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Assessment of Marine Fuels in a Fuel Cell on a Cruise Vessel

Trine Nerem

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Supervisor: Svein Aanond Aanondsen, IMT

Norwegian University of Science and Technology
Department of Marine Technology

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Trine Nerem

Assessment of Marine Fuels in a Fuel Cell on a Cruise Vessel

Background

Exploring parts of the world through a cruise ship has been popular for a long time. The cruises visit beautiful areas, which often could be a world heritage site. Though shipping is one of the most efficient transport mode, it contributed to 2.6 of global emissions of CO_2 in 2012. Both MARPOL and Paris Agreement have strict regulations regarding pollution from ships, and require less environmental impact caused by shipping. Fuel combustion has considerable environmental affect, and reduction of emissions during propulsion will reduce the environmental impact.

Objective

The objective of this thesis is to evaluate whether hydrogen, LNG or methanol is the most suitable fuel for utilization through a fuel cell on a cruise vessel. The evaluation will be based on required space, the environmental impact and the economical aspect.

Tasks

The candidate shall/is recommended to cover the following tasks in the master thesis:

a. Describe the real problem
b. Review and present relevant literature
c. Compare how much space the various fuels require
d. Evaluate the environmental impact from the fuels
e. Evaluate the economical aspect for the fuels

General

In the thesis, the candidate shall present her personal contribution to the resolution of a problem within the scope of the thesis work.

Theories and conclusions should be based on a relevant methodological foundation that through mathematical derivations and/or logical reasoning identify the various steps in the deduction.

The thesis should be organized in a rational manner to give a clear statement of assumptions, data, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, list of abbreviations, main body of thesis, conclusions with recommendations for further work, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work.
The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged reference system.

Deliverable

- The thesis shall be submitted in two (2) copies
- Signed by the candidate
- The text defining the scope included
- In bound volume(s)
- Drawings and/or computer prints that cannot be bound should be organized in a separate folder
- The bound volume shall be accompanied by a CD or DVD containing the written thesis in Word or PDF format. In case computer programs have been made as part of the thesis work, the source code shall be included. In case of experimental work, the experimental results shall be included in a suitable electronic format.

Supervision:
Main supervisor: Svein Aa. Aanondsen

Deadline: 11.06.2018

Preface

This Master Thesis is the last part of my Master of Science at the Department of Marine Technology at the Norwegian University of Science and Technology. The workload of the thesis is equivalent to 30.0 credits.

Alternative fuels and propulsion systems are highly relevant today, as the world is facing an environmental challenge. I want to expand my knowledge within this field, and chose accordingly to have this as subject on my master thesis. Though, finding necessary information has been challenging, special regarding fuel cells and which technology to choose.

The thesis is written in cooperation with Vard Design in Ålesund, Norway. I would like to express my gratitude to Kjell Morten Urke and Arnstein Rødset, both working at Vard Design, for their support and help. Furthermore, I would thank professionals from the industry for being helpful. I would give a special thanks to my supervisor, Associate Professor Svein Aa. Aanondsen, for all his guidance and help through the whole semester.

The thesis is written with the assumption that the reader has some foreknowledge in the field of marine engineering.

Trondheim June 7, 2018

Trine Nerem

Trine Nerem

Summary

Humans have explored the world through cruise vessels for several years. Most of the vessels use Heavy Fuel Oil (HFO) or Marine Diesel Oil (MDO). Simultaneously, the world is facing an environmentally challenge. Though shipping is the most environmentally friendly and efficient transport mode, it contributed 2.6 % of global emissions of CO_2 in 2012. In 2015, 195 of the world's nations signed the Paris Agreement, and by that committed to implement actions to prevent the global temperature rise to exceed 2°C. Additionally, International Convention for the Prevention and Pollution from Ships (MARPOL) has strict regulations regarding emissions from ships.

Fuel combustion has a huge affect on the environment, and ship propulsion accounts for approximately 80 % of the environmental impact for a container ship. It is reasonable to assume this will be about equivalent for a cruise vessel. Utilization of another fuel than HFO and MDO may reduce vessel's environmental footprint. Additionally, as an alternative to traditional combustion engines, Fuel Cell (FC) is assumed to be one of the most auspicious future technology.

This thesis contains an evaluation of hydrogen, Liquid Natural Gas (LNG) and methanol in an FC on a cruise vessel. The fuels will be compared based on the space they require on board the vessel, their environmental impact and their Life Cycle Costs (LCC).

An FC consist of an anode and a cathode with an electrolyte between them. In the process, chemical energy will convert to water and electrical energy. The most common way to produce electricity through FCs are by hydrogen and oxygen. FCs can be divided into different types based on the material used in their membrane. They differ in power output, operation temperature, start-up time, typical applications and electrical deficiencies. FCs can be divided into three main categories:

- Low-Temperature Fuel Cells (LT-FCs)
  Having an operation temperature of approximately 80°C
- Intermediate temperature FCs
  Having an operation temperature of approximately 200°C
- High-Temperature Fuel Cells (HT-FCs)
  Having an operation temperature of approximately 650-1000°C

HT-FCs have increased overall efficiency, and does not need an external reformer when other fuels than hydrogen is utilized. Though, they are not as flexible and commercially available as LT-FCs. A Proton Exchange Membrane Fuel Cell

(PEMFC), which is an LT-FC, has been found as most suitable for a cruise vessel, and is considered in this thesis' calculations. The need of an external reformer when utilization of other fuels than hydrogen in PEMFC, causes both increased machinery size and costs. Hence, the final result would probably have been different if another FC had been chosen.

Required spaces are found by the System Based Ship Design (SBSD) method. A purpose with SBSD is to determine Gross Tonnage (GT), Gross Volume (GV) and main dimensions for a specific vessel. To implement this, necessary areas and volumes of all equipment needed in the vessel should be determined. In this thesis, a tank capacity making it possible to sail 100 hours without bunkering is required. It was found that whether to use hydrogen, LNG or methanol as fuel does not cause any significant variations in a vessel's main dimensions. LNG causes smallest dimensions, while hydrogen and methanol cause equals dimensions, considering the system boundaries given in this thesis. HFO causes the highest dimensions, which is mainly due to the size of the combustion engine. If the tank size is increased even more, the result would have been different.

The fuels' potential environmental impact has been found by a Life Cycle Assessment (LCA). Hydrogen produced from renewable energy sources has the smallest potential environmental footprint, while hydrogen produced from Natural Gas (NG) has the highest impact. Furthermore, it was found that LNG utilized through an FC is, from an environmental point of view, a better solution than methanol utilized in an FC. Both LNG and methanol release less emissions as utilized in an FC than a combustion engine.

The economical evaluation is based on LCC. LCC is mainly divided into Capital Expenditures (CAPEX), Operational Expenditures (OPEX) and Voyage Related Expenditures (VOYEX). Methanol, hydrogen and LNG cause 1.15, 1.14 and 1.10 times higher LCC than HFO.

Sammendrag

Mennesker har utforsket verden gjennom cruiseskip i flere år. De fleste skipene bruker tungolje (HFO) eller marin diesel (MDO). Samtidig står verden overfor en miljømessig utfordring. Selv om sjøtransport er den mest miljøvennlige og effektive transportmåten, bidro det til 2.6 % av globale utslipp av CO_2 i 2012. I 2015 signerte 195 av verdens nasjoner Parisavtalen, og forpliktet seg til å gjennomføre tiltak for å hindre at den globale temperaturstigningen overstiger 2°C. I tillegg har International Convention for the Prevention and Pollution from Ships (MARPOL) strenge krav til utslipp fra skip.

Drivstofforbrenning har stor innvirkning på miljøet, og skipsfremdrift utgjør ca. 80 % av miljøbelastningen for et containerskip. Det er rimelig å anta at dette vil være omtrent likt for et cruiseskip. Utnyttelse av et annet drivstoff enn HFO og MDO kan redusere fartøyets miljøpåvirkning. Som et alternativ til tradisjonelle forbrenningsmotorer antas brenselceller å være en av de mest lovende fremtidige teknologiene.

Denne oppgaven inneholder en vurdering av hydrogen, flytende naturgass (LNG) og metanol i en brenselcelle på et cruiseskip. Drivstoffene vil bli sammenlignet basert på den plassen de trenger ombord på fartøyet, deres miljøpåvirkning og deres livsløpskostnader.

En brenselcelle består av en anode og en katode med en elektrolytt mellom. I prosessen vil kjemisk energi konvertere til vann og elektrisk energi. Den vanligste måten å produsere elektrisitet gjennom brenselceller er ved bruk av hydrogen og oksygen. Brenselcleler kan deles inn i forskjellige typer basert på materialet som brukes i membranen. De varierer i virkningsgrad, driftstemperatur, oppstartstid, typiske applikasjoner og elektriske svakheter. Brenselceller kan deles inn i tre hovedkategorier:

- Lavtemperatur brenselceller
  Har en driftstemperatur på ca. 80°C
- Mellomtemperatur brenselcelle
  Har en driftstemperatur på ca. 200°C
- Høytemperatur brenselceller (HT-FCs)
  Har en driftstemperatur på ca. 650-1000 °C

Høytemperatur brenselceller har økt total virkningsgrad, og trenger ikke en ekstern reformator når andre drivstoff enn hydrogen er utnyttet. Likevel er de ikke like fleksible og kommersielt tilgjengelige som lavtemperatur brenselceller. En Proton Exchange Membrane Fuel Cell (PEMFC), som er en lavtemperatur brenselcelle, har blitt funnet som mest egnet for et cruiseskip, og vurderes i denne oppgavens beregninger. Behovet for en ekstern reformator ved bruk av andre drivstoff enn hydrogen i PEMFC, forårsaker både økt maskinstørrelse og -kostnader. Dermed ville sluttresultatet trolig ha vært annerledes hvis en annen brenselcelle hadde blitt valg.

Nødvendige plass er funnet ved hjelp av SBSD-metoden (System Based Ship Design). Et formål med SBSD er å bestemme bruttotonnasje (GT), bruttovolum (GV) og hoveddimensjoner for et bestemt fartøy. For å gjennomføre dette, må nødvendig plass og volum for alt utstyr som trengs i fartøyet bestemmes. I denne oppgaven er det krevd en tankkapasitet som gjør det mulig å seile 100 timer uten bunkring. Det ble funnet at bruk av hydrogen, LNG eller metanol som drivstoff ikke forårsaker noen betydelige variasjoner i fartøyets hoveddimensjoner. LNG forårsaker de minste dimensjonene, mens hydrogen og metanol forårsaker like dimensjoner, basert på systemgrensene som er gitt i denne oppgaven. HFO forårsaker de høyeste dimensjonene, som hovedsakelig skyldes forbrenningsmotorenes størrelse. Hvis tankstørrelsen økes, ville resultatet ha vært annerledes.

Drivstoffenes potensielle miljøpåvirkning er funnet ved en livsløpsanalyse. Hydrogen produsert fra fornybare energikilder har minst potensiell miljøpåvirkning, mens hydrogen fra naturgass har størst påvirkning. Videre ble det funnet at LNG brukt i brenselceller vil, fra et miljømessig synspunkt, være en bedre løsning enn metanol i brenselceller. Både LNG og metanol gir mindre utslipp ved bruk i brenselceller enn i en forbrenningsmotor.

Den økonomiske evalueringen er basert på livsløpskostnader, som hovedsakelig er delt inn i kapitalkostnader (CAPEX), operasjonskostander (OPEX) og reiseavhengige operasjonskostnader (VOYEX). Metanol, hydrogen og LNG fører til henholdvis 1.15, 1.14 og 1.10 ganger høyere livsløpskostnader enn HFO.

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List of Abbreviations

AFC	Alkaline Fuel Cell
CAPEX	Capital Expenditure
DMFC	Direct Methanol Fuel Cell
ECA	Emission Control Area
FC	Fuel Cell
GHG	Greenhouse Gas
GT	Gross Tonnage
GV	Gross Volume
GWP_{100}	100-year Global Warming Potential
HFO	Heavy Fuel Oil
HT-FC	High Temperature Fuel Cell
HT-PEMFC	High Temperature Proton Exchange Fuel Cell
IGC Code	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF Code	International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels
IMO	International Maritime Organization
LBG	Liquid Bio Gas
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
LNG	Liquid Natural Gas
LPG	Liquid Petroleum Gas
LT-FC	Low Temperature Fuel Cell
MARPOL	International Convention for the Prevention of Pollution from Ships
MCFC	Molten Carbonate Fuel Cell
MDO	Marine Diesel Oil
MSC	Maritime Safety Committee
NG	Natural Gas
OPEX	Operational Expenditure
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Proton Exchange Membrane Fuel Cell
PM	Particulate Matter
RFR	Required Freight Rate
SBSD	System Based Ship Design
SOFC	Solid Oxide Fuel Cell
SOLAS	International Convention of Safety of Life at Sea
SFC	Specific Fuel Consumption
STCW	Standards of Training, Certification and Watchkeeping of Seafarers
SVO	Straight Vegetable Oil
VOC	Volatile Organic Compounds
VOYEX	Voyage Related Expenditures

CH_3OH	Methanol
CH_4	Methane
CO_2	Carbon Dioxide
H_2	Hydrogen
N_2O	Nitrous Oxide
NO_x	Nitrogen Oxide
SO_x	Sulphur Oxide

Chapter 1

Introduction

1.1 Background

1.1.1 Cruise Tourism

Exploring parts of the world through a cruise vessel has been popular for decades. The cruises visit beautiful areas, which often could be a world heritage site. During the past few years, the cruise traffic in both Arctic and Antarctic has increased rapidly. Most of the vessels use Heavy Fuel Oil (HFO) for propulsion (Burel, Taccani, and Zuliani 2013).

Arctic areas have experienced the greatest regional warming on earth in the recent decades, which has lead to melting of large amounts ice. The reduction in sea ice extent has made it possible to reach earlier inaccessible areas. In addition, the cruise season in those areas extends (Dawson, Johnston, and Stewart 2014). The 17th of October 2017, NRK showed an episode of 'Brennpunkt' which dealt with emissions from cruise ships while visiting vulnerable areas and beautiful fjords. In their work, a cruise ship from Artania was taken as an example, and the travelling route was from Bremerhaven, around Iceland to Longyearbyen, and then the vessel followed the Norwegian coast before ending its trip in Bremerhaven. The whole round trip took 17 days. Environmental coordinator at the ship, Ruslan Shevchuk, estimated that during the whole round trip, the ship polluted 578.8 tons HFO and 472 tons Marine Diesel Oil (MDO). Professor Carlo Aall, scientist at Veslandsforskning, did some calculations and found this equal to the average annual consumption of 1600 petrol-driven passenger cars, which has been illustrated in Figure 1.1. This is sensational numbers which gives cause of being worried.

