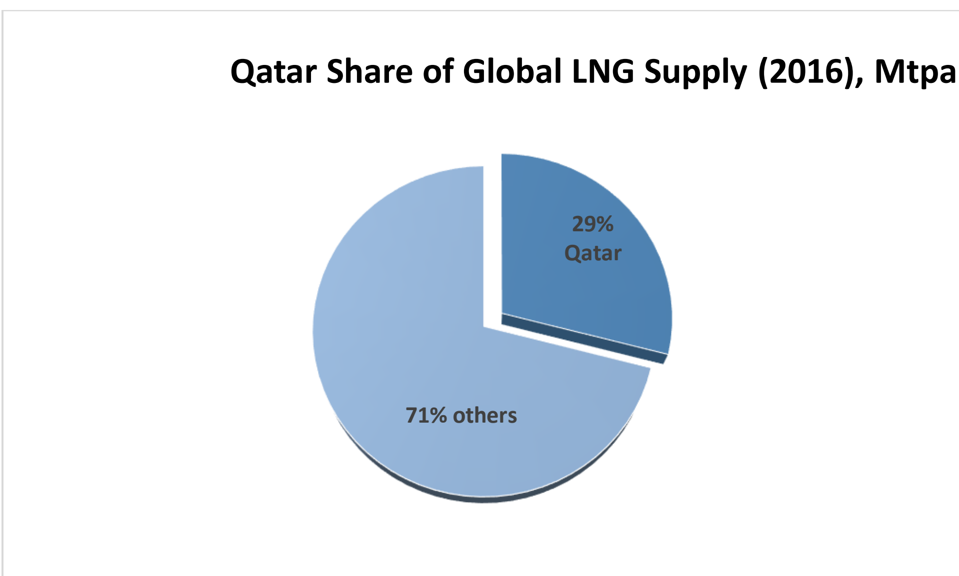



Figure 15:Qatar's share of global LNG supply- 2016 (Source: Wood Mackenzie)

As per BP Statistical Review of World Energy (2017), Qatar owns the third-largest proven reserves of natural gas after Iran and the Russian Federation at 858.1 trillion cubic feet (Tcf) with a total share of 13% by the end of 2016. Qatar's exports are produced from the offshore area of the North Field as it is the main source of the country's reserves and it is located between Qatari and Iranian borders. Along with Wood Mackenzie, it predicted that around 900 Tcf of recoverable reserves are located in the Qatari western portion and 500 Tcf is located in the Iranian eastern South Pars portion of the North Field. Adding to that, over 650 Tcf of the estimated remaining recoverable gas for Qatar is available for any further developments, as it is clear in Figure 16.

Qatar Petroleum (QP) declared lately that there would be an expansion around 43% of the current LNG capacity in the next phase of North Field development. For that reason, LNG exports would increase from 77 to 110 MMTPA. This great movement will help Qatar to remain being the world's largest LNG exporter and leader for the foreseeable future.

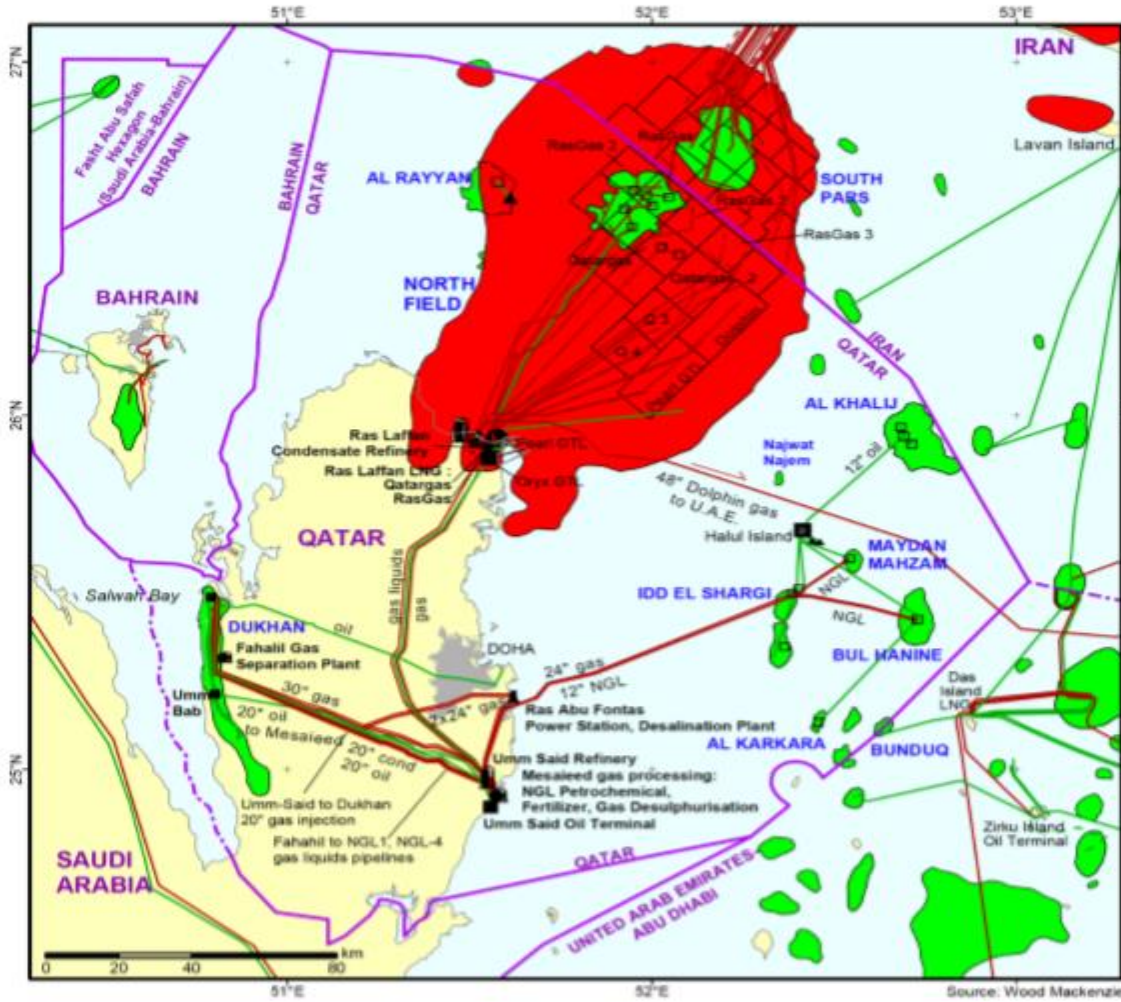



Figure 16: Qatar’s North field (Source: Wood Mackenzie)

### *2.3.2 Trade Movements of Qatar’s Natural Gas*

The trade movements of the Qatari gas are through one of the two possible ways; either through a pipeline or by using vessels to transport the LNG. According to Wood Mackenzie- Qatar's energy update (2017), the state’s LNG volumes are transported to many key customers in Europe and Asia. Because of the higher prices in the Asian markets, most of Qatar's volume were diverted to the Pacific region. Consequently, the trade volume between the Middle East and Pacific considered the second largest. In contrast, and as per IHS Markit, IGU World LNG Report (2017) the trade volumes between the Middle East and Atlantic declined by 7% of the global trade. As it is clear in Figure 17 & 18, Qatar's key LNG market destinations are Japan (Qatar's largest market), South Korea, India, United Kingdom, Taiwan, China, and Egypt.

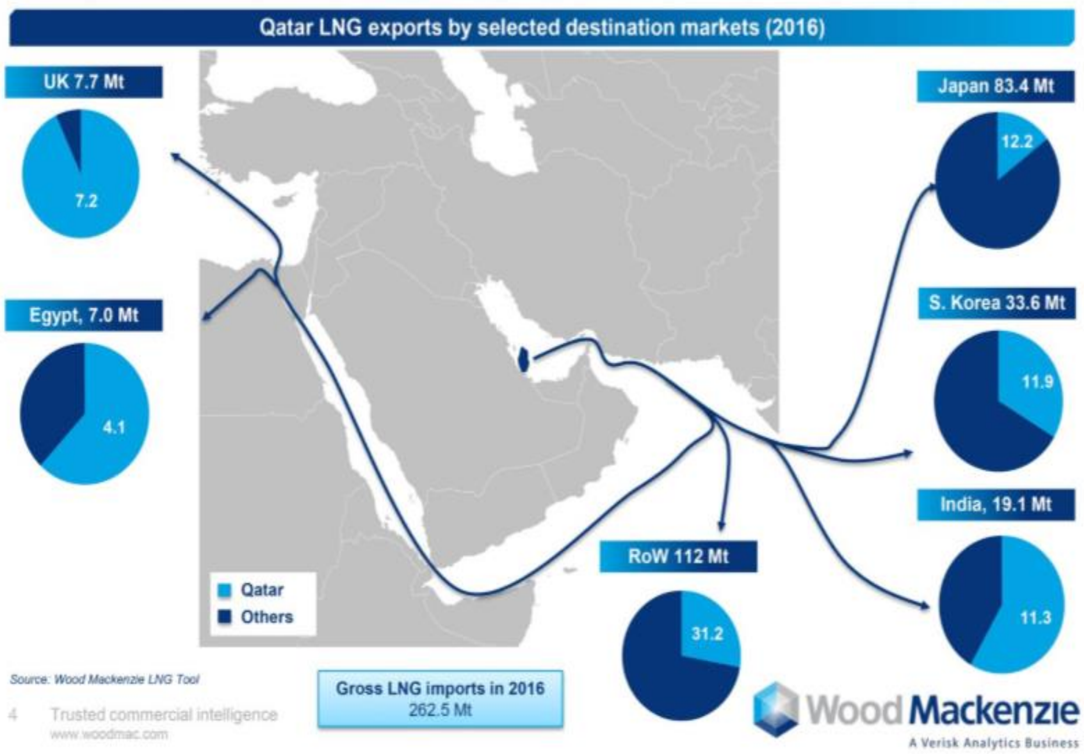



Figure 17:Qatar LNG exports by selected destination market- 2016 (Source: Wood Mackenzie)

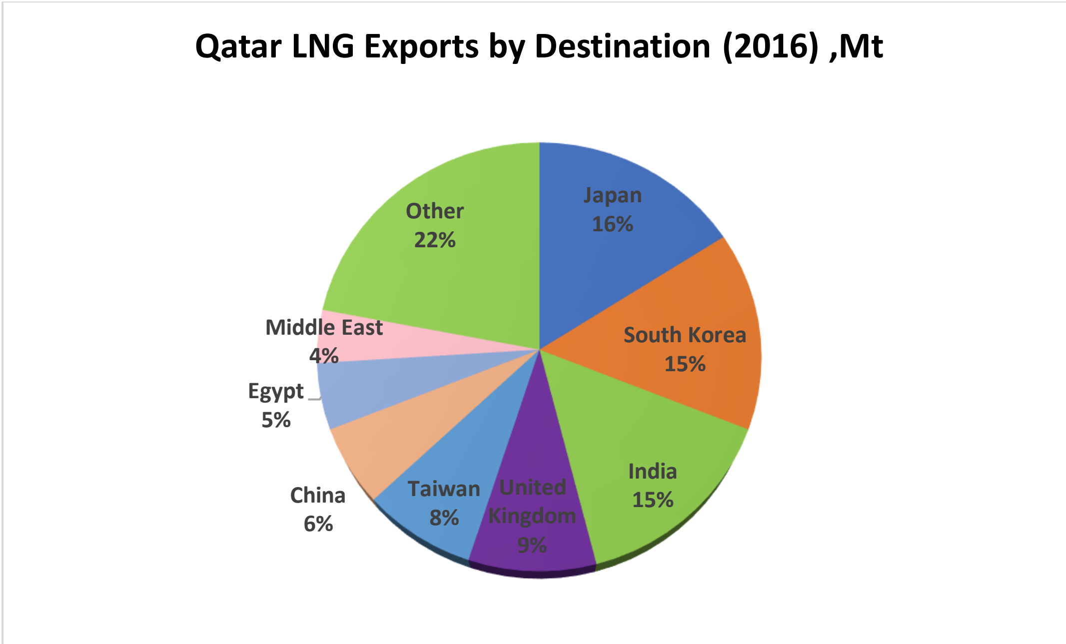



Figure 18: Qatar LNG exports by destination- 2016 (Source: Wood Mackenzie – LNG Tool (2017))

As stated by Wood Mackenzie-Global gas markets long-term supply outlook – Qatar H1(2016), Qatar provides the United Arab Emirates (UAE) and Oman with natural gas through the Dolphin Pipeline. At first, Dolphin Energy started to supply with a size of 11 bcm per annum, and now this amount has been increased to become 33 bcm per annum after expansion. As per BP Statistical Review of World Energy (2017), the movement of the natural gas trade from Qatar to UAE by pipeline in 2016 reached 17.9 billion cubic meters (bcm) and from Qatar to Oman 2.1 billion cubic meters (bcm).

### *2.3.3 QP and its Affiliates*

Qatar Petroleum (QP) and its joint venture Qatargas are both belong to the state of Qatar. As QP is a national oil company, it is the central point of contact for any hydrocarbon investment in Qatar. Therefore, QP is in charge of all the aspects of the country's hydrocarbon sector from the upstream to the downstream for oil and gas. In other words, QP is responsible for the exploration, production, transportation, storage, marketing, sales of natural gas, crude oil, natural gas liquids, liquefied natural gas, gas to liquids (GTL), refined products, petrochemicals, and fertilizers.

Because of the fact that Qatar has one of the largest gas proven reserves, its main concentration is on the development projects on the natural gas. These projects have been conducted in corporation with international oil companies (IOCs). After 1992, Qatar has a very strong IOC's partnership, which is considered as the largest in the region. Along with IHS Markit- Qatar Petroleum LNG Company Profile (2017), Qatargas Operating Company Limited (QG) operates seven LNG ventures (QG1, QG2, QG3, QG4, RL1, RL2, and RL3) and its joint ventures (JV) embrace QP, Total, ExxonMobil, Mitsui, Marubeni, ConocoPhillips, and Shell.

As said by Ibrahim and Harrigan (2012), in the 1990s, buyers from Japan had been searching for reliable sources of LNG long-term supply, and Qatar became the main candidate. The reasons behind chosen Qatar is that the reliable gas and LNG infrastructure, political stability, strong technical development, and financial backing. Qatar met the Japanese requirements, as a result, the first commercial cargo of LNG was delivered successfully to Japan in 1997. That was the first sales and purchase agreement (SPA) with Chubu Electric in 1992 for a quantity of 4 million tons per year. In spite of that achievement, the distance between Qatar and other markets was still a critical problem. For that reason, it was essential to develop a fully integrated LNG project for the purpose of monetization of the country's huge gas reserves. Qatar considered the importance of developing an LNG shipping fleet to establish the connection between Qatar as a supplier and its customers around the world. As a result, Qatar took the responsibility to collaborate with different shipbuilders and owners to build customized ships that would facilitate the transportation of huge LNG volumes to meet the market demands. Nakilat is considered the main company which is responsible for transporting and shipping LNG as its main purpose is to customize LNG tankers for efficient LNG delivery.

### *2.3.4 Nakilat: Qatargas Transport Company*

Logistics and transportation are very important and crucial part of the LNG value chain. Usually, the natural gas goes through several stages before it reaches the customer; as it needs to be produced, treated, liquefied in a liquefaction plant and stored before it is loaded into a vessel. Qatar established Nakilat – Qatar Gas Transport Company Ltd in 2004 as it is the world's largest LNG exporter. As stated by NAKILAT, Our Fleet-Vessels (2018) the company is tasked with the ownership, operation, and management of LNG vessels across Qatar's hydrocarbon sector. Shipping Qatari gas to global markets is considered the core business of Nakilat, which gives power to the company. These vessels are hired through long-term contracts with Qatargas. Nakilat owns a fleet of 65 LNG ships and today the company became the world's largest LNG vessel owner.

According to IHS Markit, IGU World LNG Report. (2017), there are two main types of Q-class ships were designed for delivering and carrying huge amounts of the LNG. These ships are Q-Flex (210,000 - 217,000 $m^3$) and Q-Max (261,700 - 266,000 $m^3$) each with a cargo capacity bigger than any other in the world as mentioned in Qatargas – Homepage (2018). Adding to that, Nakilat also has another type of vessel called conventional (135,000 – 152,000 $m^3$). Consistent with IHS Markit – IHS LNG Shipping Database (2017), Qatar charters 70 LNG carriers through Qatargas company, and this agreement contains 14 Q-Max, 31 Q-Flex, and 25 Conventional ships. It is considered a great accomplishment for Qatar to own a national company like Nakilat that provides a combination of different LNG shipping services as it will improve the international reputation for efficient delivery of LNG and associated products to its clients.

# CHAPTER 3: LNG SHIPPING

## 3.1 Overview of LNG shipping

As discussed earlier, shipping is used to transport a huge amount of LNG from suppliers to customers around the world. Therefore, shipping is considered an essential element in the value chain of LNG. On the word of Shively et al. (2005), the first LNG shipping trip was from Algeria to the United Kingdom in the 1960s, it was commercial shipping using a marine tanker. The progress and development of the LNG shipping industry took around 34 years to reach 100 active LNG vessels. The success of LNG transportation along with the increased LNG shipping demand directed to significant growth in the LNG shipping industry, and nowadays it is recognized as the most profitable subset in the gas sector.

LNG shipping continues to grow over time in response to several changes in the LNG market. Along with the study on the Cost of Gas Transportation (2012), Japan's nuclear power plants were down in March 2011 because of the Fukushima and Tsunami disasters. As a result of the increase in Japan's demand for LNG, it led to the growth in its prices in North-East Asia. Thus, the LNG trade-flow patterns changed, affecting both the Asian and European gas markets. The global LNG suppliers diverted their cargoes of European gas to the more profitable Asian market as a result of the price gap between both basins. This diversion put a lot of pressure on the request for new vessels. This deteriorated the shipping market conditions, where it experienced higher shipping spot charter rates. However, the situation has changed nowadays, where the spot charter rates fall drastically due to the oversupplied market. As per IHS Markit, IGU World LNG Report. (2017), the continuous ship's new builds will continue pushing the market deeper to an oversupply period, thus maintaining the current low spot charter rates. However, this might alternate because of the growing number of the new liquefaction size during 2017 absorbing some of the surplus sizes.

## 3.2 The Capacity of an LNG Transportation

According to Wood Mackenzie-LNG fleet summary charts (2017), the active LNG shipping fleet in the world is consisted of 460 vessels as of January 2017 with a total shipping size of 70794.07 cubic meters of operational vessels. The LNG trade progress during 2016 was 6.0% and the estimated value is anticipated to reach 9.6% by 2017. During 2016, LNG shipping capacity raised by 7.1 % because of the reason that 28 new-build ships joined the fleet and only one ship was scrapped. This growth rate could be even more if there wasn’t any interruption or delay in meeting the scheduled delivery dates. There are around 48 vessels scheduled for transport in 2017 resulting in shipping capacity progress of 11.8% without any delivery slippage or ship scrapping. Consistent with Wood Mackenzie-LNG fleet summary charts (2017), the average age of the vessels is around nine years, where almost 51.5% of the 460 ships are below ten years. This was due to the ship's new build order boom to meet the liquefaction capacity growth during the mid-2000s and early 2010s. The operating ship ages vary from less than a year up to 45 years, with a total of 38 ships over 30 years and only 6 are above 40 years old.

There are many important points where the shipowners should consider, for instance, shipping safety, efficient delivery of LNG and the economics of the ship operating especially when it exceeds 35 years and decided to retire it. On the word of IHS Markit, IGU World LNG Report. (2017), in 2016, there are around 6% of ships above 30 years and active, however, these ships will be pushed out of the LNG ship market and will be substituted by newer and more efficient vessels. However, all those retired ships can be reused in the LNG shipping market, as the shipowner has the option either to send the ship for conversion or scrappage. As said by IHS Markit - LNG Shipping Report (2017), Qatar's national transportation company – Nakilat, owns the world's largest exporting capacity with the Q-Flex and Q-Max vessels. Nakilat is followed by MISC (Malaysia International Shipping Corporation) as the largest shipowner with 27 ships. Nevertheless, this position might be taken by Teekay company if it operates its newly created 19 ships.

Along with Wood Mackenzie-LNG fleet summary charts (2017), between the time 2000 – 2017, the global LNG ships raised by around 7%. Figure 19 shows the cumulative number of ships on a yearly basis between 2000 and 2017. As it is obvious, the figure demonstrates a clear increase in ship quantity between the years 2004 and 2008, as it is reaching the highest in 2008 with a total of 296 as additional 47 ships entered service.

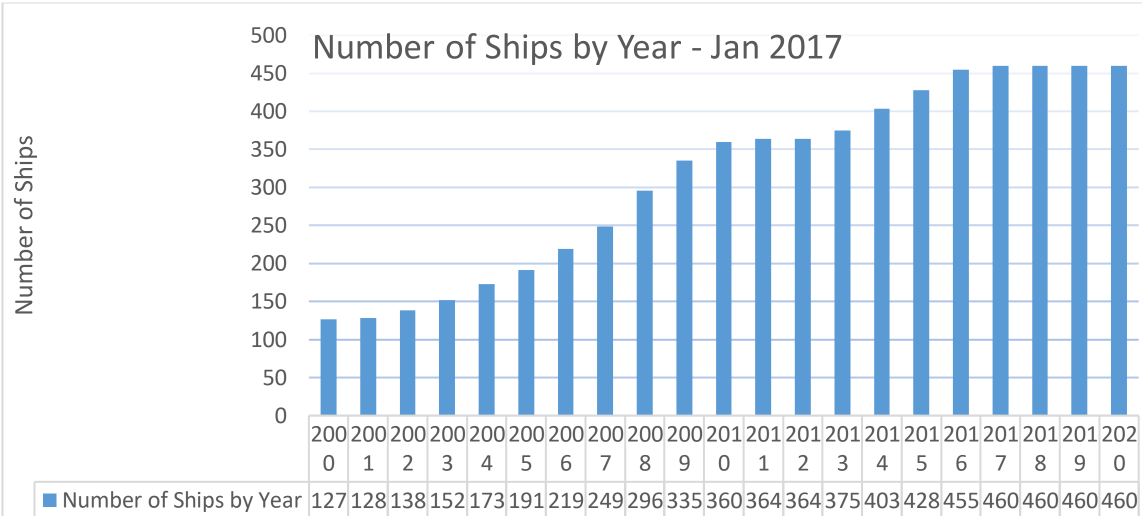



Figure 19: Number of ships by year 2017 (Source: Wood Mackenzie – LNG Fleet Summary Charts)

As a result of a decline in orders for new build ships, its growth rate affected badly between 2010 and 2012 and was quite low. However, the ship's charter rate reached the highest limit ever because of the improvement in the demand in LNG, along with the decline in orders of new-build ships. This affected the delivery of new ships positively between 2013 and 2015, where the ship quantity growth was high. Between 2016 and 2017, only 5 ships were delivered for service, so the ship's number back to its lowest levels. In general, the figure illustrates an obvious increase in the number of ships, and it is expected to increase more in the future.

