Masteroppgave

NTNU
Norges teknisk-naturvitenskapelige universitet
Fakultet for ingeniørvitenskap
Institutt for marin teknikk

Kjell Einar Sortland

Optimizing upstream logistics for distribution of LNG and hydrogen in Longyearbyen.

Applying Monte Carlo simulation to predict fuel prices.

Masteroppgave i Marine Technology
Veileder: Stein Ove Erikstad
Juni 2019

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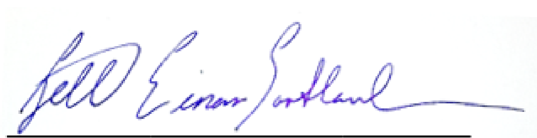
Kunnskap for en bedre verden

Preface

This master thesis is written at the Institute of Marine Technology, NTNU, in collaboration with LMG Marin AS. This project is, to a certain degree, a continuation of an earlier thesis written by NTNU student Petter Hovden, based on findings in my project thesis written last semester. The project case was constructed in cooperation with LMG Marin and NTNU, where Harald Vartdal and prof. Erikstad was of great help when creating the draft.

I would like to thank my supervisor, professor Stein Ove Erikstad, for his guidance and good advices throughout this semester. I would also like to extend my thanks to Harald Vartdal for his guidance and follow-up, as well as Dr. Per-Christian Endsjø for great help and interesting conversations. Furthermore, a big thanks to LMG Marin, who sponsored my visit to Longyearbyen and Bergen, is due. These trips functioned as a reality-check, as well as providing me with several important connections, and was of big help when gathering valuable data. Lastly, I would like to thank everyone who has taken their time to help me through meetings, phone calls and e-mails. Combined, the help of all of the above is what made it possible to ensure a report that reflects well on the status quo of Svalbard, as well as in the creation of potential future prospects.

The goal of the thesis is to optimize the upstream logistics for distribution of LNG and hydrogen in Longyearbyen, applying Monte Carlo simulation to predict fuel prices.



Kjell Einar Sortland

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Abstract

When turning on the electricity in Longyearbyen you use some of the dirtiest power you can get hold of. The entire electricity- and heat distribution is powered by coal, and this is on the archipelago used to exemplify the consequences of greenhouse gas emissions.

In recent years the Ministry of Petroleum and Energy has started to assess new, more sustainable, energy solutions for Longyearbyen. Feasibility studies published in relation to this suggest that a new energy system using an LNG-power plant, with various energy preserving systems, is a viable option.

This thesis was conducted in collaboration with LMG Marin AS and Harald Vartdal with Spitzberg Holding AS, both companies with an interest in the ongoing situation in Longyearbyen. A project thesis conducted in the fall of 2018, aimed to map the marine activity in the Svalbard FPZ, to compare the energy demand and emissions for marine- and land-based activity in Longyearbyen. The study showed that the energy demand for marine activity in the FPZ is over 7 times bigger than that of Longyearbyen, meaning the marine demand should be included when investigating the capacity of the potential storage facility. This is so it also can function as a bunkering terminal.

This study aims to optimize the upstream logistics for using LNG as a new energy-source in Longyearbyen, in addition to distributing LNG and hydrogen to marine actors operating in the Svalbard FPZ. An optimization model has been created to quantify the solutions, and the results have been evaluated from an economic and environmental aspect. Future scenarios for Longyearbyen and the marine activity surrounding Svalbard has been subject to further investigation.

The results show that given a pessimistic scenario, an LNG storage facility with a capacity of 9000m^3, should be built, and for an optimistic scenario; a capacity of 14 000m^3 to 20 000m^3, depending on willingness to take the risk. To reduce emissions and save cost, the LNG is to be imported from Melkøya. Further on, building a storage facility for hydrogen, with a capacity of 4200m^3 is suggested. These capacities are optimized to reduce cost and meet the energy needs of Longyearbyen and relevant marine actors.

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Sammendrag

Når du slår på strømmen i Longyearbyen, bruker du noe av den skitneste strømmen det går an å få tak i. Hele elektrisitets- og fjernvarmenettverket er drevet av et kullkraftverk, og dette er på øygruppen som blir brukt til å eksemplifisere konsekvensene av klimagassutslipp.

Olje- og energidepartementet har de siste årene begynt å undersøke nye, mer bærekraftige energiløsninger for Longyearbyen. Mulighetsstudier publisert i forbindelse med dette tyder på at et nytt energisystem som bruker et LNG-kraftverk, med ulike energibesparende systemer, er et levedyktig alternativ.

Denne oppgaven ble gjennomført i samarbeid med LMG Marin AS og Harald Vartdal ved Spitzberg Holding AS, begge selskaper med interesser i den pågående situasjonen i Longyearbyen. En prosjektoppgave utført høsten 2018, hadde til formål å kartlegge den marine aktiviteten i FVS Svalbard, for å sammenligne energibehovet og utslippene for marin- og landbasert aktivitet i Longyearbyen. Studien viste at energibehovet for marin aktivitet i FVS er mer enn 7 ganger større enn for Longyearbyen, noe som betyr at den marine etterspørselen burde inkluderes når man undersøker kapasiteten til det potensielle lagringsanlegget. Dette er fordi det også kan fungere som en bunkringsterminal.

Denne studien tar sikte på å optimalisere oppstrøms logistikk for bruk av LNG som ny energikilde i Longyearbyen, i tillegg til å distribuere LNG og hydrogen til marine aktører som opererer i FVS Svalbard. En optimaliseringsmodell er konstruert for å kvantifisere løsningene, og resultatene er evaluert ut fra et økonomisk og miljømessig aspekt. Fremtidige scenarier for Longyearbyen og den marine aktiviteten rundt Svalbard har vært gjenstand for videre undersøkelser.

Resultatene viser at gitt et pessimistisk scenario, skal et LNG-lagringsanlegg med en kapasitet på 9000m ^{3} bygges, og for et optimistisk scenario; en kapasitet på 14 000m ^{3} til 20 000m ^{3} avhengig av risikovillighet. For å redusere utslipp og spare kostnader, skal LNG'en importeres fra Melkøya. Videre foreslås det å bygge et lagringsanlegg for hydrogen, med en kapasitet på 4200m ^{3}. Disse kapasitetene er optimalisert for å redusere kostnadene, og møte både Longyearbyens og relevante marine aktørers energibehov .

"Well, well, well... How the turntables..."

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Abbrevations

ADO	Auto Diesel Oil
CCS	Carbon Capture and Storage
DFOC	Daily Fuel Oil Consumption
EEZ	Exclusive Economic Zone
EUR	Euro
FPZ	Fishery Protection Zone
FVS	Fiskevernsonen (ved Svalbard)
H_2	Hydrogen gas
HFO	Heavy Fuel Oil
IRENA	International Renewable Energy Agency
LHS	Left Hand Side
LNG	Liquefied Natural Gas
LNSS	LNS Spitsbergen AS
LP	Linear Programming
MILP	Mixed Integer Linear Programming
MCR	Maximum Continuous Rating
MGO	Marine Gas Oil
MMBtu	Million British thermal units
MNOK	Million Norwegian Kroner
mt	Metric Tonnes
N/A	Not Available
NCA	Norwegian Coastal Administration (Kystverket)
NCR	Normal Continuous Rating

NEA	Norwegian Environment Agency (Miljødirektoratet)
NOK	Norwegian Kroner
PAX	Passenger(s)
PM	Particulate Matter
RHS	Right Hand Side
RIB	Rigid-Inflatable Boat
RWT	Random Walk Theory
SAR	Search And Rescue
T/C	Time charter
USD	United States Dollar
ZEP	Zero Emissions Platform

Chapter 1

Introduction

The premise of this project originates from a study published in November 2016 by the Norwegian Coastal Administration. This study looked at the port structure of Longyearbyen, how it meets today's needs, and what should be done to meet the needs of the future. The study concludes that today's capacity has already been reached, and surpassed, suggesting that two new quays should be built; one for fish landing and one meant for research vessels and passenger ships (NCA, 2016). After the NCA-study, the Norwegian government started investigating the energy situation in Svalbard; assessing various potential future solutions for power- and heat generation in the settlement. This sparked the interest of LMG Marin, a Bergen-based naval architect and ship design company. They have developed a modular quay-system called GraviFloat. GraviFloat, later bought and subsidized by Semcorp Marine, functions as an LNG import and/or export terminal, built offshore and fixed near-shore. LMG Marin starting the process of developing a GraviFloat-system to be used in Longyearbyen. In 2017/2018 NTNU-student Petter Hovden was, in collaboration with LMG Marin, given the task to perform an energy study of Longyearbyen. By investigating the current total energy demand of the settlement, he was able to create a draft of what a new, more economical energy solution in Longyearbyen could look like. This work resulted in the master thesis "Optimisation of a New Energy System in Longyearbyen based on LNG and Solar Energy" where the economic and emission-related results were presented for several potential solutions. All assessed solutions were based around utilizing an LNG (Liquefied Natural Gas) power plant and storage facility, complemented with different additional energy-preserving or power generating systems.

For all the listed studies, neither had a particularly strong focus on meeting the energy demand of the marine activity surrounding Longyearbyen. A study done in 2018, by the thesis author, aims to map the energy demand in the Svalbard fishery protection zone (FPZ), to discover the magnitude of this industry. The energy demand of the marine segment proved to be over seven times that of Longyearbyen, meaning this segment should be included when developing the new infrastructure. This lays the premises for the optimization of a storage facility and transport logistics for LNG to be used in land-based power production, as well as functioning as a distribution terminal for marine actors.

A new project by Spitzberg Holding AS, in collaboration with LMG Marin AS, is developing an event ship to be based in Longyearbyen all year around. The ship is primarily meant to be a battery/LNG-hybrid, but they are investigating the possibility of utilizing hydrogen as well. This project was found to be an interesting basis to perform the optimization of a storage facility and import-logistics for a small-scale hydrogen distribution.

1.1 Intention and Objective

The overall objective for this project can be formulated as follows:

To optimize the upstream logistics for distribution of LNG and hydrogen in Longyearbyen.

The primary objective for this thesis is to optimize the upstream logistics for using LNG as a new energy-source in Longyearbyen, in addition to distributing LNG and hydrogen to marine actors operating the Svalbard FPZ. An optimization model shall be created to quantify the solutions, which will be evaluated from an economic and environmental aspect. Future scenarios for Longyearbyen and the marine activity surrounding Svalbard will be discussed, and the results from the optimization model will be assessed concerning the potential future scenarios.

1.2 Scope of work

Below, the primary tasks are listed. These tasks are leading as to how the work shall be conducted.

- Give a brief introduction to the archipelago, Svalbard
- Provide background information regarding
  - The energy situation in Longyearbyen
  - The energy situation of marine activity in the Svalbard FPZ
  - LNG and hydrogen as energy carriers
    - Production, transportation and handling
    - Advantages and challenges
    - Future outlooks
- Gather data to be used as input in the optimization model

  Create scenarios for how the marine demand of LNG and hydrogen can develop

  Create Monte Carlo simulation to be used for LNG prices

  Find seasonal variations in retail price for fuels
- Perform a stakeholder analysis
- Create optimization model
  - First step: Generic MILP-model
  - Second step: Introduce LNG
  - Third step: Introduce hydrogen
- Perform a sustainability assessment of selected outputs from the optimization model runs
- Discuss results with regards to future potential scenarios

1.3 Report Structure

In Chapter 1, a short presentation of the report, its premises and objective, is presented. Chapter 2 consists of background knowledge related to the situational awareness for the project. It also includes a brief introduction to the fuels being assessed, with important aspects that have been included in the problem solver. Chapter 3 presents assumptions made, regarding the modelling of the problem, as well as a description of how the input data has been found and produced. Chapter 4 describes how the optimization-model was made, and what tools have been used to solve it. In Chapter 5 the results of the optimization model runs are presented. A selection of the results from this chapter is subject to an environmental analysis in Chapter 6. The results are finally discussed in Chapter 7, before a summarizing conclusion is made in Chapter 8. In Chapter 9, suggestions for further research is presented.

Chapter 2

Background

This chapter will present information and insight into relevant background knowledge for this thesis. To obtain situational awareness for Svalbard, its position, function and running will be subject to further investigation. Assessing potential trends and influencing factors for its development, knowledge on relevant aspects for the future case-building was obtained.

To gain a comprehensive understanding of Svalbard as a whole, a visit to Longyearbyen was carried out in October/November 2018. Interviews and meetings with local actors functioned as a reality check; this was highly desired by both the project administrators, contractors and student. The trip was meant to obtain knowledge on how today's situation is at the archipelago, what factors and events led up to the situation they find themselves in today, and what the future may hold. Getting first-hand contact with the community has led to a better understanding of the overall picture, as well as providing important data-providing connections.

2.1 Background for the thesis/Earlier work

In 2017 NTNU-student Petter Hovden performed an optimisation of a new energy system in Longyearbyen based on LNG and solar energy; contracted by LMG Marin AS. The objective of the thesis was to find the optimal economic solution; minimizing the total lifetime costs for a 30 year-perspective (Hovden, 2018). The thesis is a direct consequence of the Ministry of Petroleum and Energy's ongoing assessment of new possible energy carriers in Longyearbyen. The current solution is a stand-alone energy system consisting of a coal power plant, with diesel generators as a backup in case of downtime. The arctic settlement is subject to challenging weather and temperatures and is depending on a steady supply of electricity and heating.

The energy study conducted by THEMA Consulting Group and Multiconsult in June 2018, assesses several solutions for future energy supply in Longyearbyen from a socioeconomically and environmentally perspective. The report assesses eleven various solutions, concluding with the following three to be the most most interesting for further investigation.

- LNG power plant without CCS.
- Cogeneration plant based on pellets.
- A combination of solar- and LNG power.

Similar to the study performed by Hovden, this study primarily focuses on the energy demand on land; disregarding the vast potential of marine activity. With an increasing focus on sustainability for all government projects, the inclusion of the environmental impact from the marine activity in the Svalbard FPZ should be taken into account. Comparing the energy demand on land and at sea, it's clear that the biggest potential for impact-altering means is for marine activity. As the marine industry is being run by numerous actors, the only impact the project owners, as defined in this thesis, can have is ensuring the availability of more sustainable fuel options.

2.2 About Svalbard

Svalbard is an archipelago situated between approximately 74° and 81° north, 10° and 35° east, and is a part of the Kingdom of Norway with its 61 022 km^2 (see Figure 2.1). Longyearbyen is the largest settlement in Svalbard and is also the northernmost civilization in the world (Thuesen and Barr, 2018). The Svalbard Treaty is what ensures Norwegian sovereignty, although it has certain limitations of how the archipelago and its territorial waters are to be managed and regulated. Even though the area is still subject to Norwegian law, the archipelago needs to remain demilitarized, as well as ensuring an equal right amongst the signatories to exercise their right to settle down to partake in commercial activity, fish and hunt. Svalbard is of political importance to Norway and is also subject to a continuous debate on how the fishery protection zone outside the territorial sea is to be managed.

In the 17th and 18th century Svalbard was mainly used as a base camp for whaling before it was abandoned. At the start of the 20th century, coal mining started to take off just Norwegian sovereignty was established in 1920, taking effect in 1925 (Knudsen et al., 2018). In the white paper issued in 1990-91 focusing on Svalbard from a business-perspective, research and tourism were highlighted as important upcoming segments.

Figure 2.1: Map of Svalbard, and its location in the Arctic (The Ocean Adventure, 2018).

The University Centre in Svalbard was established a few years later, and a plan was created for how tourism could evolve without affecting the research being done or damaging the nature (Næringsdepartementet, 1991). Regarding research, a white paper issued already in 1991 stated that that there was an increase in international interest for research in the polar regions. Today, the interest is bigger than ever because of Svalbard's geographical position and accessibility. Due to its location, climate changes are more noticeable here than in most parts of the world. This makes the archipelago very interesting to researchers, but it also makes it more vulnerable to the emission of particles (Sortland, 2018). Svalbard is also where the climate changes in the Arctic are more noticeable as it is the place where the ice has melted the quickest.

2.3 Energy situation in Svalbard

As described, this project origin from previous feasibility studies on new energy solutions for Longyearbyen. The THEMA and Multiconsult-report as well as Petter Hovden's theses describe the energy demand on land and suggest various ways of implementing new solutions made to meet the demand with a focus on sustainability. The three pillars of sustainability are the economic, environmental and social aspects. Both studies mainly assess the economic and environmental benefits of the suggested solutions. The feasibility studies are initiated by the Ministry of Petroleum and Energy, meaning it's evident that change is coming. Several actors are developing solutions for how the energy-situation in Longyearbyen can be renewed, with the Norwegian government closely following the process (Viseth, 2018).

2.3.1 Land-based activity in Longyearbyen

The energy production and distribution in Svalbard today varies for each settlement. In Longyearbyen, the electricity and district heating is delivered by the coal power plant Longyear Energiverk. The coal comes from Gruve 7 which is handled by Store Norske Spitsbergen Kulkompani. The coal mine is meant to produce 150 000 tonnes coal each year, of which 25 000 - 30 000 tonnes are being consumed by the power plant. The coal found in Svalbard is high quality and has a high calorific value of 700kcal/tonnes compared to the European standard which is 600kcal/tonnes (Tennbakk et al., 2018). This gives it a much higher sales value than e.g. brown coal, as high-grade coal is preferred in the steel industry (Store Norske - SNSK AS, 2018). The power plant in Longyearbyen produces approximately 40GWh electricity and 70GWh thermic effect each year (Hegle, 2018). The power plant is up-and-running 24/7 and has two diesel aggregates as a backup, in case of emergency or planned downtime. There are also several emergency aggregates connected to some of the consumers (the hospital, airport, SvalSat, Gruve 7, etc.) but these are not a part of the general power grid. The rest of the settlement is depending on a steady feed of electricity and heat from the power plant since it's the only supplier. Due to its location, Longyearbyen experiences extreme conditions with total darkness and cold weather during the winters, meaning the consequences of not having electricity or heating can be severe. The energy distribution in Longyearbyen for 2017 is shown in Table 2.1. All values are taken from the THEMA report, except the value for households which comes from Hovden's master thesis (number from 2016). As shown, the power plant is the largest single client, followed by households, mining activity and the satellite station.

Client	**Percentage**	
Energiverket	17,5	%
Households	14,0	%
Gruve 7	13,3	%
SvalSat	10,1	%

Table 2.1: Top consumers of electricity in Longyearbyen based on findings from Tennbakk et al. (2018) and Hovden (2018).

In Figure 2.2 the total amount of electricity and district heating energy produced, together with the population in Longyearbyen, is shown. As seen, the total amount of energy produced follows the population number somewhat. In the future, improved insulation in housing will reduce the amount of energy needed, while the increasing research and tourist activity in and around the settlement will require more electricity for charging and running of land-based operations.

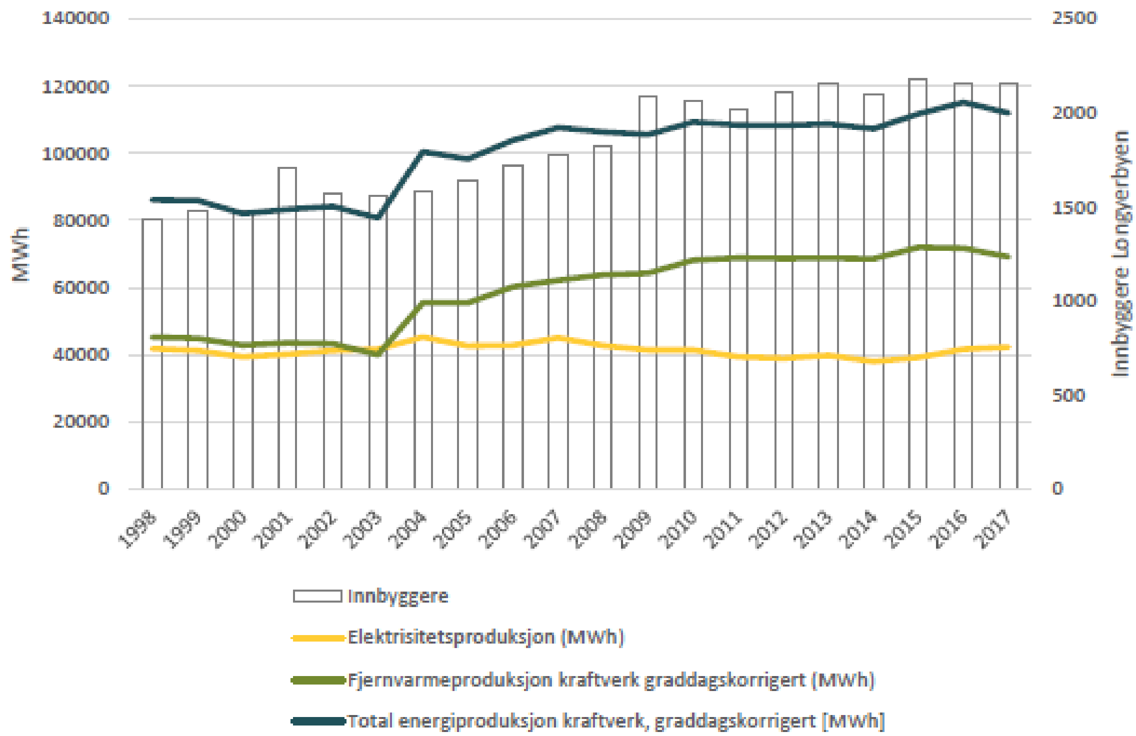

Figure 2.2: Energy production and population in Longyearbyen from 1998 to 2017. (Tennbakk et al., 2018)

With big variations in temperatures depending on the time of year, the distance heating demand naturally follows. In the winter months, the demand is significantly higher than in the summer months, mainly due to the temperature differences. According to the THEMA and Multiconsult-report, the organizing of annual leave also lessens the demand in the summer months, as the activity both in business and housing decreases.

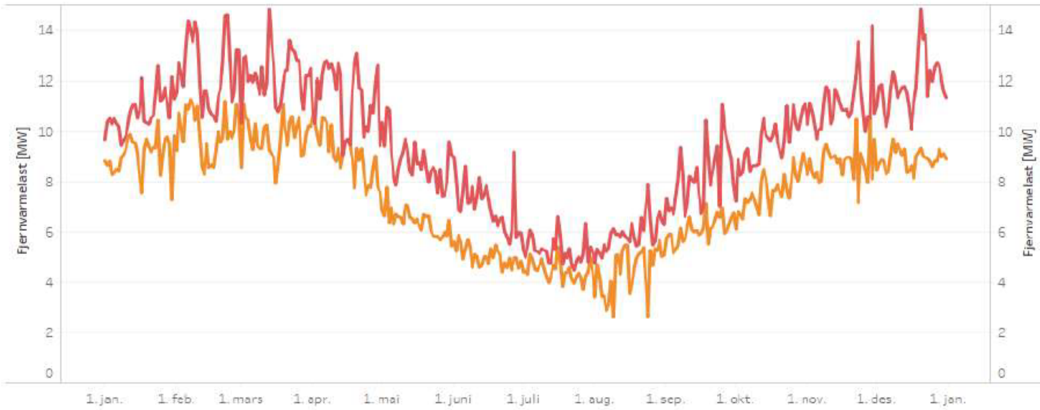

Figure 2.3: Daily measured values for maximal and minimal load in the heat network. The red line represents the maximal load and the orange represents the minimal load. Data from 2017. (Tennbakk et al., 2018)

For the yearly electricity consumption, the season variations aren't as high as for the heat network. In Figure 2.4 the yearly maximal and minimal electricity-load for Longyearbyen is shown. The maximal values are presumed to be the load during the day, while the minimum values are during the night. As seen, there is a slight change in load for the winter- versus summer months, but the difference is small compared to that of the district heating. In the winter months, the maximal and minimal values span between 6 MWh and 4 MWh, respectively, while for the summer months the figures are approximately 5 MWh and 3 MWh. The big drop in July/August is because of holiday leave in Gruve 7, which means that the third largest single electricity client (ref. Table 2.1) reduces its operations, resulting in a noticeable drop in consumption.

Figure 2.4: Daily measured values for maximal and minimal load in the electrical grid. The blue line represents the maximal load and the shadow green represents the minimal load. Data from 2017. (Tennbakk et al., 2018)

2.3.2 Marine activity in the Svalbard FPZ

The marine activity in Svalbard accounts for a large portion of the area's energy demand and emissions. To map the marine activity in a certain geographical area, the borders need to be set. For this study, the designated area has been selected to include the territorial waters of the archipelago, in addition to the fishery protection zone (FPZ). The given area is shown in Figure 2.5. (Sortland, 2018)

Figure 2.5: This figure shows the Svalbard FPZ (highlighted in blue), as well as the territorial waters (highlighted in pink within the FPZ). (Tiller and Nyman, 2015).