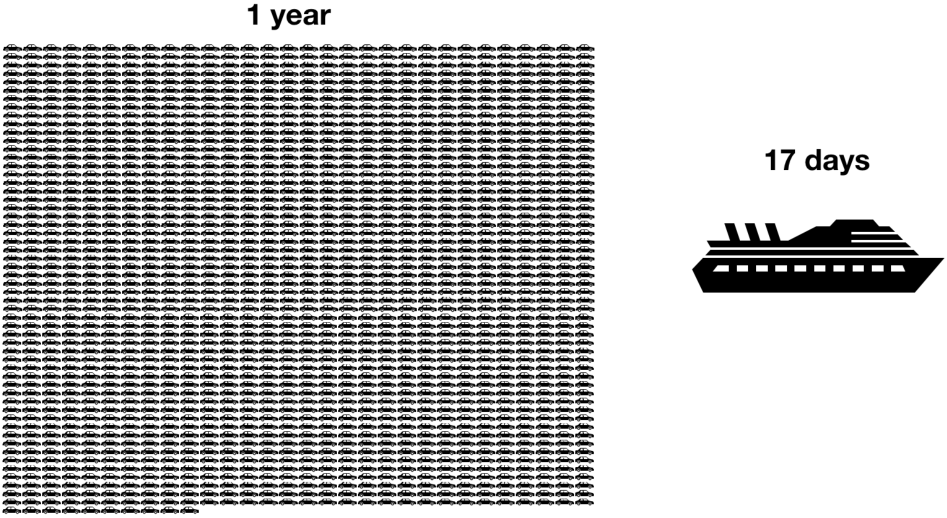


Figure 1.1: The average annual consumption of 1600 petrol-driven passenger cars is equal to the consumption from a 17 days' cruise

1.1.2 Environmental Challenges

Even though shipping is both the most environmentally friendly and efficient transport mode (Vogler and Sattler 2016), it contributed 2.6 % of global emissions of CO_2 in 2012 (IMO 2014). The International Convention for the Prevention of Pollution from Ships (MARPOL) is an International Maritime Organization (IMO) convention, and consist of six annexes. Annex VI *Prevention of Air Pollution from Ships* states that from January 1st 2020, the new global limit for Sulphur Oxide (SOx) becomes 0.5 % [m/m]. In Emission Control Areas (ECA) the limit is 0.1 % [m/m]. Additionally, the global limit for emission of Nitrogen Oxide (NOx) became stricter in 2016. Using new and greener energy sources on vessels is a way to fulfill these requirements (Vautrain 2008). In addition, the Paris Agreement was signed in 2015, where 195 of the world's nations agreed to implement actions to prevent the global temperature rise not to exceed 2°C (UNFCCC 2015).

1.2 Alternative Solutions

According to a Life Cycle Assessment (LCA) developed by Ringvold (2017), fuel combustion has considerable environmental affect and ship propulsion accounts for approximately 80 % of the environmental impact from a container ship. It is reasonable to assume this will be about equivalent for a cruise vessel. HFO is, by know, the most used fuel due to its low costs and availability (Burel, Taccani, and Zuliani 2013). By utilization of another fuel with lower emissions of Greenhouse Gases (GHGs) and acid rain, ships may reduce their environmental footprint (Elgohary, Seddiek, and Salem 2015). Some of the alternative fuels are (Gilbert et al. 2018):

- Liquid Natural Gas (LNG)
- Hydrogen
- Methanol
- Straight Vegetable Oil (SVO)
- Ammonia
- Biodiesel

As an alternative to traditional combustion engines, Fuel Cells (FCs) are assumed to be one of the most auspicious future technologies (Biert et al. 2016). When a fuel is utilized through an internal combustion engine, chemical energy is converted to electricity via thermal and mechanical energy. On the other hand, there is a direct conversion of chemical energy into electricity in FCs. Hence, the latter one is assumed to be most efficient (Biert et al. 2016). Another alternative is use of batteries. According to Hansen and Wendt (2015), for several vessels types, such as ferries, electric ship propulsion is one of the most efficient propulsion alternative. Both FCs driven by hydrogen and batteries causes zero emissions during operation (Biert et al. 2016). A challenge by use of batteries for big vessels, including cruise vessels, is that the size of the battery package might be very big and may take several hundred times larger place than a traditional vehicle battery (Mjøs et al. 2016). However, the placing of batteries and FCs are more flexible than for a traditional combustion engine (Mjøs et al. 2016) and (Tronstad et al. 2017).

Both LNG, hydrogen and methanol can be utilized through an FC, and will, according to Gilbert et al. (2018), reduce emissions of Sulphur Oxide (SOx), Nitrogen Oxide (NOx), Particulate Matter (PM) and Carbon Dioxide (CO_2). By use of hydrogen in an FC, there will be no emissions during operation. Methanol or LNG as fuel will cause some emission of CO_2, and in some cases NOx, during operation (Tronstad et al. 2017). However, an environmental friendly production is crucial to maintain a small environmental footprint (Jafarzadeh and Schjølberg 2017).

1.3 Objective and Scope

As mentioned above, there are several alternatives to make the ship industry more environmental friendly. The objective of this thesis is to evaluate whether hydrogen, LNG or methanol, all utilized through an FC, is the best fuel for an FC on a cruise vessel. The various fuels will be evaluated based on three criteria:

- **Required space**
  The objective is to compare the various fuel's specific energy per volume and efficiency. This gives information about necessary area for the various fuels. Furthermore, required space for FCs, and possible the reformer, should be determined. Finally, main dimensions obtained by utilization of the various fuels should be determined.
- **Environmental aspect**
  The objective is to compare emissions during the fuels' life cycle to determine which fuel has smallest environmental impact.
- **Economical aspect**
  The objective is to compare the Life Cycle Costs (LCC) the various fuels cause.

1.4 Limitations

Regarding emissions, pollution to air is in focus in this thesis. Pollution to sea will be disregarded, though it is an important field. The thesis should not deal with hydro dynamical- and propulsion solutions to save energy.

For all of the evaluation criteria, HFO utilized through a combustion engine is used as benchmark.

Due to the workload, the hydrogen, LNG and methanol are mainly evaluated as utilized through an FC. However, Chapter 8 includes a comparison of the fuels utilized in both FCs and combustion engine.

The thesis will not compare utilization of fuels in an FC versus in a combustion engine.

1.5 Structure

Chapter 2 presents relevant literature, including information regarding pollution for ships, FCs, alternative fuels and relevant regulations.

Chapter 3 explains the methods utilized to obtain the results. The methods explained are System Based Ship Design (SBSD), LCA and LCC.

Chapter 4 provides information about the assumed sailing route and system information for the thesis.

Chapter 5 describes the machinery configuration, including machinery requirements, efficiencies and FC selection.

Chapter 6 presents required tank sizes and main dimensions caused by utilization of the various fuels.

Chapter 7 contains an environmental evaluation by an LCA. Furthermore, it includes a comparison of utilization of fuels in an FC and a combustion engine. The last part of the chapter provides a production comparison of LNG, Liquid Bio Gas (LBG), methanol and bio-methanol.

Chapter 8 presents LCCs and Required Freight Rate (RFR) for the alternative fuels.

Chapter 9 provides discussion of the results and the various aspects in the thesis.

Chapter 10 includes concluding remarks and recommendation of further work.

Chapter 2

Literature Review

This chapter presents relevant literature within the fields pollution from ships, FCs, alternative fuels and regulations. When collecting relevant information, it is of importance to be sure that sources are reliable and contain a certain quality. The main search tools used in this thesis are the two databases Oria and Scopus. All articles in Oria are controlled, and through NTNU one can get access to most of the full texts. Scopus is an Elsevier database which contains journals, books and conference proceedings. In both Oria and Scopus the result can be filtered based on author, date of publication, document type and subject area, to mention some of them.

Additionally, DNV GL has several publications regarding alternative fuels. These publications have been of good use, by the very fact that they often include history, technical information and regulations. DNV GL's *Study on the use of fuel cells in shipping* developed by Tronstad et al. (2017) for EMSA and *LNG as ship fuel* developed by Erhorn et al. (2015) have been particularly useful.

2.1 Pollution From Ships

Shipping provides pollution, and the main emissions that will be considered in this thesis are:

- CO_2
- Methane (CH_4)
- Nitrous Oxide (N_2O)
- SOx

  - NOx
  - PM
  - Volatile Organic Compounds (VOC)

CO_2, N_2O and CH_4 are all GHGs, which means that absorbed infrared radiation from these chemicals result in the greenhouse effect (Amdahl, Endal, et al. 2014). Figure 2.1 illustrates how the atmosphere emits short wave sun rays, and that some of the sun's rays are reflected back from the earth to the atmosphere, which is the yellow line in the figure. The red line illustrates how some of the infrared radiation is absorbed from the GHGs.

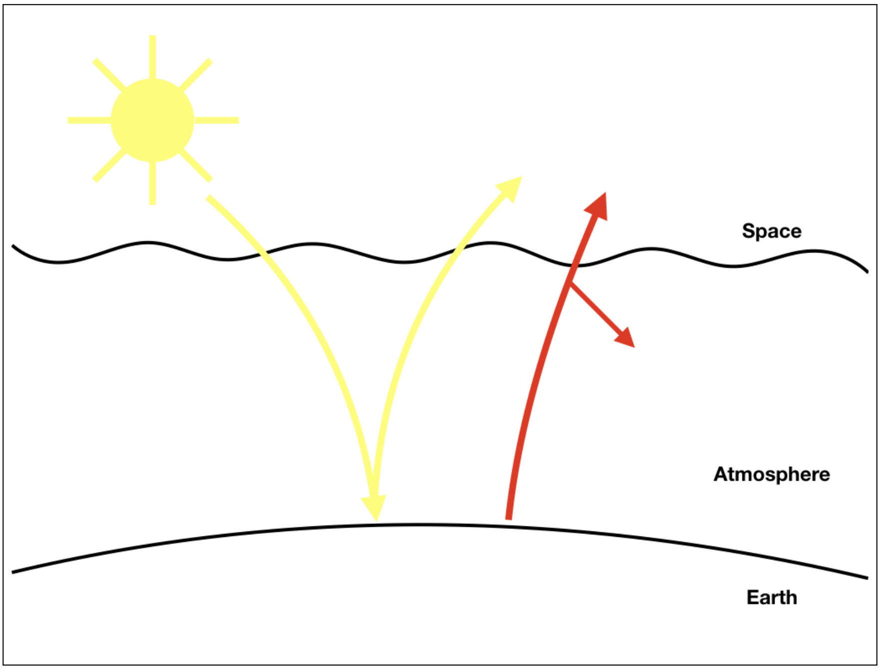


Figure 2.1: Illustration of the greenhouse effect

A percentage distribution of the three main GHGs can be seen in Figure 2.2 (Azhar Khan et al. 2014).

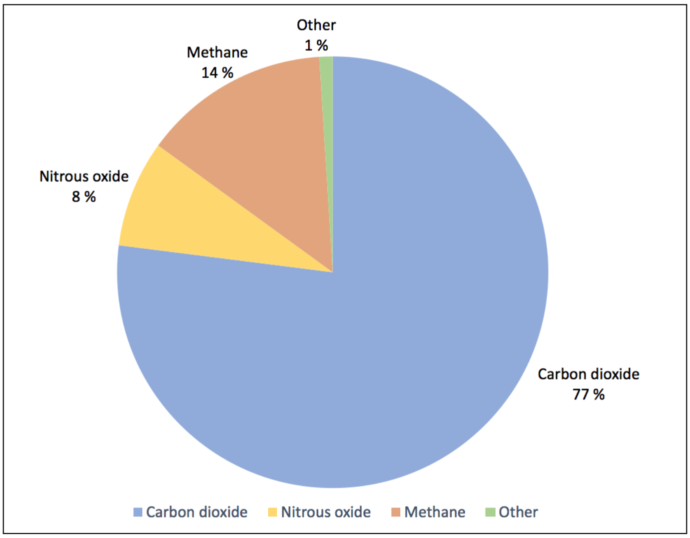


Figure 2.2: Percentage distribution of the three main GHGs. Based on: Azhar Khan et al. (2014)

CO_2 is of most significance of the GHGs. The gas is naturally produced and is a part of the photosynthesis. Thus, the gas can also be produced by humans. By combustion of coal, gas and oil, the amount of CO_2 increases to an abnormal level. Further, this will interrupt the normal heat balance on earth. In a combustion process, the relationship between consumption of fuel and amount of carbon in the fuel is proportional with the emission of CO_2. For a normal diesel engine, this is about 85 % of the fuel weight. By having this relationship and weighting, 1 kg fuel will result in approximately 3.1 kg emission of CO_2 (Amdahl, Endal, et al. 2014).

Among the GHGs, CH_4 is the one with second highest emission. Nevertheless, CH_4 has higher energy absorption than CO_2, and has 25 times higher 100-year Global Warming Potential (GWP_{100}). It is therefore considered as 25 times more harmful per unit. N_2O has a GWP_{100} of 298, which means it is significantly more harmful to the environment per unit than CO_2 and CH_4 (Myhre et al. 2013).

A summary of GWP_{100} for the main GHGs can be seen in Table 2.1 (Myhre et al. 2013).

Table 2.1: GWP_{100} values for CO_2, CH_4 and N_2O. Source: Myhre et al. (2013)

GHG	GWP_{100}
CO_2	1
CH_4	25
N_2O	298

Both NOx and SOx cause acid rain. While SOx is the main source to acid rain, NOx simultaneously creates disturbances in the ozone layer. PM are microscopic and either liquid or solid particles in the atmosphere. (Amdahl, Endal, et al. 2014).

VOCs are a chemical connection which may cause both decomposition of the ozone layer and respiratory disorders for humans (Amdahl, Endal, et al. 2014). It is expected that the emissions of VOCs will increase by 49 % within 2020, compared to the levels in 2005 (Huang et al. 2014).

2.2 Fuel Cell

An FC consist of an anode and a cathode with an electrolyte between them. In the process, chemical energy will convert to water and electrical energy. The most common way to produce energy through FCs today are by hydrogen and oxygen (Sharaf and Orhan 2014). An illustration of a general Proton Exchange Membrane Fuel Cell (PEMFC) can be seen in Figure 2.3.

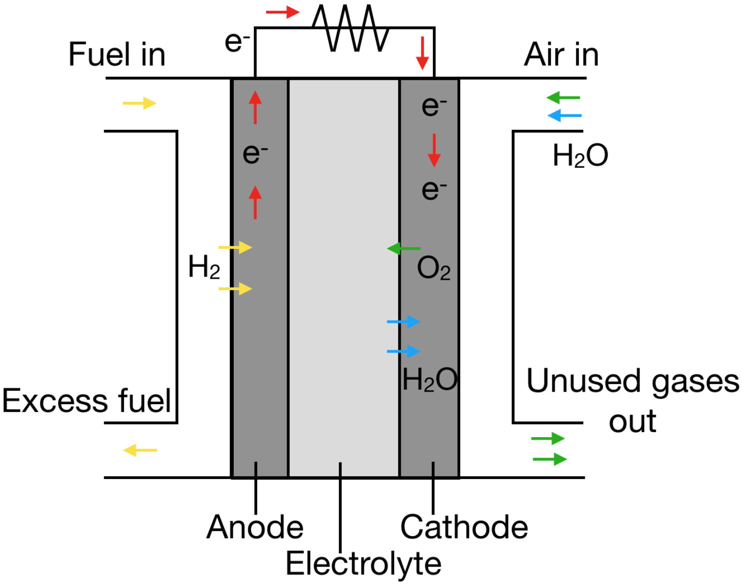


Figure 2.3: Illustration of an PEMFC. Based on: Sharaf and Orhan (2014)

There are several advantages by use of FCs. Sharaf and Orhan (2014) have in their work mentioned some of the advantages and challenges:

- \+ Renewable sources and modern energy carriers can be utilized
- \+ FCs are assumed to be the most flexible chemical-to-electrical energy conversion
- \+ Both noise emissions and vibrations will get reduced compared to traditional combustion engines
- \+ FCs are more efficient than traditional combustion engines
- \+ FCs leads to reduced harmful emissions during operation compared to traditional combustion engines. During operation, water, heat and electricity will be the only output from a FC fuelled with hydrogen. Anyway, emissions during production of fuels should be taken into consideration when evaluating the clean nature of FCs
- \- Immature infrastructure, specially for hydrogen
- \- Expensive compared to traditional combustion engines
- \- Relatively high system weight and size
- \- Safety concerns

According to Von Spakovsky and Olsommer (2002), FCs are the principal energy conversion system which provides second highest exergy efficiency, while hydroelectric plants provides the highest.