Figure 20 illustrates the number of new vessels delivery between 2000 and 2017. As it is clear, 2012 represents the lowest number after 2001 as only two vessels were delivered for service. However, the situation has been changed during 2013, as the number of ships reaches a total of 16 ships. The number of delivered ships increased even more in 2014 as a total of 34 ships joined the fleet, this was the third-highest total following 2008 and 2009. Because of the delay in delivering the scheduled ships during 2015 and 2016, only 28 ships were delivered in both years, this represents a lower amount compared to 2014. The same repeated during 2017, as the number of ships scheduled to be delivered during was 48, but only five were delivered.

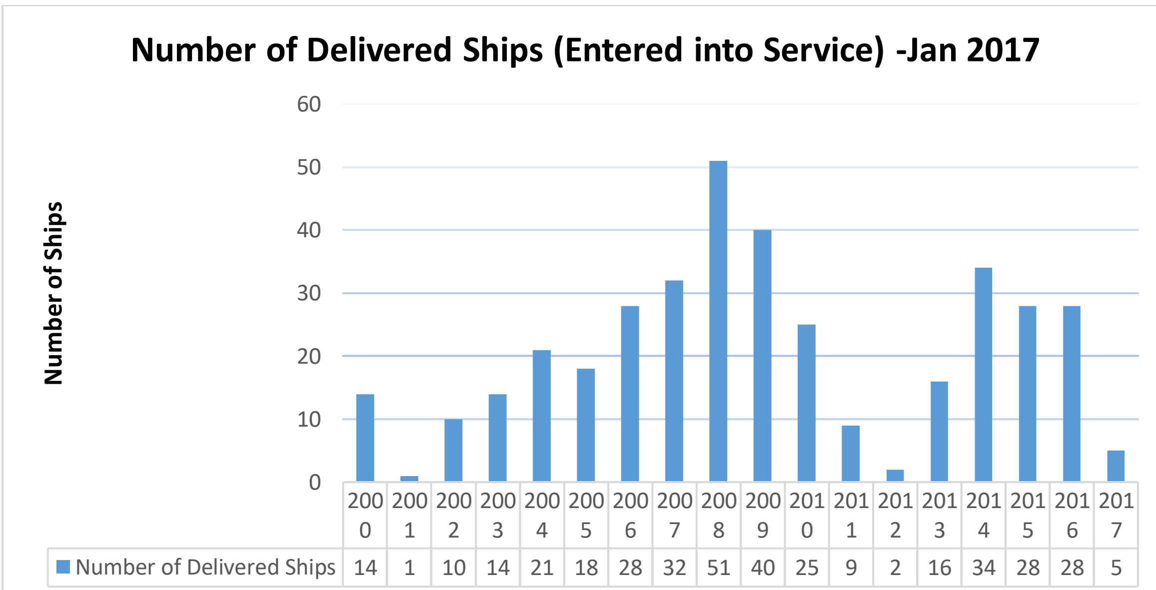


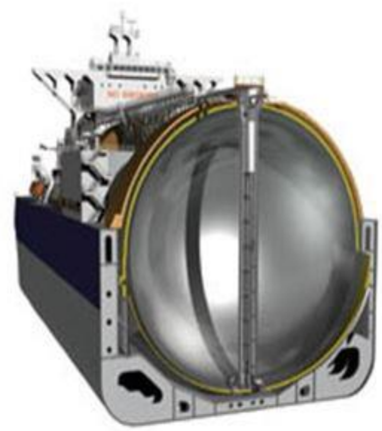

Figure 20: Number of Delivered Ships- Jan 2017

## 3.3 LNG Vessel Types

As stated by Shively et al. (2005), there are two types of LNG containment systems: The Moss sphere tanks and membrane tanks. The main purposes of these containment systems are to store the LNG and to keep the LNG in its liquid state by maintaining the temperature. According to IHS Markit, IGU World LNG Report. (2017), the Moss designs are formed from the Japanese shipyards, while membrane vessel designs are brought from Chinese and Korean shipyards. The Moss design launched in 1971 and it is famous for its independent spherical shaped tanks. These independent tanks are designed to be on the deck of the ship with half of the tank above the deck while the other half below. Figures 21 and 22 illustrate the Moss type tanker which has from four to six separate tanks.


Figure 21Moss type containment (Source: LNG World Shipping)

*Section through Moss LNG vessel*



*LNG Moss Spherical Tank*

Figure 22: Moss type containment (Source, BD Mariners)

Consistent with Shively et al. (2005), Membrane is built from the vessel hull. Membrane container is designed to have double-walled storage, as it is built to cover most of the space below the deck with only small part of it is bare to the wind. In addition, Membrane designed to have a larger storage area than the Moss design with less contact with wind drag as it is clear in figure 23.


*Section through Membrane LNG vessel*

*LNG Membrane Tank*

Figure 23: Membrane type containment (Source: BD Mariners)

As said by Gerdsmeyer et al. (2005), Moss and Membrane design to maintain the temperature of the LNG and to minimize evaporation, as they both have insulation layers. Nevertheless, LNG evaporation is unavoidable because of heat leakage into the containment system during the voyage. As stated by Shively et al. (2005), this heat escape will be ended up causing evaporation of some LNG which is identified as boil-off gas (BOG). As a result of the increase of BOG, the pressure in the tank will change and will lead to cargo warming. Accordingly, in order to prevent LNG warming and evaporation, it is very important to maintain the pressure. Consistent with Dobrota et al. (2013) in order to reduce the tank pressure, this should be done by continuous BOG elimination. The boil of the volatile components first (like nitrogen and methane) changes the composition and quality of LNG over time. This is called LNG aging, which is very important to be controlled during the LNG trade, as LNG is sold based on its energy content. Furthermore, LNG classification relies on several criteria such as density, the value of heat and the amount of some components like methane and nitrogen.

According to Shively et al. (2005), the main function of the vapor recovery system is to capture the boil-off to maintain the tank pressure. This captured boil-off brings many benefits as it can be used as a fuel for the LNG vessel, liquefied and returned to the cargo, or can be released to the atmosphere to maintain the tank pressure. Nowadays most of the recent LNG vessels are using the BOG as propulsion system fuel.

## 3.4 Comparison between Vessel Types

Moss and Membrane vessel types are both feasible in terms of technical and economical point of view. However, Membrane type is sometimes preferable than the Moss type as it has more economic and commercial advantages. Consistent with Barret, A. (2013) the Membrane type is cheaper to build and operate (low CAPEX). Adding to that in terms of space utilization, it doesn't require any spaces between the tanks like in Moss design and for that, no loss in cargo space is showing. Along with The Study on the Cost of Gas Transportation (2012), the Membrane vessel requires a low Suez Canal transit fee because of its smaller gross tonnage (cargo and lost space) than Moss type. Normally, cooling down for Moss vessel takes longer than Membrane, due to its equator temperature (LNG can't be loaded until equator temperature reaches below -130 °C) and Membrane type is more efficient in fuel consumption

As stated by Chakraborty, S. (2017). when speaking about the safety, Membrane vessels have better visibility, due to the less tanker height on the deck when compare it with Moss type. As stated by IHS Markit, IGU World LNG Report. (2017), the latest LNG

Membrane vessel is called GTT Mark V, it designed to have a low boil-off rate (approximately 0.08%) compared to the regular daily boil-off rate of 0.15%. However, Membrane design has some limitations, such as the liquid sloshing and this is due to the large tanker surface which could affect the vessel motions, stability and can lead to tanker erosions. Nevertheless, this has no significant impact on the economics of transportation. Because of all those advantages, the number of active Membrane vessels became almost 74% by end of 2016, as it is clear in Figure 24 Furthermore, it continues to enlarge in the ship order book by reaching 93%, as it turns into the most favored LNG carriage selection.

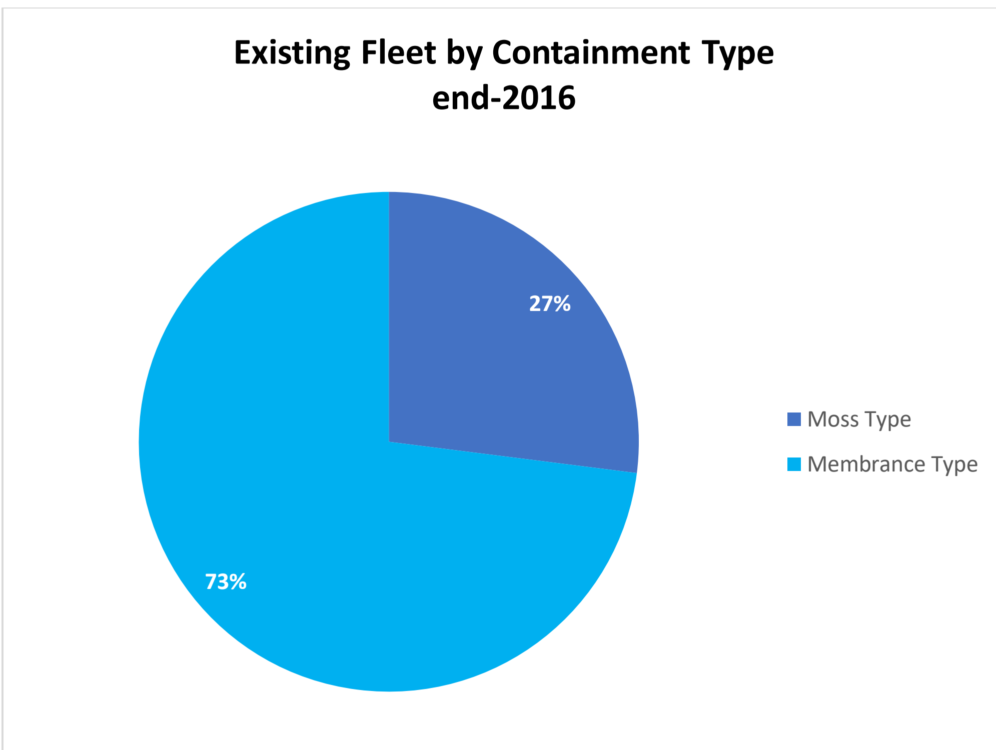



Figure 24 Percentage of existing fleet by containment type Source: IHS Markit

## 3.5 LNG Vessel Size and the environment

According to Shively et al. (2005), along with the nonstop progress in the industry of the LNG, the size of the LNG vessel has grown massively over time. The capacity of the vessels has changed and developed in an impressive way since 1960 when the vessels industry began. Generally, the LNG cargo capacity is used to group and classify the LNG vessels. So, vessels with capacities below 200,000 $m^3$ are called small or conventional as their size falls between 100,000 and 200,000 $m^3$, while vessels of size falling between 200,000 and 217,000 $m^3$ are called Q-Flex, finally, any vessel with a size more than 250,000 m3 is called Q-Max.

On the word of IHS Markit, IGU World LNG Report. (2017), among the current active fleet utilized by Qatar, 11% of them are of the Q class, and the reason behind that is to get advantage of the economy of scale, as the cost of LNG per unit decreases when increasing the cargo size. Accordingly, Qatar is using the vessels of type Q-Flex (capacity between 210,000 to 217,000 $m^3$) and Q-Max (capacity between 261,700 to 266,000 $m^3$) to carry out and deliver its LNG to all its customer around the world. However, as stated by Shively et al. (2005), large vessels are not always recommended as those big vessels require a port with deep water of 40 feet and enough space for turning the vessel around which is not valid in all ports. So sometimes using small vessels has more advantages as it gives more flexibility since not all delivery ports can accommodate large vessel requirements. In spite of the size, these vessels contribute significantly to global climate change, especially from the greenhouse gas emissions coming out from it as mentioned by Kolieb (2008) where 90 percent of the global trade is done by marine vessels that are fleeting through international waters. For that reason, international agencies commenced setting rules and regulations for the shipping sector to minimize the harmful effect of shipping emissions. Therefore, almost all those stages of the LNG value chain are regulated, and this is involving shipping to avoid any incidents that may affect shipping safety and security during the LNG transportation journey. Consistent with Shively et al. (2005), all those rules are set by the International Maritime Organization (IMO). IMO is known as a United Nations agency and its main objective is to make sure that vessels are manufactured and operated under safe and secure standards. Adding to that, it is working to minimize or eliminate unacceptable effects on the environment and on human health. Consequently, all LNG vessels have to fulfill all rules and regulations defined internationally by IMO.

According to IHS Energy - LNG Market Impact from a 2020 Marine Fuel Sulfur Reduction (2016), Greenhouse gas emissions (GHG) formed from the shipping stage are mainly containing Sulphur oxides (SOx), Nitrogen oxides (NOx), Atmospheric particulate matter (PM), Methane ($CH_4$) and Carbon dioxide ($CO_2$). The IMO committee of the marine environment protection established a new cap for the sulfur content regulation on the 27th of October 2016. The regulation is targeting to decrease the bunker fuel sulfur content from 3.5% to 0.5% in 2020. According to IMO Sulphur oxides (SOx) Regulation 14, Sulfur limitation levels varies between outside Emission Control Areas (ECA) and inside such areas which include the Baltic Sea area, North Sea area, North American area and the United States Caribbean Sea area, as listed in Table 1. in addition, IMO sets the date to be 2020 for vessels to comply with the new sulfur content limit of 0.5%.

Table 1: $SO_x$ limit inside and outside ECA (values in % m/m – by mass)

| Outside an ECA established to limit $SO_x$ and particulate matter emissions | Inside an ECA established to limit $SO_x$ and particulate matter emissions |
|---|---|
| 4.50% m/m prior to 1 January 2012 | 1.50% m/m prior to 1 July 2010 |
| 3.50% m/m on and after 1 January 2012 | 1.00% m/m on and after 1 July 2010 |
| 0.50% m/m on and after 1 January 2020 | 0.10% m/m on and after 1 January 2015 |

As stated by IHS Energy - LNG Market Impact from a 2020 Marine Fuel Sulfur Reduction (2016), the bunker fuel global demand is estimated to be around 3 million barrels per day (MMB/d). This amount is equivalent to 120 million metric tons (MMT), which represents around 5% of the overall product demand. Comparing to other types of transportation fuels, it is considered a small portion of fuels. According to IHS Markit, IGU World LNG Report. (2017), many types of fuels can be used by LNG vessels. This also depends on the vessel propulsion systems, as these fuels include mainly fuel oil (HFO), marine diesel oil (MDO), and LNG. Adding to that these types include subtypes with low sulfur, as they can be treated to produce low sulfur fuels.

Consistent with IHS Energy - LNG Market Impact from a 2020 Marine Fuel Sulfur Reduction (2016), regarding the sulfur global limit regulation, there are three main solutions to select in the shipping industry in order to reduce greenhouse gas emissions. Those solutions include: using the low sulfur fuel, using LNG as bunker fuel, and installing the scrubber. Based on the vessel's specifications like the age and the size, one of those solutions can be selected. Lately, LNG became the best choice as bunker fuel, and the reasons behind that is that LNG is a clean fuel, representing a good alternative to minimize greenhouse gas emissions. It doesn't release any $SO_x$, a minor amount of $NO_x$ and a smaller amount of $CO_2$ compared to oil-derived fuels. The other reason is its cost, as the price of the LNG is lower than the price of the petroleum-based bunker fuels including the low sulfur fuels. Figure 25 shows the bunker fuel price comparison in different regions. LNG delivered cost is estimated to fall between $8-12/MMBtu, this keeps LNG competitive against HFO and diesel.

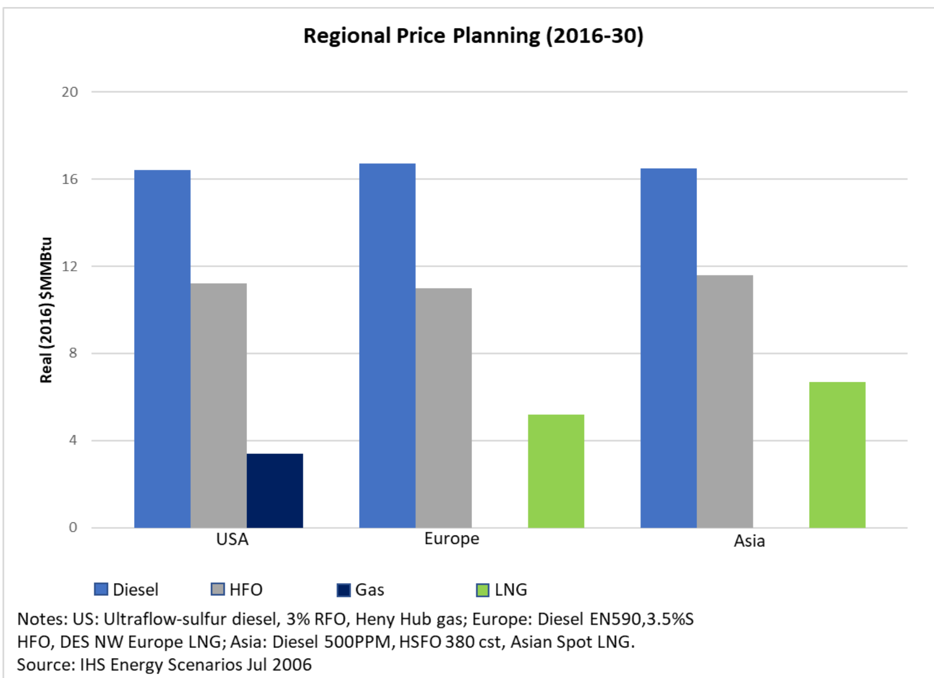



Figure 25: Regional price planning (Source: IHS Markit)

As mentioned by IHS Markit, IGU World LNG Report. (2017), LNG vessels are built with different propulsion systems, and they are categorized based on the fuel they can burn. The first category is the steam turbine, which is the most traditional propulsion system of LNG vessels. This type of vessel uses boilers to generate steam that helps to produce power in which helps to move the propulsion turbines. The boilers can also be running by HFO, and it uses boil-off gas to generate power. The second type is the Dual-Fuel Diesel Electric (DFDE), this type of system can burn diesel oil and boil-off gas, so the vessel with this system has the ability to switch between both fuels as required. The third type is the Tri-Fuel Diesel Electric (TFDE), and this type can burn HFO, diesel oil and gas. TFDE has more flexibility because of the fact that it can switch to any of the mentioned fuels along with the regional regulations and the vessel conditions. Currently, almost 25% of the current operating ships are of the TFDE type. Slow speed diesel (SSD) with a BOG re-liquefaction is mainly created for the Q-class vessels with Qatar's mega train projects. BOG is re-liquefied and fed back into the containers, as this allows any loss in the LNG cargo during the voyage representing an advantage of the Q-class.

# CHAPTER 4: METHODOLOGY

This chapter will address the methodology applied to build the structure of the thesis. It is started by data gathering, where many data were retrieved from public domains or from LNG specialized data providers. Later, the LNG shipping model is built to calculate the gross fuel consumption during LNG transportation from the inbound loading terminal which is mainly Qatar (Ras Laffan Port) to the outbound receiving terminals and returning back to Qatar. This part is essential and critical because the results are used with the emission factors to calculate the amount of gases emitted from different types of vessels during 1 round trip. Moving to the next part which is applying LCSA -the ReCiPe model to study the environmental impact on human health. Finally, sensitivity analysis is conducted to investigate the parameters that are significantly affecting the emission results. Figure 26 demonstrates the methodology applied in this research as follow:

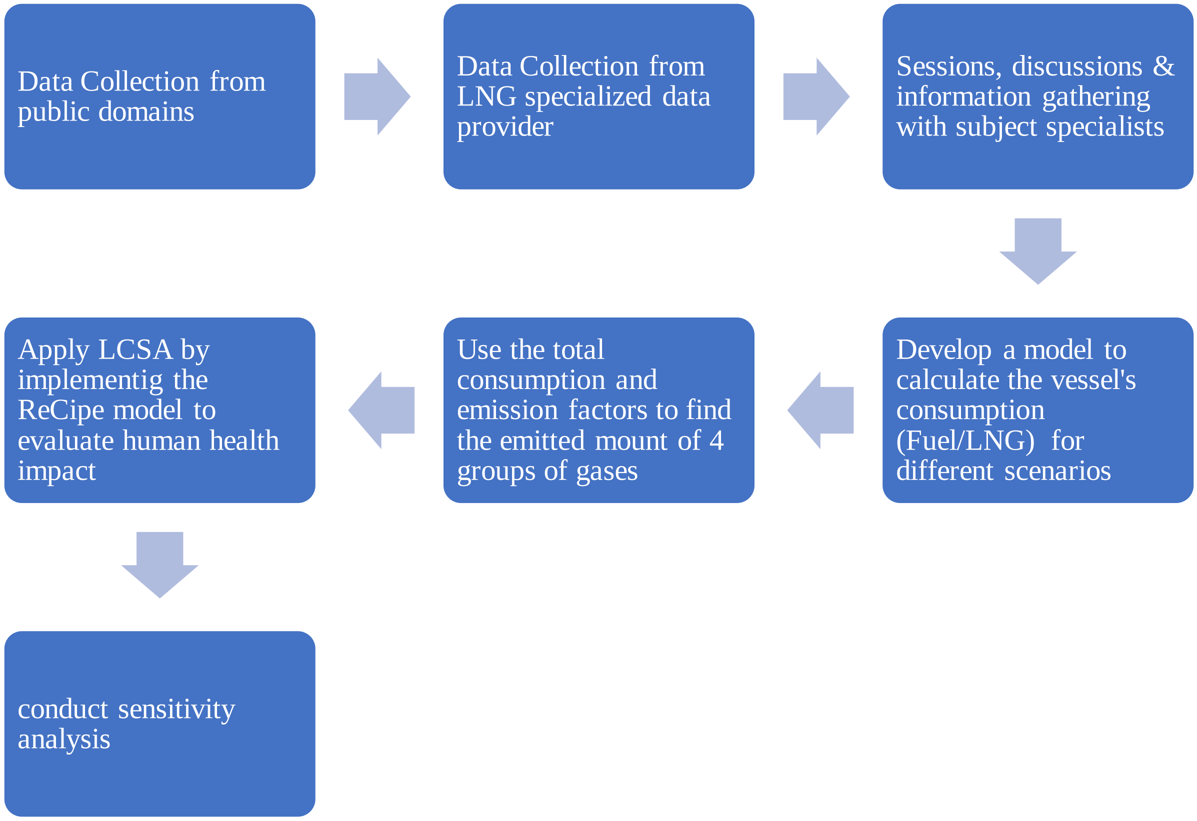



Figure 26: Methodology

## 4.1 LNG Shipping Model – Emission calculations

### *4.1.1 Data collection*

Calculating the emissions starts with gathering the necessary data and defining the assumptions to find out the emission value for each vessel as follows:

- The model is limited to some selected destinations with the respect to the shortest possible marine routes based on data availability, e.g.: through Suez Canal, Panama Canal, Northern Passage, Cape of Good Hope, and any other routes that provide the shortest possible distance. This research takes the case of one destination mainly France to explain the method. See Table 2

Table 2: Marine Routes Distance between Exporter (Qatar) and Major LNG Markets - Nautical Miles Source: PortWorld – Distance Calculation

| From | To | Marine routes/n passage | Distance (Nautical Miles) |
|---|---|---|---|
| Ras Laffan- Qatar | Chita- Japan | Direct Route | 6358 |
| Ras Laffan- Qatar | Inchon- Korea | Direct Route | 6125 |
| Ras Laffan- Qatar | Shanghai- China | Direct Route | 5716 |
| Ras Laffan- Qatar | Fos- France | Suez Canal | 4575 |
| Ras Laffan- Qatar | Isle of Grain- UK | Suez Canal | 6202 |
| Ras Laffan- Qatar | Barcelona- Spain | Suez Canal | 4602 |
| Ras Laffan- Qatar | Aliaga- Turkey | Suez Canal | 3,595 |

- The LNG vessels used in this thesis are mainly 3 types:
  - Q-Max with a capacity of 265,000 $m^3$
  - Q-Flex with a capacity of 210,000 $m^3$
  - Conventional -1 with a capacity of 145,000 $m^3$
- In order to use the mentioned vessels to deliver the LNG safely, and based on the IMO requirement, the vessel tank filling ratio should be 98%. Thus, max load capacity for each vessel will be as follows:
  - Q-Max with a capacity of 259,700 $m^3$
  - Q-Flex with a capacity of 205,800 $m^3$
  - Conventional-1&2 with a capacity of 142,100 $m^3$
- Emission evaluation for different fuel types is also available per vessel type, those types are:
  - HFO – Heavy Fuel Oil.
  - LNG – Liquefied Natural Gas.
- The conventional vessels can run by 2 moods. The first mood is running by dual-mood using both fuel oil and LNG. Due to the un-avoidable cargo BOG (Boil of Gas) resulting in increased tank pressure, the vessel is utilizing the BOG as a fuel in addition to other types of fuel oil. The second mood is when it is running with purely LNG using natural BOG and forced BOG based on the vessel need.
- Q-Max and Q-Flex vessels have re-liquefaction capability, which means BOG get re-liquefied and sent back again to the vessel tanks, thus these two types of vessels can run on fuel oil mode only.