According to the NCA, marine activity in Longyearbyen is increasing rapidly, and measures must be taken to cope with the developing trends. An increase in tourism is the main cause of rapid growth, and the capacity of Port Longyear has already been surpassed. An ongoing process of investigating a new energy future for Longyearbyen has been initiated by the Ministry of Petroleum and Energy. Resulting studies suggest, amongst other solutions, implementing new fuel alternatives, with an increased focus on sustainability. These fuel alternatives are thought to both supply Longyearbyen with energy and can also provide bunkering marine vessels.

The primary objective of this study is to map the marine activity in the Svalbard territorial waters and FPZ to discover the total fuel consumption, emissions and energy demand at sea. This will be done by analyzing bunkering data, ship calls and data obtained by interviewing relevant actors operating in the area. The data shall be distributed across the different ship segments to see the importance of each segment.

A study performed in 2018 aimed to map the marine activity in the Svalbard territorial waters and FPZ to discover the total fuel consumption, emissions and energy demand at sea. By analyzing bunkering data, ship calls and data obtained by interviewing relevant actors operating in the area, data on marine activity was quantified and distributed across ship segments. As seen in Table 2.2 the results from this study show that the annual energy consumption in the territorial waters and FPZ is equivalent to 7,3 times the annual energy consumption of Longyearbyen.

Annual amount of fuel consumption related to marine activity	70 000	t
Annual amount of energy consumption related to marine activity	800 000	MWh
Annual energy consumption Longyearbyen	110 000	MWh
Difference in energy consumption, marine activity/Longyearbyen	7,3	times

Table 2.2: Marine activity in the Svalbard FPZ, compared to land based activity in Longyearbyen (Sortland, 2018).

The fuel consumption and contribution of emissions from the marine activity are substantial compared to that of land-based activity. Emissions from the marine activity amount to approximately 241 300 tonnes CO_2, 3340 tonnes NO_X, 77 600 kg SO_X and 183 400 kg particulate matter.

The results clearly show that there is substantial demand for energy in the Svalbard territorial waters and FPZ. Where there is a demand, there is a market. The conditions today are not viable regarding the growing activity around the archipelago. With a push towards new energy solutions for Svalbard, the potential marine market, as defined by the energy demand of the surrounding fleet, should be considered when constructing the final solution. Almost all relevant actors, experts, statistics and trends point towards a level of marine activity that is only expected to increase. With an industry that is also changing its composition, the needs of tomorrow, rather than just the needs of today, is what should be considered when planning their new infrastructure.

Distribution of ship segment

In Figure 2.6 the distribution of all marine activity in the territorial waters and FPZ is shown, depending on ship segment. This activity is defined by the amount of fuel used in the area, over the course of one year. The figure clearly shows that the fishing vessels account for the largest amount for a single ship segment. With a contribution of 53%, this is the segment that has the highest level of activity in the area. The expedition cruises follow, claiming a total amount of 32% of all marine activity. Chemical tankers, overseas cruises and coal transport makes up for 5%, 4% and 3%, respectively. The remaining 4% is comprised of activity from the coast guard, Polarsyssel, research vessels and Bring's a cargo ship. The numbers are the results of the study "Mapping the energy demand and emissions related to the marine activity in and around Svalbard", performed by Sortland (2018).

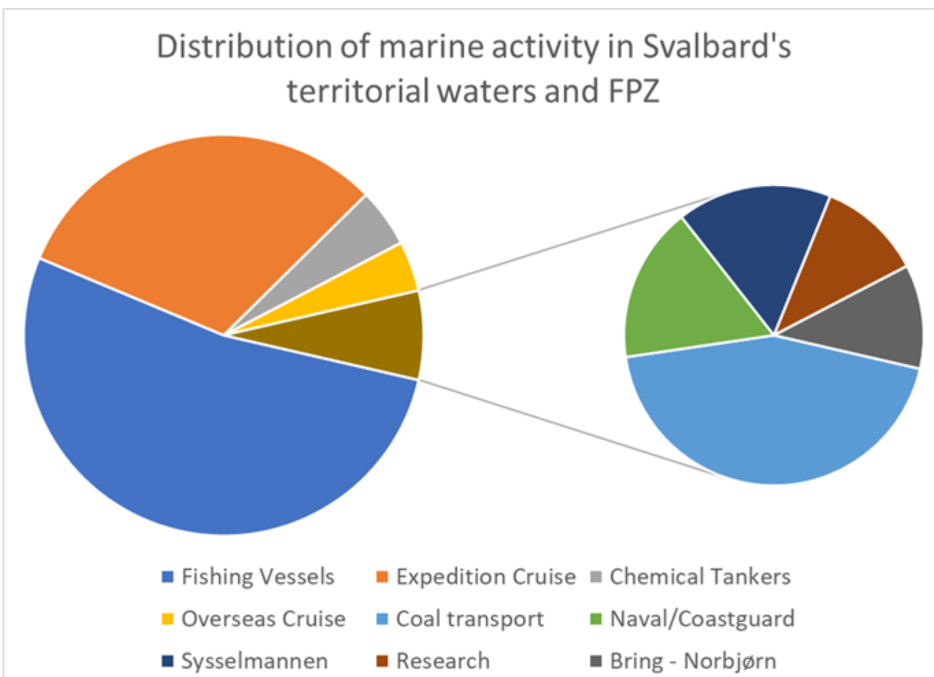

Figure 2.6: The distribution of marine activity in Svalbard's territorial waters and FPZ, depending on ship segment. See Appendix 1 for data supporting the figure.

The total distribution for marine activity in the Svalbard FPZ illustrates the fleet composition well, but it does not show the situation in Longyearbyen. In Figure 2.7 the distribution of ship segment for port calls in Longyearbyen compared to the total marine activity, based on fuel consumption, for the entire Svalbard FPZ is shown. This comparison is highly interesting for the data processing in the optimization model, as it shows what segment contributes to the largest activity in the FPZ, but at the same time is relevant to include in the predicted demand for fuel in Longyearbyen. The question to be asked is: How much of the fuel-demand for marine activity in the FPZ can be expected to be supplied in Longyearbyen. The vessels visiting, and operating in, Longyearbyen is naturally relevant to include; assuming the necessary infrastructure is present. How much of the marine activity not stopping in Longyearbyen that can be included, is harder to predict. As told by Gutteberg (2018), ship operators in the Barents Sea and Svalbard FPZ are predominantly not interested in sailing to Longyearbyen, just for bunkering purposes. The sailing time to Longyearbyen means a loss in revenue from operational purpose, in addition to fuel costs, as well as the inevitable port fee. In the figure, pilot boats, chemical tankers and "other vessels" are not included due to overlapping/different definitions for the two methods of measurement.

As seen in the figure; fishing vessels are what contributes to the greatest amount of marine activity, with their 53,1%. What is interesting for the fishing vessels, is that despite the dominance in marine activity, they rarely visit Longyearbyen. According to Gutteberg, the fishers either heads to landing facilities on the mainland, or transfers the catch to factory ships specifically designed to process and store the catch. The fishing vessels then refill the fuel at sea by bunkering ships, before the fishing commences. Time spent sailing means lost income, encouraging them to make use of the bunkering-at-sea opportunity. For many years, a discussion regarding establishing a fish landing site at Svalbard has been going on in the local community, amongst politicians and in the media. In combination with the fish stocks moving further and further north, as well as the introduction of a new, valuable, biomass in the snow crab, the resources are indisputable (Sagmoen, 2016). Building a fish landing site in Longyearbyen is however a long and inconvenient process, as the laws are very strict(Vartdal, 2019). Laws regarding import and export of natural resources are also strict, so as the fish landing site is very uncertain of when, or if, it is to be built, it is assumed in this thesis that it will not be built. This means that the potential supply of LNG to fishing vessels is disregarded, and thus the largest active ship segment in the zone is not included in the calculations.

The second largest contributor to marine activity, in regards to fuel consumption, is the expedition cruises. They make up for 31,6% of the fuel consumption in the FPZ, and 38,2% of the amount of port calls to Longyearbyen each year. In this, we have a segment that is both dominating the total fuel demand, as well as the number of port calls. This cruise segment has increased over the last year and is only expected to rise. To illustrate the impact the tourism has on Longyearbyen, CEO of Pole Position Logistics, Terje Aunevik, paints a picture of vessels visiting Longyearbyen is different from what the statistics show. In the statistics presented for the Port of Longyearbyen, there is a distinction between overseas cruises and expedition cruises. For the overseas cruises, there has been between 30-50 port arrivals the last years, while for expedition cruises the number ranges from around 150-250. What is interesting is that expedition cruises are registered as local traffic, and not overseas sailings, as several of the expedition cruises sails to Longyearbyen, do a roundtrip of Svalbard and then sails out of the Svalbard area again. Had these sailings been registered as overseas sailings, Longyearbyen would have the second highest number of overseas sailings in Norway (Aunevik, 2018). This underlines the magnitude of the location and the potential of this ship segment.

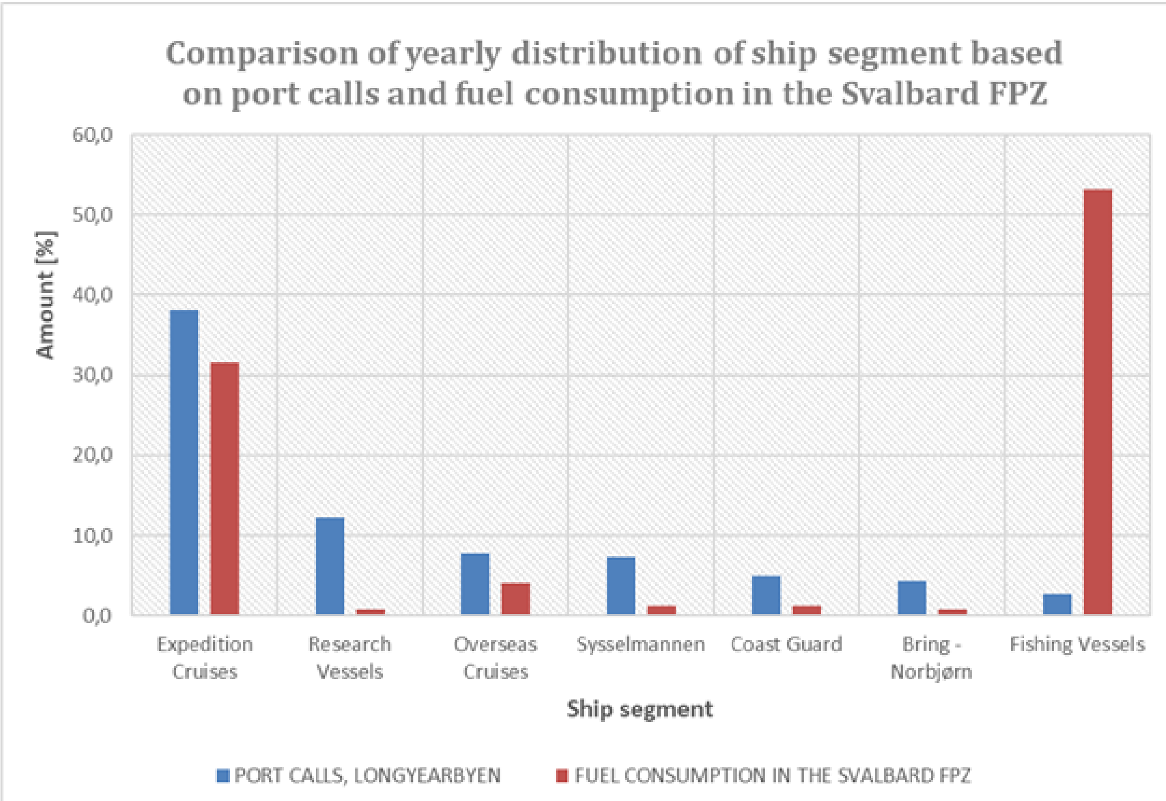

Figure 2.7: A comparison of the magnitude of each ship segment for port calls and marine activity in the Svalbard FPZ based on fuel consumption. The percentages for port calls and marine activity are individual, and displays the volume of each segment for each respective method of measurement.

Observations made from Figure 2.7 clearly shows that passenger's vessels are the most appropriate candidate to assume will have a potential for bunkering LNG at Longyearbyen. This represents the ship segment of which takes up a significant amount of activity both in the open waters and regarding port calls. In an interview with SINTEF research manager, Anders (Valland, 2019), he says that the cruise-industry separates itself from the other ship segments in regards to a focus on sustainability. Passengers on cruise ships are environmentally conscious and have the opportunity to decide on which company they want to sail with. Ships using greener fuels makes it far more attractive for the customer, making the ship owners want to make a change to be appealing. Because of this, it's the passenger-oriented industry that has been included when estimating the demand for alternative fuels.

2.3.3 Seasonal distribution of marine activity

As seen in Figure 2.7 tourism is taking up large volumes of the port calls in Longyearbyen. Tourism in Longyearbyen has exploded the last decade, with more and more actors taking part in the development. In Figure 2.8 the increase of tourism in Longyearbyen for the last ten years is shown. What is interesting about this ship segment is that its activity is highly defined by the seasons. Expedition cruises take up most of the port calls in Longyearbyen for tourism. Typical for an expedition cruise is that it operates in the Arctic waters during the summer, and moves south for the winter where the sailing conditions are better. This results in a concentration of activity, with the tourism season stretching from early May until late September, peaking in the middle of the summer (Kornfeldt, 2019).

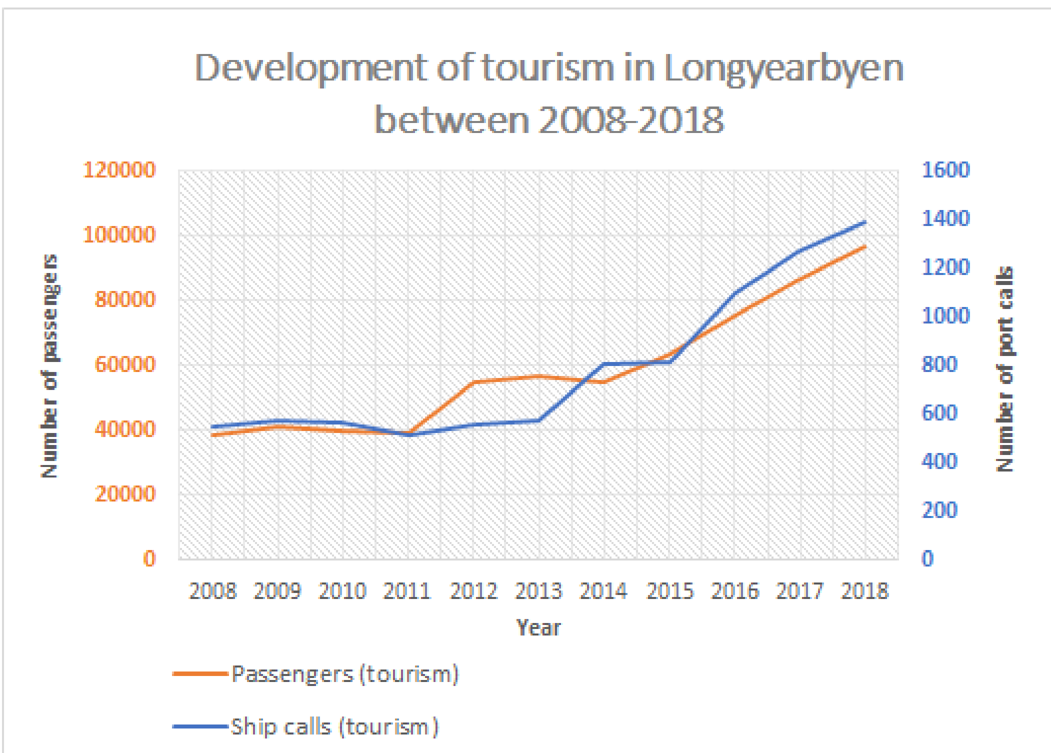

Figure 2.8: This graph shows the rapid development in tourism that Longyearbyen has experienced in the last 10 years. The data is based on numbers released by Port of Longyearbyen (2019).

LNS Spitsbergen AS (LNSS) is the sole distributor of fuel sale to marine actors in Longyearbyen. They have fuel terminals at the quay and distribute MDO and some unleaded petrol (95) to their clients. Provided by Frank Jacobsen, CEO at LNSS, all data on fuel sales from January 2014 to October 2018 were given extract marine-related sales. The raw data was to be kept confidential, but in Figure 2.9 the monthly distribution of diesel sale is shown. Clients vary and include almost all ship segments, except large cruise vessels. As the graph shows, the distribution of diesel sale is primarily concentrated around the summer months. This can be explained by comparing it to the tourist season, which, as explained earlier, concentrates its activities around the summer months. Tourist activities in the Longyearbyen-area, such as day-trip boats, results in an increased demand for fuel, hence the increased fuel sale. Other activity also increases as the sailing conditions improve; the weather conditions are better, and it never gets dark due to the midnight sun. This allows for an increased activity for both recreational- and commercial users, as well as research vessels.

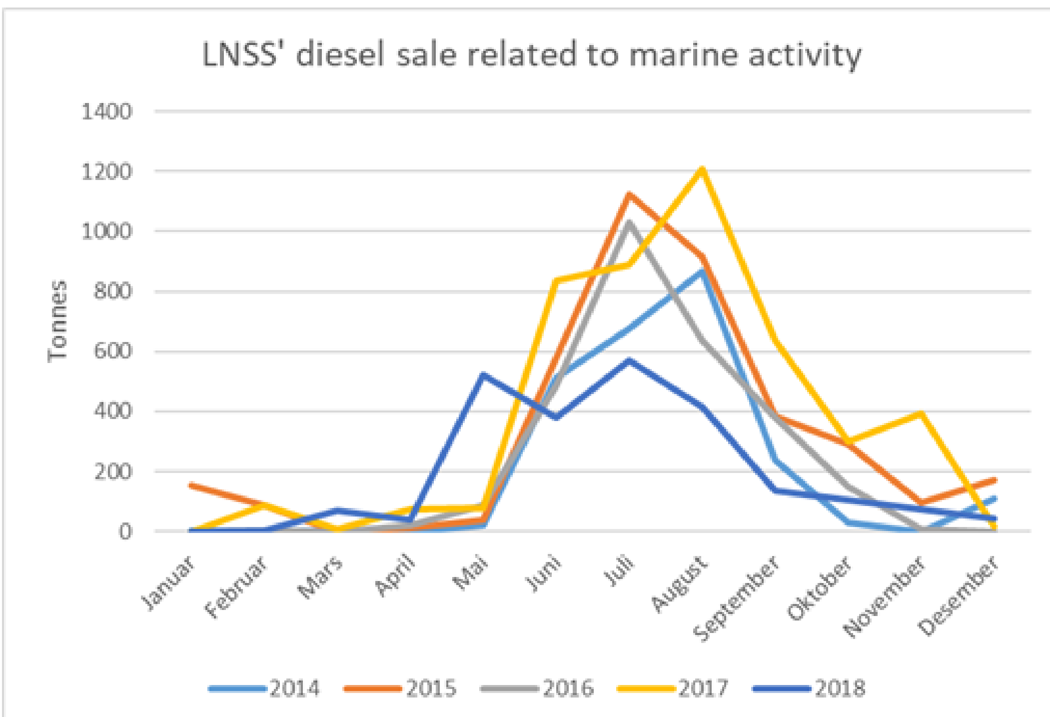

Figure 2.9: Monthly sale of diesel related to marine activity for LNSS AS in Longyearbyen (2014-2018). See Appendix 1 for data supporting the figure.

2.4 LNG as an energy carrier

Liquefied natural gas (LNG) is an energy carrier that consists mainly of methane (CH_4). This is a natural gas which has been liquefied through compression and low temperatures. With a boiling point of -164°C, the volume of the liquefied gas is reduced to about 1/600th of its gaseous state's volume. The liquefaction process is energy-demanding, but it may make for a more cost-effective transportation and storage as the volume decreases significantly. When liquefied, the fuel requires cryogenic tanks; tanks capable of keeping extremely low temperatures, in addition to regulating the high pressure. For transportation-routes where e.g. the existence of pipelines is not present, transporting large volumes over long distances favours the liquefied version as it is less volume demanding. LNG today is used as both as fuel for ships and heavy vehicles, in addition to being used for power production and as a consumer gas in housing (ClimateTechWiki, 2018).

Methane (CH_4) has the lowest carbon content of the hydrocarbon fuels, resulting in a much cleaner burn with almost complete combustion. This means a reduction in air pollution, with LNG emitting less CO_2, NO_x, SO_x and particulate matter than HFO, MDO and MGO (Gilbert et al., 2018). LNG today is used both in shipping and as fuel for power- and heat generation in housing.

Before being liquefied, the natural gas has been retrieved on a gas field production-rig. From here the gas is fed through gas pipelines to an onshore processing plant. Here the gas is liquefied through large scale heat exchanging systems. In this case, the LNG is retrieved from offshore rigs in the North Sea, before being sent to liquefaction terminals in Rotterdam and Melkøya. The LNG is then being stored in cryogenic tanks at low temperatures, before being loaded onto a mode of transport, taking it to its final location. The mean of transport to Longyearbyen is by using specialized vessels with cryogenic tanks, capable of transporting liquefied gas. LNG-tankers of various capacities are assessed in transporting the LNG to its terminal in Longyearbyen. From here the LNG is either consumed or stored for distribution (IGU2, 2015). A simplified illustration of this process is shown in Figure 2.10.

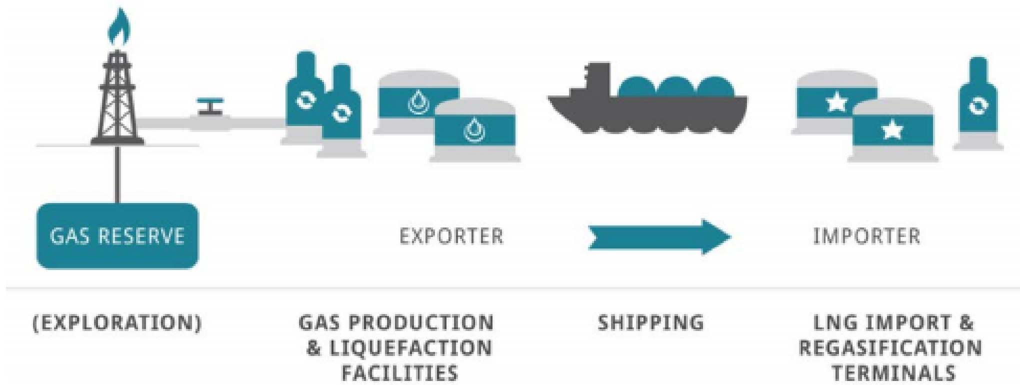

Figure 2.10: Simple illustration of the supply chain of LNG (IGU2, 2015).

When the LNG arrives at its end destination, it can be stored as LNG, or regasified to be consumed or further distributed in pipelines. In this case, the LNG that arrives in Longyearbyen is both stored as LNG and regasified to be used in power production. The intended infrastructure to be used for Longyearbyen is a design made by LMG Marin AS, called GraviFloat. The concept is illustrated in Figure 2.11. This concept meant to build the storage facility in modules offshore, before being towed to Svalbard and installed near shore. This is a more environmentally friendly solution than a land-based facility which requires more environmental intervention due to its infrastructure. It's also advantageous to build the modules offshore as there is a limited supply of building material and manpower on Svalbard.

Figure 2.11: Illustration of what the GraviFloat in Longyearbyen may look like (Vartdal, 2019)

It is necessary to distinguish between a solution being environmentally friendly and climate-friendly. Emission of local pollution such as PM and SO_x-gases, in addition to environmental intervention, such as digging and constructions on land, are examples of negative environmental impacts. The environment is all about local imprints. Climate friendliness is related to reducing greenhouse gas emissions, as the release of these gasses affects the entire planet, and not just locally.

The distinguishing of these two terms allows a selected solution to be called e.g. environmentally friendly, but not necessarily climate friendly. Such is the case for using LNG as a fuel. LNG-consumption produces almost no PM- and SO_x-emissions, and has a reduced emission of CO_2 and NO_x compared to diesel. As Svalbard is situated in a place where the effects of climate change are increased, and it's therefore particularly vulnerable to local pollution, LNG is a very applicable fuel to be used in the region.