While stationary land-based FCs must fulfill general requirements, FC systems in maritime usage have to fulfill mainly three extended requirements (Vogler and Sattler 2016):

- **Environmental conditions**
  The environmental conditions at sea may often be tougher than on land, which the FC should endure. Challenging factors are among other things salty water, humid air, oil and vibrations. In addition, they must handle accelerations due to weather conditions. These accelerations may result in both longitudinal and transverse inclinations, where the vessel should resist heels up to 22.5° and 10°, respectively.
- **Power demand and efficiency**
  The electrical efficiency of an FC must be higher than 40 %, this to be economical competitive to conventional diesel engines.
- **System integration into a vessel**
  It is well known that the space in an engine room is limited, and a lot of equipment should be placed there. Firstly, there should be enough space for both maintenance and replacement of parts of, or the whole, system. Secondly, the electrical and thermal integration to the system must be considered.

For FCs in maritime applications, there are mainly five fuels that may be used (Vogler and Sattler 2016):

- LNG
- Liquid Petroleum Gas (LPG)
- Methanol
- Hydrogen
- Synthetic fuel

2.2.1 Fuel Cell Technologies

FCs can be divided into different types based on the material used in their membrane. They differ in power output, operation temperature, start-up time, typical applications and electrical deficiencies. The seven most common FCs are (Tronstad et al. 2017):

- Alkaline Fuel Cell (AFC)
- Proton Exchange Membrane Fuel Cell (PEMFC)
- Direct Methanol Fuel Cell (DMFC)
- High Temperature Proton Exchange Membrane Fuel Cell (HT-PEMFC)
- Phosphoric Acid Fuel Cell (PAFC)
- Molten Carbonate Fuel Cell (MCFC)
- Solid Oxide Fue Cell (SOFC)

These can further be divided into three main groups, as presented in Table 2.2 (de-Troya et al. 2016). High Temperature Fuel Cells (HT-FCs) are of interest in maritime usage, due to its low fuel consumption and the overall efficiency can be increased by utilization of energy from heat recovery. In addition, the engines can operate directly with both synthetic fuel and gas (Vogler and Sattler 2016).

Table 2.2: Three main groups of FCs. Source: de-Troya et al. (2016)

Level	Temperature [°C]	FCs
Low Temperature Fuel Cell (LT-FC)	Approximately 80	AFC, PEMFC, DMFC
Intermediate temperature FC	Approximately 200	PAFC, HT-PEMFC
HT-FC	650-1000	MCFC, SOFC

The various types of FCs are described in Table 2.3-2.9, where all information is found from Tronstad et al. (2017), Vogler and Sattler (2016), de-Troya et al. (2016), Sharaf and Orhan (2014) and Biert et al. (2016).

Table 2.3: Description of AFC

Alkaline Fuel Cell	
Anode	Nickel
Cathode	Silver supported on carbon
Advantages	Low cost Can operate in a wide range of temperature Rapid start up
Challenges	If the CO_2 in the fuel react with the alkaline electrolyte, the efficiency will be reduced and eventually the cell will be blocked by potassium carbonate. Because of this, there will be need of CO_2 separation by air operations, i.e. requires pure oxygen and pure hydrogen The electrolyte is highly corrosive
Temperature [°C]	0-230
Fuel	Hydrogen Other fuels have to be transformed to hydrogen before usage
Need of reformer	Yes, external reformer when utilization of other fuels than hydrogen
Output	Electricity and water
Electrical efficiency	60-70 %
Fuel cell reactions	
Anode reaction	$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^-$
Cathode reaction	$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$
Total reaction	$2H_2 + O_2 \rightarrow 2H_2O$

Table 2.4: Description of PEMFC

Proton Exchange Membrane Fuel Cell	
Anode	Platinum supported on carbon
Cathode	Platinum supported on carbon
Advantages	High power densities and good transient performance Corrosion is not a problem, considering water is the only liquid in the FC Water is the only emission by use of hydrogen as fuel Material requirements are not that strict due to low operation temperature The low temperature allows flexible operations, such as rapid start ups
Challenges	Platina is required to catalyze the chemical reaction Limited tolerance to fuel impurities The cost is relatively high because of the platinum catalyst A pure hydrogen source is needed, because of risk of Carbon Monoxide (CO) and Sulphur (S) poisoning
Temperature [°C]	50-100
Fuel	Hydrogen Other fuels have to be transformed to hydrogen before usage
Need of reformer	Yes, external reformer when utilization of other fuels than hydrogen
Output	Electricity and water
Electrical efficiency	Hydrogen operation: 50-60 % NG operation: 35-40 %
Fuel cell reactions	
Anode reaction	$2H_2 \rightarrow 4H^+ + 4e^-$
Cathode reaction	$O_2 + 4H^+ + 4e^- \rightarrow 4H_2O$
Total reaction	$2H_2 + O_2 \rightarrow 2H_2O$

Table 2.5: Description of DMFC

Direct Methanol Fuel Cell	
Anode	Platinum-Ruthenium supported on carbon
Cathode	Platinum supported on carbon
Advantages	Methanol can be used directly in the FC, without any transformation Handling and storing is easier for methanol than for hydrogen and LNG Compact size
Challenges	Low efficiency and power output Requires large amount of platinum due to the directly reforming of methanol in the FC Fuel and water crossover Complex water management
Temperature [°C]	50-120
Fuel	Methanol Other fuels have to be transformed to methanol before usage
Need of reformer	Yes, external reformer when utilization of other fuels than methanol
Output	Electricity, water and CO_2
Electrical efficiency	35-60 %
Fuel cell reactions	
Anode reaction	$CH_3OH + 2H_2O \rightarrow 6H^+ + CO_2 + 6e^-$
Cathode reaction	$3/2\ O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$
Total reaction	$CH_3OH + 3/2\ O_2 \rightarrow CO_2 + 2H_2O$

Table 2.6: Description of HT-PEMFC

High Temperature Proton Exchange Membrane Fuel Cell	
Anode	Platinum-Ruthenium supported on carbon
Cathode	Platinum-Ruthenium supported on carbon
Advantages	Decreased system cost due to reduced complexity Increased total efficiency due to simplified heat management Reduced risk for poisoning of CO and S Water management is not needed
Challenges	Lower power density than for a PEMFC Expensive catalyst Is impossible to cold start Moisture issues
Temperature [°C]	110-200
Fuel	Hydrogen Other fuels have to be transformed to hydrogen before usage
Need of reformer	Yes, external reformer when utilization of other fuels than hydrogen
Output	Electricity and water
Electrical efficiency	50-60 % The overall efficiency can be increased by increased utilization of energy from heat recovery.
Fuel cell reactions	
Anode reaction	$2H_2 \rightarrow 4H^+ + 4e^-$
Cathode reaction	$O_2 + 4H^+ + 4e^- \rightarrow 4H_2O$
Total reaction	$2H_2 + O_2 \rightarrow 2H_2O$

Table 2.7: Description of PAFC

Phosphoric Acid Fuel Cell	
Anode	Platinum supported on carbon
Cathode	Platinum supported on carbon
Advantages	May be considered as the most mature FC technology Higher operating temperature reduces platinum loading and increases CO tolerance High efficiency by use of heat recovery
Challenges	The FC is both large and heavy due to low power density Slower start up compared to LT-FC Use of LNG or methanol as fuel leads to some emission of CO_2 and NOx during the reforming phase
Temperature [°C]	140-200
Fuel	Hydrogen LNG Methanol
Need of reformer	Yes, external reformer when utilization of other fuels than hydrogen
Output	Electricity. When use of a reforming unit, there will also be emission of CO_2 and NOx
Electrical efficiency	40 % With heat recovery: 80 %
Internal reforming of LNG	
Steam reforming Water-gas-shift	$CH_4 + H_2O \rightarrow CO + 3H_2$ $CO + H_2O \rightarrow CO_2 + H_2$
Fuel cell reactions	
Anode reaction Cathode reaction Total reaction	$2H_2 \rightarrow 4H^+ + 4e^-$ $O_2 + 4H^+ + 4e^- \rightarrow 4H_2O$ $2H_2 + O_2 \rightarrow 2H_2O$

Table 2.8: Description of MCFC

Molten Carbonate Fuel Cell	
Anode	Nickel Chromium
Cathode	Lithiated nickel oxide
Advantages	High efficiency Fuel flexibility Energy recovery system is suitable due to the high temperature Does not need platinum as catalyst
Challenges	Slow start up Less flexibility towards changing power demands compared to LT-FC. Combining MCFC with batteries leads to a more stable operation and faster start up Large size compared to other FC systems Low durability
Temperature [°C]	600-700
Fuel	Hydrogen LNG Methanol Flue gases from coal
Need of reformer	No
Output	Electricity and water When use of another fuel than hydrogen, there will also be emission of CO_2
Electrical efficiency	50 % With heat recovery: Up to 85 %
Internal reforming of LNG	
Steam reforming Water-gas-shift Total reaction	$CH_4 + H_2O \rightarrow CO + 3H_2$ $CO + H_2O \rightarrow CO_2 + H_2$ $CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$
Fuel cell reactions	
Anode reaction Cathode reaction Total reaction	$2H_2 + 2CO_3^{2-} \rightarrow 2H_2O + 2CO_2 + 4e^-$ $O_2 + 2CO_2 + 4e^- \rightarrow 2CO_3^{2-}$ $2H_2 + O_2 \rightarrow 2H_2O$

Table 2.9: Description of SOFC

Solid Oxide Fuel Cell	
Anode	Nickel yttrastabilized zirconia composite
Cathode	Strontium-doped lanthanum manganite
Advantages	High efficiency Energy recovery system is suitable due to the high temperature Fuel flexibility
Challenges	Slow start up Less flexibility towards changing power demands compared to LT-FC. Combining SOFC with batteries leads to a more stable operation and faster start up By today, this FC has high cost Strict material requirements
Temperature [°C]	500-1000
Fuel	Hydrogen LNG Methanol Hydrocarbons as diesel
Need of reformer	No
Output	Electricity and water When use of another fuel than hydrogen, there will also be emission of CO_2
Electrical efficiency	60 % With heat recovery: 85 %
Internal reforming of LNG	
Steam reforming	$CH_4 + H_2O \rightarrow CO + 3H_2$
Water-gas-shift	$CO + H_2O \rightarrow CO_2 + H_2$
Total reaction	$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$
Fuel cell reactions	
Anode reaction	$2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^-$
Cathode reaction	$O_2 + 4e^- \rightarrow 2CO^{2-}$
Total reaction	$2H_2 + O_2 \rightarrow 2H_2O$

When LNG or methanol is used as fuel and there is no internal reforming, the reformation has to take place in an external reformer. The reactions for LNG and methanol can be seen Table 2.10 (Tronstad et al. 2017) and (Speight 2011).

Table 2.10: Reactions when reforming LNG and methanol to hydrogen

Reformation of LNG	
Steam reforming	$CH_4+H_2O \rightarrow CO+3H_2$
Water-gas-shift	$CO+H_2O \rightarrow CO_2+H_2$
Total reaction	$CH_4+2H_2O \rightarrow CO_2+4H_2$
Reformation of methanol	
Steam reforming	$CH_3OH+H_2O \rightarrow 3H_2+CO_2$
Water-gas-shift	$CO+H_2O \rightarrow CO_2+H_2$
Total reaction	$CH_3OH+CO_2 \rightarrow 2H_2+CO_2$

Tronstad et al. (2017) carried out a ranking of the described FCs, based on following criteria:

- Relative cost to other FCs
- Power levels (kW) for largest available module
- Lifetime
- Tolerance for cycling
- Flexibility towards type of fuel
- Technological maturity
- Physical size
- Sensitivity for fuel impurities
- Emissions
- Safety aspects
- Efficiency (Electrical and total including heat recovery if applicable)

In the evaluation, PEMFC, HT-PEMFC and SOFC received highest score and are assumed as the most promising FC technologies for maritime applications.

2.2.2 Fuel Cell Projects

Tronstad et al. (2017) have collected information about FC projects in the maritime sector, and found 23 projects, all presented in Appendix A.1. Among them are:

- 10 using hydrogen as fuel
- 3 using methanol as fuel
- 2 using LNG as fuel

The Fuel Cell Industry Review is a yearly publication by E4tech. The publications address, among other things, FCs in various applications and shipments of FCs. Figure 2.4 and 2.5 illustrates the development of shipments by FC type and shipped MWs per FC type, respectively (*The Fuel cell Industry Review 2017* 2018). Note that this measure is for all markets, and not only in shipping. Specific values can be found in Appendix A.2

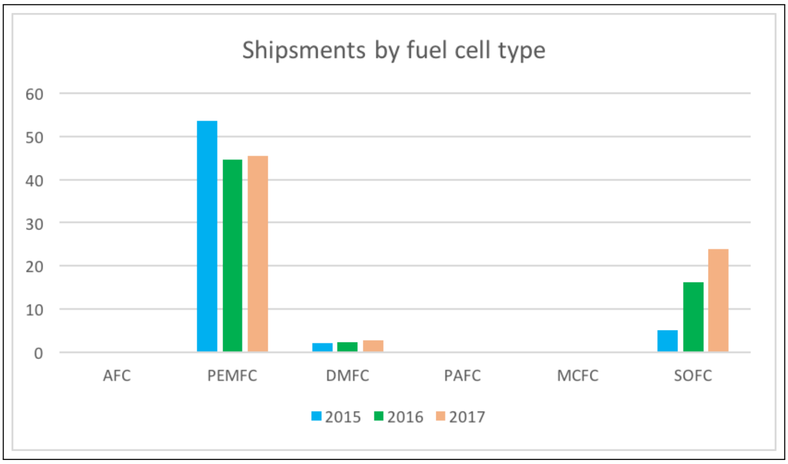


Figure 2.4: Shipments by FC type (1,000 units) 2015-2017. Based on: *The Fuel cell Industry Review 2017* (2018)

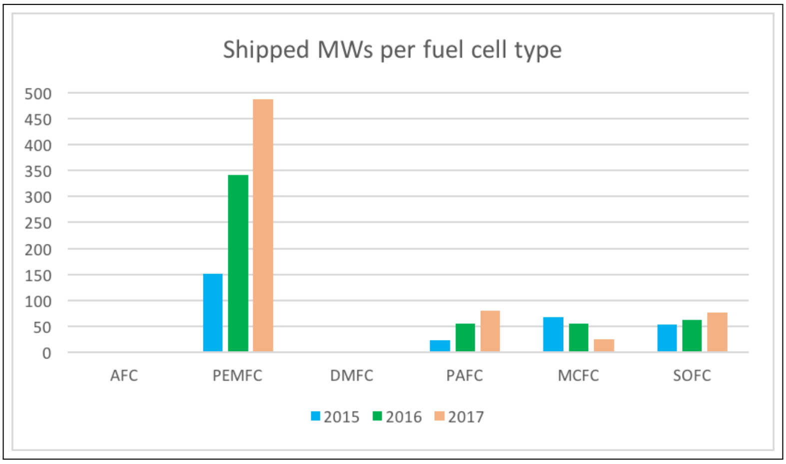


Figure 2.5: Shipped MWs by FC type 2015-2017. Based on: *The Fuel cell Industry Review 2017* (2018)

2.3 Hydrogen

2.3.1 General

Hydrogen (H_2) is both the first- and lightest element in the Periodic Table. At standard pressure, hydrogen is colorless, odorless and nontoxic, but also especially flammable (Suleman, Dincer, and Agelin-Chaab 2015). Because hydrogen can store energy, it can be considered as an energy carrier rather than an energy source (Jafarzadeh and Schjølberg 2017). Hydrogen can be utilized as power for ship propulsion through an internal combustion engine or an FC. In this thesis hydrogen will be considered as used in an FC, which will not provide any emissions during operation.