- LNG Vessel maximum speed can reach up to 21 knots. Due to the fact that with high speed more fuel consumption will occur, we assumed that the fuel consumption will be based on 19 knots.
- The boil-off rate for conventional vessels are assumed to be 0.12% per day. This rate in MMBtu will be deducted from the original loaded quantity at the load terminal to get the discharged quantity at the receiving terminal.
- The model is fed by different variable inputs, including the below conversion factors:
  - ➢ In case of natural boil-off off 1 $m^3$ (one cubic meter) of LNG ≈ 0.488 MT of HFO (metric tons of fuel oil) [1]
  - ➢ In case of forced boil-off off 1 $m^3$ (one cubic meter) of LNG ≈ 0.594 MT of HFO (metric tons of fuel oil) [2]
  - ➢ One million tones ≈ 52,000,000 MMBtu[3]
- For each vessel type, emission is evaluated in the model. Emission factors for 4 different categories are considered. Those categories are:
  - ➢ Main Pollutants: includes $NO_x$, CO, NMVOC, $SO_x$, and $NH_3$.
  - ➢ Particulate Matter: $PM_{2.5}$, $PM_{10}$, TSP
  - ➢ Priority Metals: Pb, Cd, and Hg
  - ➢ Green House Gases: $CO_2$, $CH_4$, and $N_2O$

[1] Conversion value provided by LNG shipping specialist

[2] Conversion value provided by LNG shipping specialist

[3] S&P Global Platts – Energy Industry Conversions

### *4.1.2 Q-Flex and Q-Max- Gross fuel consumption (HFO)*

As discussed earlier, Q-Flex and Q-Max vessels only use HFO fuel type as LNG is not applicable for this kind of vessel. For the loaded quantity, the Q-Flex type has a maximum load capacity of 205800 $m^3$, Q-Max type has a maximum capacity of 259700 $m^3$ and the conventional has a maximum load capacity of 142100, as shown below:

Table 3: Maximum load capacity for each type of vessel

| Vessel | Q-Flex | Q-Max | CONVENTIONAL |
|---|---|---|---|
| Load Capacity ($m^3$) | 205,800 | 259,700 | 142,100 |

The maximum loaded capacity = load capacity * Gross Calorific Value[4] (MMBtu / $m^3$ LNG)

This formula is used to calculate the maximum load capacity (the actual loaded quantity) for the vessels as follows:

- Loaded quantity (Q-Flex) (MMBtu) = 205800 ($m^3$) * 22.8[5] (MMBtu / $m^3$) = 4692240
- Loaded quantity (Q-Max) (MMBtu)= 259700 ($m^3$) * 22.8(MMBtu / $m^3$) = 5921160

[4] The conversion from BOG to HFO will consider Qatar's GCV value for model simplicity.

[5] Gross Calorific Value from RAS LAFFAN – Qatar port is 22.8

- Loaded quantity (Conventional 1&2) (MMBtu)= 142,100 ($m^3$) * 22.8(MMBtu / $m^3$) = 3239880

In following example (from Ras Laffan-Qatar port to Fos-France) we built the calculation for the following assumptions:

- In case of passing the Suze Canal, the number of days will be as following:
  - Load port days (day)= 1
  - Steam day (day)= Distance/ speed* 24
  - Canal days (day)= 1.79 (see table 4)
  - At anchorage days (day)= 1.5
  - Discharge days (in case of ballets) (day) = 2

Table 4: the assumed total days of passing the Suez Canal

| Canal | Waiting Time | Passage | Total Days |
|---|---|---|---|
| Suez Canal | 30 H maximum | About 13 H | 1.79 |

Table 5 illustrate the number of days assumed for each stage of the 4 vessel types. As measured by world port, the distance from Ras Laffan port in Qatar to Fos port in France is 4709 nautical miles.

For each stage of the voyage days other assumptions has been made to find the fuel consumption (in laden and ballast) as following:

- Canal consumption (MT /day) = Reliq on * At Anchorage Consumption
- Steaming fuel consumption (MT /day) = Consumption* Reliq on

In order to calculate the gross fuel consumption, tables 5,6,7 and 8 has been used for both scenarios of laden and ballast by multiplying the number of days at each stage by the related consumption amount as follow:

- Gross fuel consumption (MT) = Load port days (day)* Loading Consumption (MT /day) + Steam days (day)* Steaming Fuel Consumption (MT/ day) + Canal days (day)* Canal Consumption (MT/ day) +At anchorage days(day)*At Anchorage Consumption (MT/ day) + Discharge port days (day)* Discharging Consumption (MT/ day)

Table 5: Number of days at each stage for the 4 vessel types in the case of laden

| vessel type | Q-Flex | Q-Max | Conventional mood 1 | Conventional mood 2 |
|---|---|---|---|---|
| Fuel type | HFO | HFO | HFO+ LNG | LNG |
| Destination | Fos- France | Fos- France | Fos- France | Fos- France |
| Distance (NM) | 4709 | 4709 | 4709 | 4709 |
| Loaded quantity (MMBtu) | 4692240 | 5921160 | 3239880 | 3239880 |
| Load port days | 1 | 1 | 1 | 1 |
| Steam days | 10.33 | 10.33 | 10.33 | 10.33 |
| Canal days | 1.79 | 1.79 | 1.79 | 1.79 |
| At anchorage days | 1.5 | 1.5 | 1.5 | 1.5 |
| Discharge port days | 2 | 2 | 2 | 2 |

Table 6: Number of days at each stage for the 4 vessel types in the case of ballast

| vessel type | Q-Flex | Q-Max | Conventional mood 1 | Conventional mood 2 |
|---|---|---|---|---|
| Fuel type | HFO | HFO | HFO+ LNG | LNG |
| Destination | Fos- France | Fos- France | Fos- France | Fos- France |
| Distance (NM) | 4709 | 4709 | 4709 | 4709 |
| Loaded quantity (MMBtu) | 0 | 0 | 0 | 0 |
| Load port days | 0 | 0 | 0 | 0 |
| Steam days | 10.33 | 10.33 | 10.33 | 10.33 |
| Canal days | 1.79 | 1.79 | 1.79 | 1.79 |
| At anchorage days | 1.5 | 1.5 | 1.5 | 1.5 |
| Discharge port days | 0 | 0 | 0 | 0 |

Table 7: Fuel consumption at each stage for the 4 vessel types in the case of laden

| Type | Speed (Knots) | Consumption | Reliqon | At Anchorage Consumption | Canal Consumption | Loading Consumption | Steaming Fuel Consumption |
|---|---|---|---|---|---|---|---|
| Q-Max | 19 | 158 | 30 | 60 | 90 | 60 | 188 |
| Q-Flex | 19 | 148 | 27 | 55 | 82 | 55 | 175 |
| Conventional-1 | 19 | 181 | | 85 | 85 | 45 | 181 |
| Conventional-2 | 19 | 188 | | 85 | 85 | 45 | 188 |

Table 8: Fuel consumption at each stage for the 4 vessel types in the case of ballast

| Type | Speed (Knots) | Consumption | Reliq on | At Anchorage Consumption | Canal Consumption | Discharging Consumption | Steaming Fuel Consumption |
|---|---|---|---|---|---|---|---|
| Q-Max | 19 | 151 | 17 | 20 | 37 | 60 | 168 |
| Q-Flex | 19 | 134 | 13 | 19 | 32 | 55 | 147 |
| Conventional-1 | 19 | 171 | | 20 | 20 | 45 | 171 |
| Conventional-2 | 19 | 179 | | 85 | 85 | 45 | 179 |

In the case of the Q-Flex and Q-Max, the boil-off is not applicable so it will be not considered in the calculations. From the above table, the gross fuel consumption for the Q-Flex and the Q-Max will be calculated in the case of laden and ballast as follow:

Table 9: Gross fuel consumption for Q-Flex and Q-Max (Laden)

| Type | Gross Fuel Consumption-Laden (MT) | Gross Fuel Consumption-Ballast (MT) |
|---|---|---|
| Q-Flex | 2201 | 1604 |
| Q-Max | 2373 | 1831 |

For the conventional consumption will be discussed in the next section.

### *4.1.3 Conventional 1&2- Fuel consumption calculation*

For the vessels type conventional 1 &2, the same calculations from the previous section will be repeated, adding to it the boil-off calculations which is happening in such types of vessels and can't be negligible. It is measured as follow:

- Boil-off ($m^3$) =Actual conventional capacity ($m^3$) * conventional boil-off rate (%/day) * (steam days +canal days+ At anchorage days) (day)
- Boil-off (MT) = Boil-off ($m^3$) *0.488[6]
- Net outbound bunker for the conventional mood 1 (MT) = Gross Fuel Consumption (MT)- Boil-off (MT)

Table 10 illustrate the net outbound bunker for the conventional 1 during the laden and ballast as follow:

Table 10: Net outbound bunker for the conventional 1 vessel (laden & ballast)

| Type | Boil-off (MT) | Gross Fuel Consumption (MT) | Net outbound bunker (MT) |
|---|---|---|---|
| Laden | 1156 | 2284 | 1128 |
| Ballast | 1156 | 1832 | 675 |

[6] From $m^3$ to MT =0.488

Moving to the second mood – as mentioned earlier, the conventional vessel will use only the LNG for bunkering, for that we need to consider the boil-off as well as the forced boil-off. Amount is calculated as follow:

- Forced Boil off ($m^3$) = (Gross fuel consumption (MT)- (Boil-off *0.488))/0.594[7]
- Net outbound bunker (MT)=Total Boil off= Boil Off+ Forced Boil-off

As a result, the total boil-off of LNG will be required in order to calculate the emissions as follows:

- Total Boil Off (MT)= (Boil-off ($m^3$) + Forced Boil-off ($m^3$)) *0.441[8]

Table 11 shows the total boil off for the conventional 2 in case of laden and ballast as follow:

Table 11: Total Boil off for the conventional 2 vessels (laden & ballast)

| Type | Boil-off (m3) | Forced Boil-off (m3) | Total Boil Off (MT) |
|---|---|---|---|
| Laden | 2369 | 2020 | 1936 |
| Ballast | 2369 | 1472 | 1694 |

[7] To convert from $m^3$ to MT (Forced BOG)
[8] LNG Density (Kg / M3) =0.441

## 4.2 Emission Factors

After finding the amount of fuel consumed by each vessel and fuel type, the next step is to specify the targeted gas or group of gases that required to find its emitted quantity in the air. In order to find that, it is essential to have the relevant emission factor related to that gas or group of gases.  As addressed by Cooper and Gustafsson (2004), researchers calculated the emission factors for a group of gases that are emitted from different types of vessels such as SSD (slow speed diesel) and ST (steam turbine). In this research, the SSD includes Q-Flex and Q-Max, while ST includes the conventional. Regarding the fuel type, this covers 2 types of fuel: RO (residual oil) and MD (Marine distillate). HFO comes under the RO group, however, MD type is not considered in these calculations, and it is substituted with natural gas. Tables 12-15 show the emission factors for different groups for the engine types SSD (Q-Flex &Q-Max) and ST (Conventional) for fuel type RO (HFO).

Table 12: Emission Factors in g/ton fuel for Main Pollutants (source: Cooper, D., & Gustafsson, T. (2004).

| Engine Type | Fuel Type | Main Pollutants | | | | |
|---|---|---|---|---|---|---|
| | | $NO_x$ | CO | NMVOC | $SO_x$ | $NH_3$ |
| SSD | MD | 9.16E+04 | 2.70E+03 | 1.62E+03 | 8.00E+03 | 1.60E+01 |
| SSD | RO | 8.71E+04 | 2.55E+03 | 1.53E+03 | 4.60E+04 | 2.70E+01 |
| MSD | MD | 6.32E+04 | 5.34E+03 | 9.70E+02 | 8.00E+03 | 2.20E+01 |
| MSD | RO | 6.17E+04 | 5.06E+03 | 9.19E+02 | 4.60E+04 | 2.90E+01 |
| HSD | MD | 5.83E+04 | 5.37E+03 | 9.76E+02 | 8.00E+03 | 1.50E+01 |
| HSD | RO | 5.89E+04 | 5.12E+03 | 9.30E+02 | 4.60E+04 | 1.40E+01 |
| GT | MD | 1.85E+04 | 3.33E+02 | 3.33E+02 | 8.00E+03 | 1.00E+00 |
| GT | RO | 1.88E+04 | 3.28E+02 | 3.28E+02 | 4.60E+04 | 1.00E+00 |
| ST | MD | 6.67E+03 | 6.67E+02 | 3.33E+02 | 8.00E+03 | 1.00E+00 |
| ST | RO | 6.89E+03 | 6.56E+02 | 3.28E+02 | 4.60E+04 | 1.00E+00 |

Table 13: Emission Factors in g/ton fuel for Particular Matter (source: Cooper, D., & Gustafsson, T. (2004))

| Engine Type | Fuel Type | Particulate Matter | | |
|---|---|---|---|---|
| | | TSP | $PM_{10}$ | $PM_{2.5}$ |
| SSD | MD | 1.08E+03 | 1.08E+03 | 1.08E+03 |
| SSD | RO | 6.67E+03 | 6.67E+03 | 6.67E+03 |
| MSD | MD | 9.76E+02 | 9.76E+02 | 9.76E+02 |
| MSD | RO | 2.33E+03 | 2.33E+03 | 2.33E+03 |
| HSD | MD | 9.76E+02 | 9.76E+02 | 9.76E+02 |
| HSD | RO | 2.33E+03 | 2.33E+03 | 2.33E+03 |
| GT | MD | 3.30E+01 | 3.30E+01 | 3.30E+01 |
| GT | RO | 1.64E+02 | 1.64E+02 | 1.64E+02 |
| ST | MD | 1.00E+03 | 1.00E+03 | 1.00E+03 |
| ST | RO | 2.62E+03 | 2.62E+03 | 2.62E+03 |

Table 14: Emission Factors in g/ton fuel for Priority Metals (source: Cooper, D., & Gustafsson, T. (2004))

| Engine Type | Fuel Type | Priority Metals | | |
|---|---|---|---|---|
| | | Pb | Cd | Hg |
| SSD | MD | 1.50E-01 | 5.00E-03 | 5.00E-05 |
| SSD | RO | 1.50E-01 | 1.30E-02 | 3.00E-03 |
| MSD | MD | 1.50E-01 | 5.00E-03 | 5.00E-05 |
| MSD | RO | 1.50E-01 | 1.30E-02 | 3.00E-03 |
| HSD | MD | 1.50E-01 | 5.00E-03 | 5.00E-05 |
| HSD | RO | 1.50E-01 | 1.30E-02 | 3.00E-03 |
| GT | MD | 1.50E-01 | 5.00E-03 | 5.00E-05 |
| GT | RO | 1.50E-01 | 1.30E-02 | 3.00E-03 |
| ST | MD | 1.50E-01 | 5.00E-03 | 5.00E-05 |
| ST | RO | 1.50E-01 | 1.30E-02 | 3.00E-03 |

Table 15 Emission Factors in g/ton fuel for Greenhouse gas pollutants (Source: Cooper, D., & Gustafsson, T. (2004))

| Engine Type | Fuel Type | Greenhouse gas pollutants | | |
|---|---|---|---|---|
| | | $CO_2$ | $CH_4$ | $N_2O$ |
| SSD | MD | 3.18E+06 | 3.24E+01 | 1.68E+02 |
| SSD | RO | 3.18E+06 | 3.08E+01 | 1.59E+02 |
| MSD | MD | 3.18E+06 | 1.95E+01 | 1.51E+02 |
| MSD | RO | 3.18E+06 | 1.86E+01 | 1.44E+02 |
| HSD | MD | 3.18E+06 | 1.95E+01 | 1.51E+02 |
| HSD | RO | 3.18E+06 | 1.86E+01 | 1.44E+02 |
| GT | MD | 3.18E+06 | 6.70E+00 | 2.67E+02 |
| GT | RO | 3.18E+06 | 6.60E+00 | 2.62E+02 |
| ST | MD | 3.18E+06 | 6.70E+00 | 2.67E+02 |
| ST | RO | 3.18E+06 | 6.60E+00 | 2.62E+02 |

All the above factors are in G/Ton, so this will be converted to kg/Ton as shown in table 16 below:

Table 16: Emission Factors for all groups in kg/ton

| Engine/vessel Type | Fuel Type | Main Pollutants | | | | | Particulate Matter | | | Priority Metals | | | Green House Gases | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $NO_x$ | CO | NMVOC | $SO_x$ | $NH_3$ | $PM_{2.5}$ | $PM_{10}$ | TSP | Pb | Cd | Hg | $CO_2$ | $CH_4$ | $N_2O$ |
| | | (Kg/MT Fuel) | (Kg/MT Fuel) | (Kg/MT Fuel) | (Kg/MT Fuel) | (Kg/MT Fuel) | (Kg/MT Fuel) | (Kg/MT Fuel) | (Kg/MT Fuel) | (Kg/MT Fuel) | (Kg/MT Fuel) | (Kg/MT Fuel) | (Kg/MT Fuel) | (Kg/MT Fuel) | (Kg/MT Fuel) |
| SSD (Q-Flex/Q-Max) | RO (HFO) | 87.13 | 2.54 | 1.525 | 46 | 0.027 | 6.66 | 6.66 | 6.66 | 0.00015 | 0.000013 | 0.000003 | 3179 | 0.0308 | 0.159 |
| | Natural Gas | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| ST (Conventional) | RO (HFO) | 6.88 | 0.65 | 0.328 | 46 | 0.001 | 2.623 | 2.623 | 2.623 | 0.00015 | 0.000013 | 0.000003 | 3179 | 0.0066 | 0.262 |
| | Natural Gas | 6 | 0.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2690 | 0.048 | 0.0048 |

In the case of France, the emissions need to be calculated for each group according to the vessel type by multiplying the net outbound bunker (MT) by the corresponding factor. Table 17 is showing the emission values for the case of France destination for the laden case:

Table 17: The emission values of the gases coming from the 4 cases to Fos-France (Laden)

| | Q-Flex (kg) | Q-Max (kg) | Conventional mood 1 (kg) | Conventional mood 2 (kg) |
|---|---|---|---|---|
| Net outbound bunker (MT) | 2201 | 2373 | 1128 | 1936 |
| $NO_x$ Emissions | 191826.6 | 206732.8 | 14032.50 | 11614.0 |
| CO Emissions | 5602.7 | 6038.1 | 1262.12 | 967.8 |
| NMVOC Emissions | 3357.2 | 3618.1 | 369.84 | 0.0 |
| $SO_x$ Emissions | 101267.3 | 109136.4 | 51868.07 | 0.0 |
| $NH_3$ Emissions | 59.4 | 64.1 | 1.13 | 0.0 |
| $PM_{2.5}$ Emissions | 14677.1 | 15817.7 | 2957.61 | 0.0 |
| $PM_{10}$ Emissions | 14677.1 | 15817.7 | 2957.61 | 0.0 |
| TSP Emissions | 14677.1 | 15817.7 | 2957.61 | 0.0 |
| Pb Emissions | 0.3 | 0.4 | 0.17 | 0.0 |
| Cd Emissions | 0.0 | 0.0 | 0.01 | 0.0 |
| Hg Emissions | 0.0 | 0.0 | 0.00 | 0.0 |
| $CO_2$ Emissions | 6998447.8 | 7542272.3 | 6395229.53 | 5206948.8 |
| $CH_4$ Emissions | 67.8 | 73.1 | 57.60 | 92.9 |
| $N_2O$ Emissions | 350.0 | 377.2 | 300.44 | 9.3 |

The same will be calculated for the ballast as following:

Table 18: The emission values of the gases coming from the 4 cases to Fos-France (Ballast)

| Emission | Amount (kg) | Q-Max (kg) | Conventional mood 1 (kg) | Conventional mood 2 (kg) |
|---|---|---|---|---|
| Net Inbound bunker (MT) | 1604 | 1831 | 675 | 1694 |
| $NO_x$ Emissions | 139749.84 | 159556.89 | 10919.68 | 10164.3 |
| CO Emissions | 4081.70 | 4660.21 | 965.53 | 847.0 |
| NMVOC Emissions | 2445.81 | 2792.47 | 221.55 | 0.0 |
| $SO_x$ Emissions | 73775.39 | 84231.74 | 31070.66 | 0.0 |
| $NH_3$ Emissions | 43.30 | 49.44 | 0.68 | 0.0 |
| $PM_{2.5}$ Emissions | 10692.62 | 12208.11 | 1771.70 | 0.0 |
| $PM_{10}$ Emissions | 10692.62 | 12208.11 | 1771.70 | 0.0 |
| TSP Emissions | 10692.62 | 12208.11 | 1771.70 | 0.0 |
| Pb Emissions | 0.24 | 0.27 | 0.10 | 0.0 |
| Cd Emissions | 0.02 | 0.02 | 0.01 | 0.0 |
| Hg Emissions | 0.00 | 0.01 | 0.00 | 0.0 |
| $CO_2$ Emissions | 5098521.19 | 5821145.54 | 4957947.86 | 4557004.1 |
| $CH_4$ Emissions | 49.40 | 56.40 | 54.61 | 81.3 |
| $N_2O$ Emissions | 255 | 291.15 | 181.98 | 8.1 |

The above values were considering the laden case, as well as for the ballast case. In total, for one round trip, both cases need to be considered in order to find the amount of emissions for one round trip to any destination.