2.5 Hydrogen as an energy carrier

Hydrogen (H_2) is a zero-emission energy carrier that can be transferred in a liquid or gaseous state, or as a chemical compound bonded with hydrogen-"carriers". Hydrogen is the first atom in the periodic table and is found naturally on the earth in e.g. hydrocarbons and water, forming covalent bonds with other atoms. Hydrogen has a melting point of -259,2 °C, meaning that it requires a lot of energy to liquefy the gas. Liquefying the gas is desirable when transferring large amounts, as it requires a lot of tank capacity to move it in a gaseous state. In this thesis, compressed hydrogen gas is investigated to be used as a fuel for marine activity in the Svalbard FPZ.

Hydrogen gas is non-toxic but highly flammable and has a density of just 0,089 kg/m^3. The hydrogen properties used in the calculations are gathered from a study performed by (Hirth et al., 2019). In this report the evaluated state of the hydrogen is at 350 bar pressure, resulting in a density of 23 kg/m^3. The compressed hydrogen has a higher specific energy per mass than LNG, but due to its low density, compared to LNG, its energy density of 5 040 MJ/m^3 is almost 2.6 times less than for LNG. Hydrogen gas is stored in high-pressure tanks and has a low permeation. Due to its energy density, larger tanks are required to store the same amount of energy as for LNG.

Hydrogen can be produced in several ways, but the two most common are either by gas reformation of fossil fuels or electrolysis of water. In Figure 2.12 various upstream logistics of hydrogen is shown. Obtaining hydrogen with a complete absent carbon footprint is impossible today, as all equipment used in production, transportation and storage will have a carbon footprint. The least carbonized hydrogen is produced using electrolysis of water, where the energy comes from a renewable source. Electrolysis is a process where water molecules are split into hydrogen- and oxygen gas, resulting in no greenhouse emissions. Electrolysis of water is a well-established technology and is not a subject to further investigation.

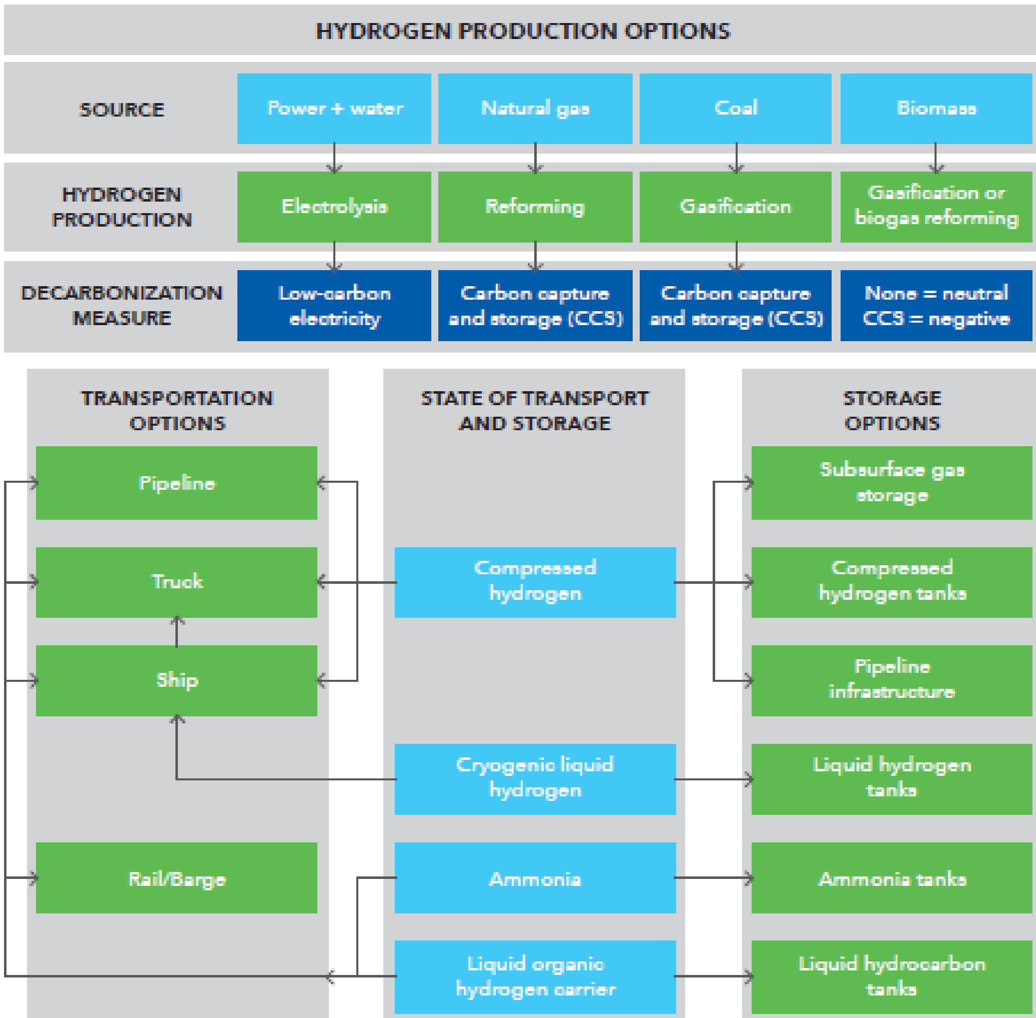

Figure 2.12: Various upstream logistics possibilities for hydrogen (Aarnes et al., 2018)

The supply chain assessed in this report utilizes production by electrolysis of water, where the electricity comes from a wind power plant. This means that the process has the lowest degree of carbon-emissions, also considering that the distance from the power-production to the hydrogen factory is small.

The hydrogen is to be compressed and transported with ships from Sør Varanger, situated in Northern Norway, to Longyearbyen where it will be transferred to a storage facility. The storage facility will consist of compressed hydrogen tanks and is assumed to be built like the GraviFloat-project, as presented in Chapter 2.4. This enables easy access for bunkering vessels, as well as a low degree of intervention on the vulnerable mainland.

The technology needed to produce and utilize hydrogen already exist and is well functioning. The biggest problem with hydrogen today is the price. Hydrogen has yet to be properly commercialized, with fixed contracts between supplier and consumers still characterizing the industry (Valland, 2019). There might not exist a proper value chain today, but the outlooks for hydrogen is also positive. Innovative hydrogen-based projects are on the rise. In Norway, the first hydrogen-powered passenger ferry is meant to be in operations in 2021, with an additional ferry planned. In the 2020 Olympics in Tokyo, it's invested big money in an Olympic village powered by hydrogen. The objective is to accelerate the development and integration of hydrogen-based technologies. These are examples of projects pushing the development of hydrogen, and helping to start to form the basis for a future value chain.

Say's law states that supply creates its demand, something of which has been pointed out by most of the relevant actors interviewed in the course of the last year (MBN, 2019). Many of the interview-objects used the simile "for hydrogen to become a regular fuel in the marine industry, a secure and cost-effective supply is needed. For the suppliers to invest in large-scale production and distribution of hydrogen, a certain demand is needed. This is like the chicken-or-egg paradox. What comes first?". The suppliers need a demand to start producing, while the consumers won't pledge to hydrogen solution unless a steady and cost-effective supply of the fuel is available.

2.6 Trends and potential future scenarios

The use of alternative fuels is steadily increasing, and its development is widely expected to grow. Price and availability have long been the two bottlenecks for utilizing new, alternative ship fuels, but the situation is improving. In this section, an insight into the potential outlooks for LNG and hydrogen are presented.

2.6.1 LNG

According to a study performed in 2014, global use will increase by over 50% from 2010 and will account for 25% of global fuel consumption by 2035(Fekene, 2014). For marine activity, LNG as a fuel has grown increasingly over the last years, with Martin Wold, head of the DNV's Alternative Fuels Insight (AFI), giving the following statement in a press flash at the 2019 NorShipping exhibition:

"There are now 163 LNG-fuelled ships in operation and a further 155 ships on order.

Order intake for LNG-fulled vessels has remained steady for several years now at around 40 ships per year. However, in 2019 we have already passed 40 new orders in the first five months, which could be a sign that the pace for LNG fuel investments is picking up."

According to statistics presented on DNV GL's AFI-webpage, the amount of LNG terminals in Europe is growing, with several projects in development and under discussion. LNG use is in other words highly expected to grow, considering more and more actors are making the switch from HFO, MDO and MGO, as told by Wold. IMO adopted a greenhouse gas reduction strategy in 2018, aiming to reach a 50% reduction in emissions from ships within 2050, and reducing the carbon intensity by 40% and 70% in 2030 and 2050, respectively (DNV GL, 2018). This is expected to pursue marine actors to investing in greener solutions, such as LNG. With Norway being the second largest LNG supplier in Europe with a share of 27% of the supply in the European union(Dediu et al., 2019). The domestic presence of the fuel is unquestionable, and Equinor continues to expand their LNG-productions (Stangeland, 2019).

Gasnor, a Shell subsidiary, is Norway's leading downstream gas company. In a statement, voicing their opinion regarding natural gas as fuel, Gasnor lists the following reasons for investing in natural gas (Gasnor, 2019):

- Natural gas reduces environmentally harmful emissions today - with immediate effect.
- Natural gas safeguards Norwegian industry and Norwegian jobs.
- Natural gas as a fuel for ships is needed to meet our NOX reduction obligations
- Natural gas will facilitate the phasing in of biogas (and Hydrogen).

Gasnor naturally has incentives for increasing the usage of LNG as they are an important provider of the fuel, but regardless of this, the arguments provided in the list are justifiable. By directly switching other fossil fuels the CO_2-emissions are immediately reduced, as for NO_x, SO_x and particulate matter (Gilbert et al., 2018).

For LNG, two scenarios have been explored. The first scenario is reasoned in Chapter 3.3.1 section, assuming demand based on current activity and announced projects. This scenario is considered to be pessimistic as it estimates the demand for a long period, only based on current affairs, and their outlooks. The second scenario explored is much more optimistic. The premises for this scenario is given by the thesis contractor. In this scenario, a comprehensive growth in demand for LNG increases over the next 30 years. In this scenario, all LNG is also imported from Melkøya.

	Scenario 1			**Scenario 2**		
	Day trip ship	Exp. Cruise (200+ PAX)	Overseas cruise	Day trip ship	Exp. cruise (50-100 PAX)	Exp. cruise (200+ PAX)
2021	1	1		1	1	(200+
2024	1	2	1	1	1	2
2031	1	2	1	2	5	10
2034	1	2	2	2	5	10
2041	1	2	2	2	7	18

Table 2.3: The two selected scenarios being explored. "Exp. cruise" stands for "Expedition cruise".

2.6.2 Hydrogen

The outlooks for hydrogen is also positive. Innovative hydrogen-based projects are on the rise. In Norway, the first hydrogen-powered passenger ferry is meant to be in operations in 2021, with an additional ferry planned. Havila Kystruten, a Norwegian shipping company, has ordered four coastal ships to be delivered in 2020 (Cruise Industry News, 2018). These are all powered by LNG and will sail between Bergen and Kirkenes all year. The four ships have a degree of flexibility enabling them to easily make a shift from LNG to hydrogen (Stensvold, 2018). The article underlines that they do so even though "the technology is not mature enough to be adopted", which can be interpreted that the shipowners anticipate hydrogen use to grow in such a way that it will be beneficial to make a switch. This indicator, provided by a renowned marine actor, only supports the expectations regarding hydrogen use to grow and become commercialized.

Assessing import of hydrogen to Longyearbyen is primarily related to a hydrogen project in Sør-Varanger, as mentioned in Chapter 2.5, and ongoing development of an event ship that will be based in Longyearbyen. By the end of 2019 Varanger, Kraft AS will have established a factory for test production of hydrogen. This will be produced by electrolysis, powered by a wind farm on Raggovidda. The wind power farm situated on Raggovidda is Norway's most effective wind power farm, meaning the area is highly suitable for green hydrogen production(Laupstad et al., 2019). The project stakeholders specifically mention transporting the hydrogen to Svalbard, and to encourage the tourist industry to focus on sustainable tourism.

2.7 Stakeholder analysis

In every project, there are stakeholders; peoples, groups or businesses with either an interest or influence in the project. This thesis assesses a notable change in the energy-situation in Longyearbyen, affecting both existing stakeholders as well as introducing new ones. Understanding the various stakeholders involved is necessary for the formulation of the optimization problem. When performing an optimization, it has to be from the stance of one of the stakeholders, so that this specific stakeholder finds a solution that is optimal for their operations. In Figure 2.13 four of the most relevant stakeholders for this project are presented. Each stakeholder has a different degree of interest and influence in the project, and are therefore of varying importance to the project. The following optimization-problem is created from the stance of the project initiator/operator.

Figure 2.13: Four relevant stakeholders for the assessed solutions in Longyearbyen.

The project initiator/operators are, in this context, thought to be the group responsible for the construction and operation of the assessed solutions. This group will have a high degree of influence and interest in the project as they are the primary driving force and investors. This stakeholder is investing large sums of money into the project and would want to minimize their expenses. This means constructing infrastructure and importing fuel to a degree that is no more than necessary, while still having the flexibility to adapt to new scenarios. The project owners will work to ensure the project's success, but the outcome of the project is also dependent on the influence of the other stakeholders.

The government represent another stakeholder with a high degree of influence for the project. They must approve of the suggested solutions before any construction can begin, in addition to having the authority to dictate fees and taxes for the relevant actors. These fees could include e.g. emissions-fees; pushing marine actors to make the switch to a more environmentally friendly operational state. This could lead to an increase in ships phasing out the use of HFO and MDO and thus increasing the market for LNG. This would be beneficial for the project operators, as an increase in demand for LNG would create a higher potential for profits generated through sales. The only income of this project is from sales, in addition to funding through potential subsidiaries from national developing banks or government enterprises providing financial support to innovative projects.

The community and industry/marine actors are the end-users. These stakeholders have a great interest in the project and a various degree of influence. For the community, an economically-, environmentally- and socially sustainable solution is very important. The community are depending on a safe and steady supply of energy, as the weather conditions during the winter can be harsh. A loss of electricity and heating could have severe consequences, as the cold is imminent. A new situation in the job market will also be a driving factor for the local inhabitants. The shift in power-generating methods will leave people working in the existing business unemployed, however, it will also create new jobs. A prerequisite for living at Svalbard, stipulated in the Svalbard Act, is that one has to be able to provide for oneself, either by having sufficient means to reside or the opportunity to feed legally (Ministry of Justice and Public Security, 2019). If one does not meet these requirements, the authorities have the right to deport the resident in question. These regulations amplify the importance of ensuring a safe job market.

For actors in the marine industry capable of using the selected fuel(s), it's decisive to have a cost-effective and secure supply. Filling up the tanks when arriving at Longyearbyen, rather than sailing with full tanks for the entire round-trip, makes for a more cost-effective sailing. This also reduces the amount of emissions into the atmosphere, as the consumption increases with the weight of the ship. As mentioned earlier, this is where the chicken-and-egg paradox arises. For marine actors to make the shift towards new fuels; a steady, predictable and economically-beneficial supply of fuel is a must. However, for the contractors of bunkering stations and storage facilities; a steady demand for a given fuel is crucial for the project's success. If there is no demand for the respective fuel, the project owner will suffer economic losses, similar to that of the marine actors should they change to environmental fuels, but without a secure supply of fuel.

As mentioned, this project also introduces new stakeholders. This includes suppliers of fuel, suppliers of building materials, construction-workers and employees working on the finalized power plant. These stakeholders are considered to be of a various degree of influence to the project. As the assessed storage facility is assumed to be built like the GraviFloat, mentioned in Chapter 2.4, the influence of suppliers of building materials and manpower is expected to be low. Since the construction of the facility is offshored and towed to its destination, the supply risk is assumed to be low. For the fuel supplier(s) the influence is uncertain. For the various fuels assessed, the supply risk will vary depending on the market and time. As mentioned in Chapter 3.1 the fuel-price may change depending on the market situation, as well as the development and increase of the industry. A change in price will directly affect the demand; again affecting the supply risk. The current hydrogen-market is limited but predictable, however, if the industry develops like the mentioned studies show, the supply risk will change accordingly.

Chapter 3

Data and assumptions

Presented in this chapter are the various assumptions made, in addition to the data calculated, that will be used as input in the computational study of the optimization problem. The values found in this chapter will be the parameters in the optimization model described in Chapter 4.

3.1 General assumptions

Some of the raw data used in the calculations have been collected by others, so it's assumed that these numbers are correct. It's also assumed that the various ratios and conversion-numbers for LNG and hydrogen used in the calculations are correct. Most of these are based on reports made by industry actors, and some, regarding physical properties, are based on scientific papers.

For the supply of LNG and hydrogen, it's assumed a low supply risk, both in terms of availability at import terminal and for transportation ships. This means that the availability-requirement implemented in the optimization model would be unnecessary in the mathematical world, but in the real world, this safety-measure is unalterable.

Related to the supply risk, it's also assumed that the development of LNG and hydrogen-production will follow the increasing demand, in such a way that the retail price of the fuels is not drastically affected by a rapid increase in demand. The relation between supply and demand is defining how much the consumer is willing to pay for a product. The higher the demand, the higher the price.

This thesis is somewhat a continuation of the thesis of Hovden (2018), optimizing the complete energy system of Longyearbyen, based on LNG and solar energy. As this thesis is a feasibility study, based on the inclusion of development in the marine sector, technical solutions for the power plant, energy conservation and land distribution is not included in the model. The situation on land has not changed and is not predicted to change in this study, meaning that optimizing the land-based energy system would only be a repetition of the earlier work done by Hovden. It's therefore assumed that the technical study, and selection of e.g. number of gas turbines for the power plant, is applicable for this study as well. This assumes that the variations in electricity loads and heat demand, as described in Section 2.3.1 is handled.

3.2 Estimating energy demand on land

The energy-consumption on land is gathered from the mentioned master thesis of Hovden (2018). The hourly demand for electricity and heat in Longyearbyen is accumulated to weekly and monthly values to be used in the computational study. Figure 3.1 shows the distribution of energy over the course of one year. In Chapter 3.3.1 a day trip vessel is introduced, operating all year, and using shore power when not in operation. This shore-power demand is also considered when estimating the energy demand on land, in addition to the energy demand from the power-plant itself. A power plant in operation is estimated to consume 2400 kWh per day (Hovden, 2018).

The energy demand for the calculated time periods is therefore expected to remain the same for electricity and heat to the community, in addition to the LNG power plant and day trip vessel(s). To convert the equivalent energy amount to an LNG-demand, it's assumed that $1m^3$ corresponds to roughly 6250 kWh energy. Using gas turbines operating with an efficiency of 88%, this gives a total of 5500 kWh energy perm^3 LNG.

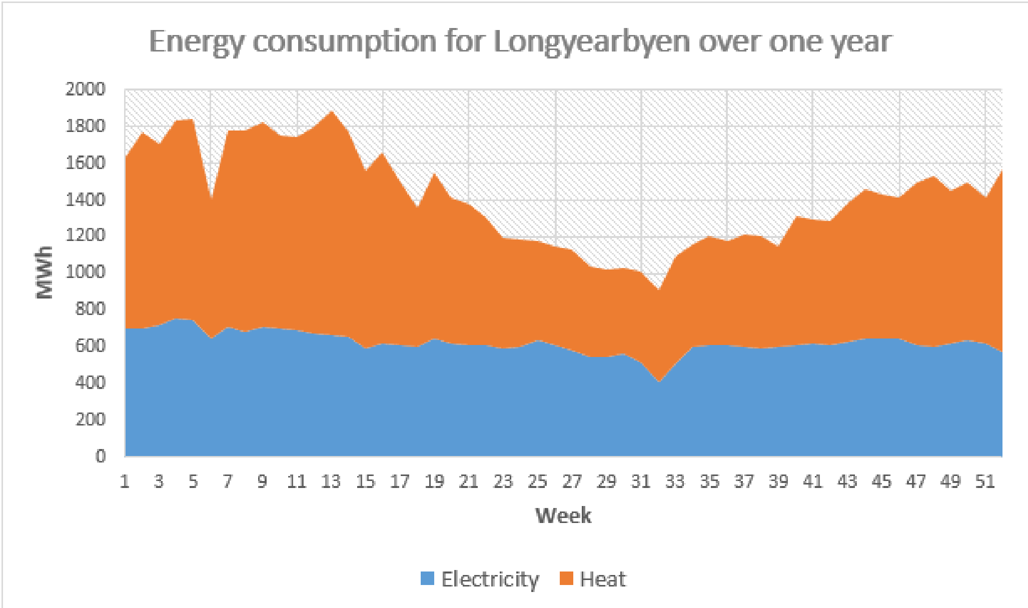

Figure 3.1: Distribution of energy consumption over one year for Longyearbyen.

3.3 Estimating energy demand for marine activity

As written in Chapter 2.6 there are two scenarios investigated for the demand of LNG. The first scenario is assuming demand based on current activity and announced projects. This scenario is considered to be pessimistic as it estimates the demand for a long period, only based on current affairs, and their outlooks. The second scenario explored is much more optimistic. The premises for this scenario is given by the thesis contractor. In this scenario, a comprehensive growth in demand for LNG increases over the next 30 years. In this scenario, all LNG is also imported from Melkøya.

3.3.1 Demand of LNG

- Disclaimer -
In the following sections, various ships and shipowners are listed with names and are put in relevance to marine activity in the Arctic. The reason being is that they are all assumed to have appropriate designs to be used in the Svalbard FPZ or existing actors in the area. The ships mentioned are merely used for exemplifying and comparison of similar types of vessels, so whatever transition suggested for their operations is not necessarily factual. The actual projects that are in development are clearly stated as such, while the actors used for exemplifying is emphasized that they are just an

assumption.

Expedition cruise ships

The expedition cruise-industry is continuing to increase both in fleet size and season length. A typical season for a Svalbard-based expedition cruise consists of doing a round trip of the archipelago that lasts about 7 days or embarks on journeys towards the North Pole. A regular expedition-cruise season now starts in mid-April and lasts until the first week of October (Kornfeldt, 2019). The expedition cruise-fleet is also expanding, with a total of 43 new build-orders to be delivered between 2019 and 2022. Of these, three are LNG-powered vessels, and all three actors are relevant candidates to be used in the Svalbard area. The French Compagnie du Ponant is already a regular visitor in Longyearbyen with ten preliminary announced port calls in Longyearbyen for the summer of 2019. These are distributed with one visit per week from the first week of June, except for the last week in June which has two port calls for two different ships owned by Ponant (Visit Svalbard, 2019). As the ordered new build, ”Le Commandant Charcot - Pioneer of the Poles”, ready in 2021 has a polar class 2 and is designed to go to the North Pole, it's assumed that this vessel can be based in Longyearbyen during the summer period. The LNG consumed during this period is therefore included in the LNG-demand from the year 2021. Information surrounding the two vessels ordered by Viking Ocean is limited, other than them being expedition cruises, powered by LNG and capable of sailing in the whole world (Cruise Industry News, 2018). Since they are expedition vessels; vessels meant to reach hard-to-access and remote places, it's reasonable to assume that it also may be used in the Svalbard Area.

Two popular remote locations, convenient for expedition cruises, is the Arctic and the Antarctic. Since the seasons are opposite, meaning when it's summer in the Arctic the Antarctic experiences winter and vice versa, the months May-August are ideal to sail in the Arctic. It's therefore assumed that an additional expedition ship, to Le Commandant Charcot, will be based in Longyearbyen from early May to early August from 2024, as the last new build might not be ready for the 2023-season. The vessel is assumed to bunker in Longyearbyen once a week, with three week's shifts. It's assumed to fill one week's need for LNG each time. It's assumed that it's based in Iceland when it rotates away from Svalbard, which is common practice amongst several industry actors (Kornfeldt, 2019). Ponant's ship has a capacity of 270 passengers, and the Viking Ocean-ship is assumed to be of a similar size. The consumption-values used for expedition ships exceeding 100 passengers is therefore used. The values are gathered from Sortland (2018). The consumption-values are converted from the expedition cruises using diesel as fuel. It has been assumed that the same amount of kWh is needed for the LNG, meaning an equal fuel efficiency. The LNG-properties are gathered from the ”Handbook of liquefied natural gas” by Mokhatab et al. (2013).

Cruise ships

AIDA had 6 visits Longyearbyen in 2018, and the announced port calls for 2019 is the same. The ships carry over 2000 passengers and have a fuel consumption of around 90 tonnes diesel per day (Sortland, 2018). Of the 24 visits from cruise ships Longyearbyen in 2018, six were from the company AIDA. AIDA launched the worlds first cruise ship capable of operating completely using the only LNG, and another two are being delivered within 2023(Cruise Industry News, 2018). The announced port calls show that Longyearbyen expects one visit in the last week of May, one in the second and third week of June, one in the first and third week of July, and one in the first week of August.