Even though hydrogen requires more space than HFO, it has much higher energy density. While the energy density for HFO is approximately 43 kJ/g, it is approximately 142 kJ/g for hydrogen, i.e. more than three times higher. These characteristics are some of the reason why hydrogen utilized in an FC is considered as the most promising solution from an environmental point of view (Jafarzadeh and Schjølberg 2017).

2.3.2 Production

Producing hydrogen in a sustainable way is challenging. Even though hydrogen does not exist naturally, it can be found in combination with oxygen from water and carbon from hydrocarbons. Thus, hydrogen can be produced from:

- **Splitting hydrocarbons**
  A hydrocarbon consists of hydrogen- and carbon atoms, and hydrogen can be produced by splitting hydrocarbons. If the carbon does not get captured during the splitting process, GHGs will be emitted, causing GHG emissions during production instead of during operation (Jafarzadeh and Schjølberg 2017). Fossil fuels are hydrocarbons, and the most common are coal and NG.
- **Renewable sources**
  Hydrogen can be produced from renewable sources, such as solar, wind, hydro, geothermic and biomass through an electrolysis. The electrolysis split water into its two elements, hydrogen and oxygen. (Veneri 2011). The environmental impact may be reduced significantly by producing hydrogen from renewables instead of splitting hydrocarbons (Jafarzadeh and Schjølberg 2017). The Norwegian coast has a great potential for production of hydrogen in a renewable way by hydro- or wind power (Meier 2014).
- **From synthesized hydrogen carriers** Additionally, hydrogen can be produced from synthesized hydrogen carriers, as for instance methanol, ammonia and synthetic fuels (Veneri 2011).

Information in Table 2.11 is found from Veneri (2011), and presents a distribution of the world's hydrogen production from various sources. As both NG, refinery oil and coal are hydrocarbons, as much as approximately 96 % of produced hydrogen will release carbon dioxide emission, assuming it is not captured.

Table 2.11: World hydrogen production from various sources. Source: Veneri (2011)

Raw material	%
Natural Gas (NG)	48
Refinery oil	30
Coal	18
Water electrolysis	4

2.3.3 Storage

According to A. Züttel (2004), hydrogen can be stored in 6 different ways:

- In high-pressure gas cylinders
- As liquid hydrogen in cryogenic tanks
- Absorbed hydrogen on materials with a large specific surface area
- Absorbed on interstitial sites in a host metal
- Chemically bonded in covalent and ionic compounds
- Through oxidation of reactive metals with water

Compressed hydrogen is normally stored at 350 or 700 bar (Vogler and Sattler 2016). When hydrogen is stored as liquid, or cryogenic as it often is referred to, it should have a temperature of at least -253°C (Biert et al. 2016). This is only 20.15°C above absolute zero, and requires a lot of energy during production (A. Züttel 2004).

The volume density for hydrogen is higher as liquid than compressed, i.e. compressed hydrogen requires more storage space (Hua et al. 2011). Furthermore, compressed hydrogen is very explosive, and it is therefore preferable to place the fuel tanks on deck in tanks with thick skin. In case of storage below deck, strict regulations should be followed regarding ventilation and ex-equipment (Tronstad et al. 2017).

Both stability and available space is challenging on cruise vessels. Taking both space and stability into account, it is in this thesis determined to store the hydrogen as cryogenic aboard the vessel, which will be further considered in this thesis.

2.3.4 Infrastructure

According to Kristian Vik, Secretary General in Norwegian Hydrogen Forum, there is none hydrogen bunkering stations for maritime usage. Norway had 9 hydrogen stations at 22th of December 2017, though they are for vehicles (Norsk Hydrogenforum 2018). As it seems now, it is Norway, Japan and California that is leading regarding development of a hydrogen infrastructure for maritime applications.

2.4 Methanol

2.4.1 General

Methanol (CH_3OH) has the easiest structure of the alcohols. Due to its similarity to gas- and diesel fuels regarding non-technical factors, such as transportation, methanol is assumed to be one of the most preferable fuels in the future (Gong et al. 2011), and can both be produced from NG and biomass. Methanol is easy to handle, specially in comparison with hydrogen and LNG, considering methanol is liquid at standard temperature and pressure (Brynolf, Fridell, and Andersson 2014). Additionally, methanol can be transported in regular product tankers.

There are several possibilities for methanol utilized as power for ship propulsion, and it can be utilized in both two- and four-stroke diesel engines, Otto engines and FCs. Regarding technology, methanol is a flexible fuel, considering all these possible prime movers. Based on which concept that is used, the emissions and energy efficiency can vary (Brynolf, Fridell, and Andersson 2014).

2.4.2 Production

Production of methanol in a renewable way is, as for hydrogen, challenging. Methanol can be produced from (Biert et al. 2016):

- Natural,- coal,- and synthetic gas
- Hydrogen with CO_2
- Biomass, which may be destructive distillation of wood and agriculture products (Deniz and Zincir 2016)

Biert et al. (2016) have found that the bulk of methanol is produced from NG.

Since 1997, there has been large scale production of methanol from NG at Tjeldbergodden, Norway. The production plant has a production capacity of about 900 000 tons methanol per year (Statoil 2018).

2.4.3 Storage

Considering methanol is liquid at standard pressure, storage is normally not a problem and it can be stored in the same way as MDO and HFO (Deniz and Zincir 2016).

2.4.4 Infrastructure

Due to methanol's properties, the configuration of bunkering- station and system is more advanced compared to conventional fuels (DNV GL 2016). According to DNV GL (2016), all technology factors needed for bunkering of methanol is mature. Anyway, considering that methanol is liquid, as HFO, only minor modifications is needed to handle methanol in existing bunkering infrastructure (Andersson and Salazar 2015).

2.5 Liquid Natural Gas

2.5.1 General

LNG as ship fuel is an available solution, and several vessels in operation makes use of it today. These are vessels within different sections, including ferries, offshore vessels, towboats and freight vessels, to mention some of them. The gas mixture used in LNG engines consists primarily of methane (Erhorn et al. 2015).

LNG can be utilized in gas-only engines, dual-fuel four-stroke and two-stroke, and FCs (Erhorn et al. 2015) and (Tronstad et al. 2017). Methane slip is a concern with LNG as fuel, which is a consequence of unburned methane which occurs at low engine loads. A dual-fuel engine combines both a diesel engine and an Otto engine, and will switch from compressing gas to burn diesel at low loads. Nevertheless, according to Tronstad et al. (2017), LNG utilized through an FC will only cause emissions of CO_2, and in some cases NOx, during operation.

2.5.2 Production

LNG can be produced from (Deniz and Zincir 2016):

- Biomass
- Synthesized from CO_2
- Renewable hydrogen
- Fossil fuels, which is the the most common way of production (Biert et al. 2016)

LNG is normally referred to as LBG when produced from biomass. LBG is methane based, and can be used in the same way as LNG is marine applications (Brynolf, Fridell, and Andersson 2014).

In Norway, huge amounts of LNG is produced at Melkøya outside Hammerfest. The gas is transported in pipelines from Snøhvitfeltet, and then transformed to LNG at the Melkøya plant (Norsk Petroleum 2018).

2.5.3 Storage

To remain liquid, LNG has to be stored below -162°C at environmental pressure. Alternatively, it may be compressed (Deniz and Zincir 2016). Biert et al. (2016) found that the optimum storage temperature for LNG is about -165.8°C. Due to space, it is most common to store LNG as liquid, which also is considered in this thesis.

LNG can basically be stored in the same ways as hydrogen, considering they are both cryogenic.

2.5.4 Infrastructure

The infrastructure for LNG is expanding, caused by a larger market demand (Deniz and Zincir 2016).

The infrastructure for LNG in Norway can be seen in Table 2.12 (Energigass Norge 2015).

Table 2.12: LNG infrastructure in Norway. Source: Energigass Norge (2015)

Place	Owner	Storage capacity [m^3]
Bunker terminals		
Hammerfest	Barents Naturgass	250
Lødingen	Barents Naturgass	250
Moskenes	Barents Naturgass	250
Bjugn	Marine Harvest	750
Kristiansund	Vestbase	400
Florø	Saga Fjordbase	500
Mongstad	Gasnor	1000
Ågotnes	Gasnor	500
Os	Gasnor	1000
Stavanger	Skangas	3000
Industry terminals prepared for bunkering		
Bodø	Barents Naturgass	130
Mosjøen	Gasnor	3500
Tjeldbergodden	AGA	-
Sunndalsøra	Gasnor	1400
Ålesund	Naturgass Møre	1400
Høyanger	Gasnor	400
Stord	SKL Naturgass	100
Husnes	Gasnor	500
Lista	Gasnor	750
Porsgrunn	Skagerak Naturgass	1000
Sandefjord	Skagerak Naturgass	250
Drammen	Skagerak Naturgass	150
Fredrikstad	Skangas	6500
Bunkering terminals which are planned/under construction		
Hitra	Gasnor	1000
Karmøy	Gasnor	-
Kristiansand	Gasnor	700

2.6 Environmental Regulations

2.6.1 General

Several countries agreed that the best way to implement safety at sea was everyone to conduct the same regulations. Based on this, United States Convention established IMO in 1948, and the regulations entered into force in 1958. Currently IMO has 173 Member States, where all of them have to follow IMO's regulations (IMO 2017a). IMO consist of several conventions and protocols. The key conventions are (IMO 2017c) and (Asbjørnslett 2017):

- **International Convention of the Safety of Life at Sea (SOLAS)**
  SOLAS was the first IMO convention, and entered into force in 1980. The focus in SOLAS is to specify minimum standards for construction, equipment and operation of ships, this to insure safety.
- **International Convention for the Prevention of Pollution from Ships (MARPOL)**
  MARPOL entered into force in 1983, and specifies regulations to protect the environment against pollution.
- **International Convention of Standards of Training, Certification and Watchkeeping for Seafarers (STCW)**
  STCW entered into force in 1984 and specifies minimum standards for training, certification and watchkeeping.

As IMO cannot control the international safety regulations, this is handed over to Flag States. Their responsibility is to control the vessel's construction and maintenance. Often, they delegate these tasks to classification societies to ensure quality (Knudsen and Hassler 2011). Both Flag States and classification societies may have stricter regulations than IMO.

To prevent for unlimited pollution from vessels, some regulations shall be followed. MARPOL and the Paris Agreement are the most relevant environmental regulations.

2.6.2 MARPOL

MARPOL is the IMO convention of current interest regarding environmental regulations. The convention consists of six Annexes, each describing rules and regulations for minimizing pollution from ships. These are (IMO 2017b):

- **Annex I**
  Regulations for the Prevention of Pollution by Oil
- **Annex II**
  Regulations for the Control of Pollution by Noxious Liquid Substances in Bulk
- **Annex III**
  Prevention of Pollution by Harmful Substances Carried by Sea in Package Form
- **Annex IV**
  Prevention of Pollution by Sewage from Ships
- **Annex V**
  Prevention of Pollution by Garbage from Ships

- **Annex VI**
  Prevention of Air Pollution from Ships

Annex VI is the one being applied in this thesis. Among the 25 regulations Annex VI consists of, regulation 13 and 14 are of most relevance in this work. These regulations deal with emissions of NOx and SOx during operation. However, ECAs should firstly be clarified.

ECAs are established for stricter regulations regarding emissions of SOx, PM and NOx (Chang 2018). The areas covered by ECAs can be seen in Figure 2.6 (EGCSA 2017). Relevant for this thesis is the ECA in the North Sea, which has its validity up to latitude 62° North and until longitude 4° West. For the ECA region in the North Sea, only regulations regarding emissions of SOx should be taken into consideration, and the area may therefore also be called Sulphur Emission Control Area (SECA) (Chang 2018).

Figure 2.6: Illustration of ECAs. Source: EGCSA (2017)

Even though vessels must pass through an ECA, it is not practice that vessels follow the regulations through their whole sailing route, but only through the specified area.

Annex VI Regulation 13 covers emissions of NOx, and applies for all ships installed with a marine diesel engine with a power output of more than 130 kW (MARPOL 2016a).

Regulation 13 deals with emissions of NOx, where following are clarified:

> *"Subject to regulation 3 of this Annex, in an emission control area designated for TIER III NOx control under paragraph 6 of this regulation, the operation of a marine diesel engine that is installed on a ship:*
> *.1 is prohibited except when the emission of nitrogen oxides (calculated as the total weighted emission of NO_2) from the engine is within the following limits, where n = rated engine speed (crankshaft revolutions per minute) (MARPOL 2016a):*

.1 3.4 g/kWh when n is less than 130 rpm;

.2 $9 \cdot n^{-0.2}$ *when n is 130 or more but less than 2,000 rpm;*

.3 2.0 g/kWh when n is 2,000 rpm or more;"

Regulation 13 also provides precise exceptions and exemptions for whether the Annex should be applied or not.

Regulation 14 deals with emissions of SOx and PM. New general regulations stating the emission of SOx should not exceed 0.50 % [m/m] takes effect from January 1st, 2020. For ECAs, regulations which entered into force at January 1st, 2015, state that SOx emissions should not exceed 0.10 % [m/m] (MARPOL 2016b).

2.6.3 Paris Agreement

The Paris Agreement, further referred to as the Convention, was adopted at the Paris climate conference in December 2015, with purpose of GHG emission mitigation, adaption and support for developing countries conversion. It is the first legally binding global climate deal and 195 countries have ratified to the Convention. All countries which are part of the Convention aim to reach a global peaking of GHG as soon as possible. The long-term goal is to keep the global increase of temperature well below 2°C above pre-industrial levels. Nevertheless, efforts are being made in order to limit the temperature increase to 1.5°C above pre-industrial levels. Countries that are part of the Convention have committed to plan, determine and regularly report its own contribution (UNFCCC 2015).