### *4.2.1 Applying the ReCiPe model on Emissions from LNG Transportation*

From the first part, we got the results of emissions that came out from the LNG transportation, and for this part, we will apply the ReCiPe model by having those results as an input for the ReCiPe model calculation. In the ReCiPe model, each category in the Midpoint consist of many elements that are directly impacting on it, however, the calculations we made will be based on the availability of those elements that we receive from the first part. The defined parameters are the following:

- Global warming: $CO_2$, $CH_4$, $N_2O$
- Stratospheric ozone depletion: $N_2O$
- Ionizing Radiation: Pb
- Fine particulate matter formation: $NH_3$, $NO_x$, $PM_{2.5}$, $SO_x$
- Photochemical ozone formation: $NO_x$, NMVOC
- Toxicity (Human carcinogenic): Pb, Hg, Cd
- Toxicity (Human noncarcinogenic): Pb, Hg, Cd

So, when applying the ReCiPe model on those available elements, we come up with the following Midpoint values:

Table 19: Midpoint values- 1

| Global Warming (kg $CO_2$ eq) | | | Stratospheric ozone depletion (kg CFC11-eq) | Ionizing Radiation (kBq Co-60 to air eq) |
|---|---|---|---|---|
| $CO_2$ | $CH_4$ | $N_2O$ | $N_2O$ | Pb |
| 1 | 34 | 298 | 0.011 | 0.0909 |

Table 20: Midpoint values- 2

| Fine particulate matter formation (kg PM2.5 -eq) | | | | Photochemical ozone formation (kg NOx -eq) | | Toxicity (Human carcinogenic) (1,4-DCB eq. emitted to urban air) | | | Toxicity (Human noncarcinogenic) (1,4-DCB eq. emitted to urban air) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| NH3 | NOx | PM2.5 | SOx | NOx | NMVOC | Pb | Hg | Cd | Pb | Hg | Cd |
| 0.24 | 0.11 | 1 | 0.29 | 1 | 0.18 | 0.084657 | 1.206 | 1.142 | 101.67 | 488.75 | 1048.8 |

To translate those values into endpoint, we need to group them as per there category. This thesis is focusing on the human health, so the related groups that directly affecting the human health and forming the endpoint will be: global warming; stratospheric ozone depletion; ionizing radiation; fine particulate matter formation; photochemical ozone formation; toxicity (human carcinogenic) and toxicity (human noncarcinogenic). the unit used for finding human health endpoints is DALYs (disability-adjusted life years), relevant for human health, represent the years that are lost or that a person is disabled due to a disease or accident.

For the endpoints:

From the ReCiPe model, we found the values for the Endpoint as following:

Table 21: Endpoint values- 1

| Global Warming (DALY/kg $CO_2$ eq.) | Stratospheric ozone depletion (DALY/kg CFC11 eq.) | Ionizing Radiation (DALY/kBq Co-60 emitted to air eq.) | Fine particulate matter formation (DALY/kg $PM_{2.5}$ eq.) |
|---|---|---|---|
| 0.000000928 | 0.000531 | 8.5E-09 | 0.000629 |

Table 22: Endpoint values- 2

| Photochemical ozone formation (DALY/kg $NO_x$ eq.) | Toxicity (Human carcinogenic) (DALY/kg 1,4-DCB emitted to urban air eq.) | Toxicity (Human noncarcinogenic) (DALY/kg 1,4-DCB emitted to urban air eq.) |
|---|---|---|
| 0.00000091 | 0.00000332 | 0.000000228 |

Above discussed gross fuel consumption, emission factors, midpoint and endpoint factors will be used as a tool to calculate the equivalent kg of gases with the volume of fuel consumed in during 1 round trip of LNG delivery to France.

From gases emission factors, fuel consumption, midpoint and endpoint factors, amount of each gas emitted is calculated by:

1. $GW = C_E * C_R + ME * M_R + N_E * N_R$

2. $SOD = N_E * N_R$

3. $IR = P_E * P_R$

4. $FPMF = A_E * A_R + NO_E * NO_R + PM_E * PM_R + SO_E * SO_R$

5. $POF = NO_E * NO_R + NMVOC_E * NMVOC_R$

6. $T_C = IR + H_E * H_R + CD_E * CD_R$

7. $T_{NC} = IR + H_E * H_R + CD_E * CD_R$

Where,

*GW = Global Warming*

*$C_E$ = Carbon Emissions*

*$M_E$ = Methane Emissions (CH4)*

*R = ReCipe value*

*$C_R$ = Carbon ReCiPe value*

*SOD = Stratospheric Ozone Depletion*

*IR = Ionizing Radiation*

*$N_E$ = Nitrous Emissions (N2O)*

*$P_E$ = Lead Emissions (Pb)*

*$A_E$ = Ammonia Emissions (NH3)*

*FPMF = Fine particulate matter formation*

*$NO_E$ = Nitrogen Emissions ($NO_x$)*

*PM = Particulate Matter*

*$PM_E$ = Particulate Matter Emissions*

*$SO_E$ = Sulphur Emissions ($SO_x$)*

*POF = Photochemical ozone formation*

*$NMVOC_E$ = Non-methane volatile organic compound Emissions*

*$T_C$ = Toxicity (Human carcinogenic)*

*$H_E$ = Mercury Emissions (Hg)*

*$CD_E$ = Cadmium Emissions (Cd)*
*$T_{NC}$ = Toxicity (Human carcinogenic)*

For the Endpoint calculations, we use the outcomes from each Midpoint category and multiply it by the Endpoint value for each category as follows:

1. GW – HH = MGW * EfGW
2. SOD – HH = MSOD * EfSOD
3. IR – HH = MIR * EfIR
4. FPMF – HH = MFPMF * EfFPMF
5. POF – HH = MPOF * EfPOF
6. $T_C$ – HH = $MT_C$ * $EfT_C$
7. $T_{NC}$ – HH = $MT_{NC}$ * $EfT_{NC}$

Where,

*GW = Global Warming*
*HH = Human Health*
*M = Midpoint*
*E = Endpoint*
*F = factor*
*MGW = Midpoint value of Global Warming*
*EfGW = Endpoint factor of Global Warming*
*SOD = Stratospheric Ozone Depletion*
*IR = Ionizing Radiation*
*FPMF = Fine particulate matter formation*
*POF = Photochemical ozone formation*
*$T_C$ = Toxicity (Human carcinogenic)*
*$T_{NC}$ = Toxicity (Human carcinogenic)*

# CHAPTER 5: RESULTS AND DISCUSSION

In order to meet the acknowledged goal of this research, the following points are addressed in this section:

1- Find out the total emission amount for each vessel/ fuel type for one round trip.

2- Assess and evaluate the total emission amount

3- Find out the result after applying the LCA ReCiPe model and assess the outcomes

4- Distinguish the most critical indicators that are influencing the emission results by applying sensitivity analysis

The findings of these investigations are discussed in this section.

## 5.1 Emission Calculation Results

From the previous part, and for the case of France, we summed up the total emission that comes out for both ballast and laden, so the total amount of emissions for each group of gases will be calculated. As it is obvious from Table 23, the emission values are varying from one vessel/ fuel to another. We found that the highest values come out from the Q-Max vessels. This is anticipated as the Q-Max is the largest in terms of size among the other vessels and therefore its consumption of the fuel will be the largest. Moving to the conventional vessels which both have a similar size, it is clear that conventional 1 which runs purely with LNG proved to have less emission outcomes than the one that is running by the dual mood (LNG+ HFO), etc. Therefore, using the LNG as fuel for the vessels will be the best option and a cleaner source of energy relying on the emission outcomes. Table 23 is showing the total amount of emissions for one round trip to Fos port in France for four different groups of gases as follow:

Table 23: The total emission values for all vessel types to Fos-France for 1 round trip

| Emissions | Q-Flex | Q-Max | Conven1 | Conven2 |
|---|---|---|---|---|
| Total $NO_x$ Emissions (Kg) | 331576.435 | 366289.644 | 24952.180 | 21778.334 |
| Total CO Emissions (Kg) | 9684.425 | 10698.301 | 2227.646 | 1814.861 |
| Total NMVOC Emissions (Kg) | 5803.044 | 6410.573 | 591.389 | 0.000 |
| Total $SO_x$ Emissions (Kg) | 175042.646 | 193368.110 | 82938.729 | 0.000 |
| Total NH3 Emissions (Kg) | 102.742 | 113.499 | 1.803 | 0.000 |
| Total $PM_{2.5}$ Emissions (Kg) | 25369.768 | 28025.765 | 4729.311 | 0.000 |
| Total $PM_{10}$ Emissions (Kg) | 25369.768 | 28025.765 | 4729.311 | 0.000 |
| Total TSP Emissions (Kg) | 25369.768 | 28025.765 | 4729.311 | 0.000 |
| Total Pb Emissions (Kg) | 0.571 | 0.631 | 0.270 | 0.000 |
| Total Cd Emissions (Kg) | 0.049 | 0.055 | 0.023 | 0.000 |
| Total Hg Emissions (Kg) | 0.011 | 0.013 | 0.005 | 0.000 |
| Total $CO_2$ Emissions (Kg) | 12096968.946 | 13363417.851 | 11353177.385 | 9763952.958 |
| Total $CH_4$ Emissions (Kg) | 117.202 | 129.473 | 112.207 | 174.227 |
| Total $N_2O$ Emissions (Kg) | 357.731 | 668.381 | 482.421 | 17.423 |

## 5.2 LCA -ReCiPe Methodology- Results

Moving to the second part of the model, which is applying the LCA- ReCiPe model to the emission results and find out the midpoint and endpoint results. The emission results from the first section were used as an input to the ReCiPe model.

As it is clear below, and along with the ReCiPe model, the highest impact of human health always comes out from the Q-Max vessel. This is observed among all midpoint to endpoint factors. For example, Global Warming to Human health factor, the amount produced from the Q-Max is 12.59 DALY/kg $CO_2$ eq, while for Q-Flex is 11.32 DALY/kg $CO_2$ eq. At the same time, it has been observed that the least effect always comes from the conventional vessels with purely LNG fuel even it has the value zero for the following factors like Toxicity - Human health (non-cancer), Toxicity - Human health (cancer), Ionizing Radiation - Human health. Tables 24-25 illustrate the midpoint and endpoint assessment results to the emission of the four different groups of vessels and fuels as follow:

Table 24: Applying midpoint calculations on all vessel

| Midpoint | Q-Flex | Q-Max | Conventional mood 1 | Conventional mood 2 | Unit |
|---|---|---|---|---|---|
| Global Warming | 12207557.6 | 13566997.48 | 11500753.85 | 9775068.619 | kg $CO_2$ eq |
| Stratospheric ozone depletion | 3.93503839 | 7.352191828 | 5.306629735 | 0.191649337 | kg CFC11-eq |
| Ionizing Radiation | 0.051884923 | 0.05731683 | 0.024584121 | 0 | kBq Co-60 to air eq |
| Fine particulate matter formation | 112630.2012 | 124421.6173 | 31526.71454 | 2395.616711 | kg $PM_{2.5}$-eq |
| Photochemical ozone formation | 332620.9827 | 367443.547 | 25058.63053 | 21778.33373 | kg $NO_x$ -eq |
| Toxicity (Human carcinogenic) | 0.11858207 | 0.130996595 | 0.056186571 | 0 | 1,4-DCB eq. emitted to urban air |
| Toxicity (Human noncarcinogenic) | 115.4944697 | 127.5857501 | 54.72360443 | 0 | 1,4-DCB eq. emitted to urban air |

Table 25: Applying endpoint calculations on all vessel types

| Midpoint to Endpoint | Q-Flex | Q-Max | Conventional mood 1 | Conventional mood 2 | Unit |
|---|---|---|---|---|---|
| Global Warming - Human health | 11.32861345 | 12.59017366 | 10.67269958 | 9.071263678 | DALY/kg $CO_2$ eq. |
| Stratospheric ozone depletion - Human health | 0.002089505 | 0.003904014 | 0.00281782 | 0.000101766 | DALY/kg CFC11 eq. |
| Ionizing Radiation - Human health | 4.41022E-10 | 4.87193E-10 | 2.08965E-10 | 0 | DALY/kBq Co-60 emitted to air eq. |
| Fine particulate matter formation - Human health | 70.84439654 | 78.26119729 | 19.83030345 | 1.506842911 | DALY/kg $PM_{2.5}$ eq. |
| Photochemical ozone formation - Human health | 0.302685094 | 0.334373628 | 0.022803354 | 0.019818284 | DALY/kg $NO_x$ eq. |
| Toxicity - Human health (cancer) | 3.93692E-07 | 4.34909E-07 | 1.86539E-07 | 0 | DALY/kg 1,4-DCB emitted to urban air eq. |
| Toxicity - Human health (non-cancer) | 2.63327E-05 | 2.90896E-05 | 1.2477E-05 | 0 | DALY/kg 1,4-DCB emitted to urban air eq. |

## 5.3 Sensitivity Results

This section will show the sensitivity analysis of the parameters that are impacting on the amount of the emitted gases to the air during the vessel voyage. It will target the 3 types of vessels for one destination during the laden and ballast. For the case of a laden, a total of 11 parameters has been considered and used for sensitivity analysis. The parameters are Load port days (Days), Steam days (Days), Canal days (Days), At anchorage days (Days), Discharge port days (Days), At Anchorage Consumption, Discharge port days (Days), At Anchorage Consumption, Steaming Fuel Consumption, Loading Consumption, Canal Consumption, Discharging Consumption and Emission Factor. Table 34 lists all the parameters used in the sensitivity analysis with a variation of ±10% for normal distribution. A combination of 4 different categories of vessel types and fuel types was used as follows: vessel type Q-Flex with fuel type HFO, Vessel type Q-Max with fuel type HFO, vessel type conventional with dual fuels (HFO and LNG), finally vessel type conventional 2 with fuel type LNG only.

Table 26: Emission parameters used for sensitivity analysis (Laden)

| Parameters | Variation |
|---|---|
| Load port days (Days) | ±10 % Normal distribution |
| Steam days (Days) | ±10 % Normal distribution |
| Canal days (Days) | ±10 % Normal distribution |
| At anchorage days (Days) | ±10 % Normal distribution |
| Discharge port days (Days) | ±10 % Normal distribution |
| At Anchorage Consumption | ±10 % Normal distribution |
| Steaming Fuel Consumption | ±10 % Normal distribution |
| Loading Consumption | ±10 % Normal distribution |
| Canal Consumption | ±10 % Normal distribution |
| Discharging Consumption | ±10 % Normal distribution |
| Emission Factor | ±10 % Normal distribution |

As it is shown in Figures 25-28, the emission factors come on the top of almost all cases with a percentage exceeds 40%. It is reasonable to have it the most powerful parameters as it depends mainly on the vessel type as well as the fuel used for that vessel, so the amount of emissions comes is highly depend on that emission factor. The second and third parameters are the steam days and steam fuel consumption with a percentage between 25-35%. The rest of the factors have a very minor effect with a percentage of less than 1%.

The same is repeated but for the case of ballast, the factor for the gas emissions has been analyzed for the same different 4 combinations of vessels and fuels. However, the parameters become less in the case of Ballast as follows: Steam days (Days), Canal days (Days), At anchorage days (Days), At Anchorage Consumption, Steaming Fuel Consumption, Canal Consumption, and Emission Factor. Again, as it is clear in Table 35, the parameters used in the sensitivity analysis are listed and a normal distribution with a variance of ±10% has been applied.

Table 27: Emission parameters used for sensitivity analysis (Ballast)

| Parameters | Variation |
|---|---|
| Steam days (Days) | ±10 % Normal distribution |
| Canal days (Days) | ±10 % Normal distribution |
| At anchorage days (Days) | ±10 % Normal distribution |
| At Anchorage Consumption | ±10 % Normal distribution |
| Steaming Fuel Consumption | ±10 % Normal distribution |
| Canal Consumption | ±10 % Normal distribution |
| Emission Factor | ±10 % Normal distribution |

Similar to the case of laden, emission factor ranked as the first among all other factors with a percentage of 35%-40%. The steaming days and the steaming fuel consumption also appeared to have a high percentage like the case of dual fuel Conventional vessel where the steaming fuel consumption comes as the top parameters with a percentage exceeds 45%. See Figure 31. The other parameters have a minor effect as the case of canal days and canal consumption, with a percentage of less than 1%

## 5.4 Sensitivity Analysis:

(Laden)

1- For the vessel type Q-Flex with laden status, $CO_2$ emission factors:

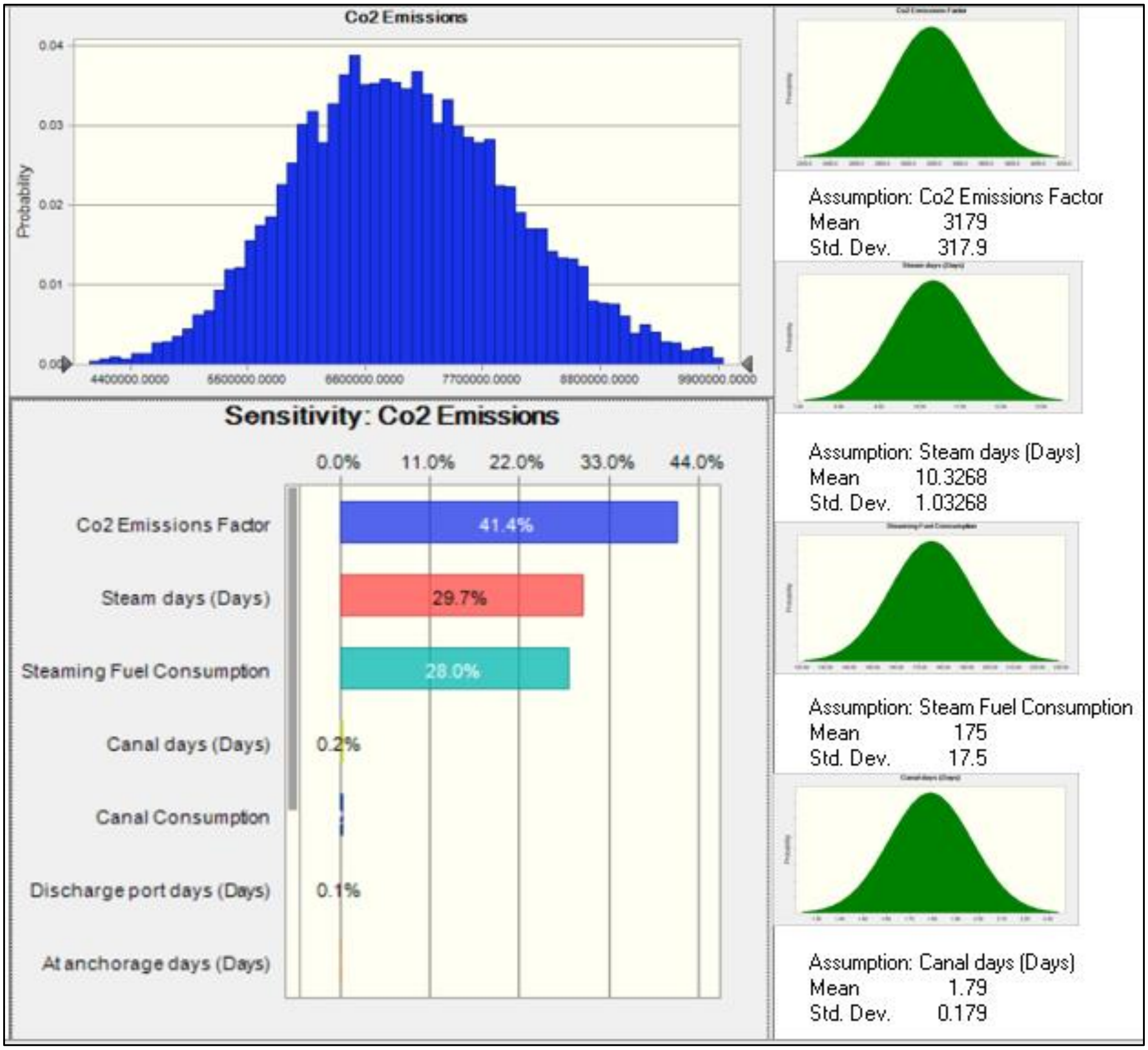



Figure 27: $CO_2$ Emission factors Sensitivity analysis (Q-Flex)

2- For the vessel type Q-Max with laden status, $CO_2$ emission factors

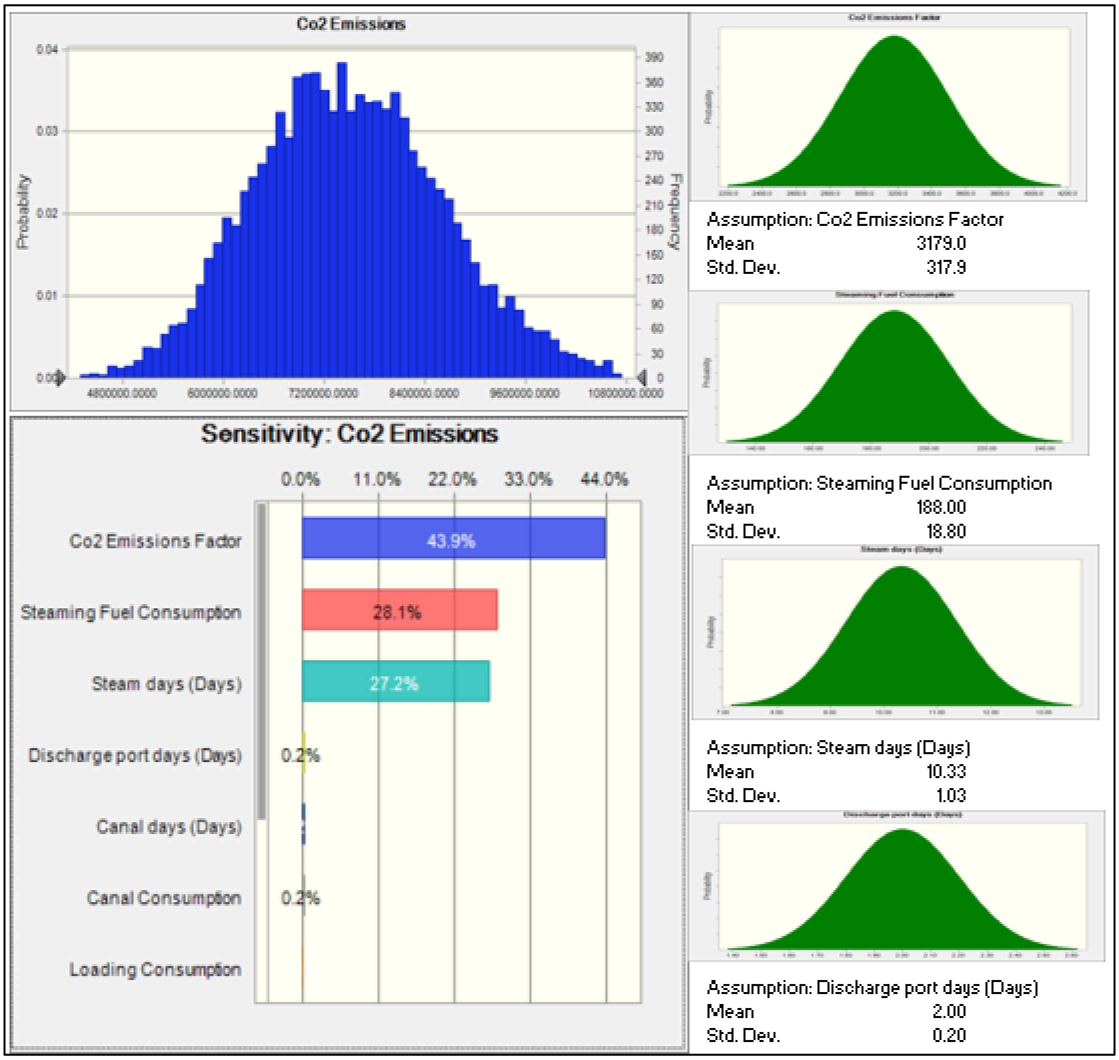



Figure 28: $CO_2$ Emission factors Sensitivity analysis (Q-Max)