The cruise order book shows that 22 of the announced large cruise vessels that are currently ordered by 2027 are LNG-fuelled. Several of these are relevant candidates to be used in the Svalbard-area as they have listed "World" and "Europe" as sailing areas. Because of this indication towards an increased fleet with LNG as fuel, and the fact that current actors in the Svalbard-area are in the order book, an assumption is made that from 2024, Longyearbyen will experience six visits from LNG-powered cruise ships each season. Further on, it's assumed that the amount will double after ten years. As both the port the cruise ships arrive from and leave to after Longyearbyen varies, the bunkering demand is assumed to be what it consumes in the Svalbard FPZ. This data is gathered from Sortland (2018).

Day trip vessel

A project regarding an event ship based on LNG and battery is currently in development. This will provide day-trips around Spitsbergen, and will be based in Longyearbyen all year. The ship is meant to provide two sailings each day from mid-March to mid-October, and one sailing each day for the rest of the year. While at the port the ship will connect to shore power. It withdraws more electricity during the day, as it's switched to a less consuming state during the night. Each sailing will last approximately 7 hours, consuming just above 3m^3 per trip. All ship data are based on specifications given by thesis contractor, in collaboration with LMG Marin AS via Odland (2019). An illustration of what the event ship may look like is shown in Figure 3.2. In the calculations of LNG-demand from marine activity, one day trip vessel is set in effect in 2021, and another in 2031. They follow the same sailing pattern as listed above.

Figure 3.2: Illustration of what the assessed event ship will look like. The draft was created by LMG Marin AS for Spitzberg Holding AS (Odland, 2019).

Bring

Bring, a Norwegian postal- and logistics company runs a cargo vessel called M/S Norbjørn that visits Svalbard almost every week the entire year. Based in Tromsø, the vessel sails to Longyearbyen, with a few, occasional visits to Ny-Ålesund (Bring, 2018). In the calculations, M/S Norbjørn is assumed to switch to LNG in the year 2021, and it will only bunker in Longyearbyen. The LNG demand of the vessel is calculated based on the energy demand in kWh, calculated by using engine data for its MAK 6M25 1800kW (750 RPM)-engine(Caterpillar, 2010) with an engine efficiency of 85%. The vessel is assumed to sail 4 days per week, with a daily diesel consumption of 7,91 tonnes. By converting the energy need to LNG, this corresponds to a weekly demand of 49,7m^3 LNG, based on conversion values from Gilbert et al. (2018).

3.3.2 Demand of hydrogen

The demand for hydrogen is assumed dependant on a fixed demand from contract-bound consumers, as explained in Chapter 2.5. The consumer is the same event ship(s)/day trip vessel(s) as estimated for LNG. Their seasonal activity is estimated to be the same, so the needed kWh per week needs to be converted to cubic meters of hydrogen. Using a conversion factor of 5040 MJ/m^3 for hydrogen, as given by Hirth et al. (2019), the consumption is estimated to be 93,7m^3 per week of hydrogen for one ship in the winter season, and 187,3m^3 per week for one ship in the summer season. By converting the ship's energy consumption directly from LNG to hydrogen, it's assumed that the ships have an equal fuel-to-propeller efficiency. The number of active ships assumed is in accord with the scenarios developed for LNG. This means that one ship is active all year from 2021 before an additional ship is introduced in 2031.

3.4 Estimating price of LNG

An important aspect of finding the optimal solution will be the scheduling of LNG-import and deciding on amount imported. A leading factor for the optimization model will be the LNG-price, as the price level dictates when its beneficial to import. Two methods have been applied to predict prices; one based on seasonal changes, and one based on historical data.

3.4.1 Seasonal variations

The first method used was to find the fluctuation in the LNG-price due to seasonal variations. Figure 3.3 shows the European Union natural gas import's summer and winter prices for the last 4 years. The blue rhombuses represent the winter prices, while the orange rhombuses show the summer prices. As seen, the blue lines, showing the price development from summer to winter, are increasing for all time periods. The price differences in December and June is approximately 24.6%, meaning there could be a significant cost reduction in good scheduling of LNG-import. It should be noted that as this thesis is written before the summer of 2019, the value for April 30. is assumed to be the summer value. The latest development is that the price is dropping, yet stabilizing around the values for April, justifying the assumption(YCharts, 2019). The average value for the last year is calculated to be 7,379USD/MMBtu (Million British thermal units). To get the value at price per cubic meter, a conversion factor of 24,0 MMBtu/m^3 for LNG is applied, found in the International Gas Union's Natural Gas Conversion Pocketbook (IGU, 2012). The currency of USD to NOK per 22. May 2019, is 8,77 NOK/USD, so by multiplying the average LNG price with the conversion factor for MMBtu and currency, the average price of LNG becomes 1553.13 NOK/m^3.

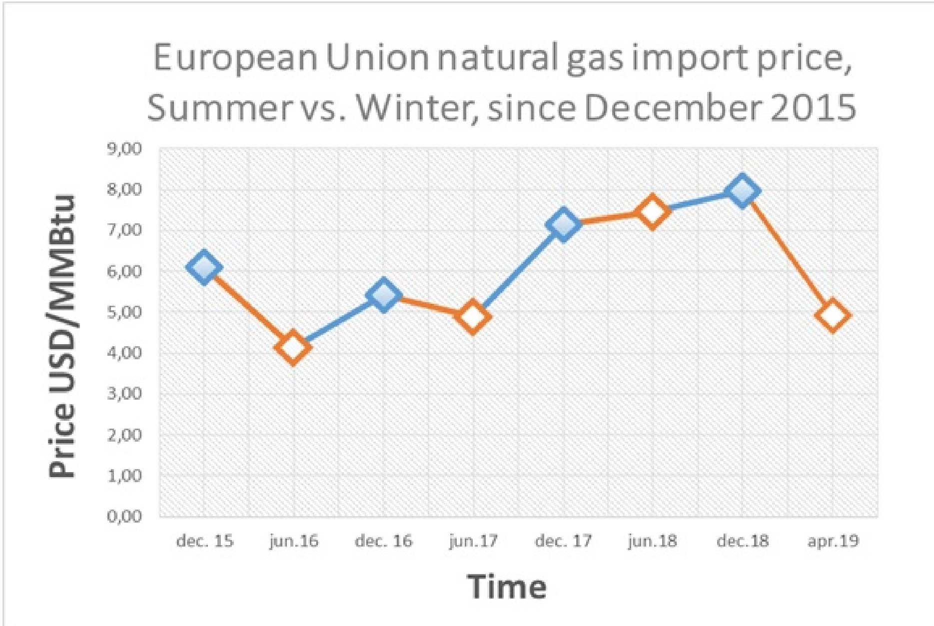

Figure 3.3: European Union natural gas import price, summer vs. winter, since December 2015 (YCharts, 2019).

To incorporate the seasonal variations in LNG-price, the following method was used in the forecasting of prices. A linear approximation was used to calculate weight/proportion numbers depending on the time of year. These weights would be implemented in the Monte Carlo simulation, to steer the simulation in such a way that it accounts for seasonal variations. The method is graphically shown in Figure 3.4. The max/min (winter/summer) prices were used as extrema, equally distributed over the average price for the last year. The graph starts in week one, where the price is equal to the winter average. The minimum point is reached in week 26, of where it shifts and increases back to the winter maximum value. These calculations produced a 52-long (52 weeks=one year) series of weight numbers, used in the Monte Carlo simulation. The Monte Carlo simulation was also done for monthly variations to be used in the 30-year simulation. In this simulation the time steps were set to one month, instead of one week, to reduce the run-time of the model. To find the monthly weight numbers, the above process was repeated. By linear interpolation, the same procedure was done, but for 12-time steps instead of 52. The maximum value was set to the first month and the minimum value to month seven. This produced a series of twelve weight numbers to be used in the Monte Carlo simulation.

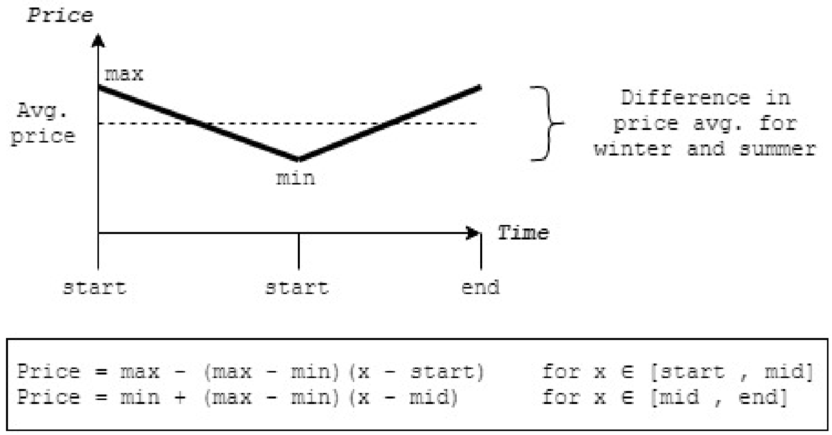

Figure 3.4: A graphical illustration of how seasonal variation in gas price was calculated.

3.4.2 Monte Carlo simulation

To simulate various outcomes of the price over the course of one, and several, years, a Monte Carlo simulation was applied. A Monte Carlo simulation is a mathematical technique allowing the user to see a range of potential outcomes and their probability, by predicting changes based on a given probability of change(Kenton, 2019). The LNG-prices in the future holds a lot of uncertainty, therefore a Monte Carlo simulation was performed. This prediction allows for a quantitative analysis of potential outcomes, something desirable for the project owner when assessing risk. Simulations were set up to simulate weekly changes over the course of a year, and also for monthly variations over a 30-year period.

To decide the range of which the price can be generated in for each time step, the volatility of LNG is needed. Volatility is, according to Kuepper (2019) "a statistical measure of the dispersion of returns for a given security or market index". The higher the volatility is the bigger the spread the price can move in. This means more unpredictability, and following a higher risk.

A study performed at the Oxford Institute for Energy Studies compares natural gas price volatility in the UK and North America. The study concludes that in both markets the weather and temperature is the main driver of demand, and, interestingly, that the average volatility for both markets is almost equivalent (Alterman, 2012). The data in this study was from 1997-2011, so as the market will have changed, the volatility from this study was not used. An article published in 2017 measures the UNG average annual volatility to be 41.4% in 2017 (Zaccardi, 2017). The UNG is the United States Natural Gas Fund, and as the study by Alterman concluded that the volatility of UK and North American gas prices are almost equivalent, a volatility of 41.4% has been utilized.

Since the simulation was performed twice with first a weekly, then a monthly, time step the volatility for the given time step is needed. The volatility found was annual, so to convert it to weekly and monthly volatility, the annual volatility is divided by the square root of 52 and 12, respectively (Naik, Surendra, 2019). This gives us the variance of the LNG-price for each time step, needed in the simulation.

The Monte Carlo simulation was performed in Microsoft Excel, using the NORM.INV-function as a random-number-generator. As the description of this function reads, it "returns the inverse of the normal cumulative distribution for the specified mean and standard deviation" (Microsoft, 2019). By adding the inverse to one, and multiplying this with the start/previous value, the new value is generated based on a predecessor, a probability of change, a mean expected change and its standard deviation. The setup of the function is shown in Equation 3.1.

$$P_{t-1} * (1 + NORM.INV(probability, mean, standard.dev) = P_t \tag{3.1}$$

The first input needed in this function is the start value. This is set to be the average price from the period April 2018 to April 2019. The next required input is the probability. This probability represents the probability of a change occurring within the limits set by the standard deviation and mean change. In this simulation, the Random Walk Theory (RWT) is applied to decide the probabilities. RWT is a hypothesis within financial theory suggesting that price changes in the stock market happen independently and are completely random. This means that historical trends cannot be used to predict the probability of the direction the price is moving if following the theory (Smith, 2019). As the name of the theory indicates; the prices are expected to evolve in a random direction, like following a random walk. Since the RWT is chosen, the function RAND() is used for the probabilities. This returns a random number greater or equal to 0, and less than 1. The third input needed is the expected mean change. As the RWT suggests, there is no reason to expect a certain change, so the mean is set to zero. The final input of the function is the standard deviation. This was found from the volatility as explained earlier.

The simulation of price change has commenced in two different ways. The input data used in all optimization models are derived from a random run for a 52-week period. As the results need to be comparable for various scenarios, an equal input for LNG is needed. The price change for LNG used in all simulations is shown in Figure 3.5. The blue line shows the random simulation of the LNG price, while the orange shows the altered version after introducing the seasonal variations. It's the latter of the two that is utilized in the optimizations. For the 30-year optimization run, this price is repeated for the entire run.

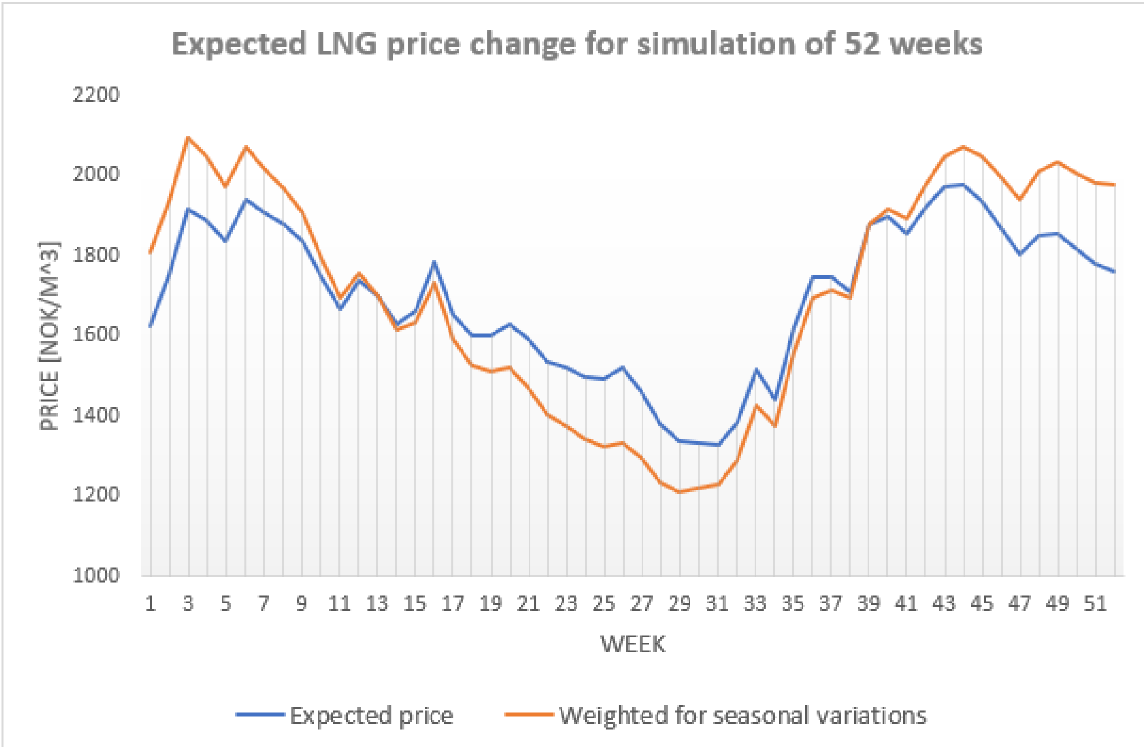

Figure 3.5: Expected price for the 52-week runs. The graph is based on the numbers used in the computational study.

The second way of simulating the price change is by performing the actual Monte Carlo simulation. This simulation needs to be based on a large number of runs, to quantify the ranges of which the prices' is expected to be in. After performing all the steps listed above, the first expected value for month one is generated. Since this value can differ largely, the function needs to be run a large number of times to find a mean number that can be verified quantitatively. The Microsoft Excel-function "Data table" is therefore utilized to perform 1000 runs of Equation 3.1. After running this function 1000 times, generating 1000 different expected prices, a mean value is extracted. This mean value becomes the start-value for the next month, and so it continues until month twelve.

12 000 expected prices for various paths have now been simulated, and the mean values are collected in a column. These numbers are then being weighted based on the numbers found through the calculation of seasonal variables. An example of what this price development could look like is shown in Figure 3.6.

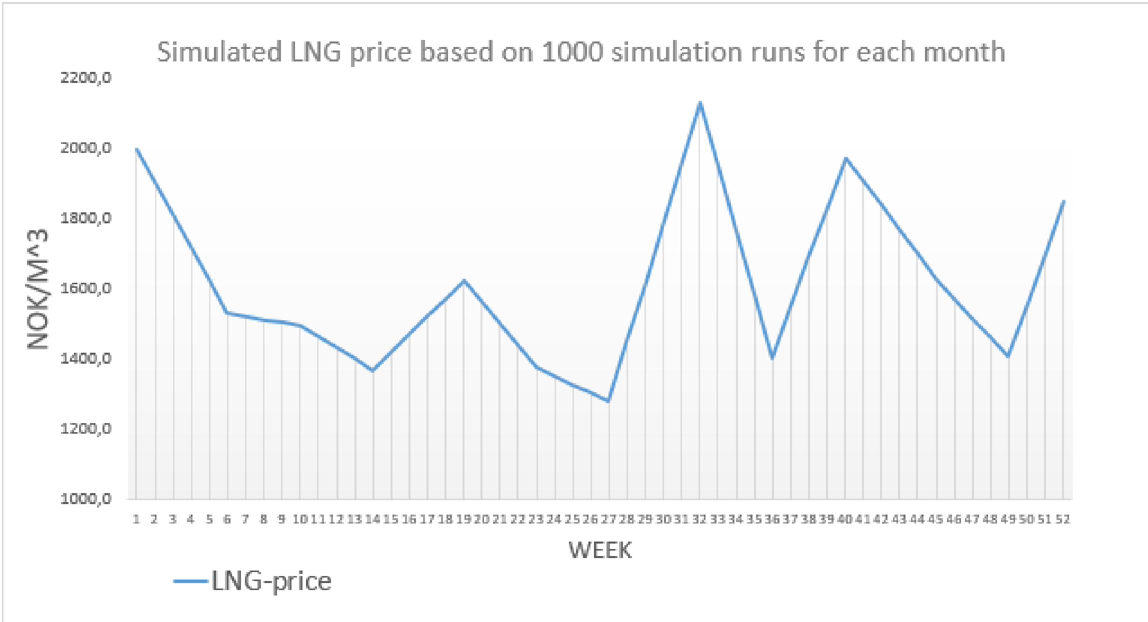

Figure 3.6: Illustration of how a Monte Carlo simulation returns weekly values for a simulation run of 1000 for each month. The example is taken from a random run of the data tables in Appendix B

After calculating all 1000 outcomes for each month, some statistics and distribution are found to evaluate the solution. The mean and median price, in addition to the standard deviation, for each month is found. This is done by using the Microsoft Excel-functions AVERAGE, MEDIAN and STDEV.S. To further investigate the probability of the solution ending within certain limits, some percentiles are calculated. The function PERCENTILE.EXC is applied; calculating the value of which the total outcomes have a certain probability of ending below. This is done for 5%, 95%, 25% and 75%, meaning it returns the value of which it is a 5%, 95%, 25% and 75% chance of ending below.

Example of price distribution from simulation

As the prices vary with each run of the model, an example is shown as to what the distribution of the prices looks like. A simulation of one year was performed, and the distribution and properties for four months are presented below. In Figure 3.7 histograms for the four months is shown. These show the continuous probability distribution of the LNG prices for this run.

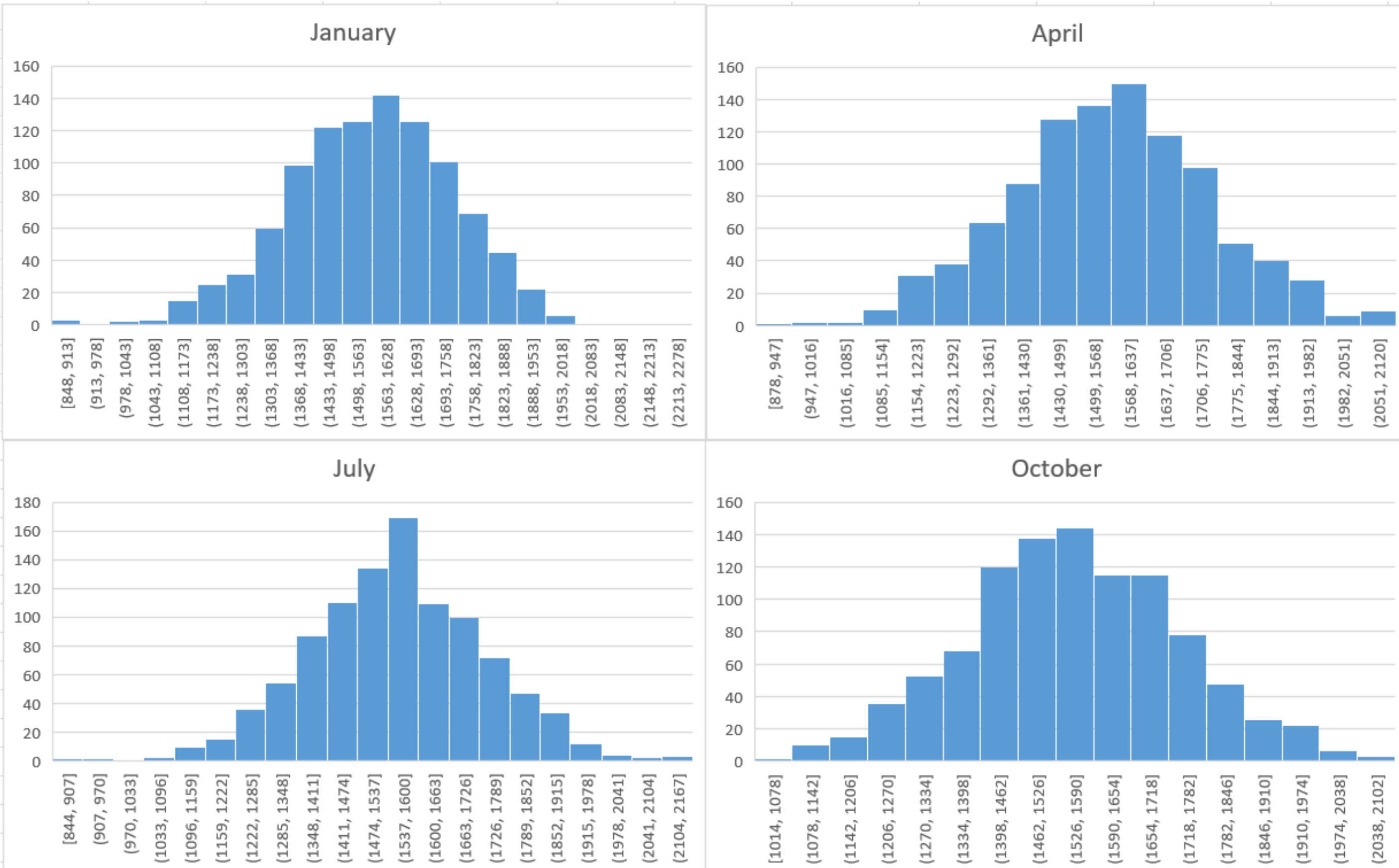

Figure 3.7: Example of how the distribution of LNG prices is for one year, using the Monte Carlo simulation with seasonal variations. The example is taken from a random run of the data tables in Appendix B

The histograms shown above follows a normal distribution, due to the selected Microsoft Excel function applied in the calculations. Along the x-axis, various price intervals are shown, while the y-axis shows the number of occurrences for a given interval. In Table 3.1 their mean and median values is shown. As seen the mean price, the median price and standard deviation vary in range both for each individual month and across the whole year. There is no correlation between the changes, seeing as e.g. the mean price can be higher than the median one month, and lower the next. The same goes for the standard deviation, which its size varies independently of the size of the median and mean price.

$[NOK/m^3]$	**January**	**April**	**July**	**October**
Mean price	1563	1565	1557	1556
Median price	1569	1568	1555	1552
Standard deviation	187	196	179	182
Percentiles				
5 %	1243	1238	1263	1250
95 %	1858	1893	1859	1862
25 %	1438	1436	1442	1439
75 %	1691	1694	1676	1684

Table 3.1: Statistics and distribution of the four months shown in Figure 3.7.

Percentiles showing the distribution is also shown. In the first column of the percentiles-list, the number says that it's a 5% chance of the utilized price being less than the listed number. Following, the 95%, 25% and 75% also show the probability of the utilized value being lower than the number listed for the given percentile. This gives us an empiric probability of the range the expected price may lie within.