2.7 Financial Expenses

2.7.1 NOx Expenses

NOx expenses apply to vessels with an overall engine power of more than 750 kW, and applies for emissions within Norwegian territorial waters. The rate for 2018 is 21.94 NOK per kilo emitted NOx. The NOx expenses do not apply for units connected to the environmental NOx agreement 2018-2025, vessels used for fishing and vessels in direct foreign trade (Skatteetaten 2018).

The environmental NOx agreement 2018-2025 is an agreement signed by 15 business communities May 24th, 2017. Communities in the NOx-fond contribute a payment rate to the fond instead of taxes to the government. Furthermore, the payments to the fond returns to the industry which initiates environmental measures (Staten v/Klima- og miljødepartementet 2017).

2.7.2 CO2 Expenses

Mineral oil, petrol, gas, NG and LPG produced in, or imported to, Norway shall be paid taxes on. Rates for 2018 can be seen in Table 2.13, where all prices are given in NOK. The taxes do not apply for vessels in direct foreign trade and bio-diesel (Skatteetaten 2017)

Table 2.13: Rates for CO_2 taxes in 2018. Source: Skatteetaten (2017)

Mineral product	Tax rate
Mineral oil, unmarked	5.08 pr. liter
Mineral oil, marked	2.96 pr. liter
Petroleum, free from sulphur	6.33 pr. liter
NG	1.00 pr. Sm^3
LPG	1.50 pr. kg

2.7.3 Financial Support

Both ENOVA and Innovation Norway may give financial support to companies investing in measures which directly causes an energy reduction (ENOVA 2018) and (Innovasjon Norge 2018).

According to Ingrid Aune, senior advisor in ENOVA, the amount of financial support depends on various factors. New technology is more expensive and contains higher risk, causing possibilities of more support. Furthermore, it is differentiated between small,- medium-sized- and large companies. A profitability assessment is developed for each individual case.

2.8 Regulations Regarding Cruise Ships

There are several regulations the vessel should follow. Regulations which are especially relevant for this thesis are mentioned in this chapter. Regarding safety, all regulations in SOLAS should be followed. According to SOLAS, ships carrying more than 12 persons are categorized as passenger ship, and should therefore follow regulations adapted for passenger ships.

2.8.1 Safe Return to Port

Regulation II-2/21 *Casualty threshold, safe return to port and safe areas* has been mandatory since 2010. The regulation is applicable for every ship constructed on and after 1 July 2010, having a length of 120 m or above, or having three or more main vertical zones (SOLAS 2014). The main objective of safe return to port is that in case of casualty or flooding, the ship should be able to return safe to port under its own power. Additionally, the rules have requirements to ensure that essential critical systems are working during orderly evacuations of the ship.

Essential system for safe return to port are, among others, propulsion including auxiliary system and fuel oil system. Safe return to port requires redundancy for these systems and segregation.

2.9 Fuel Cell Regulations

By now, there are no international conventions covering regulations regarding FCs as ship power. Though, in the January 2018 edition of DNV GL rules for classification and offshore standard there is an own section, *Section 3 Fuel Cell Installations - FC* (Karlsen 2018), dealing with regulations for FC installations.

2.9.1 Hazardous Areas

Hazardous areas occurs when having an explosive or flammable gas with a flash point below 60°C. These hazardous areas should be divided into three zones; Zone 0, 1 and 2. Definitions of these zones, according to DNV GL's rules, are presented below (DNV GL 2012):

> *"Zone 0*
> *Area in which an explosive gas atmosphere or a flammable gas with a flash point below 60°C is present continuously or is present for long periods*
> *Zone 1*
> *Area in which an explosive gas atmosphere or a flammable gas with a flash point below 60°C is likely to occur in normal operation*
> *Zone 2*
> *Area in which an explosive gas atmosphere or a flammable gas with a flash point below 60°C is not likely to occur in normal operation and, if it does occur, is likely to do so only infrequently and will exist for a short period only"*

Ignition sources cannot be placed inside a hazardous zone. Electrical equipment placed inside the hazardous zone should be certified for the specified zone. Typical places hazardous zones will be present are around direct gas- and ventilation outlets and in enclosed areas with gas sources (Erhorn et al. 2015).

2.10 Maritime Safety Committee Codes

Maritime Safety Committee (MSC) has adopted *International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk* (IGC Code) (IMO 1993) and *International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels* (IGF Code) (SOLAS 2017).

Chapter 4 in IMO (1993) concerns cargo containment. Since no other information regarding tanks for cryogenic fuels is found, it is assumed that these regulations are applicable for fuel tanks as well. The tanks can mainly be divided into 5 different tank types (IMO 1993) and (Central Commission for the Navigation of the Rhine and Oil Companies International Marine Forum 2010):

- **Integral tanks**
  These tanks form a primary structural part of the ship, and are affected by the loads coming onto the hull structure. These tanks shall not be used for fuels with boiling point below 10°C, and can therefore not be used for either LNG nor liquid hydrogen.
- **Membrane tanks**
  These tanks are non-self-supporting and based on a thin primary barrier, or membrane, which usually is 0.7-1.5 mm thick. Normally, membrane tanks have a more rectangular shape than other tanks.
- **Semi-membrane tanks**
  This is a variation of membrane tanks, which contains a thicker primary barrier. The tank is self-supporting when empty, and non-self-supporting in loaded condition.
- **Independent tanks**
  These tanks are self-supporting, both in loaded- and unloaded condition. Independent tanks can further be divided into three categories:
  - Type A
    Often constructed for plane surfaces. The tanks are mainly designed based on Recognized Standards. A secondary containment system is required, as the material of the tank is not crack propagation resistant. The pressure cannot exceed 0.7 bar.
  - Type B
    Often constructed for plane surfaces, but may also be designed as spherical or prismatic. The tanks are mainly designed based on model tests, analytically tools and analysis methods, with purpose of determine stress levels, fatigue life and crack propagation characteristics. Because of the analytically design, these tanks only require a drip tray as secondary barrier. The pressure cannot exceed 0.7 bar.

  - Type C
    These tanks may also be referred to as pressure vessels, and are normally spherical or cylindrical. They are designed based on a pressure criteria, having a design vapour pressure not less than:
    $P_o = 2 + AC(\rho_r)^{1.5}[bar]$
    where
    $A = 0.0185\left(\frac{\sigma_m}{\Delta\sigma_A}\right)^2$
    This cause a design pressure not less than 4 bar.
- **Internal insulation tanks**
  These tanks are non-self-supporting, and consist of thermal insulation materials. They may be divided into two types, Type 1 and Type 2. For Type 1, the insulation is the only primary barrier, while for Type 2, the insulation is both primary and secondary barrier. The pressure should normally not exceed 0.25 bar.

The loads will be higher for a tank having a rectangular shape than for cylindrical- or spherical tank. However, the hull area can be more utilized when having a rectangular shape.

According to the IGF code developed by MSC, fuel tanks shall be located at a minimum distance of the smallest of B/5 or 11.5 m from ship side (SOLAS 2017). Additionally, the general safety level shall be similar as achieved by conventional driven main- and auxiliary machinery, and risk assessment and explosion analysis shall be implemented.

Chapter 3

Methodology

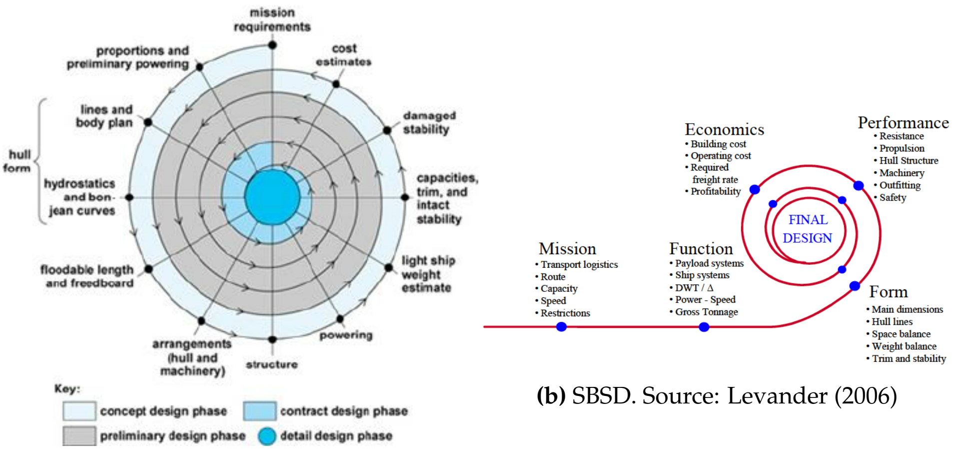
Mainly three methods are utilized to obtain the result. These are SBSD, LCA and LCC, which all are described in this chapter.

3.1 System Based Ship Design

Since Evans (Evans 1959) presented point-based design, often illustrated as the design spiral model, in 1959, it has been widely used in ship design. The process does first propose a form, which often is a benchmark ship, and then analyze the functional performance. Even though the design process has been successful in several cases, there are some drawbacks. Among other things, the process does not allow for a wide range of concept exploration. Because the process is based on a benchmark ship, it is difficult to derive innovative or creative designs from the process. Flexibility is important in the beginning of the concept development stage, this because both the designers and stakeholders often do not know exactly what they want. In this phase, the designers must be able to respond to possible requirement changes. This makes the point-based design method both inefficient and inflexible.

SBSD is an approach to tackle this, and was first presented at IMDC in Kobe in 1991 (Erikstad and Levander 2012). Since that, the method has been applied in development of several ship design. The prime difference compared with the spiral process, is that SBSD determines the final design based on design synthesis, this by mapping between the functional domain and physical domain. This rational bottom-up process enables ship designers to be more open to creative solutions (Levander 2006).

The difference between point-based design and SBSD is presented graphically in Figure 3.1.



(a) Design spiral model. Source: Ang, Goh, and Li (2015)

(b) SBSD. Source: Levander (2006)

Figure 3.1: Design spiral and SBSD

A purpose with SBSD is to determine Gross Tonnage (GT), Gross Volume (GV) and main dimensions for a vessel. To implement this, necessary areas and volumes of all equipment needed in the vessel should be determined. To ensure that all needed information is considered, SBSD is divided into 13 main categories, where system information should be filled in (Levander 2006). These categories are:

1. Transport task
2. Function description
3. Cargo spaces, cargo securing, cargo related spaces
4. Ship equipment
5. Accommodation
6. Machinery
7. Tanks and voids
8. System summary
9. Lightweight and deadweight
10. Building cost estimate
11. Main dimensions and hull form

12. General arrangement
13. Stability check

3.2 Life Cycle Assessment

According to Guinée et al. (2011), products' environmental impact has been studied ever since the 1960s. Since that time, it has been found that a lot of the environmental footprint from products has its origin in production, transportation and disposal. The idea of LCA was a result of this, where the objective is to compare the environmental impact through the products' lifetime, including production, transportation, disposal and the use of the product, i.e. cradle-to-grave. Today, use of LCA is encouraged by governments all over the world and can be seen in several sectors, among others military systems, tourism and waste incineration (Guinée et al. 2011).

LCA is defined in the ISO 14040 series, and according to ISO 14040/44 an LCA study has four phases (Kikuchi 2016):

- **Goal and scope definition**
  In this phase, the objective of the LCA is specified. Additionally, system boundaries, functional unit and impact categories are evaluated. Functional unit specifies how the product's emission should be evaluated, for instance transportation of one person by one kilometer or one day living in a house in Norway.
- **Life Cycle Inventory Analysis (LCI)**
  In an LCI, the total environmental footprints generated within life cycles' phases, as defined in the goal and scope description, are analysed. The collection of data may generally be divided into *foreground*- and *background* data. While foreground data deals with data attributable to the target products in an accurate way, background data deals with data that can be obtained from special or temporal averages. Inventory data can be found by converting on-site process data, or operation results. The aim of the LCI is to obtain *mass-environmental loads/functional unit*.
- **Life Cycle Impact Assessment (LCIA)**
  An LCIA evaluates the environmental impact by multiplying the results of the LCI with impact factors. Impact factors are defined as *environmental impact/environmental load*. Comparison of environmental impacts must be implemented according to the ISO standard by use of characterization factors. Additionally, fate and exposure analyses for environmental footprints can be addressed using characterization factors quantified in LCIA methods or other factors. For instance, GWP is an indicator of the climate change, areas of protection can be quantified by use of damage factors and disability adjusted life years can be an indicator of human health in some LCIA.

- **Interpretation**
  The last phase has to main roles; the intermediate phase or the decision making phase. As intermediate phase, a temporary result of the LCI may be returned to phase 1; goal and scope definition, to request redefinition of the conditions set in the LCA studies. As decision making phase, all phases in the LCA shall be understood by the practitioners.

When evaluating the fuel's environmental impact, LCA is recommended to be utilized (Guinée et al. 2011). Because the whole life cycle is taken into consideration, various concepts can be evaluated against each other in a rational way.

Gilbert et al. (2018) developed an LCA for two traditional fuels and eight alternative fuels, all listed below;

- Low Sulphur Heavy Fuel Oil (LSHFO)
- MDO
- LNG
- Liquid hydrogen produced from LNG
- Renewable liquid hydrogen produced by wind power
- Methanol, produced from NG
- Straight Vegetable Oil (SVO) Soy
- SVO Rape
- Biodiesel Soy
- Biodiesel Rape

The difference between soy- and rape SVO and biodiesel is the production, where they are produced by soybeans and rapeseed, respectively. Neither SVO nor biodiesel should be evaluated in this thesis, hence these production ways will not be explained any further.

The environmental evaluation will in thesis be based on the LCA developed by Gilbert et al. (2018). In their work, they only present their results in diagrams, without further values. Assistant Professor Svein Aanond Aanondsen has studied these results and found their respective values, which have been used in this thesis.

Furthermore, Brynolf, Fridell, and Andersson (2014) have carried out an environmental assessment of LNG, LBG, methanol and bio-methanol, which will be used for production comparison for these fuels.

A sketch of the system boundaries for the LCA developed by Gilbert et al. (2018) and Brynolf, Fridell, and Andersson (2014) can be seen in Appendix D.1. Further, the functional units used in their work are [g/kWh] and [g/MJ fuel], respectively. For detailed information about system boundaries and functional units in the LCAs, it is recommended to read Gilbert et al. (2018)'s and Brynolf, Fridell, and Andersson (2014)'s articles.

ReCiPe 2016 is used at impact method for the LCIA. ReCiPe was first developed in 2008, and was a cooperation between RIVM, Radboun University Nijmegen, Leiden University and Pré Consultants. The LCIA has 18 midpoint indicators and three endpoint indicators, which can be seen in Appendix D.2. While midpoint indicator focus on single environmental problems, endpoint indicators shows the environmental impact. The endpoint indicators in ReCiPe 2016 are (Huijbregts et al. 2016):

- Damage to human health
- Damage to ecosystems
- Damage to resource availability

CO_2, CH_4, N_2O, SOx, NOx, PM and VOC are considered as most critical pollutants regarding the environmental effects in marine applications, and are therefore the emissions considered in the LCA (Biert et al. 2016) and (Suleman, Dincer, and Agelin-Chaab 2015).