3- For the vessel type Conventional mood 1 with laden status, $CO_2$ emission factors

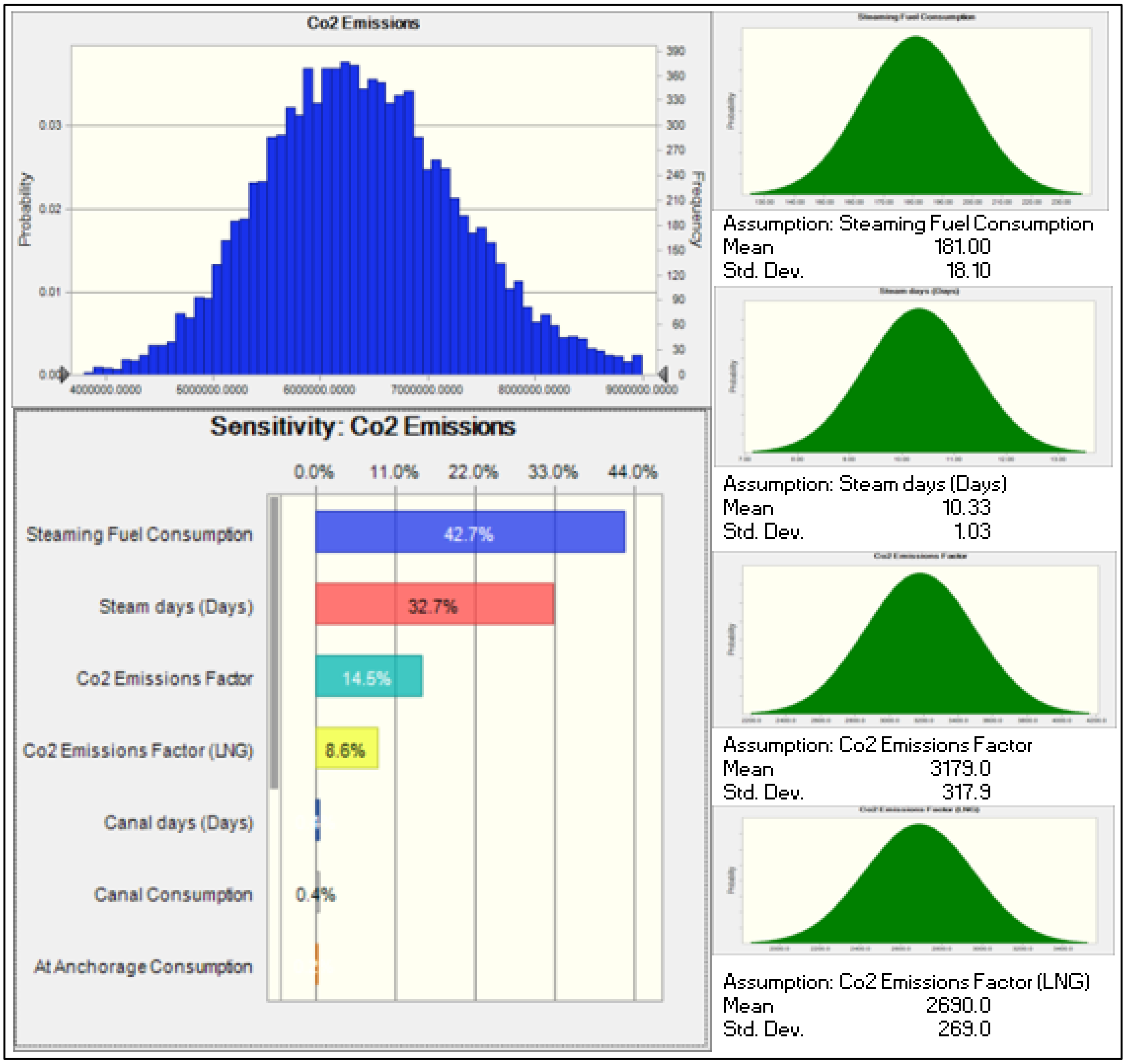



Figure 29: $CO_2$ Emission factors Sensitivity analysis (Dual Conventional)

4- For the vessel type Conventional mood 2 with laden status, $CO_2$ emission factors

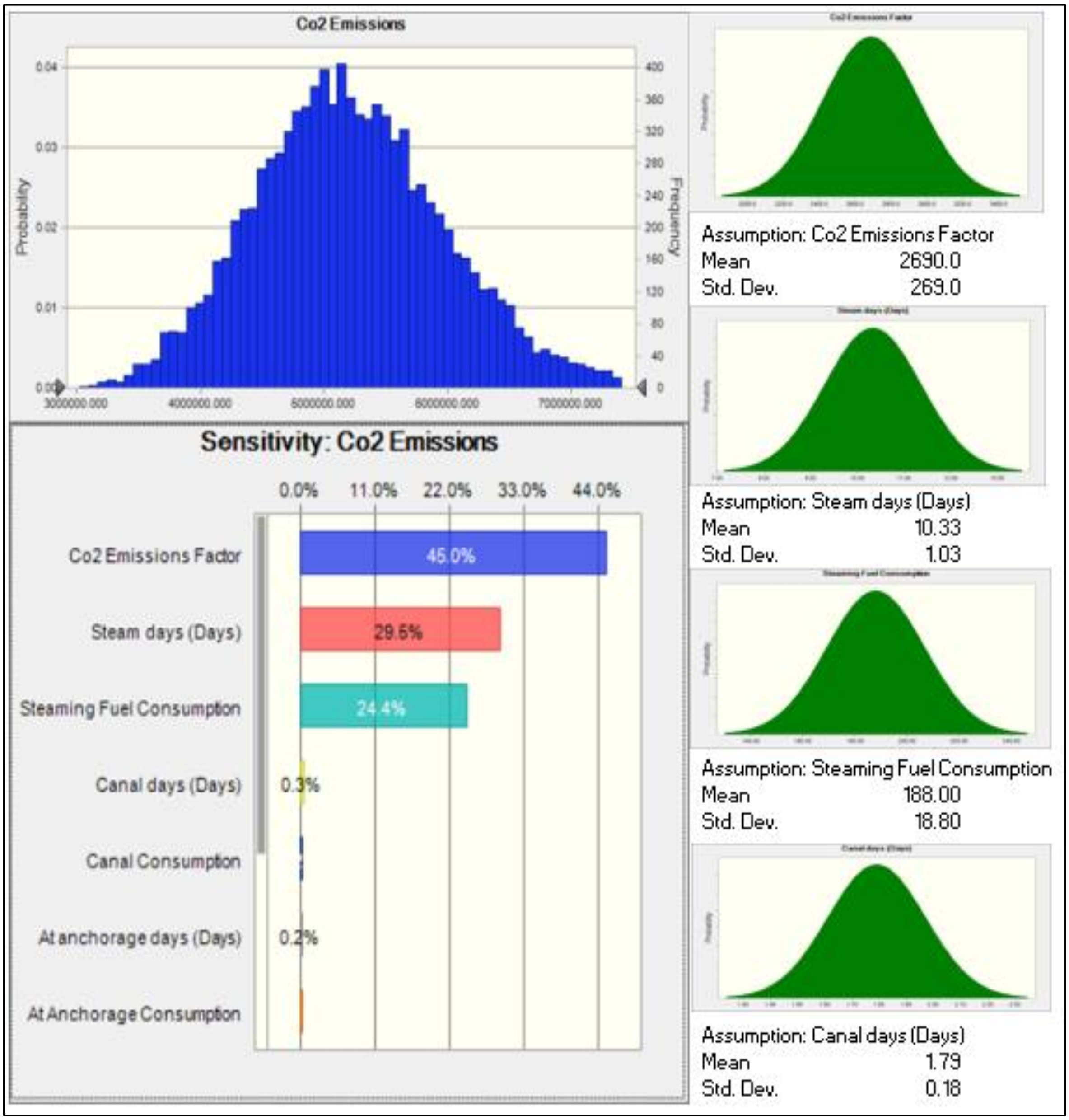



Figure 30: $CO_2$ Emission factors Sensitivity analysis (LNG Conventional)

Ballast

1- For the vessel type Q-Flex with Ballast status, $CO_2$ emission factor

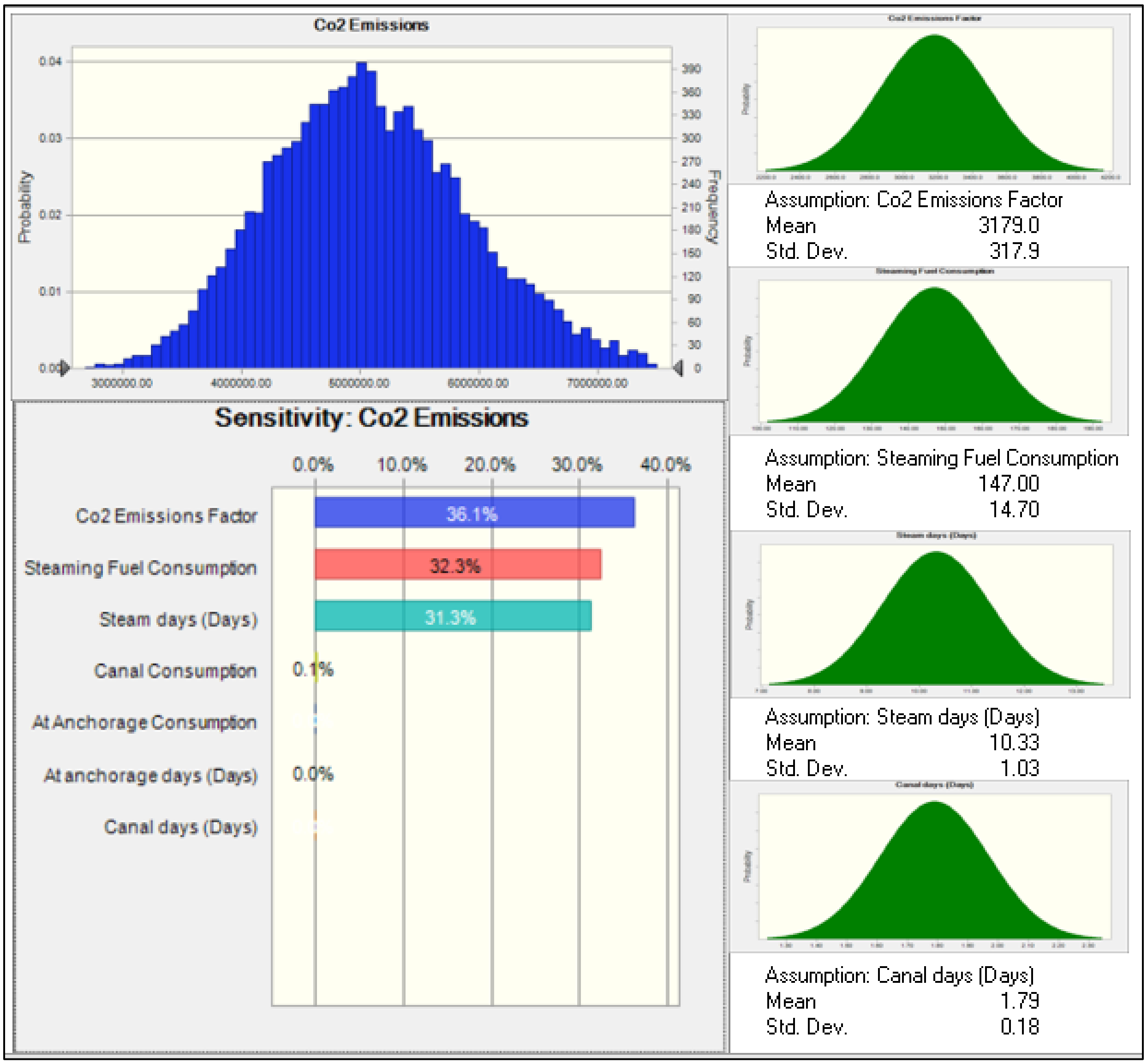



Figure 31: $CO_2$ Emission factors Sensitivity analysis (Q-Flex)

2- For the vessel type Q-Max with Ballast status, $CO_2$ emission factors

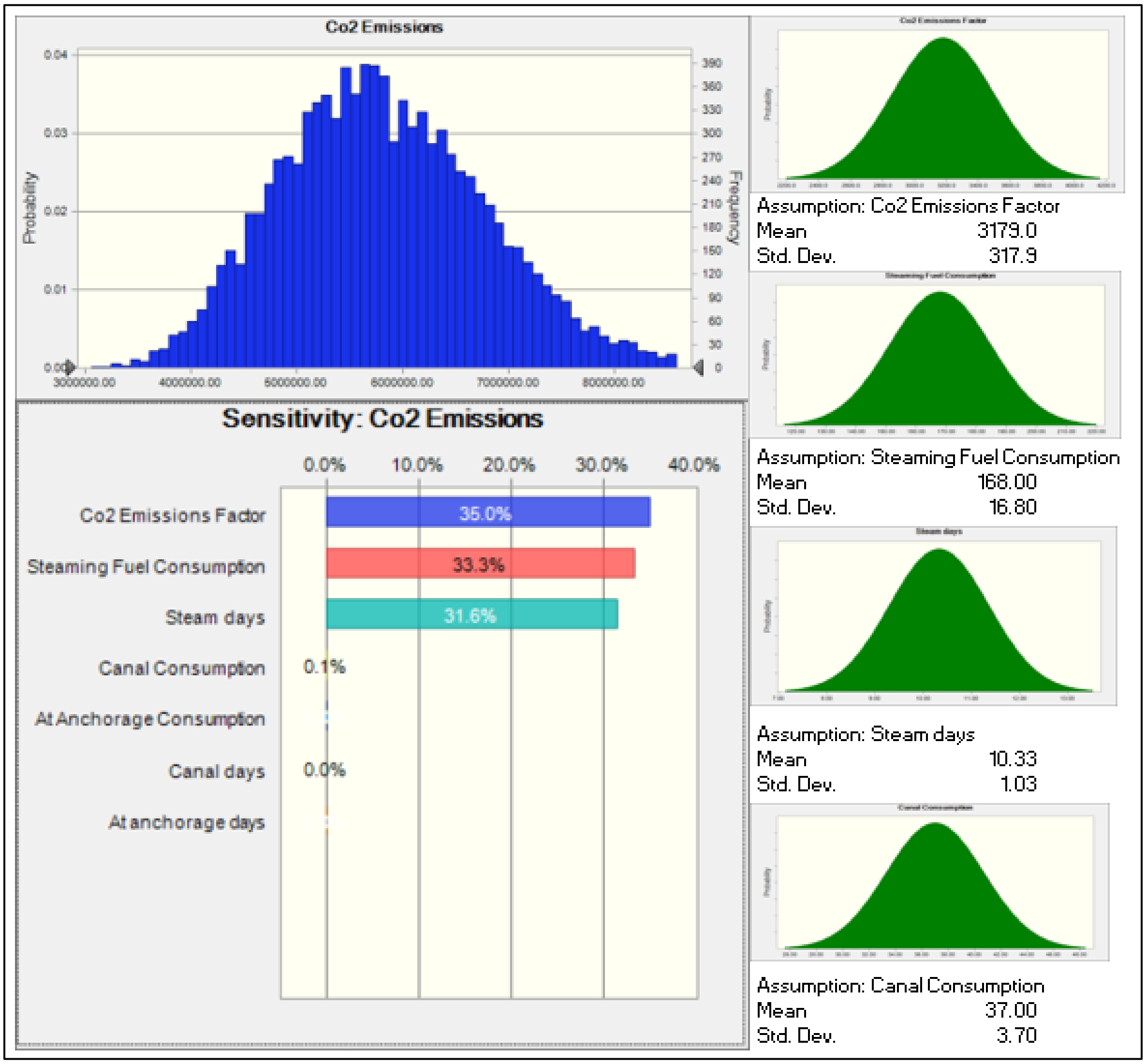



Figure 32: $CO_2$ Emission factors Sensitivity analysis (Q-Max)

3- For the vessel type Conventional mood 1 with Ballast status, $CO_2$ emission factors

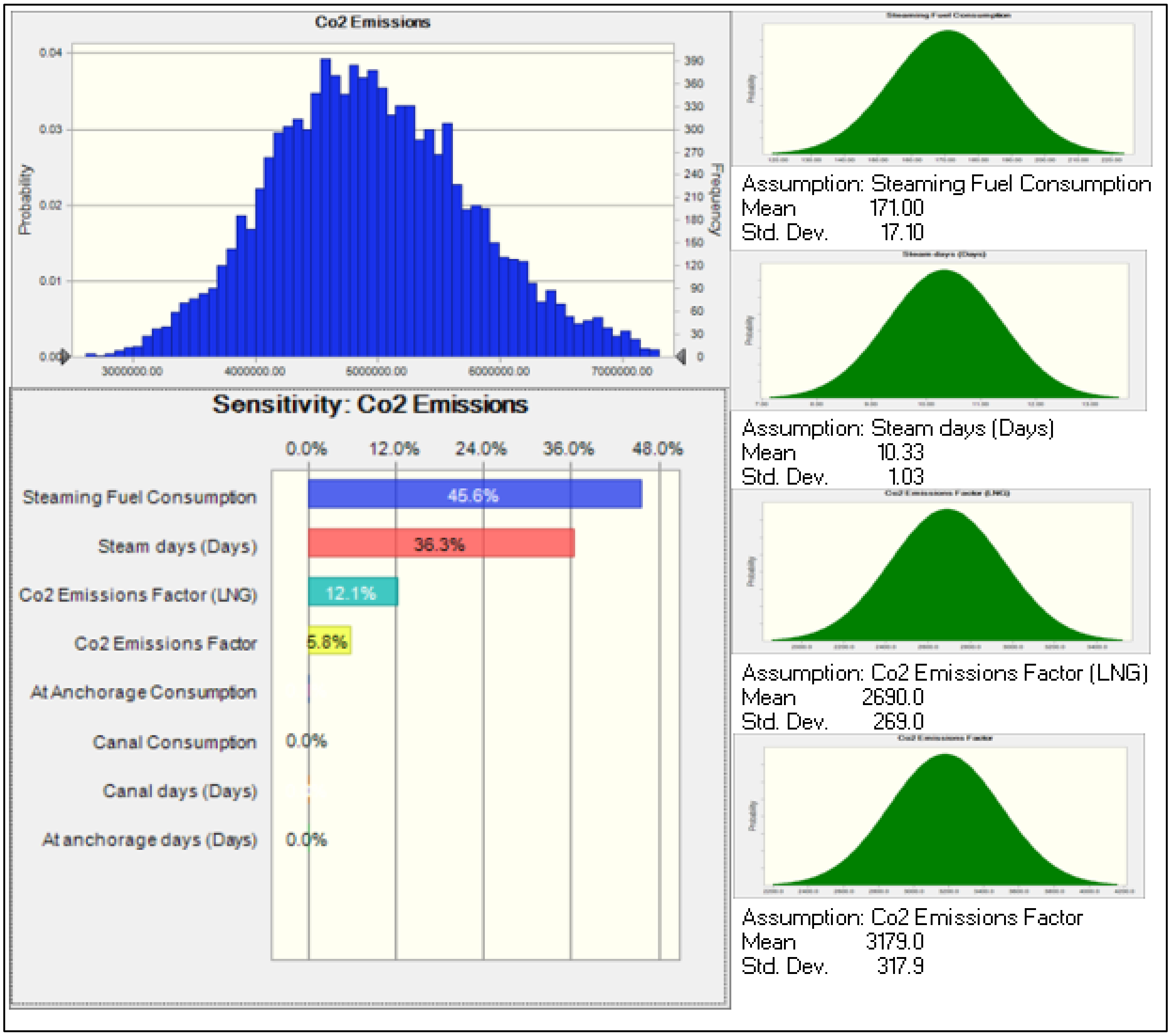



Figure 33: $CO_2$ Emission factors Sensitivity analysis (Dual mood)

4- For the vessel type Conventional mood 2 with Ballast status, $CO_2$ emission factors