3.4.3 Deterministic versus stochastic input

In the computational implementation, the price development of the LNG price is deterministic as one of the main objectives of the thesis was to compare various scenarios and transportation routes. To compare the scenarios in question, it's decisive to compare them on the same basis. The pricing of LNG is estimated through a stochastic process, randomly generating values based on a randomly generated value based on a historical standard deviation. In practice, this means that one of the randomly generated price-developments was selected and used in all calculations. For the 30-year period, the development was repeated for each year. This ensures comparable results, and can be justified to say is also the most realistic way of performing the optimization. If a stakeholder was to decide on a project, it would be based on the current market, as well as market indicators, and not a known, randomly simulated future. The Monte-Carlo simulation is, however, programmed to continuously produce new scenarios, so the optimization can still be performed with this stochastic input.

3.5 Estimating price of hydrogen

The hydrogen is estimated to be imported from Sør-Varanger in Northern Norway. Sør-Varanger lies 580nm in sailing distance from Longyearbyen, and is, therefore, a short travelled energy source, considering Svalbard's location.

Estimating the price of hydrogen for the next 30 years is impossible to do without a monumental amount of uncertainty, as there exists no value chain today (Valland, 2019). The non-existence of a value chain is because there is a lack of supply and demand, meaning that the market for hydrogen is yet to be commercialized. Several feasibility studies have been conducted, and regarding production cost for compressed hydrogen, many converge towards 2-3 EUR/m^3. The distribution cost, however, is higher. Hydrogen produced through electrolysis is consistently more expensive than from gas reformation or coal gasification (Hirth et al., 2019). The electrolysis-process is more energy demanding, hence the higher costs. The studies separate between production costs and retail price.

A study done in 2019 by NCE Maritime Cleantech and partners, explores what a future hydrogen value chain in Norway may look like. Greensight, a subsidiary of Greenstat, in collaboration with Norled was in charge of the research and analysis of the Maritime Cleantech study. They have estimated a retail price of 11 EUR/kg in 2020, included distribution, for compressed hydrogen produced by electrolysis, given a long-term contract in the Oslo-area in Norway. They have also estimated a price of 7,5 EUR/kg, included distribution, for the same criteria in 2023/24. The International Renewable Energy Agency (IRENA) has also analyzed how the hydrogen price might develop and has estimated a current market price of 11,5-14,5 EUR/kg. This is assumed to be in accord with the studies performed by Greensight, as it was based on production in Norway where the electricity price is one of the world's lowest. This means a lower production cost, presumably coinciding with the lower range of IRENA's study. IRENA has also conducted an estimation of what the hydrogen-price will be in 2030; 4,4-6,1 EUR/kg. Zero Emissions Platform (ZEP) is a coalition of various stakeholders working towards zero carbon emissions in fossil power plants. ZEP is an appointed advisor for the European Commission and works with both CCS of existing fossil power plants and new, green alternatives(ZEP, 2019). ZEP estimated, in 2017, the production cost of compressed hydrogen, produced through electrolysis, to be 4-8 EUR/kg. This coincides with IRENA's estimation made the following year, of 4,4-5,5 EUR/kg, furthering affirming IRENA's estimations.

As the Greensight study, performed specifically for hydrogen production in Norway, is in accord with IRENA's report for the current hydrogen prices, it's assumed that the values of IRENA's estimates for 2030 can be used in the calculations. It's assumed a continuous decrease in price, using IRENA's 6,1 EUR/kg for 2030, decreasing towards 4,1 EUR/kg for the end of the optimization. This means that a current hydrogen-price is estimated to be 11 EUR/kg, dropping to 7,5 EUR/kg in 2024 and 6,1 EUR/kg in 2030 before ending at 4,4 EUR/kg in 2049. ZEP has predicted the production cost to be 3 EUR/kg in 2045-2050, but as it does not estimate any retail prices for this or previous time periods, no ratio between production cost and retail price can be established. It's therefore unjustifiable to assume a retail price based on ZEP's estimations, resulting in maintaining IRENA's estimations until the end of the model run.

When estimating the retail price of LNG, seasonal variations were included in the calculations. These variations are a result of a change in supply and demand over the year. For hydrogen, seasonal variations have not been included in the model. The reason is, at least for the coming years, there exists no established value chain today, meaning that the fuel is yet to be fully commercialized for this scope of use. There is no clear open market with several suppliers and consumers, hence the market prices won't be driven by changes in supply and demand for the time being. What could be argued is that the electricity prices are higher during the winter months, resulting in a more costly production of hydrogen through electrolysis. The factory assessed in this thesis is run by the power company, Varanger Kraft, operating the wind farm on Raggovidda. Since the factory produces its own electricity, it's assumed that the seasonal variation will be kept to a minimum, and therefore neglected in the calculations.

In Figure 3.8 the estimation of the retail price's development for the next 30 years is shown.

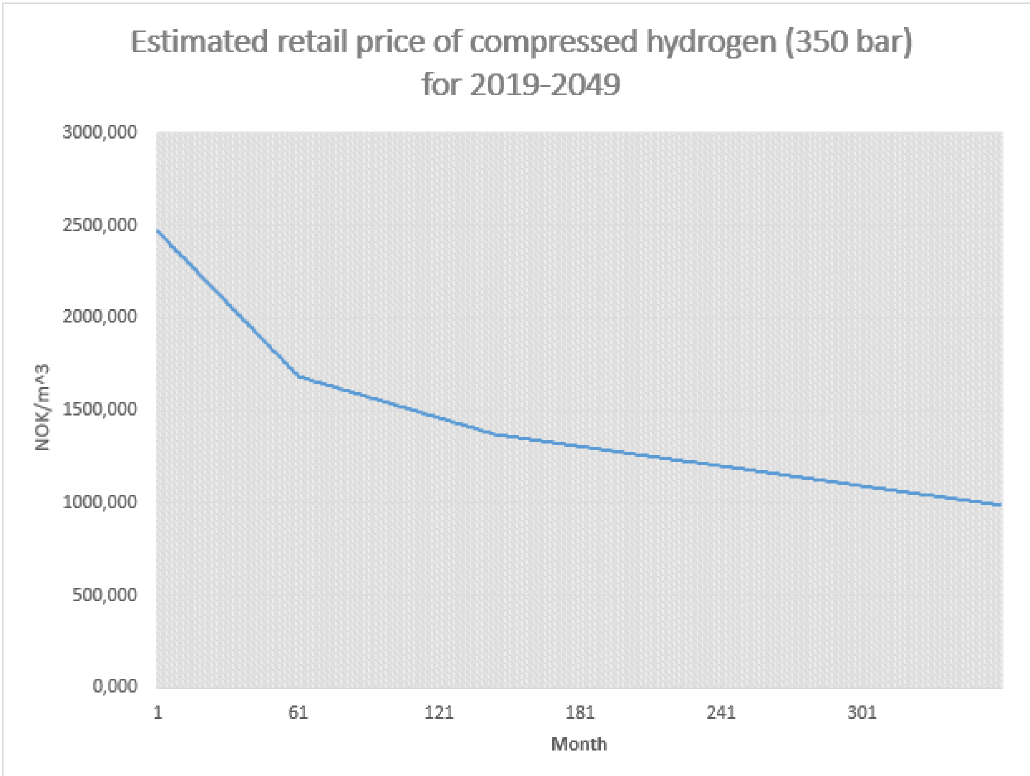

Figure 3.8: Estimation of retail price development for compressed (350 bar) hydrogen. The months in the figure represents every fifth year from 2019-2049.

3.6 Transportation of fuels

The transportation costs regarding the import of LNG is depending on the distribution center chosen. Two distribution centers have been evaluated. For LNG, import from the VOPAK terminal in Rotterdam has been considered, in addition to LNG from the Norwegian-based Snøhvit-field with distribution on Melkøya. These are both established LNG-terminals, capable of meeting Longyearbyen's LNG-demand. Both terminals are shown in Figure 3.9 marked with green circles on the map.

For the hydrogen, only one terminal is evaluated. This is located in Finnmark, Northern Norway, shown with the dark blue circle on the map in Figure 3.9. This means that the only parameters altering the total import costs for hydrogen are the choice of ship capacity, and what the retail price is when it's imported.

Figure 3.9: Assessed distribution centres for import of LNG (green) and hydrogen (blue) (eMapsWorld, 2019).

The transportation costs are a combination of a variable cost, depending on amount imported, and a fixed cost for chartering the vessel. The charterer must pay all costs related to transportation from the distribution center to Longyearbyen and back. The ships that have been assessed are actual designs but remain confidential. The ships' specifications are listed in Table 3.2. All the specifications were given by thesis contractor, Vartdal (2019), except for the DFOC for ship A, and the time/charter rate for ship B. These values were found using linear interpolation, based on MCR and ship capacity, respectively.

	Capacity [mt]	**Speed** [kn]	**Main engine MCR** [kW]	**DFOC at NCR** [mt/d]	**T/C Rate** [NOK/d]
Ship A	3000	14,0	2040	8,8	25200
Ship B	5000	13,3	2700	10,4	28300
Ship C	10000	14,0	4050	13,6	36000
Ship D	16000	16,0	7000	26,5	42000

Table 3.2: Ship specifications used for transportation of LNG (Vartdal, 2019).

The distances between the distribution centers and the port in Longyearbyen are measured to be 513nm for Melkøya and 1663nm for Rotterdam, using Google Maps. By using the ship specifications listed above, the transportation costs are calculated, and shown in Table 3.3

		Sail time [$days$]	**Charter rate** [$NOK/trip$]	**Fuel consumption** [$m^3/trip$]	[$NOK/trip$]	**Total costs** [$NOK/trip$]
Melkøya	Ship A	3,43	86 400	30,3	164 850	289 050
	Ship B	3,61	102 084	37,5	204 251	348 763
	Ship C	3,43	123 429	46,6	253 743	431 171
	Ship D	3,00	126 000	79,5	432 622	621 622
Rotterdam	Ship A	9,74	245 400	86,0	468 219	751 419
	Ship B	10,25	289 946	106,6	580 130	912 505
	Ship C	9,74	350 571	132,4	720 700	1 125 271
	Ship D	8,52	357 875	225,8	1 228 766	1 649 641

Table 3.3: LNG-transportation costs for four different ships from two distribution centres.

The same vessel specifications are adapted to the calculation of hydrogen import. As the yearly total demand for hydrogen only amounts to 7867,1m^3 from 2021 and 15734,3m^3 from 2031, only ship A and B are assessed. They sail from Sør-Varanger, a route measured to be 580 nm to Longyearbyen. The costs for the two ships are shown in Table 3.4.

	Sail time	**Charter rate**	**Fuel consumption**		**Total costs**
	[days]	*[NOK/trip]*	*[m^3/trip]*	*[NOK/trip]*	*[NOK/trip]*
Ship A	3,45	87 000	30,5	165 995	290 795
Ship B	3,63	102 793	37,8	205 669	350 891

Table 3.4: Hydrogen-transportation costs for two different ships from Sør-Varanger. The ships have the same specifications as those used for LNG. Fuel type is diesel oil.

For all transports, there are two additional costs that arise when the ship is at the port. A port fee is introduced at each destination, estimated to be 1xT/C for Rotterdam and Melkøya and 0.5xT/C for when in Longyearbyen. This means the port fee is higher for the larger vessels and thus favoring smaller vessels. In Table 3.5 the total costs are shown.

Ship A	37 800	NOK
Ship B	42 400	NOK
Ship C	54 000	NOK
Ship D	63 000	NOK

Table 3.5: Total port fees for each ship. Including both the port at the distribution center and Longyearbyen.

Another additional cost related to transport is a handling/filling cost imposed when at the distribution centre. This cost is estimated to be 1USD per MMBtu for LNG (Vartdal, 2019). Converting this to NOK/m^3, by using the same conversion factors as in Chapter 3.4.1, the handling cost is calculated to be 210.48 NOK/m^3. For hydrogen, it's assumed that the cost per kWh is equal to that of LNG. By converting the cost per cubic meter to NOK/kWh for LNG, the handling cost per cubic meter of hydrogen can be found using the property-number found in the report by Hirth et al. (2019). The calculations show that the cost for hydrogen equals to 52,4 NOK/m^3.

Other external factors affecting the fuel transportation costs can include the influencing of weather- and climate conditions. The daily fuel oil consumption (DFOC) for each ship is at normal continuous rating (NCR). NCR is used for when the ship operates at the highest efficiency, with regards to cost-effectiveness and minimal maintenance, and is what's usually stipulated in the contract. The NCR typically lies around 85%-95% of the maximum continuous rating (MCR), which is the maximum possible power output designed for the propulsion system. The ship's data used in the optimization are actual designs but are required to be confidential due to competitive reasons. The numbers are considered to be typical for LNG tankers. The NCR of the assessed ships lies between 75%-85% of the MCR, which can be considered to be a realistic number as it is not too optimistic. The weather conditions in the North Sea can be very harsh, so it is preferable to use an NCR that is not too high as it can be considered to be more realistic to the conditions it's meant to operate in. The numbers used for DFOC origins from the same contractual output used for NCR, and are used to calculate the transportation cost for each ship, depending on distribution centre.

Another natural external factor that could affect the sailing cost, due to necessary ship qualifications, is ice. Situated in the Arctic waters, Svalbard is at risk of experiencing ice in the various fjords, making it difficult to sail in the waters. If Isfjorden, the fjord of which Longyearbyen is situated, freezes over, ships with ice-class are required. These are more expensive to charter, due to higher building costs and simply as the market supply of ships is lesser than for regular LNG-transport vessels (Vartdal, 2019).

The last decade-or-so have seen a drastic decrease in sea ice in Isfjorden, making navigability easy. The average sea ice thickness has declined both in regards to a seasonal and spatial extent. As seen in Figure 3.10 the western part of Spitsbergen was completely ice-free on March 13.th, 2019. This was the day with the highest recorded sea ice extent in the Arctic so far in 2019. The trend is clear, and as explained by Vartdal (2019), considering ice class when investigating ships that only are meant to visit Longyearbyen is not necessary. As it has not been needed for many years, and the trend is that the sea ice-level is decreasing, ice class has not been included in the optimization model. Table 3.6 shows that the top four lowest satellite recordings of Arctic sea ice, based on square kilometres, for the last 40 years is recorded in the previous four years(Gautier, 2019).

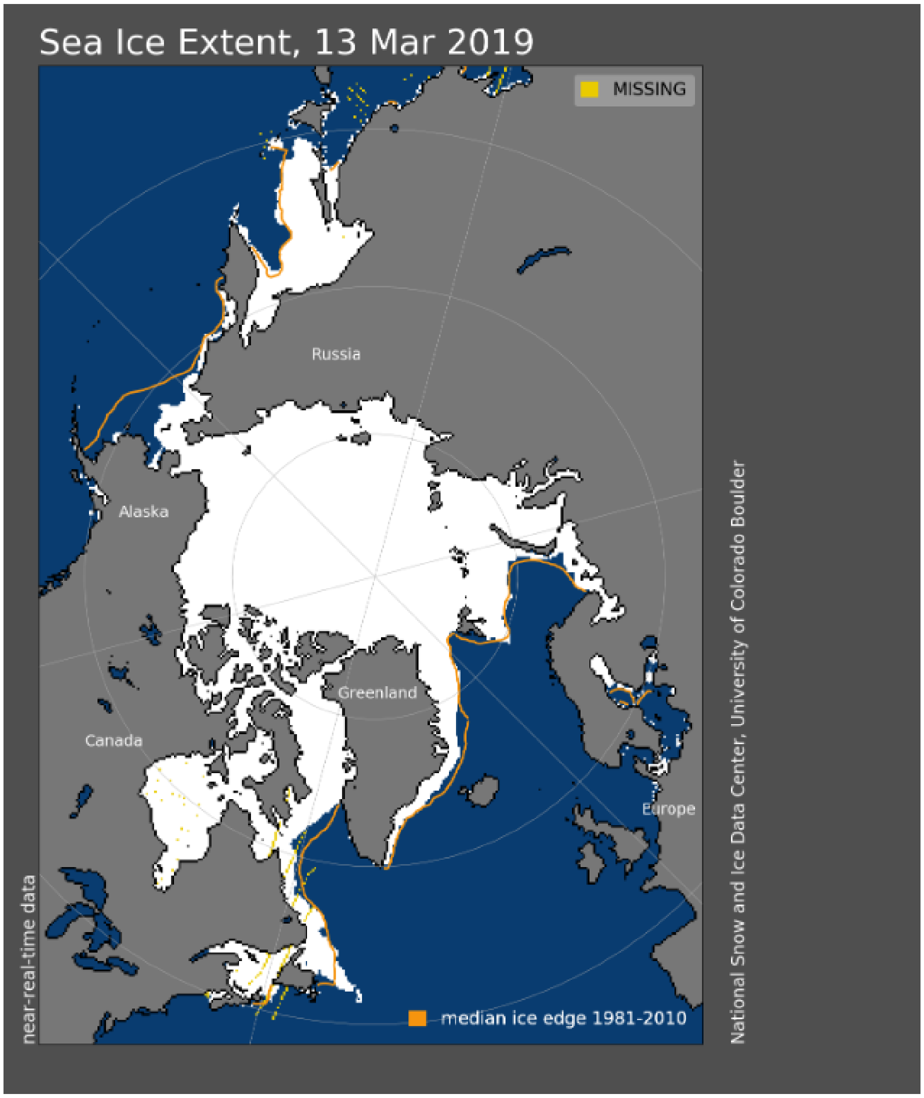

Figure 3.10: An illustration of the sea ice's extent in the Arctic on March 13th. 2019, when the ice had reached its maximum yearly extent (Gautier, 2019).

Rank	Year	Millions of square kilometers	Date
1	2017	14.41	March 7.
2	2018	14.48	March 17.
3	2016	14.51	March 23.
4	2015	14.52	February 25.

Table 3.6: Top four lowest satellite recordings of Arctic sea ice in sq. km, since 1979 (Gautier, 2019).

3.7 Storage facilities

There are three parameters connected with the storage facility. The building cost of building one cubic meter of storage is set to 26 749 NOK and is assumed to be linear(Hovden, 2018). The cost is primarily due to the procurement of steel and insulation. The building cost is assumed to equal for both LNG and hydrogen, as told by the thesis contractor, Vartdal. The storage facility for LNG is shown in Figure 2.11. The storage facility for hydrogen is projected to be in direct collaboration with the event ship. Figure 3.11 shows an illustration of what this could look like. The storage facility is directly connected to the event ships' main base, making fuelling effective.

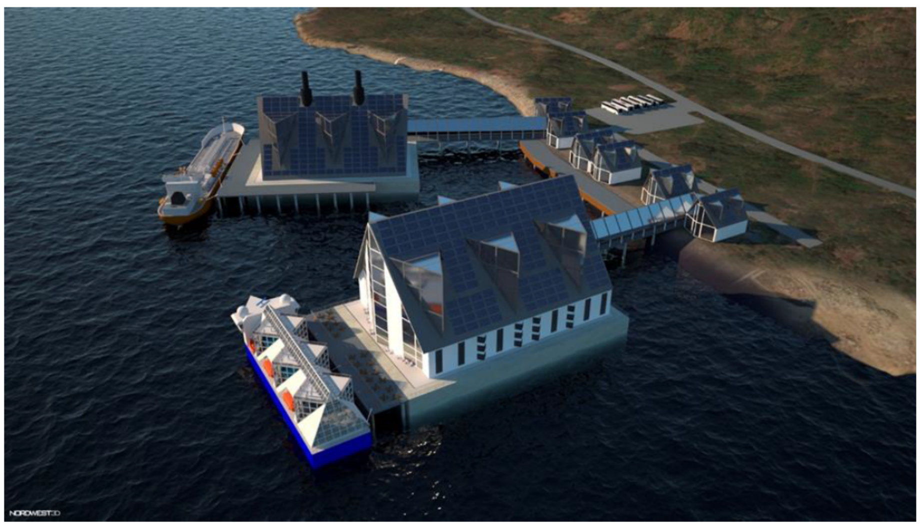

Figure 3.11: An illustration of what a potential storage facility, in combination with the event ship, could look like (Vartdal, 2019).

The other parameter regarding the storage facility is the availability-limit. For the LNG, this amounts to 1000m^3. This is equivalent to approximately one month's worth of land-based energy for the winter months. As written in Chapter 2.3.1 due to the exposed location of Longyearbyen, the community relies on a safe and steady supply of electricity and heat, hence the availability-requirement. For the hydrogen, the limit is set to one summer month's worth of consumption. The safety limits are to account for delays in import, sudden over-consumption or leakage.

Each facility has an initial value prescribed. For the LNG, three times the availability-limit, meaning 3000m^3, is given. For the hydrogen, one summer month's worth of hydrogen is given. Since the simulation starts in January, the initial value will, therefore, cover almost two winter months.

Chapter 4

Method

In this chapter, the methods used to find the final solutions are described. A step-by-step walk-through of how the mathematical model was formulated is presented, followed by a description of the main functions and algorithms used in the computational study.

4.1 Model formulation

The objective of this thesis is to optimize the storage capacity in Longyearbyen and the import of fuels, depending on cost. The minimization problem is formulated to minimize the costs over a certain time period, where several feasible solutions will be presented to compare the economics and environmental aspect of the findings. Profit has not been calculated as the premise for the model is that all potential demand is to be met.

The optimization model created is a Mixed Integer Linear Programming (MIP)-problem. It uses both continuous variables, as well as integer (binary constraint). The model is deterministic, with the possibility for stochastic input to be utilized. The input for the computed scenarios uses the same input-basis to justifiably compare them.

4.1.1 First step: Generic optimization model

The first step of the optimization is to create the generic model, useable for both investigated energy carriers. The generic model introduces all necessary sets, parameters, constants and variables for both energy carriers. In the mathematical formulation, the objective function will apply to both energy carriers. The objective function is subject to a set of constraints that are made applicable for both energy carriers but require additional clarification in the form of deriving formulas and additional constraints. These will be added in Chapter 4.1.2 and 4.1.3, when adapting the model to a specific energy carrier.

Sets

D	Distribution centers, indexed by d
S	Ships, indexed by s
T	Time periods, indexed by t
E	Energy carriers, indexed by e

The sets implemented are finite, and is used to describe a certain amount/set of elements. The sets are all indexed by a letter used in the introduced parameters, constant, and decision variables to denote a specific quantity or identify a specified element investigated. The sets introduced all impact the solution depending on their assigned value, but they are not to be mixed with the decision variables as they are not a quantifiable decision being made (Hillier and Lieberman, 2010). The optimization-model will be run separately for each energy carrier, e, which is why the element is equal to "LNG" and "H_2" in the second and third step of the optimization model, as it doesn't necessarily have to be a numerical value.

Parameters

C_e^B	Building cost of storage facility for energy carrier, e	[NOK/m³]
C_{et}^D	Distribution cost of energy carrier, e, at time period, t	[NOK/m³]
C_{eds}^T	Transportation cost of energy carrier, e, from distribution center, d, for ship, s	[NOK/m³]
F_t^L	Consumption of energy for land-based activity in time period, t	[kWh]
F_{et}^M	Predicted consumption of energy carrier, e, for marine-based activity in time period, t	[m³]
F_{et}^T	Total consumption of energy carrier, e, in time period, t	[m³]
A_e	Availability-requirement for energy carrier, e	[m³]
I_e	Initial storage of energy carrier, e	[m³]
K_{es}	Capacity of energy carrier, e, on ship, s	[m³]
q_{et}	Quantity of energy carrier, e, in storage tank in time period, t	[m³]

The parameters introduced are values for various combinations of the sets, which is decided based on findings from data research, and requirements from the thesis' contractor. The value and basis of the various parameters are explained in Chapter 3.

Constants

J_e	Energy-conversion factor for energy carrier, e	[kWh/m³]

This constant is used to convert the land-based energy consumption into volumes of fuel so that the calculations are performed for equal units.

Variables

z_e	Tank storage capacity at Longyearbyen for energy carrier, e	[m³]
x_{esdt}	Amount of energy carrier, e, imported with ship, s, from distribution center, d, in time period, t	[m³]
σ_{esdt}	$\begin{cases} = 1, if\ energy\ carrier, e, is\ imported\ with\ ship, s, \\ \quad from\ distribution\ centre, d, in\ time\ period, t \\ = 0, otherwise \end{cases}$	

These are the decision variables of which the whole problem is optimizing for. The variables are what the computer will solve to find the optimal decisions to make; hence the name decision variables.