Evaluation of CO_2 emissions from biomass combustion have been discussed for decades. The Organization for Economics Cooperation and Development stated in 1991 that these emissions should not be included in the official emission inventory (Meeting et al. 1991). Other studies follow the EcoInvent database and state that CO_2 emissions with biomass- and fossil origin should be considered as equal (Werner et al. 2007). Further, Cherubini et al. (2011) developed a study showing that none of the methods are totally correct, and CO_2 emissions with biomass origin not can be totally neglected, but should neither be considered as harmful as CO_2 with fossil origin.

3.3 Life Cycle Cost

Traditionally, the most common way to evaluate a project is by an economical assessment (Amdahl, Endal, et al. 2014). LCC is a methodology taking all costs during a life cycle into account. The costs can normally be divided into three main groups (Crespo Márquez et al. 2012):

- Capital Expenditures (CAPEX)
- Operational Expenditures (OPEX)
- Voyage Related Expenditures (VOYEX)

CAPEX, OPEX and VOYEX consider all costs during a construction's lifetime.

Final cost calculations in a shipbuilding project shall be very precise to avoid disagreements between yard and ship owner. This thesis will consider cost estimates, and not detailed cost calculations. Further information regarding CAPEX, OPEX and VOYEX is based on costs in shipping.

CAPEX includes building costs and various administration costs. In the case in this thesis, there are limited information about the ship. A common approximation method to tackle this is unit methods (Amdahl, Endal, et al. 2014). Building costs can be divided into three main parts, and are presented with their respective unit costs bellow.

- Hull costs. Price per unit steel
- Machinery costs. Price per installed kW
- Outfitting costs. Price per m^2 deck area

Administration costs can be divided into four main parts. According to Amdahl, Endal, et al. (2014), these can be estimated as:

- Administration costs: 8-10% of building costs
- Engineering costs: 2-10% of building costs
- Financing: 5% of building costs
- Yard Profit: 5-10% of building costs

OPEX includes (Amdahl, Endal, et al. 2014):

- Docking
- Repairs and maintenance
- Crew costs
- Spare parts
- Administration
- Insurances
- Classing

VOYEX includes (Amdahl, Endal, et al. 2014):

- Fuel and lube oil
- Port costs
- Loading- and unloading costs
- Cost of off-hire days

3.3.1 Cost Calculation

LCC can be calculated as described below (Amdahl, Endal, et al. 2014):

$$\text{LCC} = \text{CAPEX} + \text{Present value of (OPEX+VOYEX)} \tag{3.1}$$

Relevant expressions to calculate LCC can be found in Table 3.1.

Table 3.1: Relevant expressions to calculate LCC

Expression	Symbol
Inflation	f
Market rate	p
Real interest	p′
Number of years/periods	n
Present value factor	P′
Future amount	F
Present value	P
Annual number of passengers	C

Real interest, p′, can be found from following equation:

$$p' = \frac{1+p}{1+f} - 1 \tag{3.2}$$

Present value can be found from:

$$P = \frac{F}{(1+p)^n} \tag{3.3}$$

For a series of future amounts, this can be written as:

$$P = F \times \left[\frac{(1+p)^n - 1}{p \times (1+p)^n}\right] \tag{3.4}$$

RFR is used to determine the cargo price, in this case price per passenger, so the incoming costs should be equal to the outgoing costs (Amdahl, Endal, et al. 2014). For the shipowner to have business profit, it is desirable that the costumer pays more than RFR. RFR can be found from:

$$RFR = \frac{LCC}{\left[\frac{(1+p)^n-1}{p\times(1+p)^n}\right] \times C} \tag{3.5}$$

Chapter 4

System Boundaries

This chapter presents information regarding SBSD, the sailing route and schedule for the vessel as well as bunkering description.

4.1 System Based Ship Design Information

The input in SBSD used in this thesis is based on the system information developed by Angvik et al. (2014), and was a part of their contribution to Dr. James A. Lisnyk Student Ship Design Competition 2013-2014. The only parts from their sheet which have been changed are:

- Mission, sailing route and schedule
- Size of main- and auxiliary engine room and fuel tanks
- Cost

All SBSD information can be seen in Appendix F.

4.2 Sailing Route

In this thesis, a specific sailing route is defined, which is based upon a sailing route from the cruise ship company Hapag-Lloyd. The route will start in Hamburg, Germany, sail along the Norwegian coast to Nordkapp, Norway, around Svalbard, along the Norwegian coast and end its trip in Hamburg. The whole route is illustrated in Figure 4.1. Relevant information for the sailing route can be found in Table 4.1. The percentage distribution of time in port, time at manoeuvring in port and time at sea is based on work developed by Angvik et al. (2014).

Table 4.1: Relevant information for sailing route

Information	Value	
Voyage range	3900nm	7300km
Endurance	417 hours	18 days
Time in port	146 hours	35%
Maneuvering in port	8 hours	2%
Time at sea	187 hours	63%
Number of trips	25 per year	
Operating days	325 per year	

Figure 4.1: Sailing route

Additionally, the cruise will dock in Bergen, Geiranger, Tromsø, Hammerfest and Bodø during its trip. Relevant information regarding the laps can be found in Table 4.2. It should be noted that the lap from Hammerfest to Bodø includes sailing around Svalbard. The values are estimates based on distances found from Google Maps.

Table 4.2: Distances between docking

Sailing route		Distance [km]	Time at sea [hours]
Hamburg	Bergen	870	31
Bergen	Geiranger	770	13
Geiranger	Tromsø	1160	42
Tromsø	Hammerfest	380	14
Hammerfest	Bodø	2660	96
Bodø	Hamburg	1860	67
Total		7300	263

4.3 Bunkering

The total distance of the sailing route is 7300 km. During the trip, the vessel will bunker in Hammerfest and Bodø, i.e. two times during its voyage. As mentioned previous, there is still not developed any bunkering facilities for hydrogen and methanol in Norway. Both Hammerfest and Bodø have bunkering facilities for LNG. The longest sailing route without bunkering is between Hamburg and Bodø, and requires 100 sailing hours. Tank sizes will be determined based on this distance.

4.4 Functional Unit

Though the passenger capacity is set to be 500 PAX, it is not reasonable to assume that the cruise will be fully booked all the time. It is assumed that the cruise on average will transport 70 % of the passenger capacity, causing average passengers per trip to be 350 PAX.

The functional unit in the environmental- and economical evaluation is PAX/round trip, where the estimate of average passengers per trip of 350 PAX is assumed.

Chapter 5

Machinery Configuration

5.1 General

This chapter presents information regarding the machinery configuration, and contains both system information affecting the machinery and FC selection.

5.2 Machinery Requirements

As mentioned in Chapter 4.1, system information for the considered vessel is taken from Angvik et al. (2014). The operation profile during one round trip can be seen in Figure 5.1.

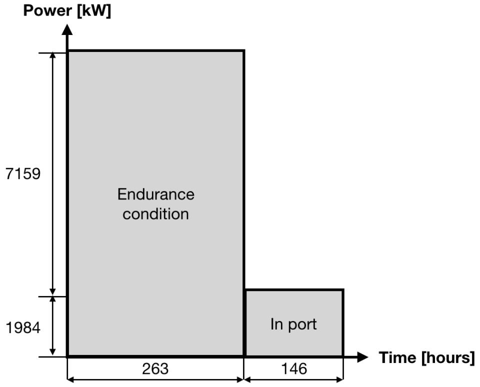


Figure 5.1: Operational profile during one round trip

5.3 Efficiency

According to Amdahl, Endal, et al. (2014), total efficiency can be divided into mechanical efficiency, η_T, and propulsion efficiency, η_M. Mechanical efficiency represents loss due to friction in shaft and gear box, and is normally between 95-99 %. Propulsion efficiency can further be divided into (Schneekluth 1998):

- η_H = hull efficiency
- η_0 = open-water propeller efficiency
- η_R = relative rotative efficiency

According to Amdahl, Endal, et al. (2014), total efficiency can be estimated as 50-60 %.

Figure 5.2 illustrates the system boundary for definition of total efficiency. As can be seen, total efficiency is set to be the efficiency for power transmission and power conversion. Note that power generation is not included in the definition of total efficiency.

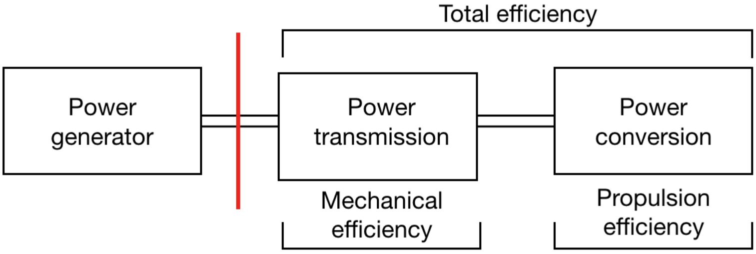


Figure 5.2: System boundaries for definition of total efficiency

Though, there are losses during power generation as well. For a traditional combustion engine, the efficiency is approximately 40-50 % (Amdahl, Berge, et al. 2014).

The efficiency for an FC during power generation is normally given as electrical efficiency. The electrical efficiency is dependent on both the efficiency of the power source and electrical interface, see Figure 5.3. P_{el} is electrical power.

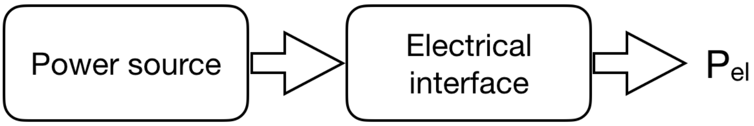


Figure 5.3: Electrical efficiency for an FC

This can also be written as:

$$\eta_{PS} \times \eta_{EI} = \eta_{EL} \tag{5.1}$$

Where η_{PS} is much smaller than η_{EI}. η_{EL} is electrical efficiency. Anyway, the overall efficiency can be increased by utilization of energy from heat recovery for HT-FCs. Though, this energy cannot be used for propulsion, but for instance heating of hotel.

A summary of efficiencies for the various fuels can be seen in Table 5.1.

Table 5.1: Efficiencies

Fuel	Efficiency [%]
During power generation	
HFO	45
Hydrogen	55
Methanol	40
LNG	40
During power transmission and power conversion	
All	55

The various fuels' Specific Fuel Consumption (SFC) can be seen in Table 5.2, where all necessary calculations can be found in Appendix B.1.

Table 5.2: SFC

Fuel	SFC [g/kWh]
HFO	186
Hydrogen	46
LNG	173
Methanol	429

5.4 Fuel Cell Selection

As mentioned in Chapter 2.2.1, the three most promising FCs for maritime application are:

- PEMFC
- HT-PEMFC
- SOFC

As can be seen in Figure 2.4 and 2.5 in Chapter 2.2.2, PEMFC are the most commercial used FC, with both highest number of shipped FCs and highest value of shipped MWs. SOFCs have increased every year since 2015 in both graphs.

The FC types mentioned above are the ones to be further evaluated in this section.

5.4.1 Alternatives

There is a lot of information in both books and articles regarding FCs, but there is a lack of recommendations regarding which FC technology to use in maritime sector. This may be related to the fact that there are limited number of ships using FCs for ship propulsion today (Tronstad et al. 2017). Both PEMFC, HT-PEMFC and SOFC operate on different temperatures, which affect their start-up time, handling of load variations, efficiency and need of reformer. **Start-up and changing power demand**
PEMFC is the FC with shortest start up-time and highest flexibility regarding handling of load variations, while SOFC is on the other end of the scale. This is caused by the operation temperature for the FCs. Need of flexibility, in this context, is dependent on the vessel's operational profile.

Hybrid solution
A hybrid solution combining FCs and batteries is an alternative, where an auxiliary propulsion system is used for start-up and peak shaving. Theoretically, both batteries and LT-FCs can be used as auxiliary. Use of LT-FCs as auxiliary are most relevant for a system utilizing HT-FCs for main propulsion. However, it is not found any examples of vessels combining HT-FCs and LT-FCs as a hybrid.

Operational profile
Figure 5.4 illustrates the operational profile for a cruise vessel operating in the Baltic Sea between Stockholm, Sweden, and Mariehamn, an Åland island (Baldi et al. 2015). As can be seen in the figure, the main engine load, illustrated by the orange line, has big variations during operating. Peak shaving by an external energy source will therefore require a lot of power. Furthermore, it is reasonable to assume that a ship operating in the North Sea will be more exposed to load variations than a vessel operating in the Baltic Sea.

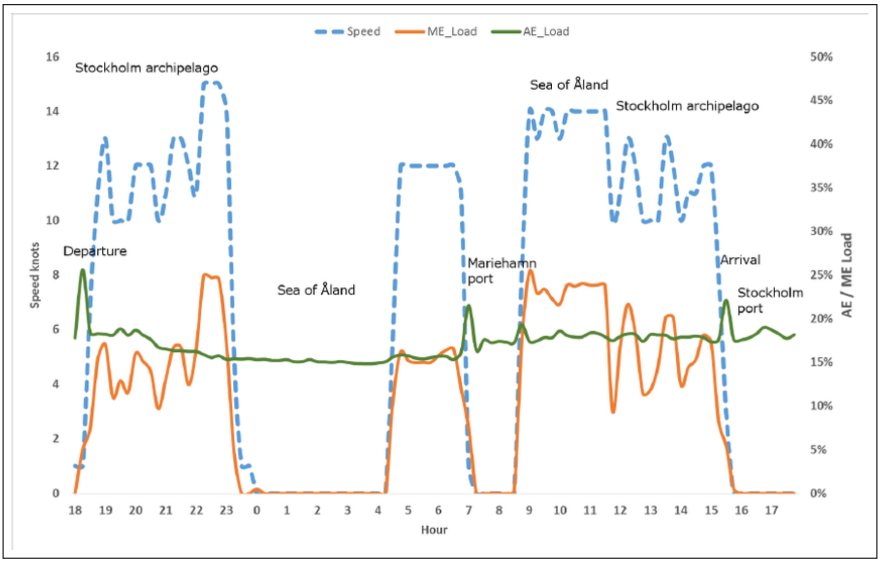


Figure 5.4: Operational profile for a cruise vessel operating in the Baltic Sea. Source: Baldi et al. (2015)

Efficiency
An advantage with HT-FCs, in this case HT-PEMFC and SOFC, is the high efficiency by utilization of heat recovery. Heat recovery may increase the overall efficiency with up to 25 % (Tronstad et al. 2017). PEMFC operates on a temperature between 50 and 100°C, and some heat can be used to increase the overall efficiency, though it will not be as much as for SOFC.

Reformation of fuels
As the reformation of LNG and methanol occurs within the FC due to high operation temperature for SOFC, there will not be need of an external reformer. On the other hand, both PEMFC and HT-PEMFC will need an external reformer when use of other fuels than hydrogen, which can be both space-requiring and expensive.

5.4.2 Selection

There are both advantages and challenges with the three evaluated FCs. Both HT-PEMFC and SOFC are of high interest. Though, HT-PEMFC's low maturity and SOFC's low flexibility regarding handling of load variations are challenging. As the situation is today, PEMFC is assumed to be the most suitable FC for a cruise vessel. This is, among other factors, due ti its high commerciality and flexibility. Based on this, PEMFC is to be further evaluated in this thesis.