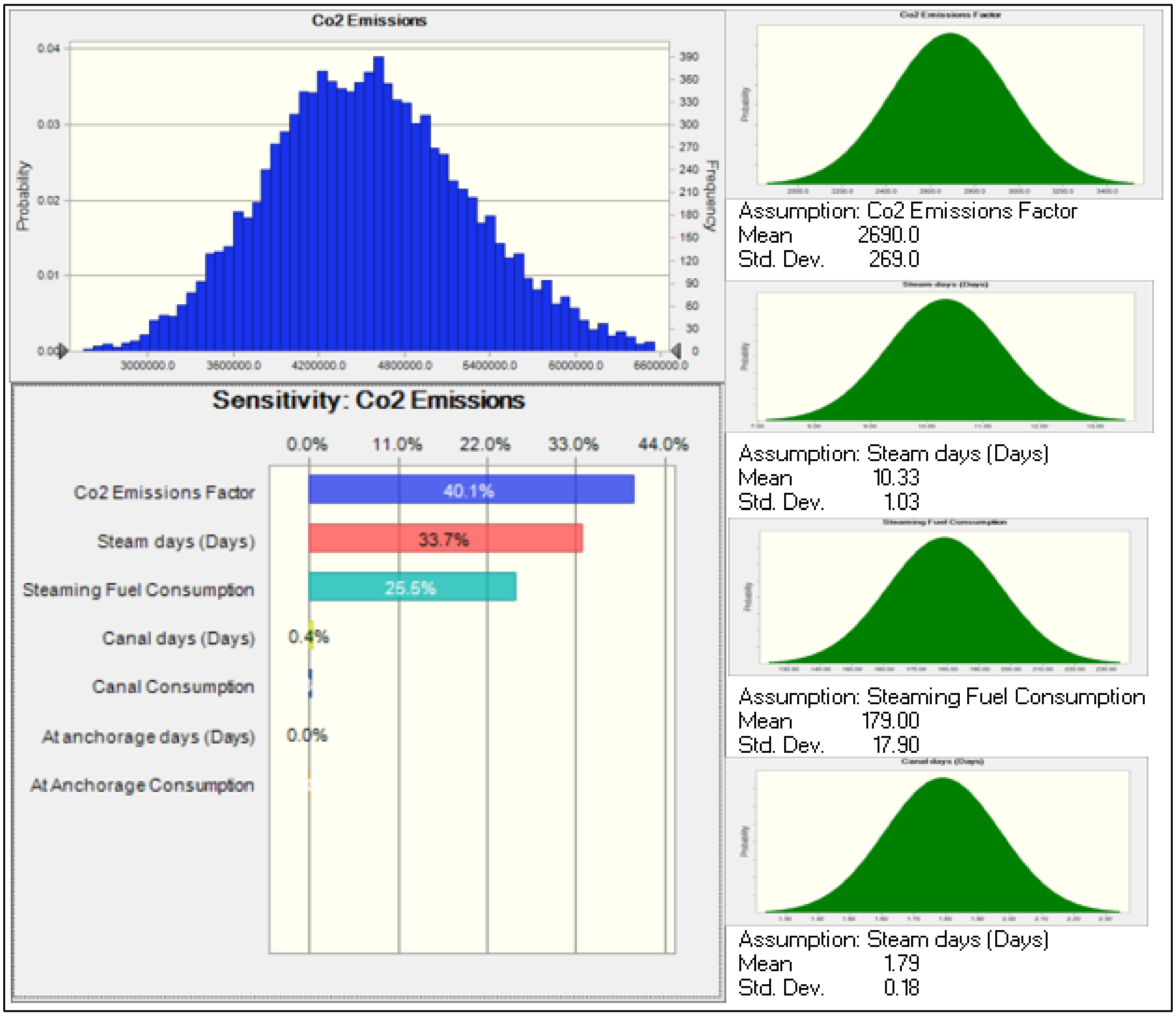



Figure 34: $CO_2$ Emission factors Sensitivity analysis (LNG Conventional)

# CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

## 6.1 Research Summary and Conclusion

In this research, the focus was to shed light on the transportations of LNG from Qatar to its customers around the world in terms of evaluating gas emissions and its impact on human health. Therefore, this started by defining the destinations which are a group of 7 international ports from different countries in order to calculate the emission values for one round trip (the case of laden and ballast). Different types of fuel and vessel were used and grouped to find out the emission values of 4 different groups of gases. After finding the amount of emitted gases, the ReCiPe model has been applied by calculating the midpoint and endpoint values to find the impact on human health. To apply the ReCiPe model, midpoint and endpoint need to be calculated for each category. The midpoint consists of many elements that are directly impacting on it, however, the calculations were based on the availability of those elements that we got from the first part. To translate those values into endpoint, those elements were grouped to the required category (human health) as it is the main focus of this thesis. After that, it moved to the last part which is the sensitivity analysis. Sensitivity analysis for the emission factors were applied to see the effect and the power of each parameter during the transportation journey. A normal distribution with a variance of ±10% was applied to the parameters in order to study the changes and their impact.

## 6.2 Research Findings

From the emission calculation results, many observations have been noticed which might impact the decision of selecting the vessel or the fuel type in the future. Firstly, the type and size of vessel used for shipping the LNG make a difference in terms of the amount of emitted gases that comes out from it. The vessel type Q-Max produce more emission amount than the Q-Flex although both are traveling the same distance and are using the same fuel type. The second observation is that the fuel types are also affecting the emission values. Like the case of the 2 conventional vessels (the dual-Fuel Conventional and the LNG-Conventional), the one that is running with only LNG proved to have fewer emission values than the one run with dual-mode. Moving to the second part of the thesis which is evaluating the human health impacts coming from each vessel/ fuel emission. Again, it has been clear that the fuel type LNG that is used in the conventional vessel has less impact than the other vessel/ fuel types, especially when talking about the toxicity impact (cancer/ non-cancer) or the Ionizing Radiation endpoint as both of them have a zero value. Finally, the last part of this research was the sensitivity analysis, which has been conducted to understand the effect of each parameter on the emission results. It has been very obvious that the “Emission Factor value” has the most powerful impact and this is reasonable as it depends mainly on the type of vessel as well as the fuel used for that vessel, so the amount of emissions comes is highly sensitive and relying on that parameter.

## 6.3 Limitations and Recommendations

Recently, this topic became very significant, especially with the growing interest by environmental organizations and institutions, however, very limited studies have been conducted to cover such important areas' especially in Qatar. This leads to have many complications and difficulties particularly during data collections, as the emission factors for many gases did not exist or provided by Qataris companies. As a result, external resources from foreign organizations and agencies were used to perform the calculations. Therefore, it is recommended by Qatari's LNG companies to spend more effort on studying the emissions of LNG transportation and publishing annual reports to extend further studies in the future. Those reports must be consistent with data that can be used easily to reflect sustainability performance. In addition, they must be easily used for benchmarking purposes domestically and internationally.

## 6.4 Future Works

This research was focusing on studying emissions and evaluating its impact on human health in the case of Qatar. In the future, this can be extended to cover more other aspects like the environmental and economic impact of LNG vessel shipping as part of the Life Cycle Sustainability Assessment (LCSA). Therefore, more efforts can be dedicated to analyzing and evaluate all environmental, social and economic impacts, which help in decision-making processes towards more sustainable products or methods. Although transportation is the focus of this research, it can be extended to cover the complete value chain starting from the exploration and production stage, ending up with the regasification and final use of LNG.

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# Appendix A: Sensitivity analysis for the vessel types for 1 round trip

(Laden)

1- For the vessel type Q-Flex with laden status, $CH_4$ emission factors:

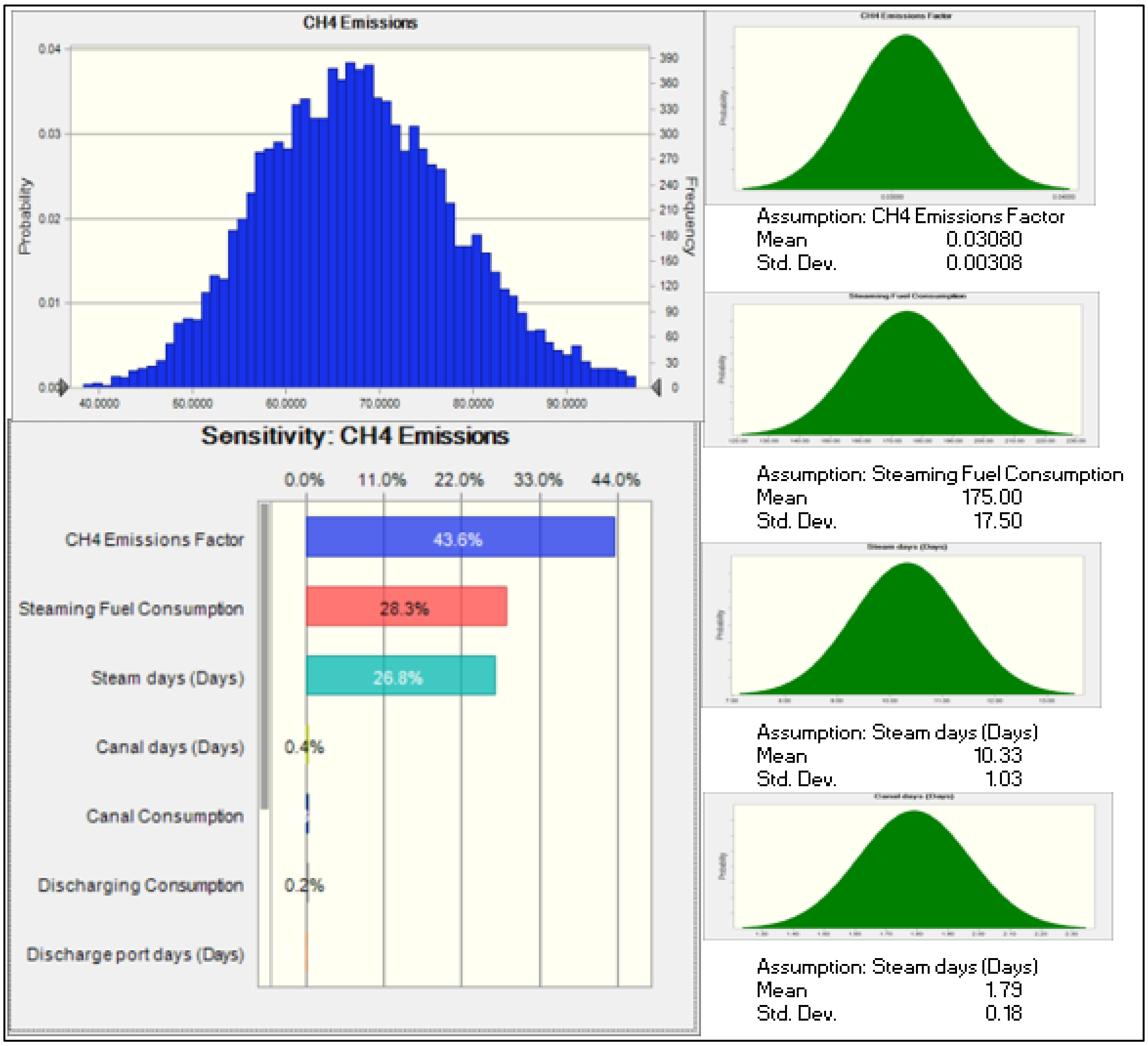



Figure 35: $CH_4$ Emission factors Sensitivity analysis (Q-Flex)

2- For the vessel type Q-Flex with laden status, $N_2O$ emission factors

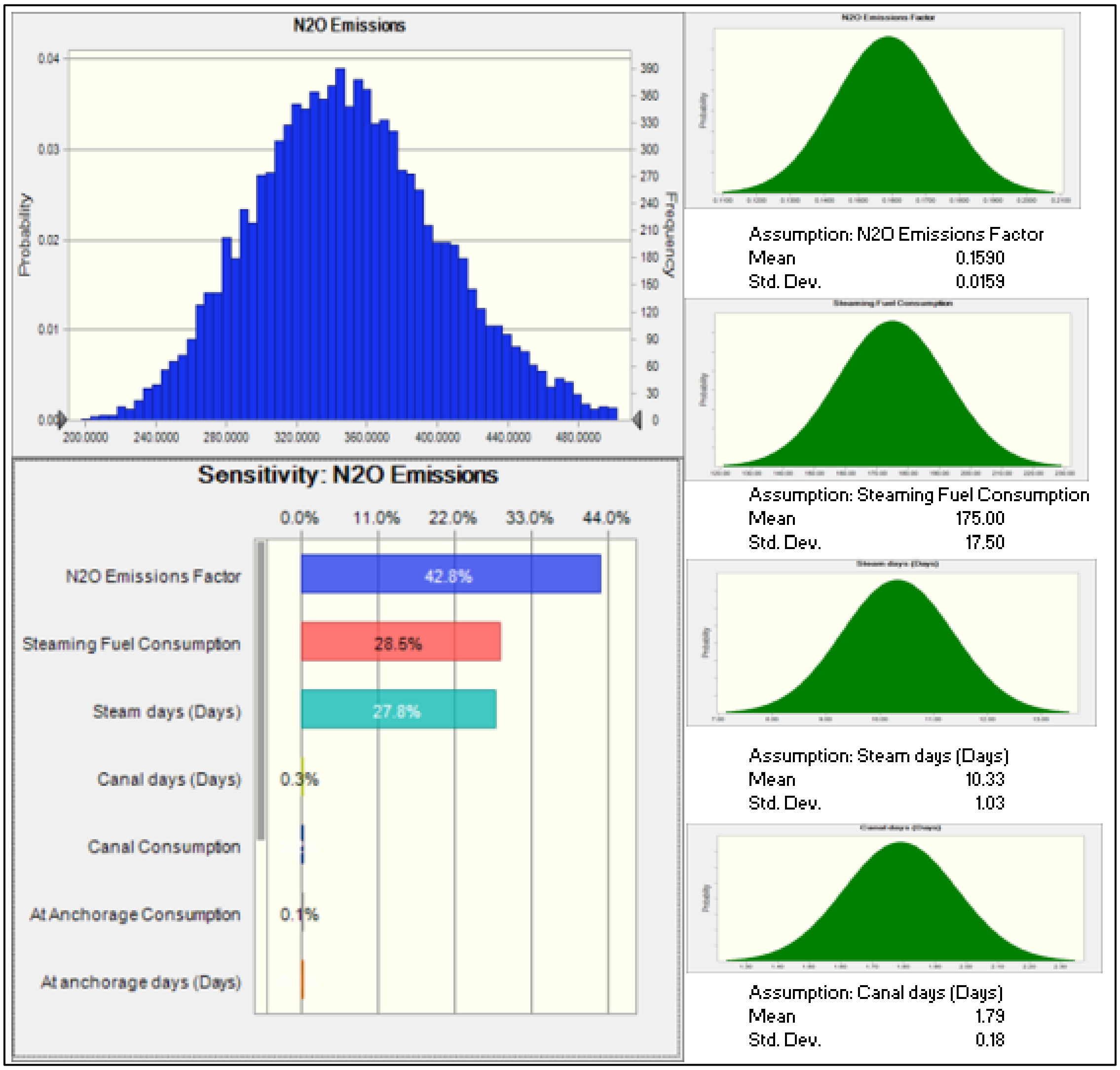



Figure 36: $N_2O$ Emission factors Sensitivity analysis ($N_2O$)

3- For the vessel type Q-Max with laden status, $CH_4$ emission factors

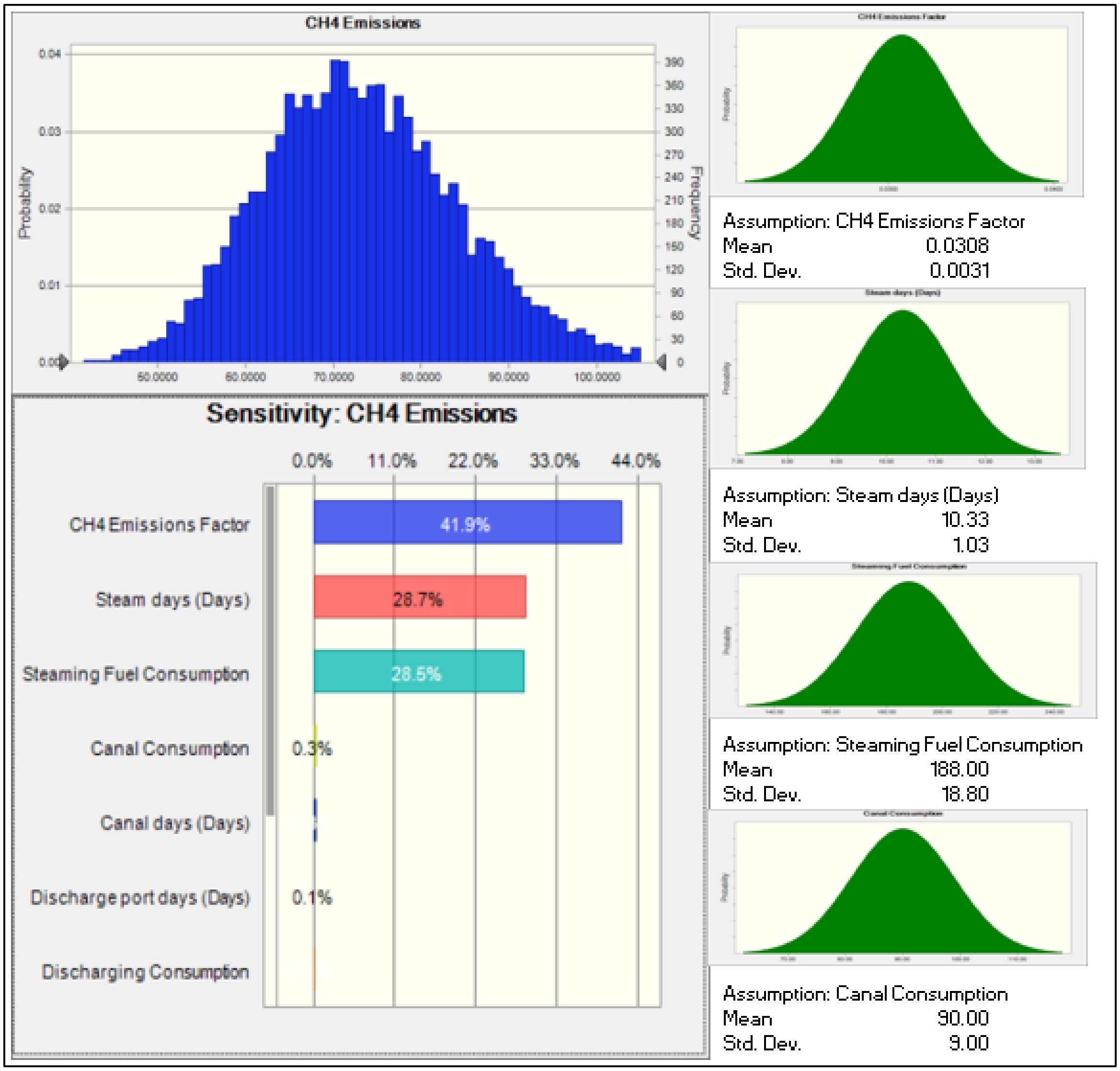



Figure 37: $CH_4$ Emission factors Sensitivity analysis (Q-Max)

4- For the vessel type Q-Max with laden status, $N_2O$ emission factors

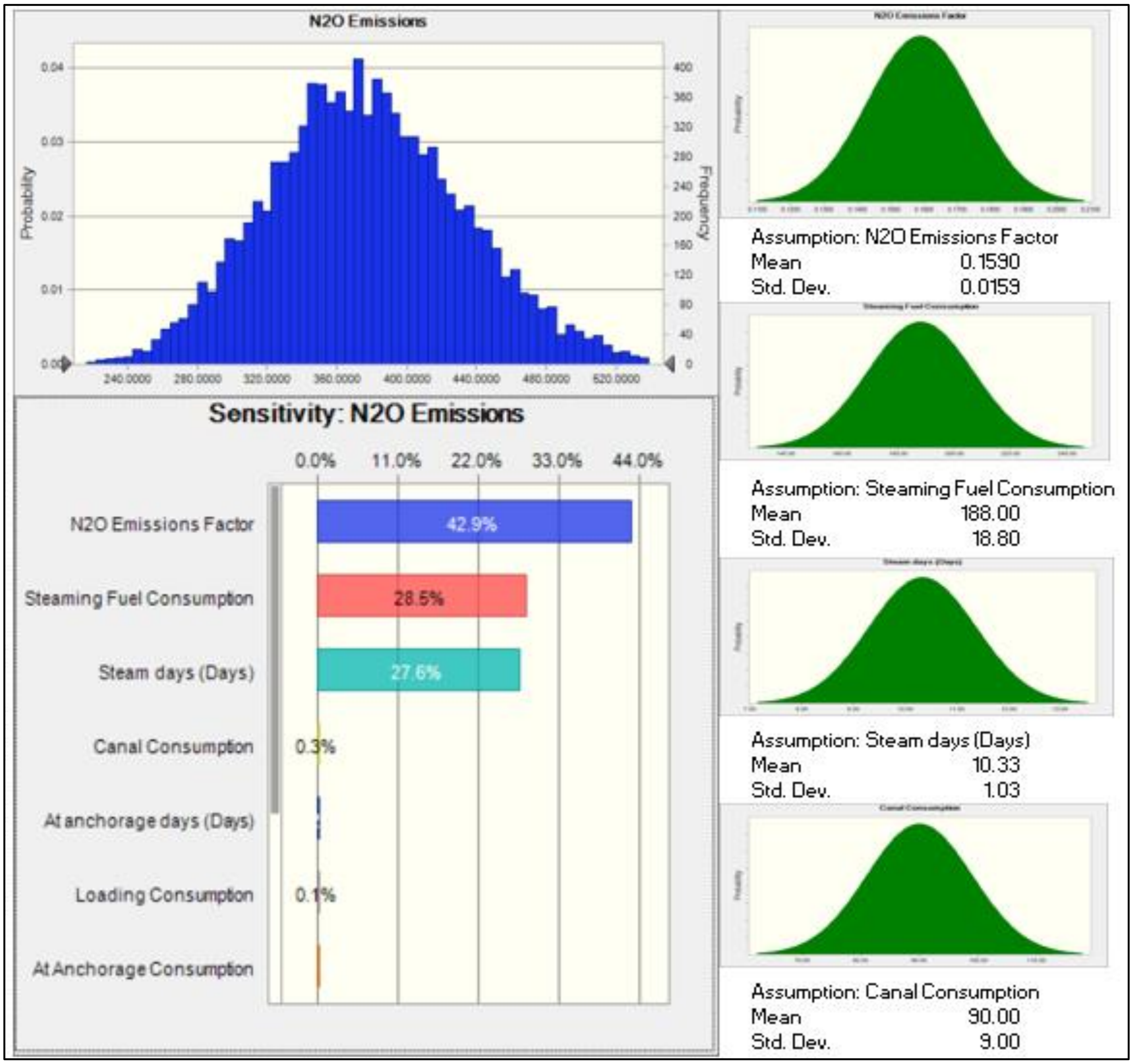



Figure 38: $N_2O$ Emission factors Sensitivity analysis (Q-Max)