Objective function:

$$min\, z = \sum_{e\in E} C_e^B z_e + \sum_{e\in E}\sum_{t\in T}\sum_{d\in D}\sum_{s\in S} C_{et}^D x_{esdt} + \sum_{e\in E}\sum_{t\in T}\sum_{d\in D}\sum_{s\in S} C_{eds}^T x_{esdt} + \sum_{e\in E}\sum_{t\in T}\sum_{d\in D}\sum_{s\in S} C_{eds}^T \sigma_{esdt} \tag{4.1}$$

Subject to:

$$\sum_{d\in D} x_{esdt} \leq \sum_{d\in D} K_{es}\sigma_{esdt} \qquad e\in E,\ s\in S,\ t\in T \tag{4.2}$$

$$M\sigma_{esdt} \geq x_{esdt} \qquad e\in E, s\in S, d\in D, t\in T \tag{4.3}$$

$$q_{e,1} = I_e \qquad e\in E \tag{4.4}$$

$$q_{e,t+1} = q_{et} + \sum_{s \in S} \sum_{d \in D} x_{esdt} - F_{et}^{T} \qquad e \in E, \; t = \{1,2,\ldots,T-1\} \tag{4.5}$$

$$q_{et} \geq A_e \qquad e \in T, \; t \in T \tag{4.6}$$

$$q_{et} + \sum_{s \in S} \sum_{d \in D} x_{esdt} \leq z_e \qquad e \in E, t \in T \tag{4.7}$$

$$\sum_{t \in T} \sum_{d \in D} \sum_{s \in S} x_{esdt} - \sum_{t \in T} F_{et}^{T} = A_e \qquad e \in E \tag{4.8}$$

$$x_{esdt} \geq 0 \qquad e \in E, s \in S, \; d \in D, t \in T \tag{4.9}$$

$$z_e \geq 0 \qquad e \in E \tag{4.10}$$

$$q_{et} \geq 0 \qquad e \in E, t \in T \tag{4.11}$$

$$\sigma_{esdt} \in \{0, 1\} \qquad e \in E, s \in S, \; d \in D, t \in T \tag{4.12}$$

The objective function, Equation 4.1 decides what is being minimized; in this case the costs. The first term minimizes the building costs of the storage facility, based on a cost per cubic metre of storage. The next three terms are for the purchase and import of the energy carrier. The first of the three is a cost for handling and filling, that depends on the amount that is being purchased. The second term is the actual sales cost of the fuel, while the last term is a fixed cost for transportation. This depends on the distance from the distribution centre to the storage facility and includes fuel consumption, time charter costs, and port fees in both ports. The objective of the function is in other words to decide the decision variables that gives the optimal relation between cost of storage capacity, and -import of fuel.

The mathematical model is meant to behave like the actual world, so a set of requirements and limitations are needed to make sure that delivers real results. A set of constraints is introduced, restricting the feasible region of the solution. Equation 4.2 ensures that the amount imported on a ship (LHS), for all distribution centres, energy carriers, and time periods, is not exceeding the ship's capacity (RHS). This means e.g. that if the calculations decide on a certain amount of imported energy carrier for a specific time period that exceeds a ship's capacity, either several ships or a ship with bigger capacity, is needed.

In Equation 4.3 a Big M is introduced. The Big M-method is a way of solving LP-problems forcing a certain relation between variables. The M represents a huge positive number, and can be used for -greater/less than or equal to- constraints (Hillier and Lieberman, 2010). In this case, the Big M is used to ensure that if the x, meaning any amount of energy carrier imported on a specific ship from a specific destination in a specific time period, has a value greater than zero, the corresponding binary value shall be 1. This ensures that, in addition to the variable costs that will be added to the objective function, the fixed cost for each transportation is included. A disadvantage with the Big M method is deciding how big the M should be, as an enormous number could cause numerical errors when computing. In addition to risking numerical errors, the computing time can increase equally. The M needs to be a number so large that any possible number generated on the RHS is lower or equal to the LHS. In this case, it suffices to use an M equal to largest ship capacity, as the x_{esdt} will never be bigger than the largest capacity due to Equation 4.2.

Equation 4.4 makes sure that the storage level in time period 1 equals the initial storage; a parameter set by the model operator. For each energy carrier, there is an availability-requirement to ensure supply of power to the community, and fuel for the marine actors. This constraint is introduced in Equation 4.6, ensuring that the amount of energy carrier in the storage facility will always be above the availability-requirement for all individual time periods.

Equation 4.5 is introduced to monitor the stored amount of energy carrier in the storage facility. It says that the amount of stored fuel in the coming time period equals what was stored at the beginning of the assessed time period, in addition to what may have been imported and consumed in the period. This constraint applies to all time periods t, except for the last element in the set. This is because of the notation "t+1" in the first term of the equation, meaning if the value for t ran to the final element in T, it would end up in T+1; hence, out of the range. Equation 4.7 ensures that it will not be imported more than the capacity of the storage level can hold, in addition to what was already stored.

To ensure that there is no superfluous amount of energy carrier imported after running the model through all time periods, Equation 4.8 is introduced. This forces the storage level to end up as the same amount as the availability requirement is, after all, T periods.

Equation 4.9, 4.10 and 4.11 are non-negativity constraints, while Equation 4.12 is a binary constraint, stating that a ship either imports an energy carrier from a certain distribution centre for a certain time period, or not. The first three constraints are introduced due to it being physically impossible for them to be negative when adapted in the real world. The last variable is needed for calculating the fixed costs for transportation and is binary since a transport either happens or not.

4.1.2 Second step: Introducing LNG

The second step to the optimization model is the introduction of LNG. This requires an additional constraint, in addition to creating a mathematical definition of a parameter used in the generic model. Since the land-based energy consumption is based on LNG, the total consumption of LNG will include both this and the demand from marine activity. The periodic amount of LNG consumed is specified in Equation 4.13. The land-based energy consumption is divided on an energy conversion factor, converting the energy demand [kWh] to a volume-based demand for LNG [m^3]. This is added to the demand from the marine actors, giving a total consumption that is measured in cubic metres of LNG. As seen in Equation 4.5 the amount of LNG in the storage facility is calculated by subtracting the consumption from the amount already in the storage, in addition to what may be imported. After calculating the total consumption of LNG in Equation 4.13, the storage level will now be correct for all time periods, t. Equation 4.8 is also dependent on this definition to prevent superfluous import.

$$F_{et}^{T} = \left(\frac{F_t^L}{J_e} + F_{et}^M\right) \qquad e = LNG, \; t \in T \tag{4.13}$$

4.1.3 Third step: Introducing hydrogen

The third step of the optimization is the introduction of hydrogen. As for LNG, there is a need to specify the total consumption of hydrogen so that Equation 4.5 and 4.8 gets the correct values for consumption. For hydrogen, the only predicted consumption is that of the evaluated local marine passenger vessel. The total consumption for hydrogen, therefore, equals the marine activity demand, as defined in Equation 4.14.

$$F_{et}^{T} = F_{et}^{M} \qquad e = H_2\,,\ t \in T \tag{4.14}$$

4.2 Computational study

This section will explain the computational formulation of the optimization model. Microsoft Excel and MATLAB were used to complete the calculations. The generic MATLAB-code can be found in Appendix A.

4.2.1 Implementation

The mathematical model has been written in MATLAB; a mathematical computational program using its own scripting language based on the programming language C. It has been created two similar models as the optimization of the different energy carriers are performed individually. Microsoft Excel, a spreadsheet-based computational program, has also been used for the calculation of the input data, meaning the parameters. By pre-processing the values for the parameters, the amount of calculations performed in the MATLAB-code is therefore reduced. The data in the spreadsheets are directly retrieved by the MATLAB-code, simplifying the process of modifying the parameters without needing to rewrite the code. Microsoft Excel has also been used in the post-processing of the results.

All computations were performed on a HUAWEI MateBook D Signature Edition, with an Intel ©Core ®i5-8250U CPU @1.50GHz 1.80GHz and 8,00 GB RAM. The operating system installed is Windows 10 Home.

Two separate, yet similar, scripts were used in the calculations. One for the 52-week model runs, and one for the 360-month model runs. The scripts are almost identical, apart from some input data in the script adjusting the parameters to the time steps evaluated. The reason the files have been separated is to simplify and fail-safe modifications made through re-trials. This lessens the modifications needed in the script, reducing it to deciding on which/how many ships are being included, and for what scenario the test is run.

Most input parameters are specified in accompanying excel-documents. A separate .xlsx-file has been created for each scenario and year tested. The .xlsx-files are comprised of the LNG consumption for the given time period, the LNG retail price for the given time period, in addition to the transportation and handling cost. The point of dividing the model runs in this many pieces was to simplify the process of re-testing for third parties.

The generation of LNG-prices is created in a stochastic process, using the Monte Carlo simulation. The model input is, however, deterministic to ensure equal assessment basis.

4.2.2 Modelling the problem in MATLAB

The MATLAB algorithm chosen to run the optimization was the function 'fmincon'. In the early process of the thesis, the optimization model was non-linear, resulting in the choice of fmincon. This aims to find the minimum of a nonlinear multivariable function, subject to a certain set of constraints. As the project developed, the mathematical model was linearized to reduce the complexity of the problem. The algorithms applied in MATLAB remained unchanged, but the input variables and function setup were adjusted.

The setup of the fmincon-function is shown in Equation 4.15

$$\min_{x} f(x) \text{ such that } \begin{cases} c(x) \leq 0 \\ ceq(x) = 0 \\ A \cdot x \leq b \\ Aeq \cdot x = beq \\ lb \leq x \leq ub, \end{cases} \tag{4.15}$$

f(x) is the function of which the decision variables are to be decided. "x" in this case is a vector containing the value for the two decision-variables z, storage facility, and x, the amount imported in time period, t.

’c’ and ’ceq’ are functions used for the nonlinear constraints, returning vectors to be used in the solver. ’b’ and ’beq’ are real vectors used for setting the limits of the inequality- and equality constraints, respectively. The two matrices ’A’ and ’Aeq’ represent the linear inequality- and equality constraints. No linear constraints have been used in the computational model, setting beq=[] and Aeq=[]. A is a MxN-matrix, where M is the number of inequalities, and N represent the number of elements in x0, meaning the number of variables. The A-matrix encodes the inequality-constraints, and as seen in Equation 4.15 they are multiplied with the column vector x, constrained by the b-column vector.

The A-matrix used is defined in a function at the end of the script. The A-matrix is encoded to be a block diagonal-matrix to easily compile the various parameters and constraints in one matrix. The structure of the matrix can be seen in Equation 4.16. The setup of the A-matrix and b-vector is found in the script, and consist of three constraints. A non-negativity constraint, a ship capacity constraint, and a storage-level constraint.

$$\mathbf{A} = \begin{bmatrix} A1 & 0 & 0 & 0 \\ 0 & A2 & 0 & 0 \\ 0 & 0 & \ddots & 0 \\ 0 & 0 & 0 & AN \end{bmatrix} \tag{4.16}$$

The last to be defined in the problem specifications is the lower bound, ’lb’, and upper bound, ’ub’. These have been defined as vectors, where the lb is a vector of zeros, and the ub is a vector consisting of a number above the highest ship capacity. The vector is (n+1)-elements long, where n is defined as the multiplication of all sets.

The syntax for the minimization-problem is given in Equation 4.17. The fmincon-function is used, while the objective function, ’fun’, is a vector for the decision variables dependant on building cost, fuel price and transportation costs.

$$x = fmincon(fun, x0, A, b, Aeq, beq, lb, ub, nonlcon, options) \tag{4.17}$$

’X0’ is an array that represents the initial point of which the solver will start it’s exploration. The X0 is an initial guess of values for the decision variables that lies within the feasible area. In the script, the initial point is defined as X0 = [z0; x0], subject to the capacity constraints. z0 represents the storage capacity, while x0 is the amount of imported fuel.

Moving on in the syntax, A, b, Aeq, beq, lb and ub is already described. 'nonlcon' is a function handle, a data type that stores an association to a function (MATLAB, 2019). In this case, it's used to return the two arrays c and ceq to the fmincon-function, based on the function for the fixed, non-linear transportation cost.

'options' contains the algorithms chosen to optimize the problem, in addition to a set of tolerances set to decide the steps used in the optimization. Three global search algorithms have been chosen in this script; 'interior-point', 'sqp', and 'active-set'. The interior-point algorithm is the default, and recommended to be used first (MATLAB2, 2019). This algorithm is a large-scale algorithm can handle problems of all sizes and can recover from unfeasible solutions. A large-scale algorithm does not operate with full matrices but uses sparse linear algebra when possible to reduce computational complexity. The sqp-algorithm is then used to further investigate the problem. This satisfies all bounds at all iterations, as for the interior-point algorithm, but differs from the interior-point algorithm as this is not a large-scale algorithm. Finally, the active-set algorithm is applied to induce a quick search of a large feasibility area. The end product for each algorithm is used as the starting point in the following algorithm.

Finally, the optimization is run, as shown in Equation 4.18. The 'gs' refers to the global search algorithms, while 'problem' is the optimization as defined in the fmincon-function. 'X' contains the two decision variables, while 'fval' represents the value of the objective function for a solution.

$$[X, fval, exitflag, output, solutions] = run(gs, problem) \tag{4.18}$$

The fval is found by transposing the f-function and multiplying with the decision variables to find the costs for storage capacity and import. The fixed transportation cost is also added, by making a binary number for if fuel is imported with a specific ship, in a given time period. The vector for transportation-cost is multiplied with the transposed x-vectors divided by each other. To avoid a computational error caused by having dividing on zero, the x in the denominator is added to a small number of 0,001, negligible to the final solution. This ensures no computational errors in time periods where no transportation occurs. This sequence of actions cause the model to be non-linear, hence the 'nonlcon' in the syntax.

'exitflag' is an integer number defining the reason the fmincon-function stopped searching (MATLAB2, 2019). The integer that returns represents a specific error for a specific search algorithm. 'output' gives information on how the optimization has commenced and returns the information as text.

A set of error messages depending on the model run has been created to reveal potential errors in the process. Confirmation-messages regarding various conditions that have been met is also created. Verification of the final obtained solution is also created to ensure that the local minimum found in the last search algorithm equals that of the global minimum.

Finally, the results are plotted in graphs, in addition to interesting values displayed as text.

Chapter 5

Results

For model runs including all four ships, there is a computational error as it delivers poorer results than what the model runs for a single ship with the same premises does. Model runs including all four ships is shown for the 52-week model runs in Scenario 1, to display the error in question.

5.1 LNG

The optimization of LNG-import and facility-construction has been conducted for two different scenarios, as shown in Table 2.3. The first scenario has a two-step increase in LNG demand; first in 2021, and then in 2031. In Section 5.1.1 the output generated for these conditions is presented. The second scenario experiences a three-step increase in LNG demand, namely in 2021, 2031 and 2034. The results found in Section 5.1.2 show the optimal solutions regarding storage facility and transportation costs for ships using Rotterdam as the distribution terminal.

5.1.1 Scenario 1

As seen in Table 5.1 and 5.2 the storage capacities seem to converge towards a range between 8 000m^3 to 10 000m^3. The solution using ship B is the cheapest option for transport from Rotterdam, while ship A is the cheapest from Melkøya. These are model runs based on the predicted LNG-demand in the year 2021.

Rotterdam, 2021

Ship(s) evaluated	Storage facility: **Size** *[m^3]*	Storage facility: **Tot. build cost** *[MNOK]*	Transportation (per year): **Charter cost** *[MNOK]*	Transportation (per year): **Cost of transp. and import** *[MNOK]*	Transportation (per year): **No. of trips**	**Lifetime cost** *[MNOK]*
All ships	7644	204	23,5	53	14*	1794
Ship A	7942	212	9,2	39	12	1378
Ship B	**8447**	**226**	**4,6**	**35**	**5**	**1288**
Ship C	9463	253	3,4	35	3	1305
Ship D	8956	240	5,0	36	3	1319
avg	*8702*		*only uses ship A			

Table 5.1: Scenario 1: Output for import of LNG from Rotterdam, 2021

Melkøya, 2021

Ship(s) evaluated	Storage facility: **Size** *[m^3]*	Storage facility: **Tot. build cost** *[MNOK]*	Transportation (per year): **Charter cost** *[MNOK]*	Transportation (per year): **Cost of transp. and import** *[MNOK]*	Transportation (per year): **No. of trips**	**Lifetime cost** *[MNOK]*
All ships	2698	72	7,3	40	28*	1270
Ship A	**8447**	**226**	**1,8**	**33**	**7**	**1209**
Ship B	8911	238	1,3	34	4	1244
Ship C	8956	240	1,9	32	5	1214
Ship D	8956	240	2,8	33	5	1227
avg	*8818*		*only uses ship A			

Table 5.2: Scenario 1: Output for import of LNG from Melkøya, 2021

Figure 5.1 and 5.2 shows how the import of LNG commences for the entire model run. As seen, most of the imports are conducted during the summer months, as this is when the LNG price is the lowest. The crossing between importing large amounts when the price is low, combined with building bigger storage facilities is the point of which the solution is optimal.

Rotterdam, 2021

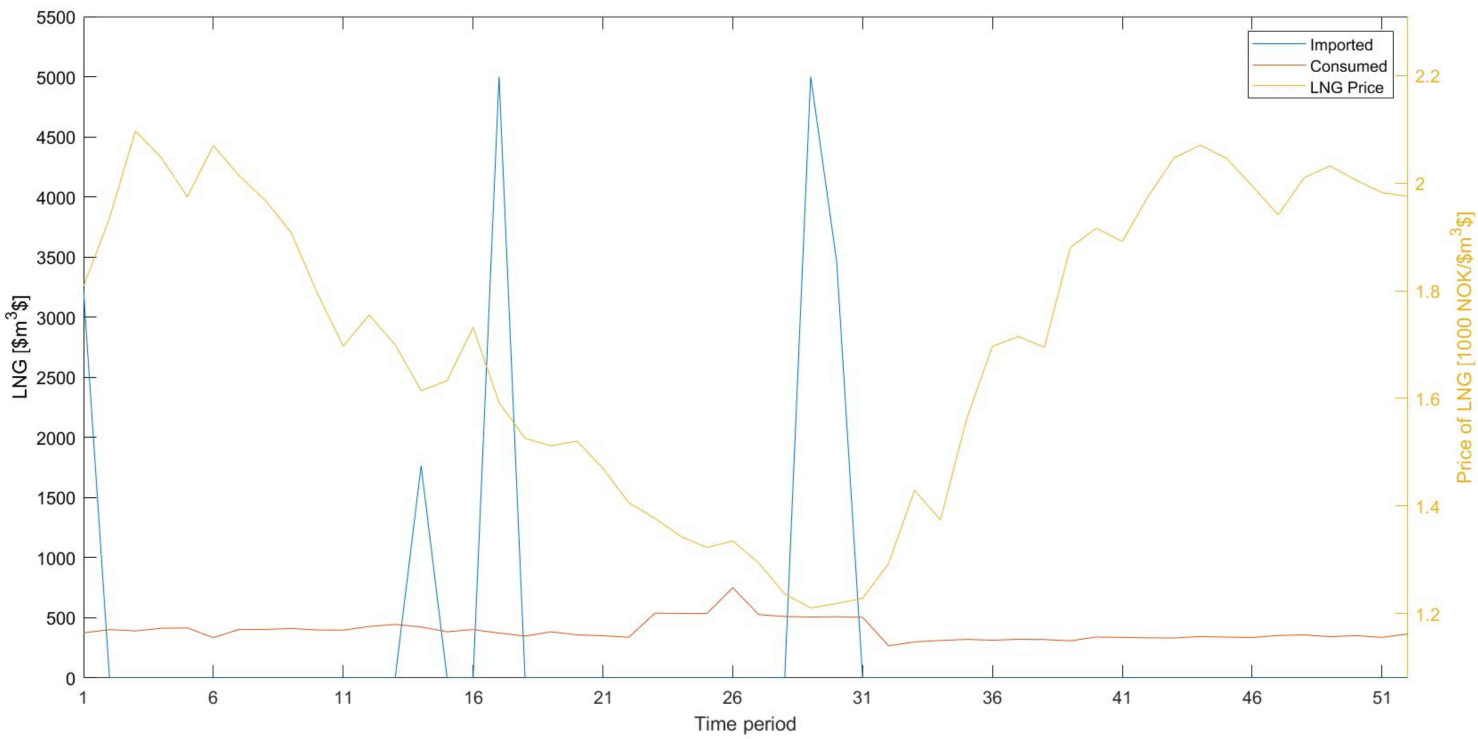

Figure 5.1: Import, consumption and price development in year 2021, for ship B sailing from Rotterdam.

Melkøya, 2021

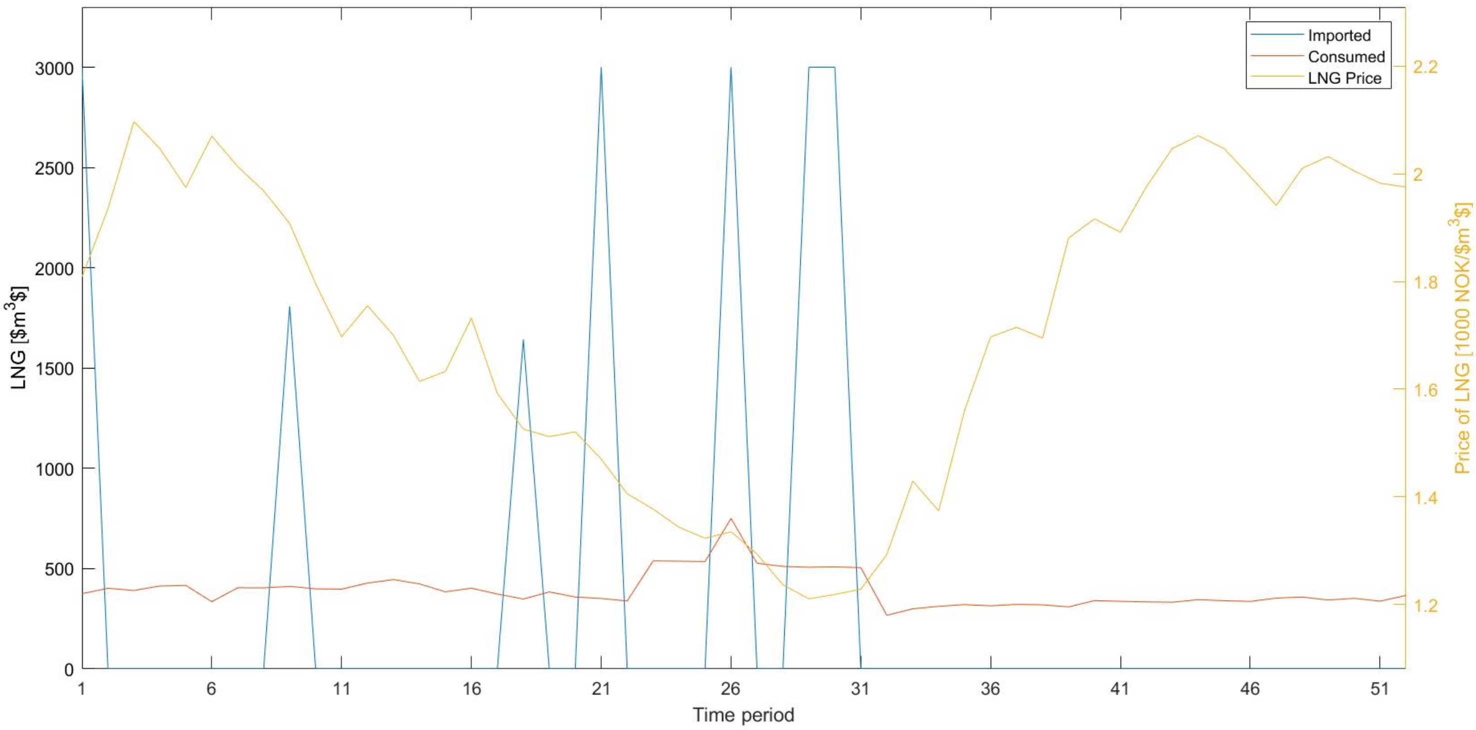

Figure 5.2: Import, consumption and price development in year 2021, for ship A sailing from Melkøya.

Table 5.3 and 5.4 shows that the storage capacities seem to converge towards a range between 9 000m^3 to 11 000m^3 for ships deploying from both distribution terminals. Ship C used from Melkøya deviates from this, with a storage capacity of 18 619m^3, resulting in the very high lifetime cost. The solution using ship B is again the cheapest option for transport from Rotterdam, while ship A is the cheapest from Melkøya. These are model runs based on the predicted LNG-demand in the year 2024.