There are several producers of PEMFCs. Among them are:

- PowerCell, located in Sweden
- Hydrogenics, located in Canada
- Proton Motor Fuel Cell GmbH, located in Germany

The PEMFC chosen in this thesis is MS-100 delivered by PowerCell. There are not any main reasons for the choice, other than a recommendation by Johan Burgren, Business Manager in PowerCell.

As mentioned above, a hybrid solution combing FCs and batteries is normal. To evaluate if that is beneficial in this case, a standard battery package from Corvus Energy (Corvus energy 2018) has been compared to the PowerCell MS-100 PEMFC (PowerCell 2018). The comparison can be seen in Table 5.3. According to Halvard Hauso, ECP Sales and Marketing at Corvus Energy, the efficiency of the battery is about 98 %.

Table 5.3: Product comparison between PowerCell's MS-100 and a standard battery package from Corvus Energy. Source: PowerCell (2018) and Corvus energy (2018)

Specification	Fuel Cell	Battery Package	Unit
Gross power	182	125	kW
Net power	100	123	kW
Efficiency	55	98	%
Height	750	2200	mm
Width	750	870	mm
Depth	520	710	mm
Floorage	0.39	0.62	m^2
Volume	0.29	1.36	m^3
Weight	98	1550	kg

As the battery package is almost 16 times as heavy and 5 times as big as an FC, it is considered to not have any batteries supporting the propulsion and start-up.

When evaluating usage of shore when hydrogen or LNG is used as fuel, necessary volume of fuel needed to power the hotel should be compared with the amount of boil-off. Boil-off occurs for cryogenic gases, and is a measure of how much fuel that will vapour per unit time. The amount of boil-off is a function of the tank's size, shape and thermal insulation (Andreas Züttel 2003). In this case, the amount of boil-off is less than necessary power in port, causing the ship will utilize shore power during docking. Calculations supporting this can be seen in Appendix B.2.

Total required power for the vessel is approximately 11.5MW. An MS-100 has a capacity of 100kW, which leads to a demand of 115 FCs. According to Prasad Rohit, sales manager in Proton Motor Fuel Cell GmbH, and Mark Kammerer, business development manager in Hydrogenics GmbH, the lifetime of an FC is approximately 20 000-25 000 hours. However, definitions of end of life for an FC may vary for distributors. In this work, the lifetime of the FC is assumed to be 25 000 hours.

Obtaining information regarding the reformer needed when using LNG and methanol in a PEMFC has been hard. Anyway, some dimensions were found from Battelle Memorial Institute (2016), which can be seen in Table 5.4.

Table 5.4: Dimensions of reformer for a 100kW PEMFC. Source: Battelle Memorial Institute (2016)

Size of reformer		
Overall diameter	609	mm
Overall length	3710	mm
Floorage	2.26	m^2
Total volume	1.08	m^3
Estimated weight	365	kg

It has not succeeded finding information regarding lifetime and weight of the reformer. It is assumed that the reformer has equal weight per square meter as the FC. By that, the estimated weight of one reformer is 365 kg. Furthermore, the lifetime of the reformer is assumed to be equal as the lifetime of the FC.

Chapter 6

Required Spaces

This chapter will present required spaces for FCs, reformers and tanks as a result of utilization of hydrogen, LNG and methanol. HFO is used as benchmark.

According to SOLAS (2014), there are requirements regarding redundancy and safe return to port. For safe return to port, system defined as essential need to remain operational after casualty, which among other includes both propulsion system and fuel oil system. Propulsion redundancy is obtained by placing FCs in two rooms separated by a watertight bulkhead. Furthermore, the fuel will be placed in two separated tanks.

6.1 Fuel Cell

As described in the previous chapter, PEMFC MS-100 designed by PowerCell is used as an example in this thesis. There will be need of 115 FCs, each with a volume of 0.29 m^3, causing a total FC volume of 33.35 m^3. It is assumed that the FCs can can be stacked as modules which can be placed right next to each other. Due to safe return to port, the FCs will be distributed in two separate engine rooms, one containing 58 FCs and the other 57 FCs. The height of the machinery room is set to be 3.6 m. Additionally, there should be enough space between the FCs to be able to implement maintenance, replacement etc.

The FCs can be stacked in several ways, both next to- and on top of each other, which will lead to different required spaces. Figure 6.1 illustrates an alternative of how the FCs in one of the machinery rooms may be stacked, seen from above. It is assumed that both machinery rooms will have the same area.

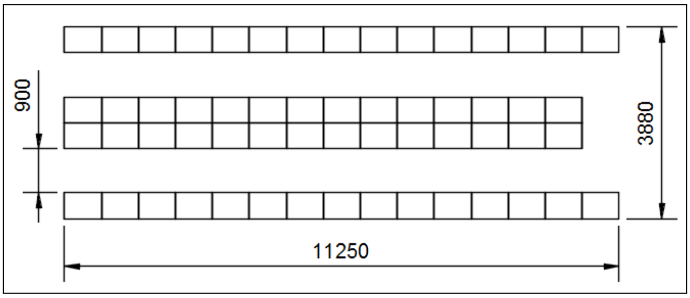


Figure 6.1: Stacking of FCs

According to this setup, the volume of the machinery rooms will be:

$$V = 2 \times 11.25m \times 3.88m \times 3.6m = 314m^3 \tag{6.1}$$

The total volume will be reduced by placing the FCs on top of each other. Considering the height of the machinery room is 3.6 m, while the height of an FC is 0.75 m, a lot of space could potentially be saved. Nevertheless, there are uncertainties of how much space ventilation, cooling system etc. requires, and stacking the FCs as described above causes a conservative volume of the engine room.

When LNG or methanol is utilized in a PEMFC, a reformer must reform the fuels to hydrogen. The size of one reformer is 1.08 m^3. As there are 115 FCs, there will be need of 115 reformers as well. This is added to the total volume. Then, the volume of machinery room included reformers is:

$$314m^3 + (115 \times 1.08m^3) = 438m^3 \tag{6.2}$$

From the formulas above, it can be found that FCs powered by LNG or methanol requires 1.4 times bigger space than FCs powered by hydrogen.

6.2 Fuel Tank

For simplification, it is determined to use a membrane tank with rectangular shape.

A comparison of the fuel's densities can be found in Table 6.1 (Hua et al. 2011), (Deniz and Zincir 2016) and (Demirel 2016). Further, Table 6.2 illustrates the increased volume the fuels require to obtain the same amount of energy for propulsion as HFO. Both efficiencies for power generation, power transmission and power conversion have been considered.

Table 6.1: Properties alternative fuels

Fuel	Specific energy [kJ/kg]	Volume density [kg/m^3]	Specific energy per volume [kJ/m^3]
HFO	43000	954	41.0×10^6
LNG	52000	450	23.4×10^6
Methanol	21000	798	16.8×10^6
H_2 liquid	142000	70.8	10.1×10^6
H_2 700 barg	142000	25.5	36.2×10^6
H_2 350 barg	142000	17.4	24.7×10^6

Table 6.2: Volume increase factor

Fuel	Efficiency [%]	Energy for propulsion [kJ/m^3]	Increase factor
HFO	45	18.5×10^6	1
LNG	40	93.6×10^6	1.97
Methanol	40	67.0×10^6	2.75
H_2 liquid	55	55.3×10^6	3.34
H_2 700 barg	55	19.9×10^6	9.27
H_2 350 barg	55	13.6×10^6	13.58

Volume of the fuel tanks can be found from following equation:

$$\text{Volume} = \frac{\text{Total energy demand} \times \text{Safety factor}}{\text{Specific energy} \times \text{Volume density} \times \text{Efficiency}} \tag{6.3}$$

where total energy demand is:

$$\text{Total energy demand} = \text{Total power} \times \text{Voyage duration} \tag{6.4}$$

Input for calculation of tank volume can be found in Table 6.3. Specific energy and volume density for the various fuels is the same as in Table 6.1. Efficiencies were described in Table 5.1 in Chapter 5.3.

Table 6.3: Relevant factors to determine tank size

Factor	Value	Unit
Endurance power	9200	[kW]=[kJ/s]
Specific energy	-	[kJ/kg]
Volume density	-	[kg/m^3]
Voyage duration	100	[hours]
Electrical efficiency	-	[-]
Safety factor	1.2	[-]
Tank breadth	9.2	[m]
Tank height	3	[m]

The breadth and height of the tanks are equal for all the fuels, this to compare the tank sizes in a good way. The breadth of 9.2 m is found from:

$$\frac{B}{5} \times 2 = \frac{23m}{5} \times 2 = 9.2m \tag{6.5}$$

The height is set randomly to be 3 m.

Fuel tank sizes can be seen in Table 6.4, and are based on the sailing route given in Chapter 4.2 and information presented in this chapter. The values are given in increasing order.

Table 6.4: Fuel tank sizes

Fuel	Volume [m^3]	Length [m]
HFO	391	14.2
LNG	772	28.0
Methanol	1078	39.1
Hydrogen	1307	47.3

All needed information and calculation of tank sizes can be found in Appendix C.

6.3 Main Dimensions

The vessel's final main dimensions as a result of utilization of the various fuels can be seen in Table 6.5. The sailing route given in Chapter 4.2, requiring 100 sailing hours without fuelling is considered.

Table 6.5: Main dimensions

Parameter	Hydrogen	LNG	Methanol	HFO
Length over all [m]	142.6	142.6	142.3	144.9
Breadth [m]	21.6	21.6	21.6	22
Draught [m]	5.6	5.6	5.6	5.6

As can be seen in the table above, there are only small values distinguishing the main dimensions for a vessel powered by hydrogen, LNG and methanol through an FC. Utilization of HFO in a combustion engine causes the highest main dimensions, and a length more than 2.5 m longer than the other alternatives. Though this may seem somewhat odd, it is caused by the area required by the combustion engine. The estimated machinery space, [m^3/kW], for the combustion engine is found from information given in Levander (2006).

A sensitivity analysis of GV and GT is developed and illustrated in Figure 6.2 and 6.3, respectively. The aim is to illustrate how increased tank size will affect GV and GT, which is directly connected to main dimensions.

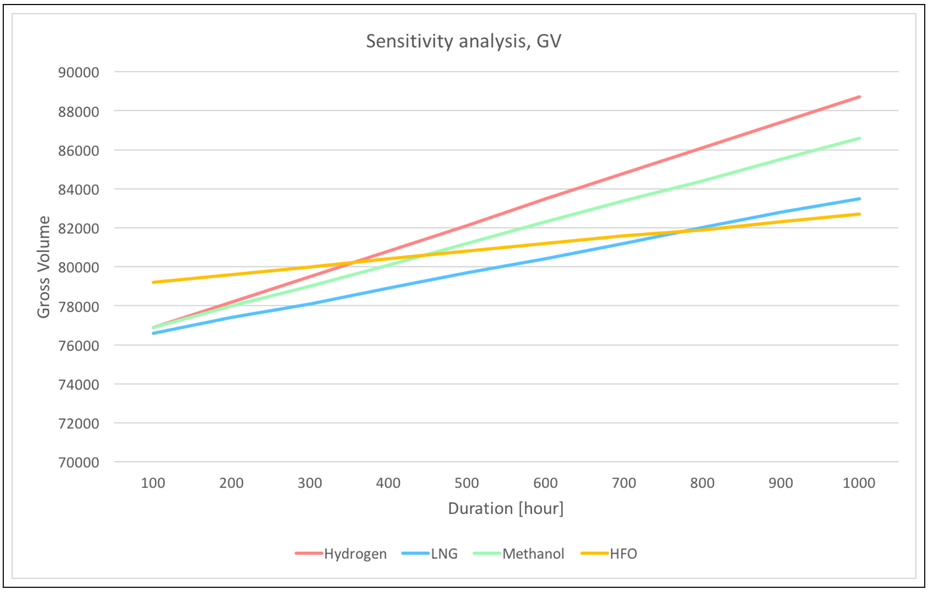


Figure 6.2: Sensitivity analysis of GV

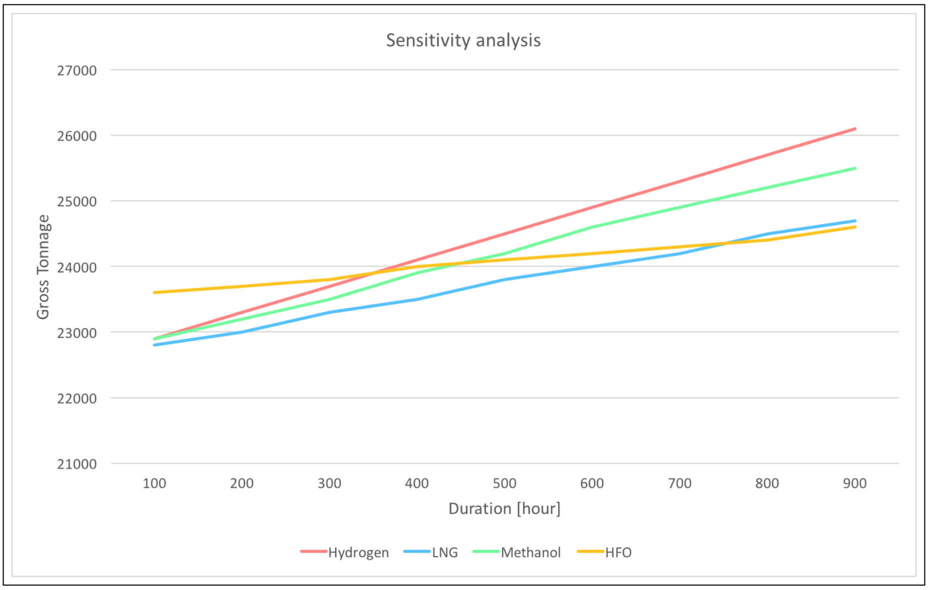


Figure 6.3: Sensitivity analysis of GT

The fuel's specific energy per volume determines the curves' slope. While hydrogen has the steepest slope, HFO has the gentles.

Chapter 7

Environmental Impact

The LCA in this thesis is mainly an indication, with the intention to find whether hydrogen, LNG or methanol is most suitable for utilization in an FC, from an environmental point of view. HFO is used as a benchmark.

The impact factors between the various types of emission, among others GHGs and acid rain, are much discussed. Various impact methods can be used, which also will cause different results. As mentioned in Chapter 3.2, ReCiPe 2016 is used to compare the various fuels' potential environmental impact against each other.

This chapter will firstly present values of the emissions from the various fuels through an LCI. Secondly, the weighted result from the LCIA will be presented. Furthermore, a comparison of emissions caused by utilization of fuels in an FC and a combustion engine is developed. Finally, a comparison of the production method for LNG and methanol is presented.

7.1 Reformation of LNG and Methanol to Hydrogen

In the LCA developed by Gilbert et al. (2018), LNG and methanol was utilized in a combustion engine, while hydrogen was utilized through an FC. By utilization of hydrogen in a PEMFC, the efficiency is approximately 0.55 % (Tronstad et al. 2017). The need of a reformer by use of LNG and methanol in a PEMFC, will cause a total efficiency for both the reformer and the PEMFC of about 40 % (Vogler and Sattler 2016). By this, the efficiency of the reformer can be found as $\frac{0.40}{0.55} \times 100\% = 73\%$. The explanation is illustrated graphically in Figure 7.1.