5- For the vessel type Conventional 1 with laden status, $CH_4$ emission factors

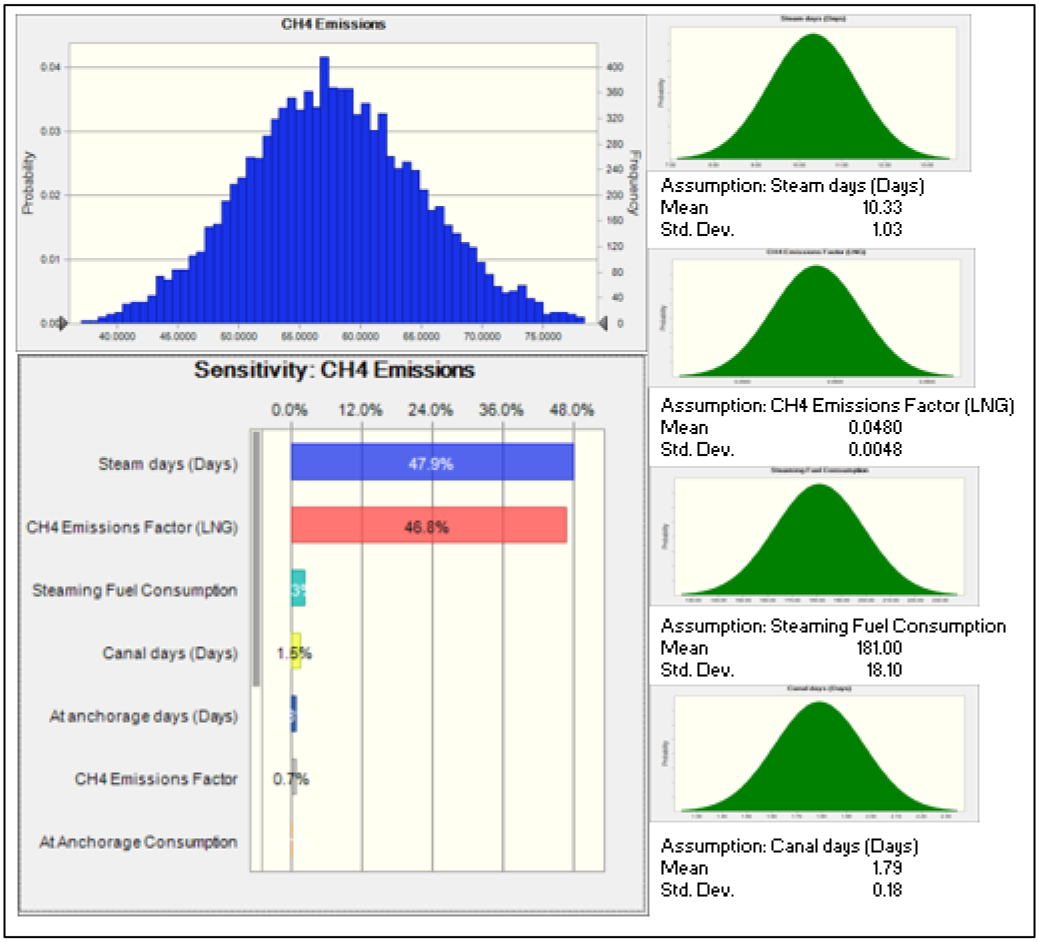



Figure 39: $CH_4$ Emission factors Sensitivity analysis (Dual Conventional)

6- For the vessel type Conventional 1 with laden status, $N_2O$ emission factors

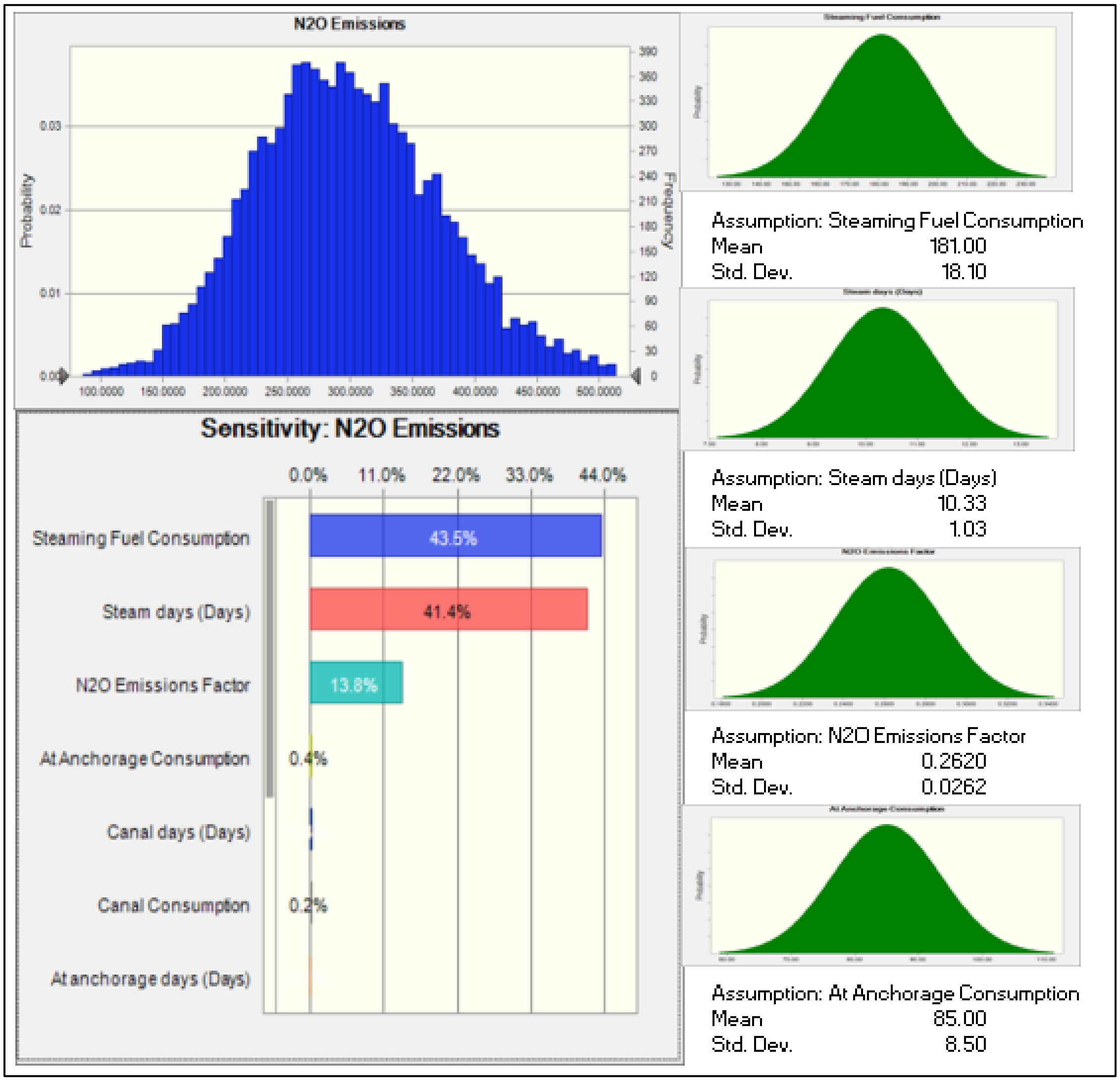



Figure 40: $N_2O$ Emission factors Sensitivity analysis (Dual Conventional)

7- For the vessel type Conventional 2 with laden status, $CH_4$ emission factors

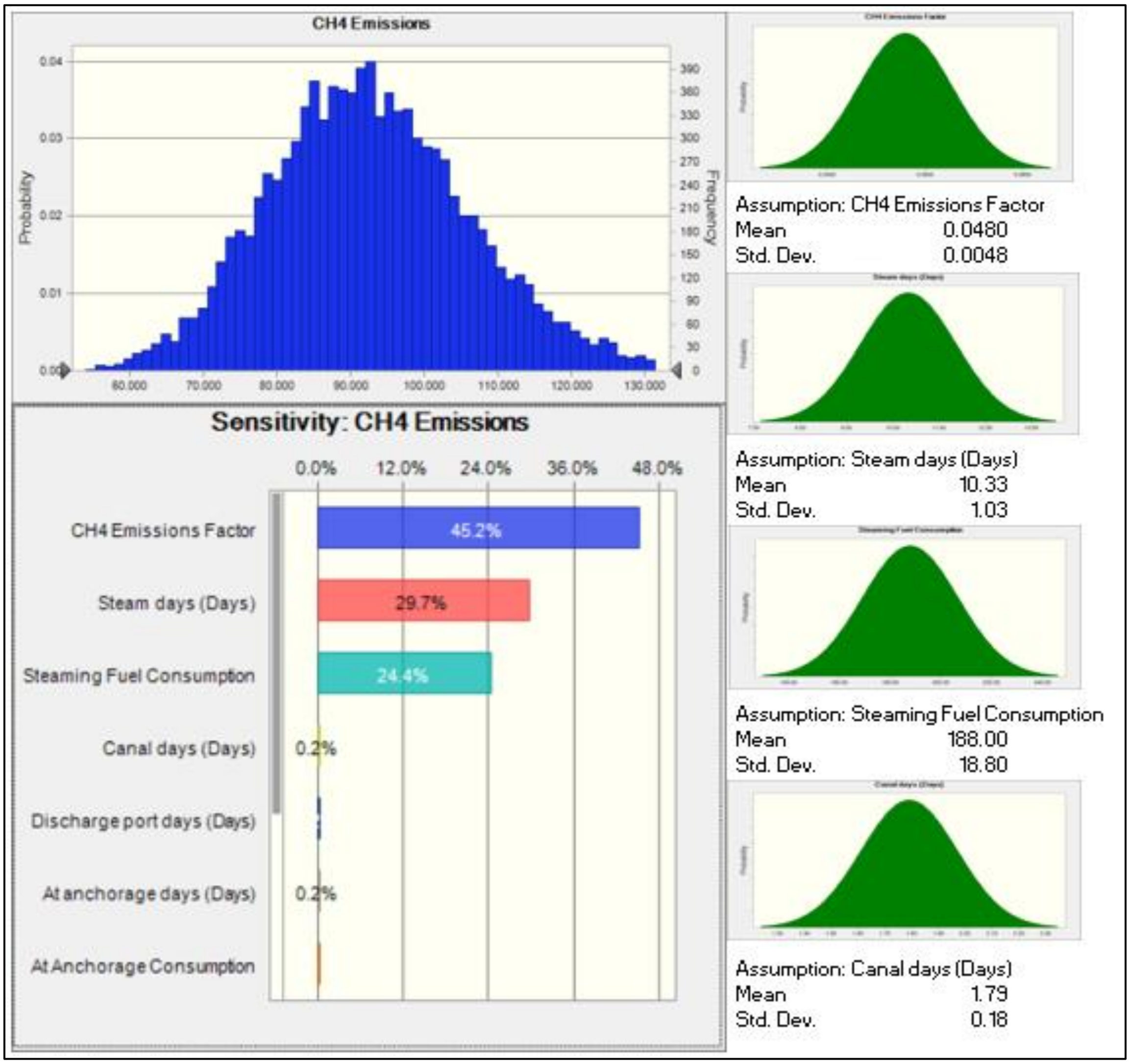



Figure 41: $CH_4$ Emission factors Sensitivity analysis (LNG Conventional)

8- For the vessel type Conventional 2 with laden status, $N_2O$ emission factor

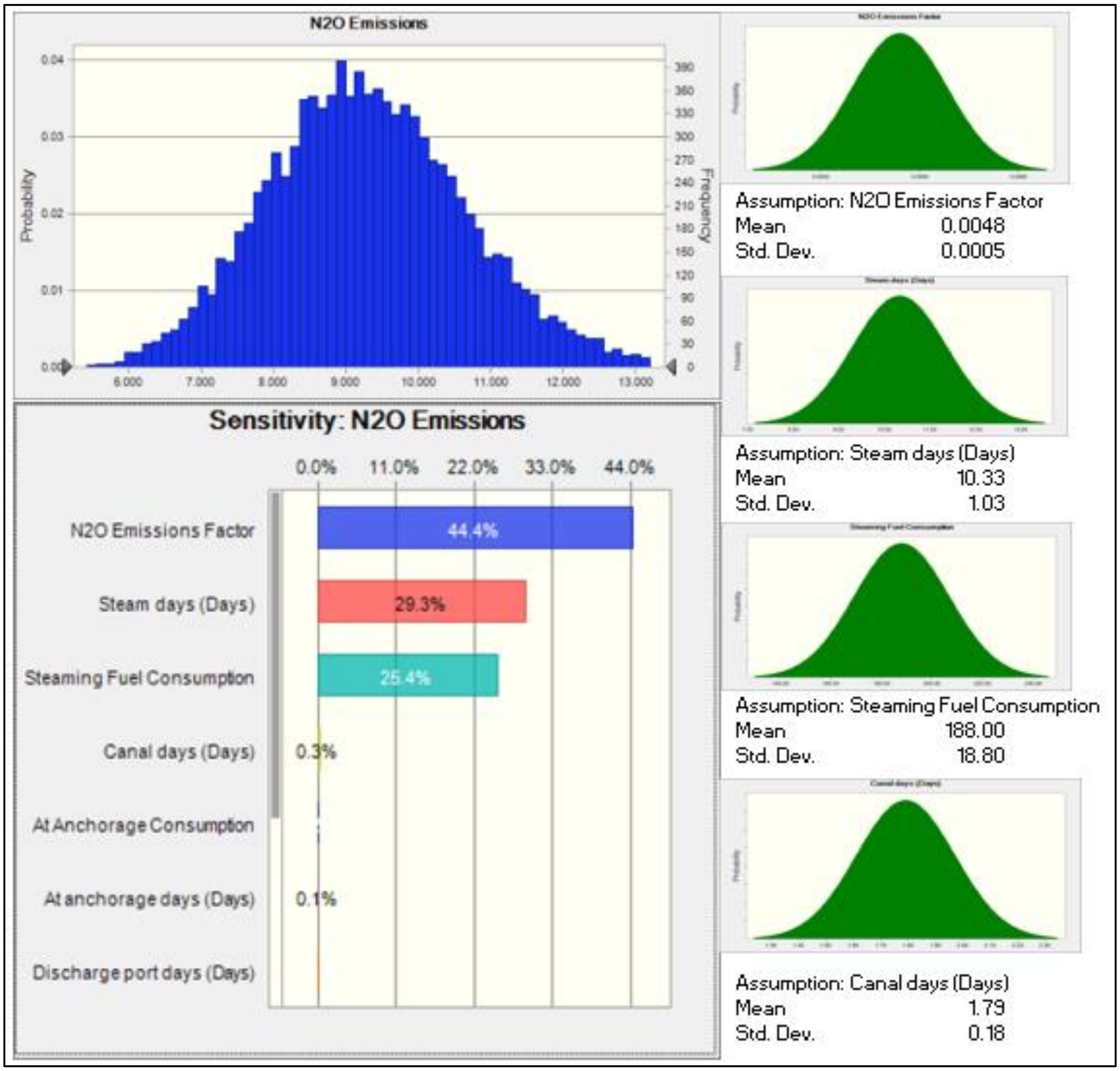



Figure 42: $N_2O$ Emission factors Sensitivity analysis (LNG Conventional)

Ballast

1- For the vessel type Q-Flex with Ballast status, $CH_4$ emission factors

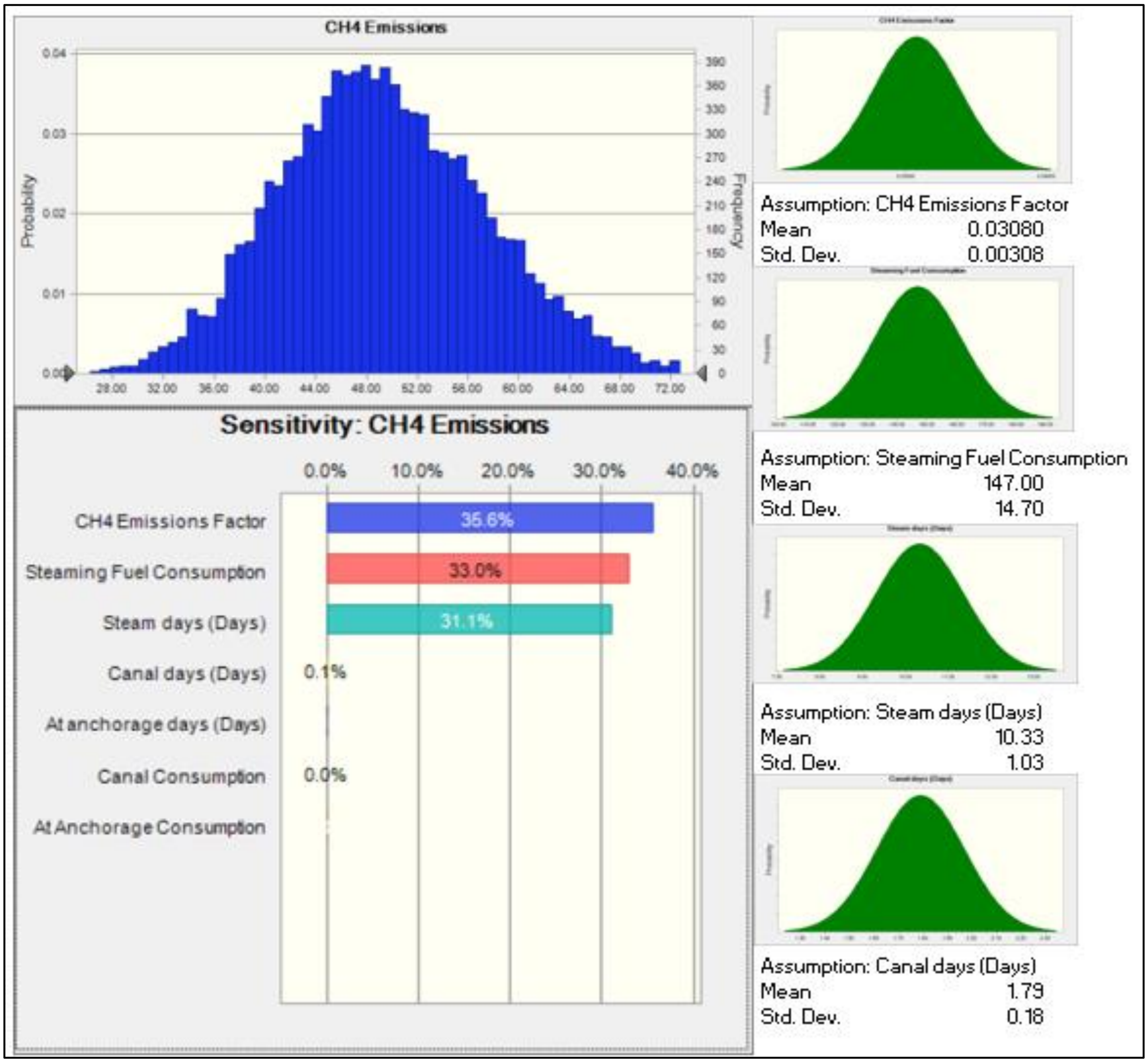
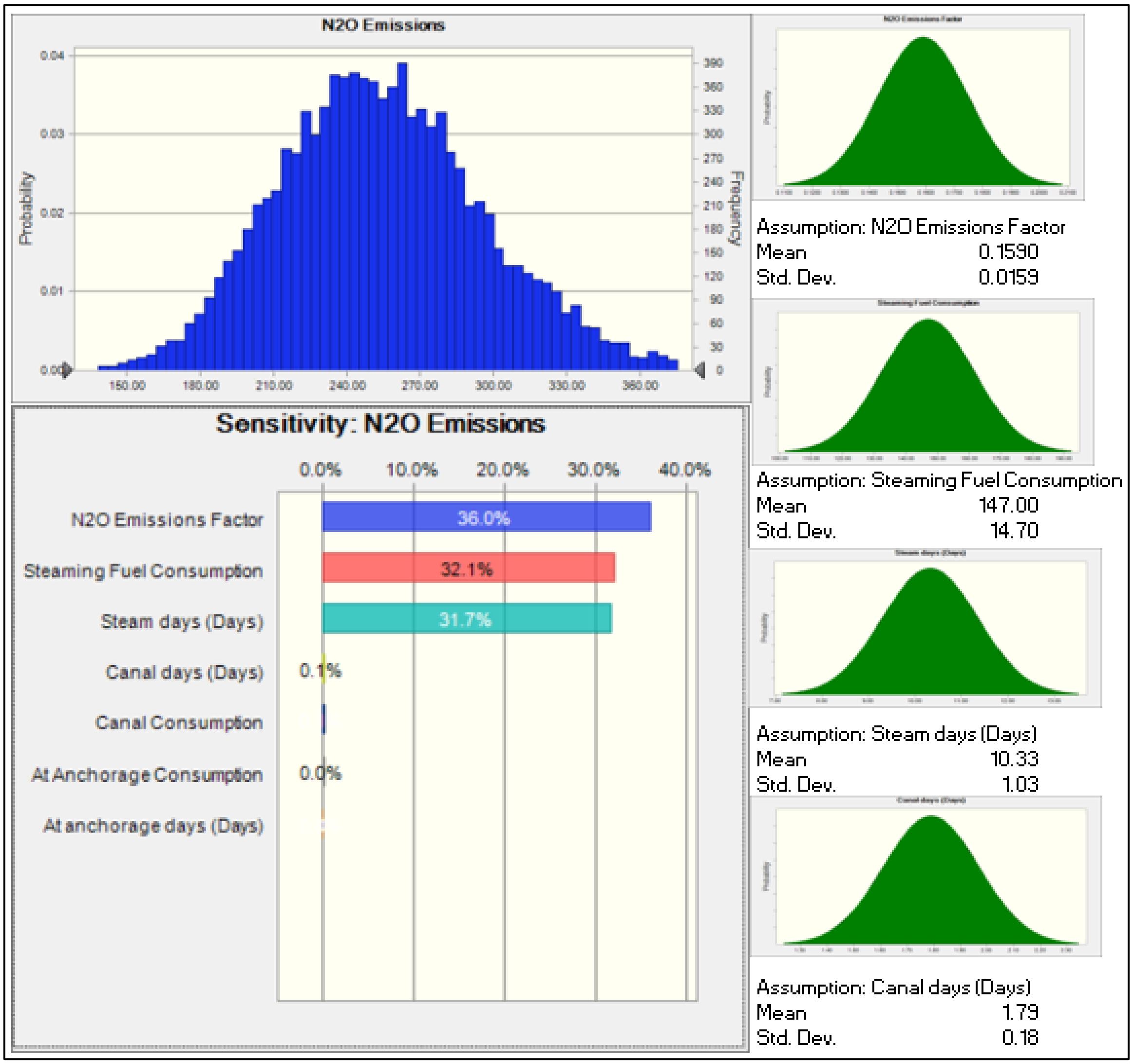



Figure 43: $CH_4$ Emission factors Sensitivity analysis (Q-Flex)

2- For the vessel type Q-Flex with Ballast status, $N_2O$ emission factors




Figur43: $N_2O$ Emission factors Sensitivity analysis (Q- Flex)