Rotterdam, 2024

Ship(s) evaluated	Storage facility		Transportation (per year)			Lifetime cost
	Size	**Tot. build cost**	**Charter cost**	**Cost of transp. and import**	**No. of trips**	
	[m^3]	*[MNOK]*	*[MNOK]*	*[MNOK]*		*[MNOK]*
All ships	2625	70	21,4	61	27*	1891
Ship A	8993	241	8,4	45	11	1582
Ship B	**9693**	**259**	**4,6**	**43**	**5**	**1540**
Ship C	10898	291	4,6	44	4	1610
Ship D	10731	287	5,0	43	3	1591
avg	*10079*		*only uses ship A			

Table 5.3: Scenario 1: Output for import of LNG from Rotterdam, 2024

Melkøya, 2024

Ship(s) evaluated	Storage facility		Transportation (per year)			Lifetime cost
	Size	**Tot. build cost**	**Charter cost**	**Cost of transp. and import**	**No. of trips**	
	[m^3]	*[MNOK]*	*[MNOK]*	*[MNOK]*		*[MNOK]*
All ships	2625	70	7,6	61	29*	1477
Ship A	**8993**	**241**	**2,6**	**39**	**10**	**1412**
Ship B	9693	259	1,9	39	6	1423
Ship C	18619	498	1,6	43	4	1777
Ship D	10397	278	2,8	40	5	1476
avg	*11926*		*only uses ship A			

Table 5.4: Scenario 1: Output for import of LNG from Melkøya, 2024

Figure 5.3 and 5.4 shows how the import of LNG commences for the entire model run. As seen, most of the imports are conducted during the summer months, as this is when the LNG price is the lowest. The crossing between importing large amounts when the price is low, combined with building bigger storage facilities is the point of which the solution is optimal.

Rotterdam, 2024

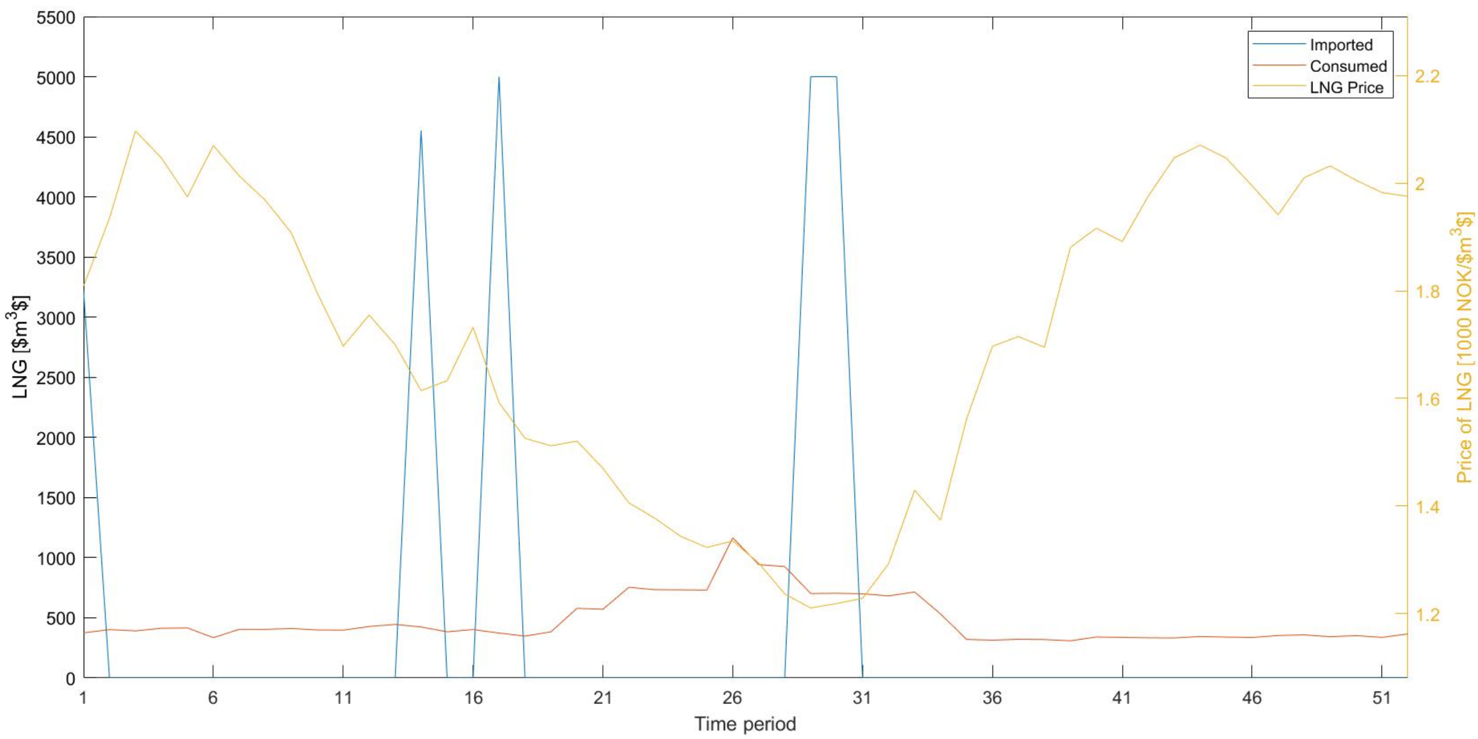

Figure 5.3: Import, consumption and price development in year 2024, for ship B sailing from Rotterdam.

Melkøya, 2024

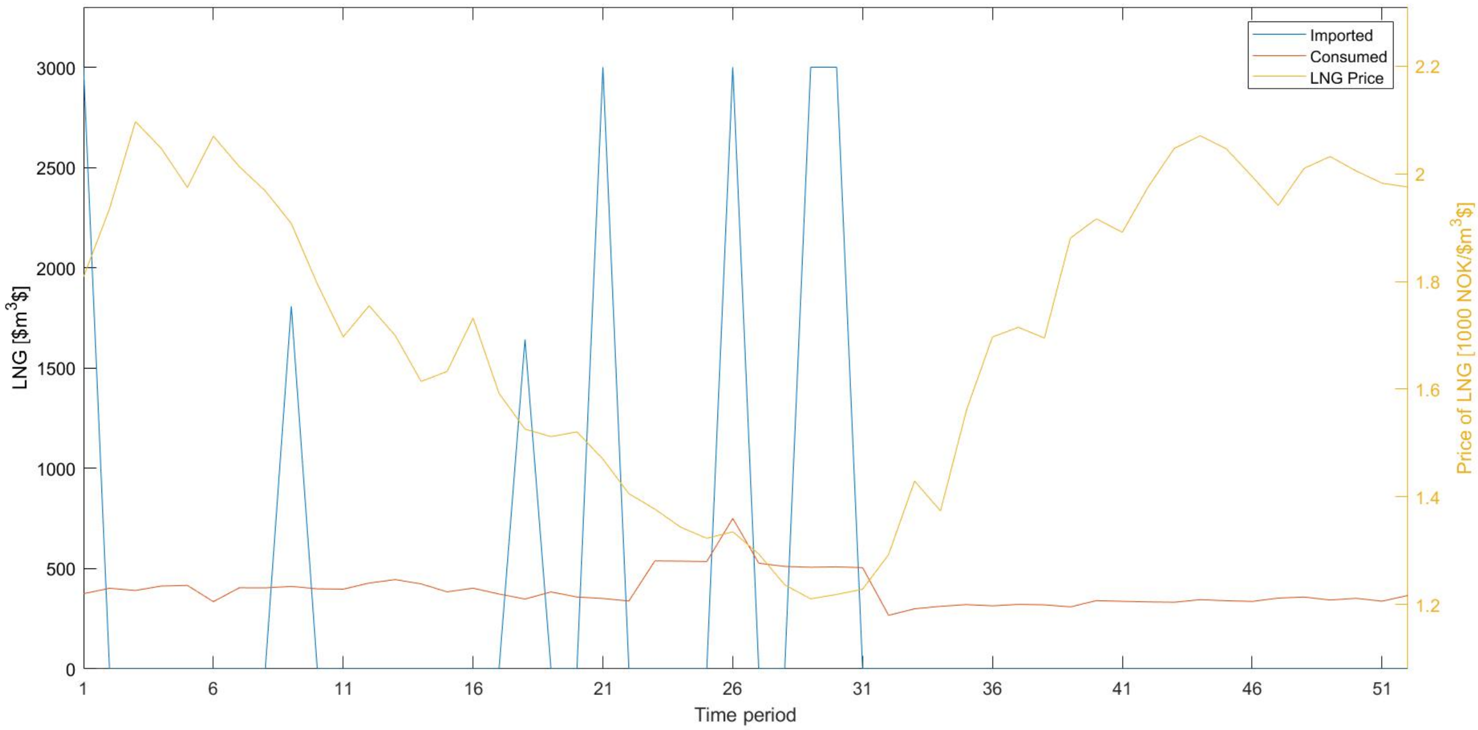

Figure 5.4: Import, consumption and price development in year 2024, for ship A sailing from Melkøya.

5.1.2 Scenario 2

Scenario 2 has an optimistic view on how much the LNG-demand will increase for marine actors bunkering in Longyearbyen. 12 model runs have been completed; one for each of the four ships in year 2021, 2031 and 2034. These three years are selected due to an expected increase in demand starting then.

Rotterdam, 2021

The first model runs are done for the estimated demand in year 2021. As seen in Table 5.5, the size of the storage facility converges towards a range of 12 500m^3 to 14 200m^3. This is an increase of around 40-50% of the estimated size-ranges for the same year in scenario 1. The total LNG demand in year 2021 is estimated to be 33 700m^3, with its biggest concentration in demand around the summer months.

The table shows that the lowest lifetime costs are for when ship D is selected, with a final storage capacity of 14 205m^3.

Ship(s) evaluated	Storage facility		Transportation (per year)			
	Size	**Tot. build cost**	**Charter cost**	**Cost of transp. and import**	**No. of trips**	**Lifetime cost**
	[m^3]	*[MNOK]*	*[MNOK]*	*[MNOK]*		*[MNOK]*
Ship A	12653	339	13	64	17	2254
Ship B	14205	380	6,5	62	7	2250
Ship C	13421	359	8	60	7	2173
Ship D	**14205**	**380**	**5,0**	**58**	**3**	**2122**
avg	*13621*					

Table 5.5: Scenario 2: Output for import of LNG from Rotterdam, 2021

Rotterdam, 2031

In year 2031, a total demand of 105 500m^3 is predicted, with its main demand during the summer months. Table 5.6 shows the output from the four model runs. The spread in the size of the storage capacity is bigger than for previous runs, with an average of ca.29 000m^3. The solution with the lowest lifetime cost is when using ship D, which results in a storage capacity of only around 20 200m^3. As seen, both the storage capacities and the total lifetime cost for all model runs have increased drastically from year 2021.

Ship(s) evaluated	Storage facility		Transportation (per year)			
	Size	**Tot. build cost**	**Charter cost**	**Cost of transp. and import**	**No. of trips**	**Lifetime cost**
	[m^3]	*[MNOK]*	*[MNOK]*	*[MNOK]*		*[MNOK]*
Ship A	29873	799	26,7	219	35	7387
Ship B	29666	794	19,5	192	20	6545
Ship C	35875	960	14,9	182	13	6421
Ship D	**20171**	**540**	**15,1**	**192**	**9**	**6296**
avg	*28896*					

Table 5.6: Scenario 2: Output for import of LNG from Rotterdam, 2031

Rotterdam, 2034

For the simulation of the demand in year 2034, ship A did not manage to deliver the required amount of LNG throughout the year. This is listed as not available (N/A) in the output table.

A total demand of 167 000m^3 is predicted in year 2034, with additional marine actors entering the market. The four model runs returns only three sets of output, where the output for ship B differs very for that of ship C and D. The model run for ship C finds a final storage capacity of just 13 373m^3. This is because the demand is so high that the ship only just reaches transporting the weekly consumption during the summer months, meaning the storage level is kept to a minimum. Of the 33 sailings for ship C, only one is not fully loaded.

The output shows that ship B is the ship of which the lowest lifetime costs occurs. All lifetime costs for year 2034 lies around 40% higher that than for the optimal solution in year 2031.

Ship(s) evaluated	Storage facility		Transportation (per year)			
	Size *[m^3]*	**Tot. build cost** *[MNOK]*	**Charter cost** *[MNOK]*	**Cost of transp. and import** *[MNOK]*	**No. of trips**	**Lifetime cost** *[MNOK]*
Ship A	N/A	N/A	N/A	N/A	N/A	N/A
Ship B	**13373**	**358**	**30,6**	**319**	**33**	**9932**
Ship C	45728	1223	19,4	294	17	10049
Ship D	55728	1491	20,1	288	12	10119
avg	*38276*					

Table 5.7: Scenario 2: Output for import of LNG from Rotterdam, 2034

5.2 Hydrogen

The demand for hydrogen is predicted to happen in two steps. First in year 2021, and the second in 2031. Three time-intervals have been investigated in the optimization of storage and import of hydrogen. The predicted changes in demand for hydrogen in year 2021 and 2031 lays the premises for the first two model runs. The final model run is performed for a 30-year period, starting in 2019.

5.2.1 Year 2021

In Table 5.8 the output from the model run of year 2021 is shown. The solution using ship A proves to be the least expensive with a lifetime cost of 662 MNOK. All values for both ships are much the same, with only a 5% difference in the storage facility's capacity. The total yearly import of hydrogen accumulates to 7867m^3.

Ship(s) evaluated	Storage facility		Transportation (per year)			Lifetime cost
	Size	**Tot. build cost**	**Charter cost**	**Cost of transp. and import**	**No. of trips**	
	[m^3]	*[MNOK]*	*[MNOK]*	*[MNOK]*		*[MNOK]*
Ship A	**4120**	**110**	**1,5**	**18**	**5**	**662**
Ship B	4308	115	1,8	19	5	675
avg	*4214*					

Table 5.8: Output for import of hydrogen from Sør-Varanger, in 2021.

5.2.2 Year 2031

In year 2031 a total accumulated import of 15 734m^3 is predicted. Table 5.9 shows that the solution using ship A is the least expensive with its total lifetime cost of 1111 MNOK. This is less than twice the amount of that for 2021, with the demand having been doubled. The storage facility, that goes with the optimal solution, is found to have a capacity of 1311m^3.

Ship(s) evaluated	Storage facility		Transportation (per year)			Lifetime cost
	Size	**Tot. build cost**	**Charter cost**	**Cost of transp. and import**	**No. of trips**	
	[m^3]	*[MNOK]*	*[MNOK]*	*[MNOK]*		*[MNOK]*
Ship A	**1311**	**35**	**13,7**	**36**	**47**	**1111**
Ship B	13111	351	2,8	25	8	1103
avg	*7211*					

Table 5.9: Output for import of hydrogen from Sør-Varanger, in 2031.

5.2.3 Year 2019-2049

For the full model run of all 30 years, the optimal solution found is the one where ship B is utilized. This has a total lifetime cost of 708MNOK, which lies above the predicted cost for 2021, and below that of 2031. This is naturally, as the two previous runs assume the same demand for the whole 30-year period, while the 360-month-long run experiences changes in demand. The optimal solution found also has a storage capacity of $4120 m^3$, similar to the one found in the year 2021 model run.

Ship(s) evaluated	Storage facility		Transportation		
	Size *[m³]*	**Tot. build cost** *[MNOK]*	**Charter cost** *[MNOK]*	**Cost of transp. and import** *[MNOK]*	**Lifetime cost** *[MNOK]*
Ship A	25287	676	68	557	1233
Ship B	**4120**	**110**	**114**	**598**	**708**
avg	*7211*				

Table 5.10: Output for import of hydrogen from Sør-Varanger, from 2019 to 2049.

Chapter 6

Environmental aspect of selected solutions

In this chapter, a comparison of the emissions regarding the choice of import terminal location for scenario 1, is presented. The fuel consumption of the various ships used for different sailing-routes is based on the results found in the model runs. The values used for converting fuel-consumption to emissions of greenhouse gases are based on numbers from the Gilbert et al. (2018), shown in Table 6.1.

	CO_2	NO_x	SO_x	PM
	[mt]	[mt]	[kg]	[kg]
MDO	5,3	4,1	3,2	1,6

Table 6.1: Emissions from consuming 1m^3 of MDO.

The ships that are highlighted in each table represent the ship that ensures the least expensive lifetime cost, regarding both transportation/import and building costs for the storage facility. The lifetime cost is calculated based on the assumption that the demand for the given time period, is applied to the whole 30-year period. This does not give a correct answer in regards to the actual lifetime cost, but it's functional to use for comparison of emissions for the various solutions.

6.1 Year 2021

Shown in Table 6.2 is the yearly emissions for a ship sailing from Rotterdam, based on the LNG demand in 2021 for Scenario 1. Using ship B to import LNG was the cheapest alternative according to the optimization. In Table 6.3 the emissions when sailing from Melkøya, based on the same premises, is shown. Ship A produced the least expenses when used from Melkøya. As seen there is a significant reduction in emissions when sailing from Melkøya rather than Rotterdam. Comparing the vessels to each other, ship A has an emissions-reduction of 82%, ship B 75%, ship C 49% and ship D 49%.

Ship(s) evaluated	CO_2	NO_x	SO_x	PM
	[tonnes]	*[tonnes]*	*[kg]*	*[kg]*
Ship A	5531	4348	3377	1689
Ship B	**2855**	**2245**	**1744**	**872**
Ship C	2128	1673	1300	650
Ship D	3629	2853	2216	1108

Table 6.2: Emissions related to transport from Rotterdam in 2021. Ship B is the least expensive alternative.

Ship(s) evaluated	CO_2	NO_x	SO_x	PM
	[tonnes]	*[tonnes]*	*[kg]*	*[kg]*
Ship A	**995**	**782**	**608**	**304**
Ship B	705	554	430	215
Ship C	1094	860	668	334
Ship D	1865	1467	1139	570

Table 6.3: Emissions related to transport from Melkøya in 2021. Ship A is the least expensive alternative.

In Table 6.4 the emission and cost reductions acquired, when comparing the optimal ships to be used for Rotterdam and Melkøya, is shown. For Rotterdam ship, B is chosen, while for Melkøya ship A had the lowest lifetime cost. The emissions are reduced by 75% when importing from Melkøya. The charter costs per year are reduced with 61% and the total costs are reduced by 6%.

CO_2	NO_x	SO_x	PM	Charter costs	Lifetime costs
[tonnes]	*[tonnes]*	*[kg]*	*[kg]*	*[MNOK]*	*[MNOK]*
1860	1463	1136	568	2,8	79

Table 6.4: Emission- and cost reductions when comparing optimal solutions for Rotterdam and Melkøya in 2021.

Ship A is, however not the most climate-friendly solution for the ships transporting LNG from Melkøya. Using ship B from Melkøya gives an emissions-reduction of 29% compared to ship A. The lifetime cost is, however, 3% higher, as the storage facility is calculated to be 464 m^3 larger.

6.2 2024, reductions if imported from Melkøya

Shown in Table 6.5 is the yearly emissions for a ship sailing from Rotterdam, based on the LNG demand in 2024 for Scenario 1. Sailing from Rotterdam, ship B is the least expensive alternative, while for Melkøya it's cheaper to use ship A. The various ships' emission when sailing from Melkøya is shown in Table 6.6. The reduction in emissions is significant, but does not correspond with the differences as seen in Table 6.2 and Table 6.3. Sailing from Melkøya is, however, unquestionably more climate-friendly that sailing from Rotterdam, based on emissions. Comparing the vessels to each other, ship A has an emissions-reduction of 72%, ship B 63%, ship C 69% and ship D 49%.

Ship(s) evaluated	**CO_2** *[tonnes]*	**NO_x** *[tonnes]*	**SO_x** *[kg]*	**PM** *[kg]*
Ship A	5070	3986	3096	1548
Ship B	**2855**	**2245**	**1744**	**872**
Ship C	2838	2231	1733	866
Ship D	3629	2853	2216	1108

Table 6.5: Emissions related to transport from Rotterdam in 2024. Ship B is the least expensive alternative.

Ship(s) evaluated	**CO_2** *[tonnes]*	**NO_x** *[tonnes]*	**SO_x** *[kg]*	**PM** *[kg]*
Ship A	**1422**	**1118**	**868**	**434**
Ship B	1057	831	645	323
Ship C	875	688	534	267
Ship D	1865	1467	1139	570

Table 6.6: Emissions related to transport from Melkøya in 2024. Ship A is the least expensive alternative.

Table 6.7 shows the reduction in emissions for the two least expensive choices of ships. Compared to the difference between the two optimal ships for the year 2021-calculation, the reduction in emissions is not as big. This is because the optimal solution for Melkøya is to increase the number of sailings, and reducing the storage capacity. This gives a cheaper solution, but not the most climate-friendly as the number of sailings is twice that for the Rotterdam-based vessel.

CO_2 *[tonnes]*	**NO_x** *[tonnes]*	**SO_x** *[kg]*	**PM** *[kg]*	**Charter costs** *[MNOK]*	**Lifetime costs** *[MNOK]*
1434	1127	876	438	2,0	128

Table 6.7: Emission- and cost reductions when comparing optimal solutions for Rotterdam and Melkøya in 2024.

Like for the year 2021-calculations, ship A is not the most climate-friendly solution; just the cheapest. Ship C has an emissions reduction of 38% to that of ship A. Using ship B will also reduce the emissions compared to ship A, with a total of 26%. Ship A is, however, the cheapest option, with ship B and C having a lifetime cost that is 26% and 1% higher, respectively.

Chapter 7

Discussion

In this chapter, discussions will be conducted regarding the choice of the optimization model, computational implementation, as well as for the results obtained. An assessment of how uncertainty and flexibility will form the continuation of the project is also discussed. Finally some remarks regarding how future scenarios can influence activity on mainland Svalbard.

7.1 Results for optimization of LNG

The model runs where all four ships were assessed at the same time, did not return an optimal solution. The reason that this final solution can be declared as incorrect, is that for model runs in the same time period, a single ship produces a lower final cost when simulated individually. The solutions presented are therefore the optimal solutions if a single given ship had to be selected for a longer run. This does not give a correct lifetime expectancy of either cost, emissions or the size and logistics of the storage facility and transportation of LNG. It does, however, illustrate the current situation for the modelled year, and can be used for comparison together with model runs for later time periods.

When assessing the optimal solutions for handling of LNG in scenario 1, except for a notable deviation for ship C used from Melkøya in 2024, there is a clear correlation between the assessed solutions. The demand in 2021 suggest a storage facility with a capacity in the range of 8 000m^3 to 10 000m^3 to be built, while the capacity for handling the demand in 2024 suggest somewhere between 9 000m^3 to 10 400m^3, disregarding the deviation for ship C. For both time periods, it's cheapest to use ship A from Melkøya, and ship B from Rotterdam. This can be explained with the fact that the total transportation costs are almost three times as high, transporting the fuel from Rotterdam versus Melkøya. The low transport cost from Melkøya means that for ships sailing from Melkøya, it's more cost effective to increase the number of trips and reducing the storage facility's capacity to save money on building costs. The port fees only make up for a fraction of the transportation cost, hence this is not a barrier for an increasing amount of sailings. For the ships sailing from Rotterdam, the sailing costs are high, and they want to reduce the number of sailings as much as possible. The environmental consequences of these two strategies are however completely opposite; favouring the ships sailing from Rotterdam. By reducing the amount of sailing time, the emissions will be reduced accordingly.

For the second scenario, the optimal solution found in the model runs for year 2021 and 2034 suggest a storage capacity in the range of 13 300m^3 to 14 200m^3. The model run for year 2031 finds the optimal storage capacity to be 20 171m^3, but then again this is also the lowest storage capacity calculated for the various ships' model runs for this period. Ship D is chosen as the optimal ship to be used in year 2021 and 2031, while ship B is selected for year 2034. The price difference between ship D and B for year 2034, is however only 1,8%. It could, therefore, be argued that increasing the storage capacity to a level closer to what ship D utilizes in year 2021 and 2031, will be beneficial.

7.2 Results for optimization of hydrogen

The results for import of hydrogen finds some related solutions, but also returns some extreme deviations. For the model run in year 2021, both selections of ships result in a storage capacity of just over 4000m^3. This complies with the result from the model run for ship B in year 2019-2049, where it finds an optimal storage capacity of 4120m^3. The cost for the 30-year period is 708MNOK, a little over the projected lifetime costs for the year 2021 model runs. The fact that the total cost for the 30-year period model run is higher than for year 2021, is expected, as the year 2021 operates with a demand that is twice as low for over half of the system's lifetime.