3- For the vessel type Q-Max with Ballast status, $CH_4$ emission factors

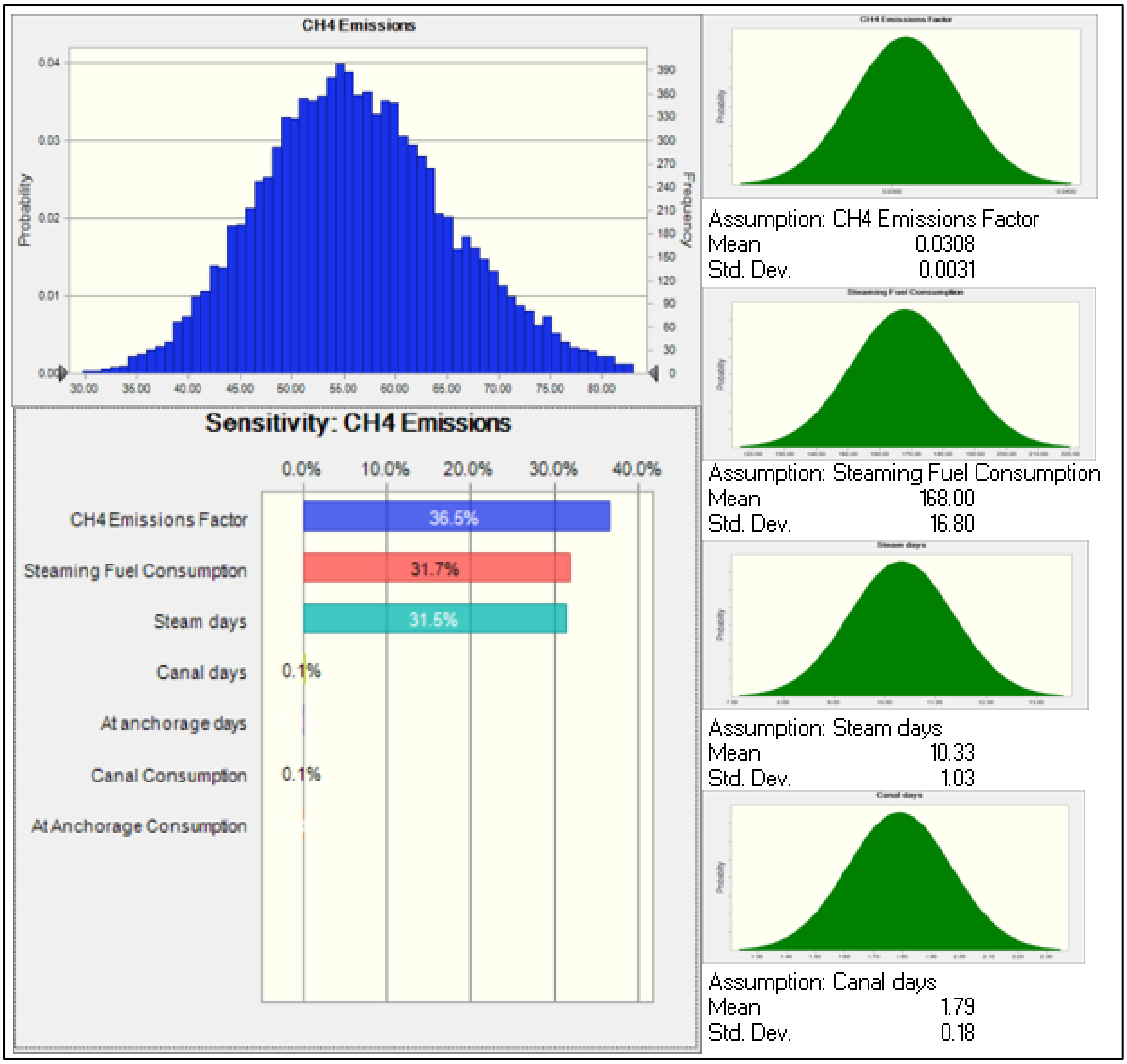



Figure 44: $CH_4$ Emission factors Sensitivity analysis (Q-Max)

4- For the vessel type Q-Max with Ballast status, $N_2O$ emission factors

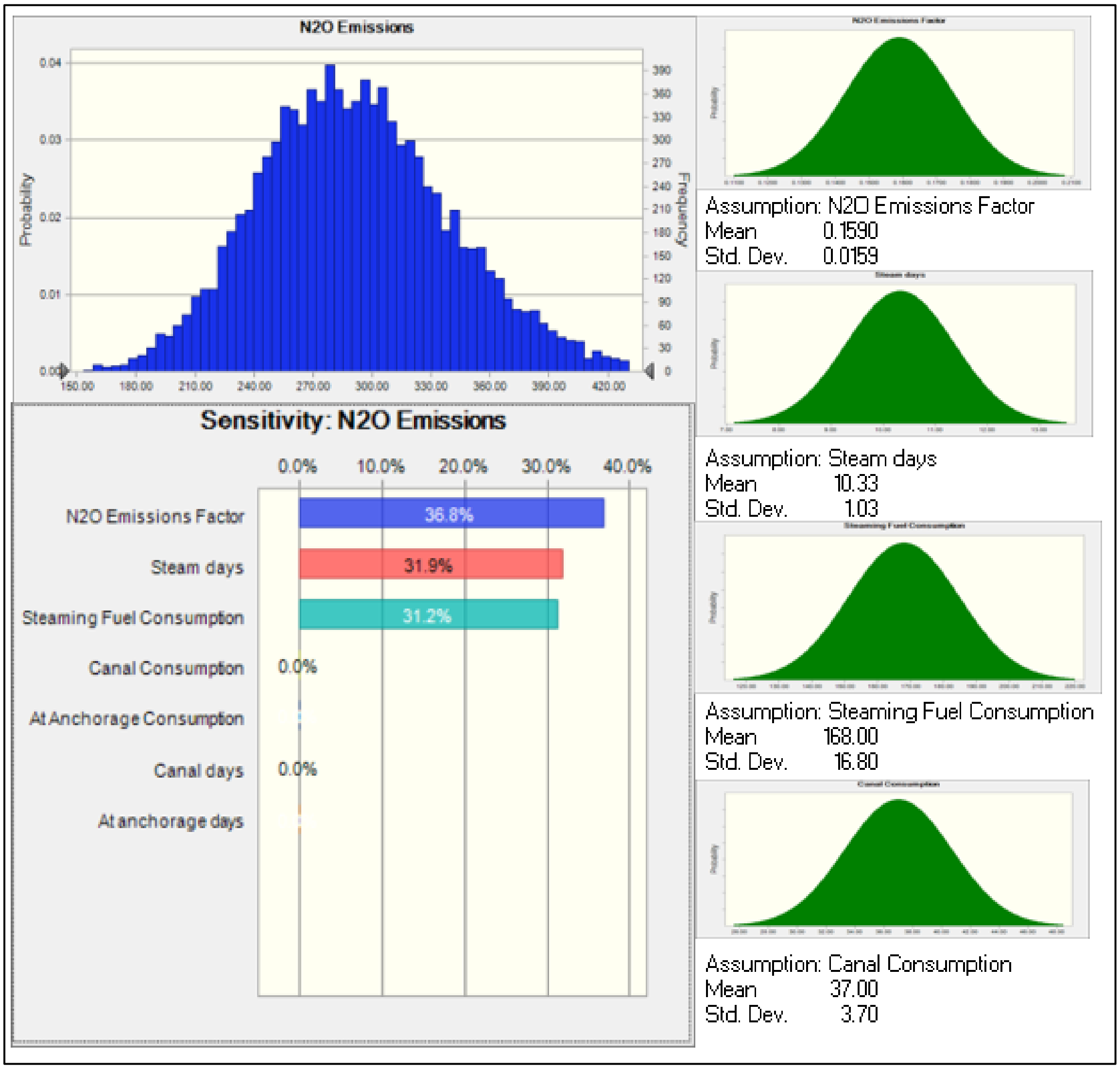



Figure 45: $N_2O$ Emission factors Sensitivity analysis (Q-Max)

5- For the vessel type Conventional 1 with Ballast status, $CH_4$ emission factors

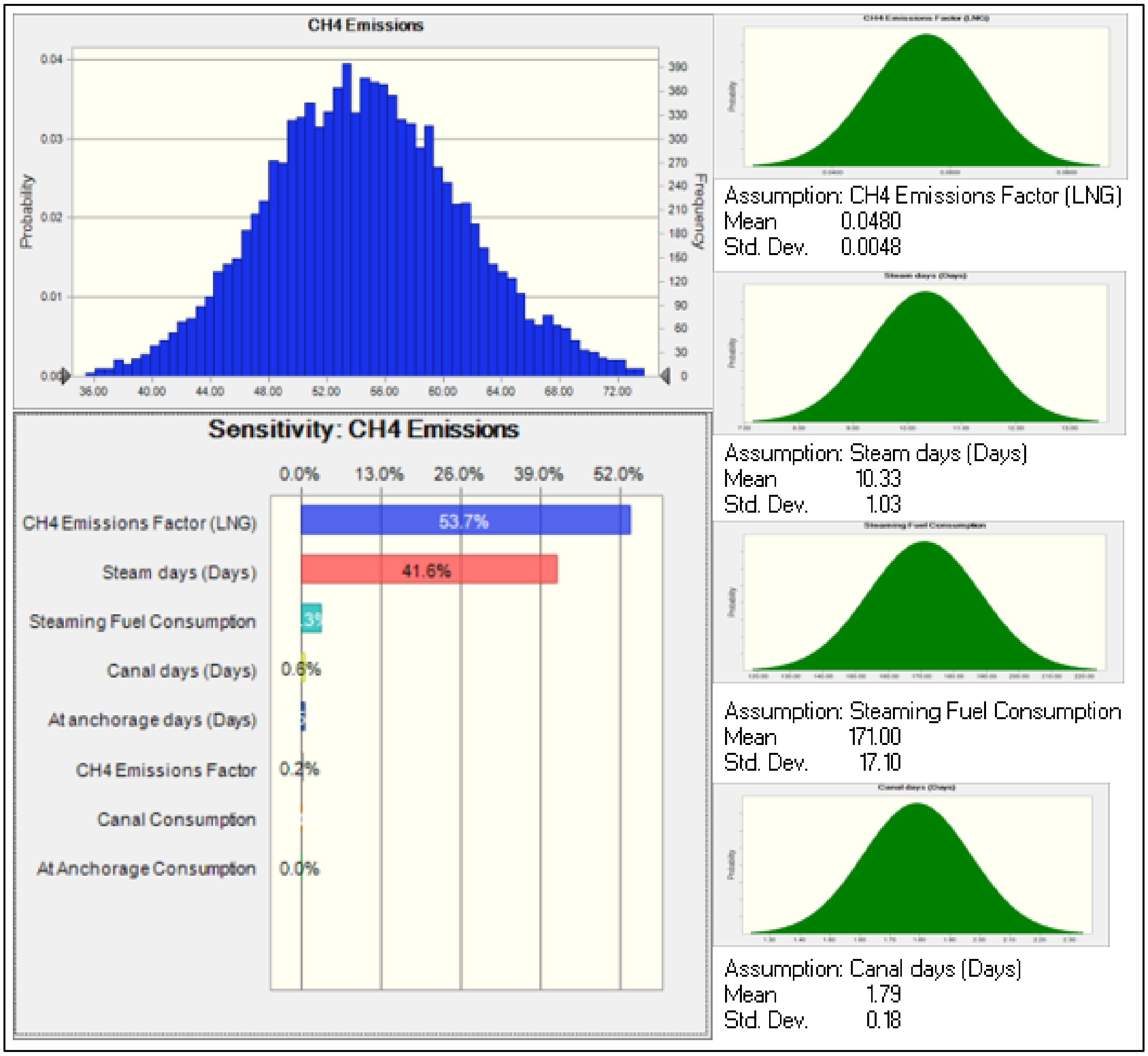



Figure 46: $CH_4$ Emission factors Sensitivity analysis (Dual Conventional)

6- For the vessel type Conventional 1 with Ballast status, $N_2O$ emission factors

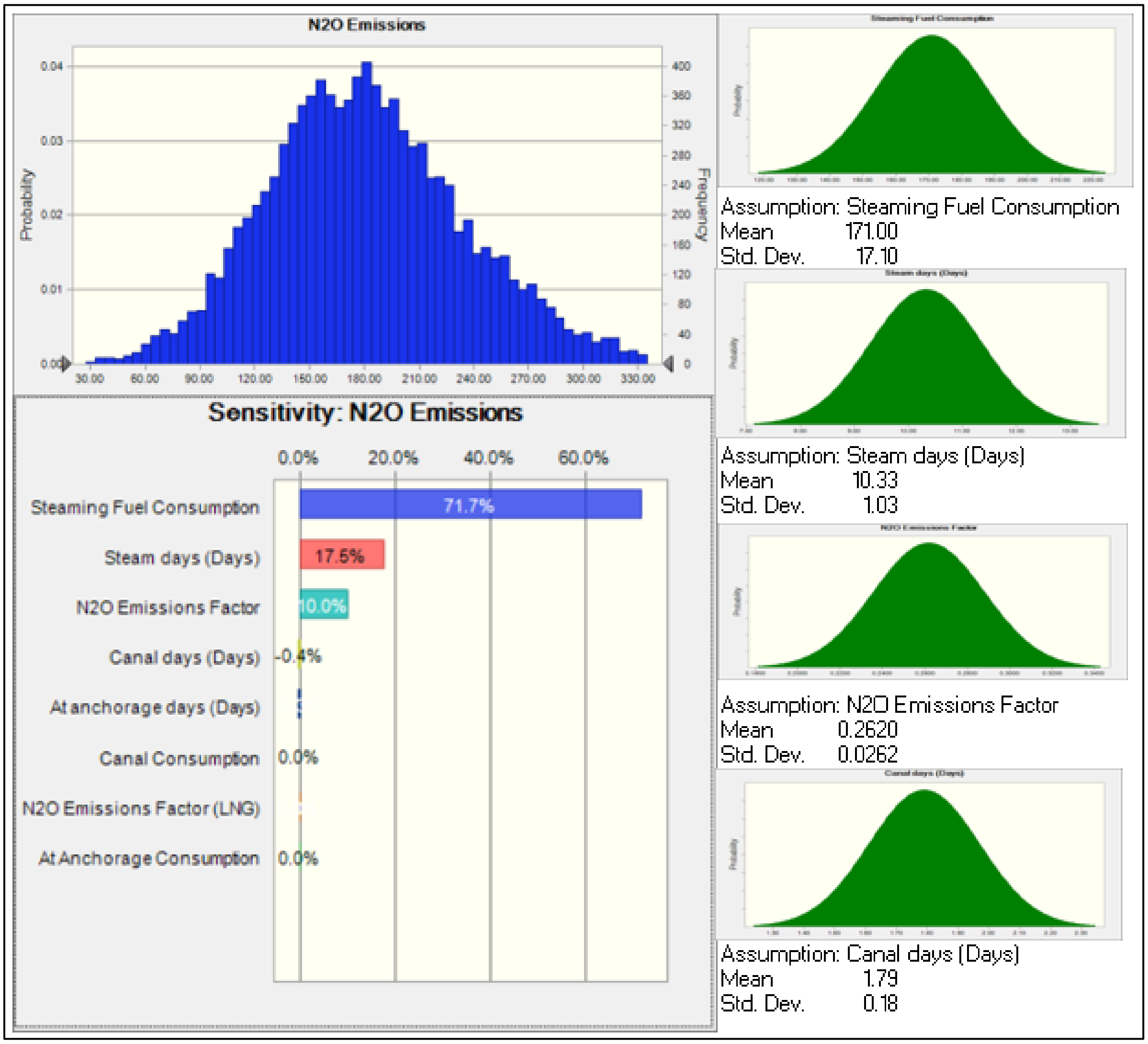



Figure 47: $N_2O$ Emission factors Sensitivity analysis (Dual Conventional)

7- For the vessel type Conventional 2 with Ballast status, $CH_4$ emission factors

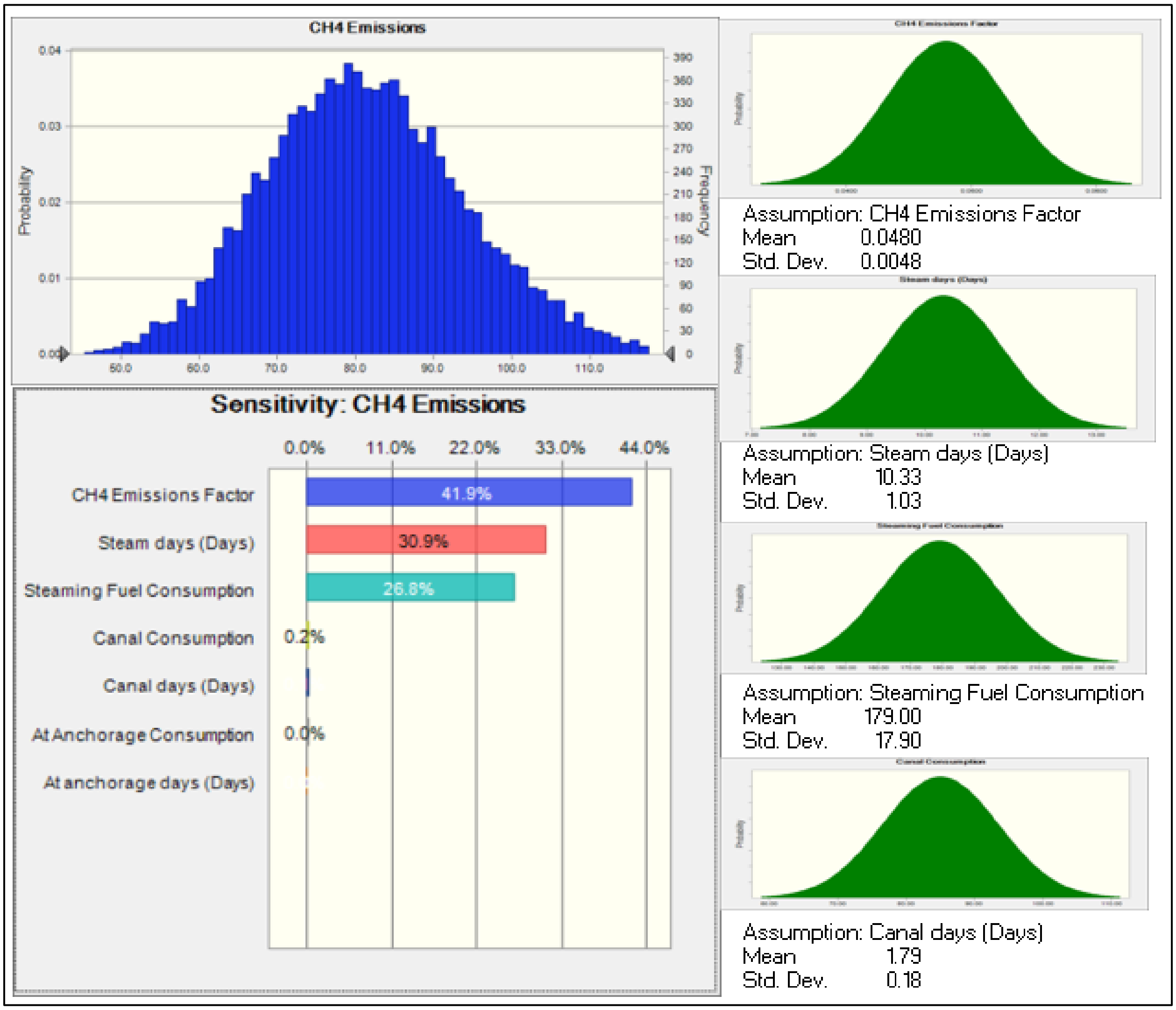



Figure 48: $CH_4$ Emission factors Sensitivity analysis (LNG Conventional)

8- For the vessel type Conventional 2 with Ballast status, $N_2O$ emission factors

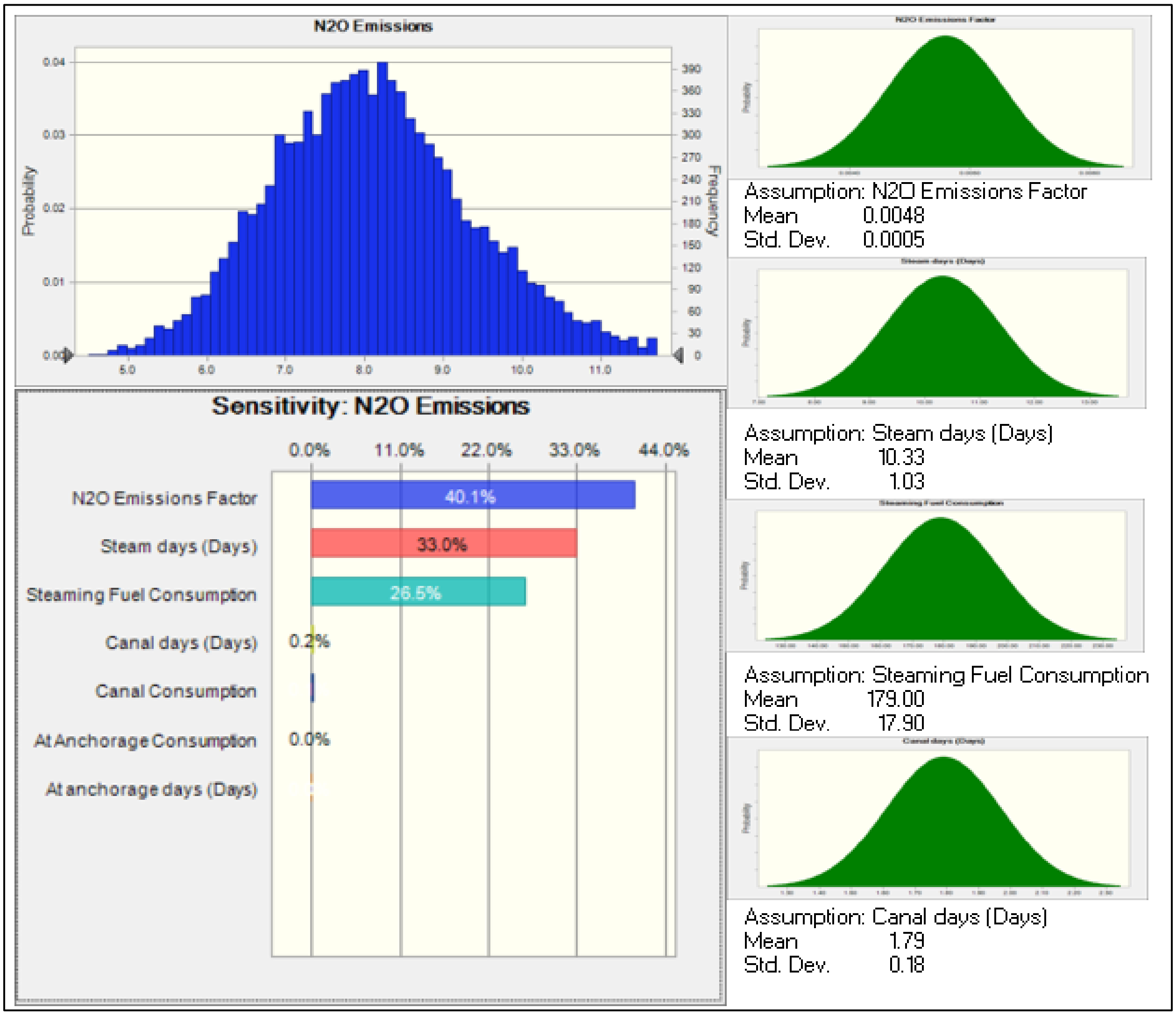



Figure 49: $N_2O$ Emission factors Sensitivity analysis (LNG Conventional)