The results for the model run for year 2031 deviates for what was found in year 2021. It's a bit surprising that, for ship A, it returns a storage capacity which is 68% less than for a time period with only half the yearly demand. Similarly, for ship B it's also questionable that it finds a storage capacity 10 times the size of one used for a ship that has a capacity that is only 40% smaller.

7.3 Computational execution of optimization model

A source of error in the optimization model is that the power plant, and storage facility, in itself has only been given a small fixed energy consumption, not a variable cost depending on its size. This would also prevent a situation where it's beneficial to build an enormous storage facility, just to import large amounts of LNG and hydrogen, when the prices are low. An operational expense like this would lead to a decreased profitability of building large, underutilized storage facilities.

Another reason for the model not delivering the anticipated results might be due to numerical errors. The costs and numbers being calculated are high; the larger the numbers, the higher the error for numerical errors. As a way of mitigating this occurrence, the numbers used in the beginning were in NOK, so all numbers were converted to 1000 NOK, to reduce the size of the numbers in the calculation. This proved successful for long model runs, but it was not decisive for shorter time periods. This can be interpreted as a confirmation of the suspicion that was that large numbers give numerical errors.

Another computational error was that the program did not return the correct solution for when assessing all four ships at once. The error has not been found, and it's unclear whether the error is that the problem formulation is not in compliance with the algorithms used, or if the code is produced wrong. Model runs produce results both where the optimal solution is a switch between several ships being used, and somewhere only one ship is being used. The values returned for these model runs are, however, consistently poorer than model runs for just one ship at a time.

The various solutions calculated for 52-week model runs were compared with regards to their lifetime costs. The lifetime cost was found by distributing the building cost over 30 years, and assuming the same demand and prices for all 30 years, as the 52-week model run used. This means that it neglects the potential change in demand and price, resulting in that the optimal solution found might not be optimal in the longer model runs. This is why several models run for various years, selected depending on an estimated increase in demand, is performed. These simulations were compared when deciding on what is the optimal solution for the entire lifetime.

As mentioned earlier, the optimization model was, in the beginning, a non-linear optimization problem, before being redefined into a mixed integer linear problem. The optimization tools used to solve the problems was however not changed. The input to the fmincon-function in the MATLAB-script was made linear, except for the fixed transportation cost for a specific sailing, which was formulated using a fraction where the decision variable was divided by itself. This made the computational model non-linear and may be the reason for some of the unexpected results obtained. By just assessing the input to the model, the constraints and objective function is defined correctly, but the way the nonlcon-function was used might not work with the algorithms chosen to run the model.

7.3.1 Uncertainty and flexibility

In the origins of this thesis, the optimization model was supposed to be stochastic, in the meaning that the possible scenarios would be given a probability of occurring, and thus finding the optimal solution for one model run. This would mean that the optimal solution would be a combination of creating an infrastructure ready to meet the needs of the most probable scenario, but in the same time mitigate the needs of other scenarios if the cost minimization would allow it. As the probability of the various scenarios' potential occurrence is too uncertain, it was decided to discontinue this method. A part of the reason for this was that the thesis was created in collaboration with a company seeking realistic numbers, something of which the result of a stochastic, scenario-based, approach could not deliver due to the vast degree of uncertainty. Instead, two scenarios were created in compliance with the thesis contractor; one pessimistic based on confirmed numbers and announced developments, and one optimistic where a notable switch towards greener solutions for marine actors was expected. This allowed insight into how the infrastructure and logistics of Longyearbyen should be constructed based on the needs of today but keeping in mind what a potential, ideal, future needs may hold. This enlightens the question regarding the flexibility of the final solution.

The tables shown in Chapter 5.1.1 and 5.1.2 indicate a range of which the storage capacity should be for the individual scenarios. The results from the "as is"-scenario will be used when developing a final solution, but the numbers from the optimistic scenario should be accounted for in the planning. This will encourage the finalized product to have a degree of flexibility, making it more easily adaptable to later modifications. This can prove economically favourable; investing in a little more expensive, but flexible solutions today, so that a later change/modification will have a reduced cost. This thesis is made to be a feasibility study, suggesting various solutions, to various costs, to a various degree of environmental- and climate friendliness, so that decisions can be made with these numbers in mind.

The flexibility aspect regarding the choice of the final product does not need to be limited to only account for size. By investigating the possibility of acquiring technology and infrastructure capable of shifting to another fuel in the future can also prove profitable. Building an LNG-infrastructure with hydrogen-ready features simplifies a potential change in energy carrier for Longyearbyen in the future. This would also be beneficial if somehow the demand for hydrogen amongst marine actors in Longyearbyen, suddenly would prove more profitable than the distribution of LNG.

7.4 Future influences on mainland Svalbard

7.4.1 Society

The obtained solutions have so far been discussed from a sustainability point of view, focusing on the economic and environmental part of sustainability. The term sustainability also includes a third aspect; namely the society. It was not well received in the community when the old mines were shut down, and that it was announced that a new energy solution for Longyearbyen was due. Coal-miners feared for losing their jobs, one of the premises for being allowed to live on Svalbard.

The coal being mined in Svalbard is high-grade, meaning it has a very high BTU or energy density. Coal with such good quality is highly sought for in the steel-making industry, so even if it stops being used as the primary source of energy in Longyearbyen, there will still be a significant demand for coal of this quality.

The introduction of a new energy system will also generate new jobs and new possibilities for technological development and research. If the scenarios investigated were to play out, this would also mean that the switch to a new energy carrier would generate more income, more activity, and therefore a bigger demand for labour.

7.4.2 New markets

Svalbard has an absolutely unique location considering the increase in activity around the North Pole. With the ice melting, there has been an increasing interest of sailing along the northeast- and the northwest passage. With the climate change continuing to cause the ice to melt, and with no clear signs that the trend is turning, Svalbard as a strategic connection-point for arctic shipping seems more and more interesting.

With the opening of the northern passages, the fuel demand of ships visiting and crossing Svalbard will increase. Establishing a major distribution centre, for both intermediate storing and vessel bunkering, could be interesting to look into. This, however, requires a little patience as the northern sailing routes still isn't as established as the southern routes.

Chapter 8

Concluding remarks

In this chapter, some remarks regarding the choice of the optimization model, and implementation in the data solver is presented. The final, presumed best solutions are also presented, before giving some comments regarding the environmental differences of transporting LNG from Melkøya and Rotterdam.

8.1 Implementation of optimization model

The optimization model lacked certain inputs that would have altered the outcomes. With greater computing power, the Monte Carlo simulation could have been applied to the model run, generating a numerous model runs with various LNG-price inputs, to find a probability distribution for the final solutions.

Up until the mathematical formulation of the problem was changed from a non-linear problem to MILP, the computational method chosen was perceived as valid. When the model changed, the choice of solver should have been changed accordingly. Switching from a non-linear to a linear solver in the computer program could have improved the model runs. The solutions generated by the model run was of mixed validity, but the solution of which the final decisions were based on are considered to be valid. This is based on corresponding values for several model runs, and expected solutions presumed based on findings in previous studies.

8.2 Final results

The final storage capacity is calculated to be higher than what the previous studies show, but this is natural as this model includes the distribution of fuel to marine actors. For LNG a storage facility with a capacity of approximately $9000m^3$ should be built, according to the optimal solutions found for scenario 1. Melkøya is, naturally, preferred over Rotterdam in every model run, as it means lower transportation costs.

For scenario 2, it is suggested that a storage capacity of between $14\,000m^3$ to $20\,000m^3$ should be built, depending on the risk the project owner is willing to take. As this scenario is highly optimistic, a degree of flexibility should be implemented; preparing today for what could happen tomorrow.

For the storage facility for hydrogen, three model runs found a very similar storage capacity, with three deviations. The model runs in year 2021 are almost equal, and the same for year 2031, but the full lifetime model run suggests a solution closer to the one found for year 2021. Building a storage facility of approximately $4200m^3$ is therefore concluded, based on these findings.

8.3 Environmental aspect

The environmental aspect regarding transporting the LNG from Rotterdam versus Melkøya was as expected. A huge reduction in greenhouse gas emissions was found for the solutions were Melkøya was selected as an import terminal. The optimal solution found for Melkøya was, however, not the most climate-friendly as it consistently utilized ship A, and increased the number of trips, rather than sailing with higher loads.

A potential yearly reduction of 65%, given the LNG-demand for year 2021, and 50%, given the LNG-demand for year 2024, is expected. This is for when the cheapest solution is adopted.

Chapter 9

Further work

In this chapter, two interesting cases that could be subject to further investigation is presented. The first is regarding performing an analysis based on the perceived value of a new energy solution, and the second is regarding Svalbard as a strategic location to include in increasing the accessibility of the northern passages.

9.1 Optimization based on utility/perceived value

The optimization performed has been done to minimize costs. The environmental aspect of the coming solutions is also very important as Svalbard lies in a vulnerable location and suffers from local pollutants and climate change. Svalbard could also be an important showcase of Norwegian technology to the world, and manifesting its stand in the process of reducing greenhouse gas emissions. An optimization-model created in the intention of minimizing emissions would be interesting to use as a comparison with this model. This model would favour a solution consisting of a hydrogen power-plant, combined with hydrogen produced through electrolysis, with its energy originating from renewable resources. This is, as concluded in the feasibility studies performed by the various consulting agencies, a very costly solution. A differentiation between the value of cost and utility is needed to make a decision. The project owners must decide how the project's success' is to be weighed depending on cost and environmental friendliness. Its perceived value must be stipulated by the project owners. An optimization or epoch/era analysis of this could then be performed.

9.2 LNG-hubs

As mentioned, Svalbard has a unique location in the events that the northern passages becomes readily available and frequently used. Deploying hubs and distribution terminals across the archipelago could be a crucial logistical contribution in increasing the accessibility of the northern passages. Investigating the locations and logistics of these hubs would be interesting to discover their potential as an influential step for increased use of the northern passages. The study "Supply Chain and Uncertainty", by (Fekene, 2014), investigates locating LNG distribution centres in an emerging market with uncertain demand. This study could lay the premises for how the formulation of the investigation should commence.

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Appendices

A MATLAB code - optimization model

```
clc % Clear command window
tic
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Storage properties
I_LNG = 3000; % Initial amount of stored LNG [m^3]
V_min = 1000; % Availibility requirement [m^3]

% Ship properties
n_s = 4;  % Number of ships to be used
s_inv = 2;  % If specific ship is being investigated, set s_inv=ship.id.
            %If several are being investigated, set =0, and n_s to as many
            % that are being investigated.

% Distribution center properties
n_d = 1;  % Number of distribution centers to be used

% Time properties
n_t = 52;

% Cost of storage facility [1000 NOK/m^3]
C_B = 26.749/(52*30)*n_t;                    % Yearly building cost; downpay
                                             %over 30 years
C_B = C_B;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Initialization
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Gathering data from the tested .xlsx-file.


% LNG data                                     - Price and
```

```
consumption of LNG
[LNG_data,Time_period] = xlsread('data1a.xlsx','LNG_data',['A2:C' num2str(n_t+1)]);
Time_period = num2str(LNG_data(:,1));
C_LNG_t = LNG_data(:,2).';

F_LNG_t = LNG_data(:,3).';

% Ship data                    - Gathering ship capacity and charter costs
[ship_data,ships] = xlsread('data1a.xlsx','ship_data',['A2:C' num2str(n_s+1)]);
if s_inv > 0
    n_s = 1;
    ship_inds = s_inv;
    ships = ships(s_inv);
else
    ship_inds = 1:n_s;
end
K_s = ship_data(ship_inds,1).';
C_LNG_s = ship_data(ship_inds,2).';

% Distribution center data                    - Handling costs of 1MMBtu
[dist_center_data,dist_centers] = xlsread('data1a.xlsx','distribution_center_data',['A2:C' num2str(n_d+1)]);
C_LNG_d = dist_center_data(:,1).';



% Define sets                  - Using sets to control size of matrices used
                               %in calculations and results
n = n_s*n_d*n_t;
s = 1:n_s;
d = 1:n_d;
t = 1:n_t;
N = 1:n;
S = repelem(s,1,n_t*n_d);
D = repmat(repelem(d,1,n_t), 1, n_s);
T = repmat(t,1,n_s*n_d);

```

```
%LNG import cost for each ship, at each distribution center and time period
C_LNG_sx = repelem(C_LNG_s,1,n_t*n_d);              % Fixed transp.cost
                                                    %(fuel, T/C, port fees)
C_LNG_dx = repmat(repelem(C_LNG_d,1,n_t), 1, n_s); % Handling cost
C_LNG_tx = repmat(C_LNG_t,1,n_s*n_d);      % Cost of LNG for time period t
C_LNG_x = C_LNG_dx + C_LNG_tx;                % Total cost for importing x
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Variable bounds
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
lb = zeros(n+1,1);                          %Non-negativity
ub = 1e9*ones(n+1,1);                       %Randon, high upper bound
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Objective function and nonlinear constraints
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
f = [C_B C_LNG_x].';                     % Linear cost, as defined in linprog
obj_fun = @(x) objective_function(x,f,C_LNG_sx);
nonlcon = @(x) nonlinear_constraints(x, S, D, T);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Inequality constraints
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Amount of stored LNG to be above minimum value
A_t = zeros(n_t,n);
A_t(sub2ind([n_t n], T, 1:n)) = 1;  % Matrix that gets time periodic values
```

```
A_t_acc = tril(ones(n_t))    % Matrix that accumulates time periodic values

V_0 = [I_LNG;zeros(n_t-1,1)];                  % Time periodic initial values

A_min = -A_t_acc*A_t;              % Inequality matrix for minimum LNG amount
b_min = A_t_acc*(V_0 - F_LNG_t.') - V_min; %Ineq. vector for min. LNGamount

% Amount of imported LNG on each ship to be below capacity of ships
a_capacity = repmat(eye(n_t), 1, n_d);
A_capacity = block_diag(a_capacity, n_s);
b_capacity = repelem(K_s, 1, n_t).';
%b_capacity_low = repelem(min_load, 1, n_t).';

% Storage level to be above amount of imported LNG
A_storage = A_t_acc*A_t;
b_storage = A_t_acc*(F_LNG_t.' - V_0);

% Total inequality constraints
A = [zeros(size(A_min,1),1) A_min
     zeros(size(A_capacity,1),1) A_capacity
     -ones(size(A_storage,1),1) A_storage];
b = [b_min; b_capacity; b_storage];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Equality constraints
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Aeq = [];
beq = [];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Input validity tests
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
try
    load('do_not_delete.mat')
```

```
catch
    error('''do_not_delete.mat'' has been deleted')
end

if n_s < 1
    error('Number of ships, n_s, must be a positive integer')
end
if n_d < 1
    error('Number of destination centers, n_d, must be a positive integer')
end
if n_t < 1
    error('Number of time periods, n_t, must be a positive integer')
end

x0 = zeros(n,1);
available_capacities = K_s;
for i = 1:n_d
    if isempty(available_capacities)
        break
    end
    [max_capacity,max_capacity_ind] = max(available_capacities);
    x0(D == i & S == max_capacity_ind) = max_capacity;
    available_capacities(max_capacity_ind) = -max_capacity;
end
z0 = I_LNG + sum(x0);
X0 = [z0; x0];

objective_function(X0,f,C_LNG_sx)
[c,ceq] = nonlinear_constraints(X0, S, D, T);
nonlcon_tol = 1e-3;

if all(A*X0 <= b)
    disp('Initial point satisfies linear inequality constriants')
else

    if any(A_capacity*x0 > b_capacity)
        str = 'Ship capacity is exceeded';
    elseif any(A_min*x0 > b_min)
        str = 'Amount in storage is below availibility
```

```
            requirement';
    else
        str = 'Storage capacity is exceeded';
    end
    error(['Initial point violates linear inequality constriants\n' str],1)
end
if all(abs(ceq) <= nonlcon_tol)
    disp('Initial point satisfies nonlinear equality constriants')
else
    x_sym = sym('x%d%d%d', [n_s n_d n_t]);
    x_sym = sort(x_sym(:));
  viol_inds = ceq > nonlcon_tol;
    [~,ceq_sym] = nonlinear_constraints(x_sym, S, D, T);
    ceq_sym(viol_inds)
    error('Ship or distribution center is used multiple times')
end
X0(X0 == 0) = 1e-7;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Define and run global optimization problem
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Algorithm: Use sqp or sqp-legacy (or active-set, but active-set may not
% recover from nan or Inf).
opts = optimoptions('fmincon');
opts.MaxFunctionEvaluations = 1000*(n + 1); % Default is 100*n_variables
opts.MaxIterations = 1000; % Default is 400
opts.FunctionTolerance = 1e-9;
opts.StepTolerance = 1e-9;
% opts.MeshTolerance = 1e-6;
% opts.ConstraintTolerance = 1e-6;
% opts.UseCompleteSearch = true;
% opts.UseCompletePoll = true;
% opts.UseParallel = true;
% opts.UseVectorized = false;
% opts.InitialMeshSize = 1;
% opts.ScaleMesh = false;
```

```
problem = createOptimProblem('fmincon', ...
    'objective', obj_fun, ...
    'x0', X0, ...
    'Aineq', A, ...
    'bineq', b, ...
    'Aeq', Aeq, ...
    'beq', beq, ...
    'lb', lb, ...
    'ub', ub, ...
    'nonlcon', nonlcon, ...
    'options', opts);

rng('default')
gs = GlobalSearch;
gs.NumStageOnePoints = 200*10; % Default is 200
gs.NumTrialPoints = 1000*10; % Default is 1000
gs.MaxWaitCycle = 20*10; % Default is 20
gs.BasinRadiusFactor = .2; % Default is .2

% Algorithms to be used. Recommended: {'interior-point'},
% {'interior-point','sqp'} or {'interior-point','sqp','active-set'}
gs_algorithms = {'interior-point','sqp','active-set'};
%solution from interior-point becomes start-value for sqp etc.

warning ('off','all');
res_tol = .1;

k = 0;
for i = 1:numel(gs_algorithms)
    res = res_tol + 1;
    opts.Algorithm = gs_algorithms{i};
    problem.options = opts;
    while res > res_tol && k < 5*i
        fprintf('\n')
        disp(['Searching for global mimimum with the ' gs_algorithms{i} ' algorithm ...'])
        [X,fval,exitflag,output,solutions] = run(gs, problem);
        fprintf('\n')
        k = k + 1;
```

```
        disp(['Global search no. ' num2str(k) ' is complete'])
        res = max(abs(X - problem.x0));
        problem.x0 = X;
    end
end
fprintf('\n')
disp('Result of global search:')
disp(output)
if exitflag < 1
    error('Unable to find optimal solution')
end

% Verify obtained solution
warning ('on','all');
[X_local,fval_local,exitflag_local,output_local] =
    fmincon(problem);
disp('Result of local optimization at global minimum:')
disp(output_local)
if abs(X - X_local) > res
    warning('Global solutions does not equal local solution')
    disp(fval)
    disp(fval_local)
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Display and plot results
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
z = round(X(1));
x = round(X(2:end));
% Display information
t_str = strcat('Time_period_', split(num2str(t)));
for i = t
    P = table;
    for j = d
        x_dt = x(D == j & T == i);
        P_tmp = table(x_dt);
        P_tmp.Properties.VariableNames = dist_centers(j);
        P = [P P_tmp];
    end
    P.Properties.RowNames = ships;
    disp(['Time_period ' num2str(i) ' LNG quantities'])
```

```
    disp(head(P))
end

Stored_LNG = A_t_acc*A_t*x + A_t_acc*(V_0 - F_LNG_t.');
figure(1)
clf
plot(t, Stored_LNG)
ax = gca;
xticks(t)
xlabel('Time period')
xlim([t(1) t(end)])
xticks(t(1):5:t(end))
ylim([0 1.1*ax.YLim(2)])
ylabel('Stored LNG [$m^3$]')
[~,V_min_ind] = min(abs(V_min - yticks()));
ax.YTickLabel(V_min_ind) = {'$V_{min}$'};

Imported_LNG = A_t*x;
Consumed_LNG = F_LNG_t.';
figure(2)
clf
plot(t, Imported_LNG, t, Consumed_LNG)
ax = gca;
ylim([.9*ax.YLim(1) 1.1*ax.YLim(2)])
xticks(t)
xlabel('Time period')
xlim([t(1) t(end)])
xticks(t(1):5:t(end))
ylabel('LNG [$m^3$]')
yyaxis('right')
plot(t, C_LNG_t)
ylabel('Price of LNG [1000 NOK/$m^3$]')
ax = gca;
ylim([.9*ax.YLim(1) 1.1*ax.YLim(2)])
legend('Imported','Consumed','LNG Price')

Build_cost_MNOK = C_B*z/(10^3*n_t)*ones(n_t,1);
Import_cost_MNOK = A_t*diag(C_LNG_x)*x/10^3;
figure(3)
clf
plot(t, Import_cost_MNOK, t, Build_cost_MNOK)
ax = gca;
ylim([.9*ax.YLim(1) 1.1*ax.YLim(2)])
```

```
xticks(t)
xlabel('Time period')
xlim([t(1) t(end)])
xticks(t(1):5:t(end))
ylabel('Cost [MNOK]')
yyaxis('right')
plot(t, C_LNG_t)
ylabel('Price of LNG [1000 NOK/$m^3$]')
ax = gca;
ylim([.9*ax.YLim(1) 1.1*ax.YLim(2)])
legend('Import cost','Investment cost','LNG Price')

disp(table(Time_period, Stored_LNG, Imported_LNG,
    Consumed_LNG, Import_cost_MNOK))

final_storage_cap = z;                                    %[m^3]
total_LNG_import = sum(x);                                %[m^3]
total_build_cost_period = C_B*z/10^3;                     %[MNOK]
total_build_cost = C_B*30*52/n_t*z/10^3;                  %[MNOK]
import_cost_period = C_LNG_tx*x/10^3;                     %[MNOK]
                %import_cost_period does not include charter
                    cost and handling
charter_cost_period = sum(C_LNG_sx(x > 0))/10^3;          %[MNOK]
handling_cost_period = C_LNG_dx*x/10^3;                   %[MNOK]
total_import_cost_period = import_cost_period +
    charter_cost_period + handling_cost_period;%[MNOK]
total_cost_lifetime = total_build_cost +
    total_import_cost_period*30*52/n_t;
disp(['Final storage capacity [m^3]: '
    num2str(final_storage_cap)])
disp(['Total amount of LNG imported for period [m^3]: '
    num2str(total_LNG_import)])
disp(['Building cost for period [MNOK]: '
    num2str(total_build_cost_period)])
disp(['Total building cost [MNOK]: '
    num2str(total_build_cost)])
```

```
disp(['LNG cost for period [MNOK]: ' num2str(import_cost_period)])
disp(['Charter cost for period [MNOK]: ' num2str(charter_cost_period)])
disp(['Handling cost for period [MNOK]: ' num2str(handling_cost_period)])
disp(['Total import cost for period [MNOK]: ' num2str(total_import_cost_period)])
disp(['Total cost for period [MNOK]: ' num2str(import_cost_period+charter_cost_period+total_build_cost_period)]
disp(['Total lifetime cost [MNOK]: ' num2str(total_cost_lifetime)])
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

toc

function [c,ceq] = nonlinear_constraints(X, S, D, T)
x = X(2:end);

% Get indices of quadratic terms that should be zero
S_eq = S == S.';
T_eq = T == T.';
ST_eq = S_eq & T_eq;
DT_eq = (D == D.') & (T == T.');
ST_eq = triu(ST_eq,1) | tril(ST_eq,-1);
DT_eq = triu(DT_eq,1) | tril(DT_eq,-1);

% Calculate quadratic terms
x_quad = x*x.';

% Equality constraint
ceq = x_quad(ST_eq | DT_eq); % Extract quadratic terms that should be zero

% Inequality constraint
c = [];
end

function fval = objective_function(x,f,C_LNG_sx) %import, storage cap, and transp cost
fixed_cost = C_LNG_sx*(x(2:end)./(x(2:end) + .001)); %The fixed cost is multiplied and divided by x(with a neglectible
```

```
                                                  %difference in x+.001)so that the binary constraint for fuel,
                                                  %charter and port costs is given a value of 1 if used
% fixed_cost = sum(C_LNG_sx(x(2:end) > 0));
fval = f.'*x + fixed_cost;
end

function A = block_diag(a,n)
[r,c] = size(a);
A = zeros(r*n,c*n);
for i = 1:n
    A((i-1)*r+1:i*r,(i-1)*c+1:i*c) = a;
end
end
```

B Prediction of LNG-price.xlsx

See attached .zip-file. This Microsoft Excel-document contains auto-generating LNG-price predictions, hence the .xlsx-file is needed to see the setup.

NTNU

Norwegian University of
Science and Technology