The efficiency of the combustion engine in the work developed by Gilbert et al. (2018) is not specified, and it is therefore assumed an engine efficiency of 45 %. The total efficiency by use of LNG and methanol in a PEMFC is $\frac{0.40}{0.45} \times 100\% = 89\%$ of the efficiency these fuels receive in a combustion engine. This shall be taken into consideration when evaluating the environmental aspect, and emissions from LNG and methanol in a PEMFC shall be multiplied with 1.125.

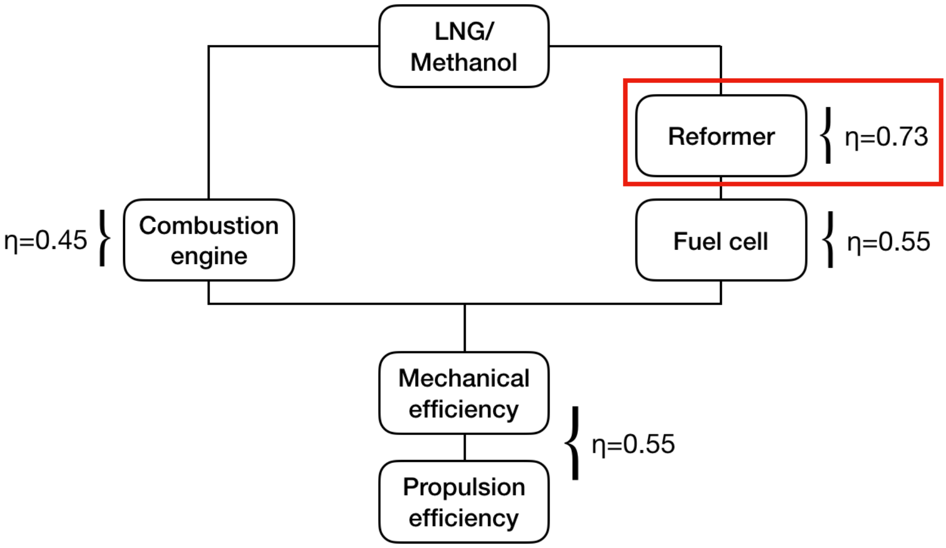


Figure 7.1: Efficiency for FC and combustion engine

As can be seen in Chapter 2.2.1, reformation of LNG and methanol will both cause CO_2 emissions. The chemical reaction occurring by utilization of LNG in a combustion engine is (Demirbas 2010):

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \tag{7.1}$$

While the chemical reaction for LNG in a reformer is (Tronstad et al. 2017):

$$CH_4 + 2H_20 \rightarrow CO_2 + 4H_2 \tag{7.2}$$

As can be seen from the equations above, the only outcome from the reactions are CO_2 and water for the first one, and CO_2 and hydrogen for the latter one. LCA of LNG in a combustion engine shows that there are emissions of NOx, PM and CH_4 as well (Brynolf, Fridell, and Andersson 2014) and (Gilbert et al. 2018). According to, among others, Tronstad et al. (2017) and Sharaf and Orhan (2014), the only outcome from the reformation reaction for LNG are CO_2, hydrogen, and in some cases NOx. Anyway, it has not succeeded finding and LCA for LNG in an FC confirming this.

Nevertheless, the evaluation of environmental impact is in this thesis based on information given in Tronstad et al. (2017), and it is therefore assumed that the only outcome from the reformation of LNG and methanol is CO_2, NOx, water and electricity. According to the equations above, CO_2 emissions from LNG and methanol during operation in a PEMFC will be equal for as for utilization in a combustion engine. Furthermore, NOx emissions, which is included to obtain a conservative result, is also assumed to be equal as in a combustion engine.

In the LCI and LCIA in the two subsequent sections, all values are based on the work done by (Gilbert et al. 2018). All emissions for LNG and methanol are multiplied with 1.125.

7.2 Life Cycle Inventory Analysis

The applied result from the LCI developed by Gilbert et al. (2018) can be seen in Figure 7.2. Due to the amount of CO_2 is considerable higher than for the other emissions, a diagram of emissions excluded CO_2 emissions can be seen in Figure 7.3. Concrete values can be found in Appendix D.3.

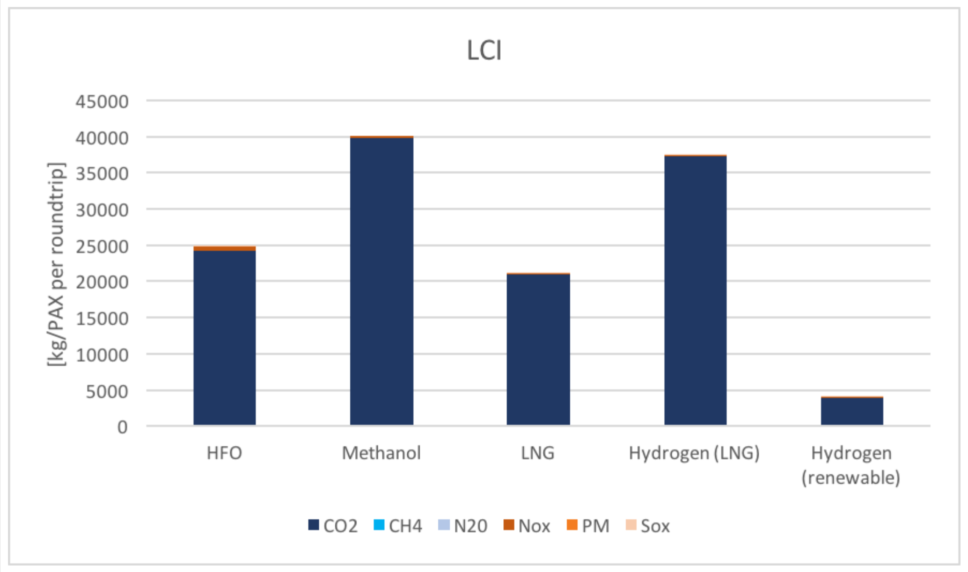


Figure 7.2: LCI for HFO, methanol, LNG and hydrogen

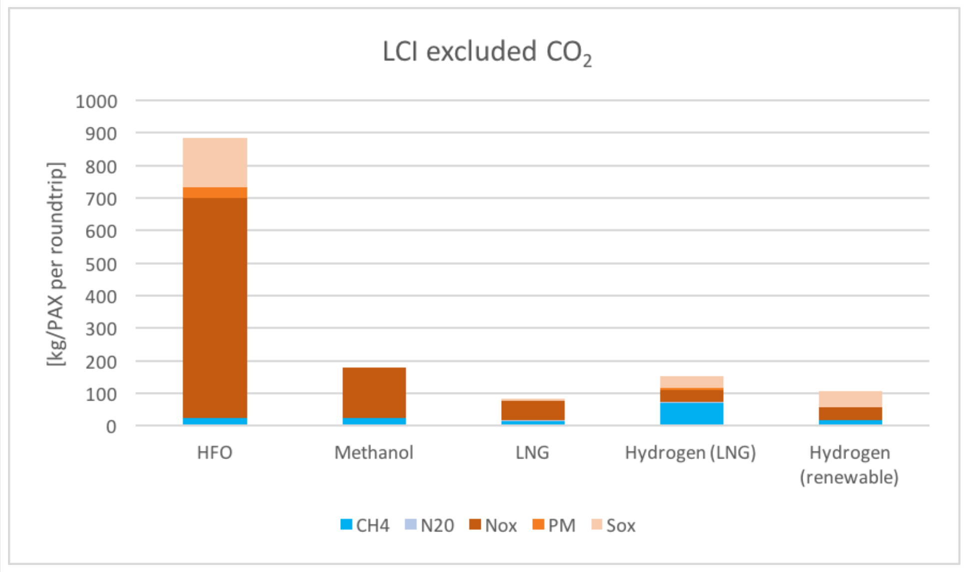


Figure 7.3: LCI for HFO, methanol, LNG and hydrogen excluded CO_2 emissions

Each passenger causes several thousand kg of emissions during a round trip. The values may seem somewhat high, and are therefore investigated further. The emissions are estimated based on needed power, hours at sea and the LCI developed by Gilbert et al. (2018), presenting emissions in [g/kWh]. The main source of error is the estimated needed power. The vessels will have a GT of approximately 23 000 tons, which, according to Levander (2006) causes just below 20 MW installed power. Installed power for the vessels evaluated in this thesis is about 11.5 MW. Hence, there is not any reason to assume that the values obtained are significantly high.

7.2.1 Fulfillment of Requirements

MARPOL claims requirements regarding emissions of both SOx and NOx. It is of interest to control that the alternative fuels fulfill these requirements. The result can be seen in Table 7.1. Regarding Annex VI Regulation 13, the legal NOx emission depends on the engine's rotation per minute. An FC does not have any rotation per minute, but the strictest requirement is assumed, which is 3.4 g/kWh (MARPOL 2016a).

As can be seen, hydrogen, both produced from renewables and LNG, and LNG fulfill both Regulation 13 and Regulation 14.

Table 7.1: Control of fulfillment of MARPOL requirements

	Hydrogen renewable	Hydrogen LNG	LNG	Methanol	HFO
SFC [g/kWh]	46	46	173	429	186
Annex VI Regulation 13, NOx emission Requirement: 3.4 [g/kWh]					
NOx emission [g/kWh]	0.00	0.00	1.34	3.43	16.60
Fulfillment	Yes	Yes	Yes	No	No
Annex VI Regulation 14, SOx emission Requirement: 0.1 % [m/m]					
SOx emission [g/kWh]	0.00	0.00	0.00	0.00	3.40
Relationship [m/m]	0.00	0.00	0.00	0.00	0.02

7.3 Life Cycle Impact Assessment

The result of the LCIA can be seen graphically in Figure 7.4 and specific values in Appendix D.4. As can be seen from the figure, HFO is, as assumed, the fuel causing highest potential environmental footprint during a life cycle. Among the other three fuels, hydrogen has both the best and worst result, depending on whether it is produced from renewable wind power or LNG, respectively.

There are several sources of error in this evaluation. Among others, several factors have not been taken into consideration, as only six of very many emissions have been considered.

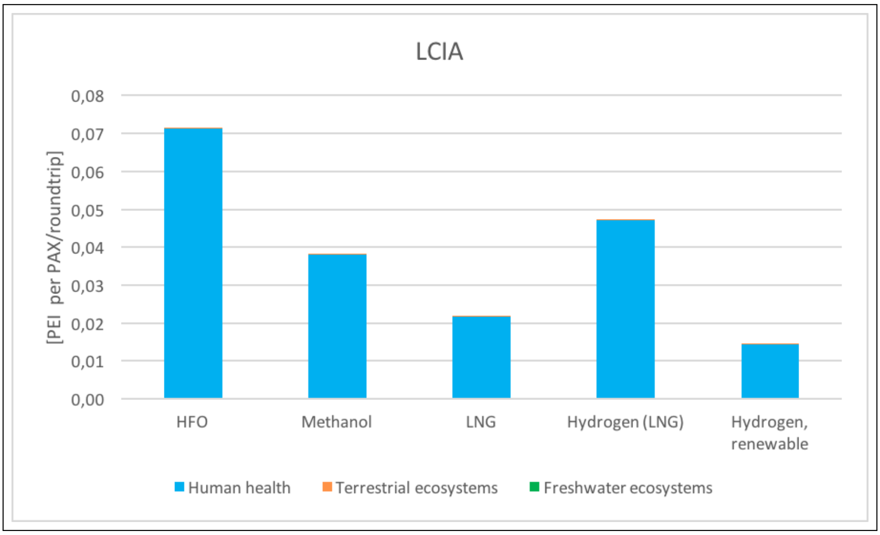


Figure 7.4: LCIA for HFO, methanol, LNG and hydrogen

7.4 Comparison of Fuel Cell and Combustion Engine

Both hydrogen, LNG and methanol can be utilized through a combustion engine as well as through an FC. From an environmental point of view, it is preferable to utilize hydrogen through an FC, since there will be no emissions during operation. On the other hand, both methanol and LNG cause some emissions during operation in an FC. Hence, it is of interest to compare emissions from these fuels when they are utilized through a combustion engine and an FC. The LCIA comparing emissions from HFO, LNG and methanol utilized through a combustion engine and LNG, methanol and hydrogen utilized through an FC can be seen in Figure 7.5, and is based on the work done by (Gilbert et al. 2018). Concrete values can be seen in Appendix D.5.

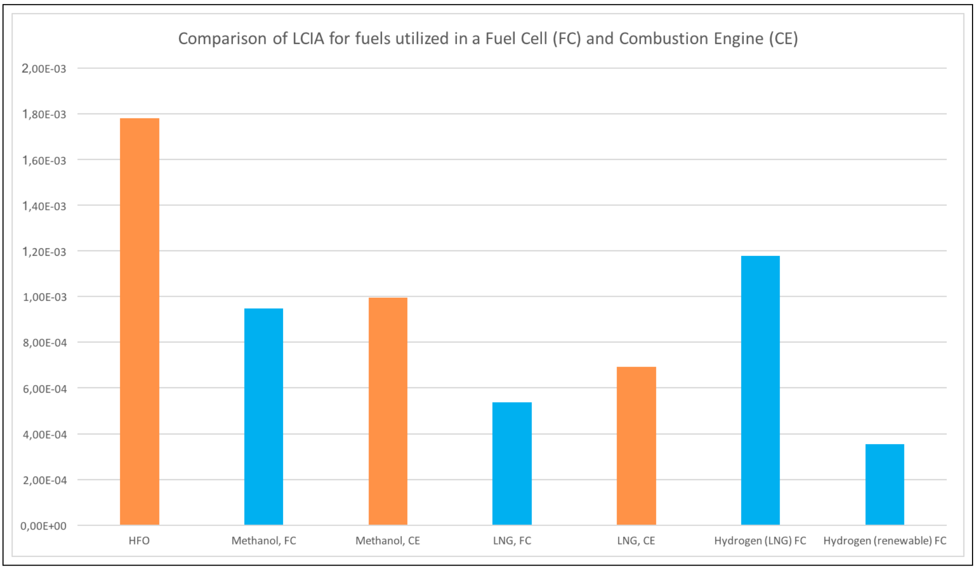


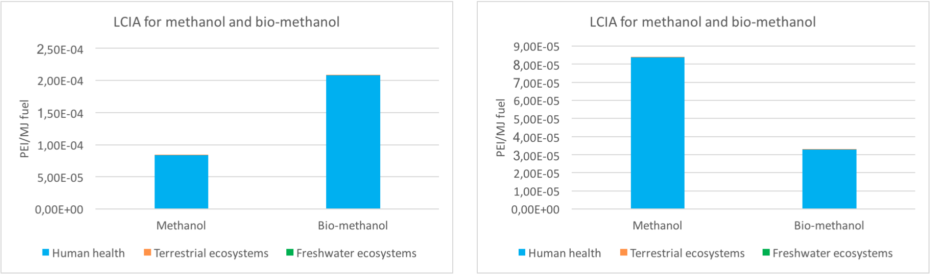
Figure 7.5: LCIA comparing utilization of fuels through a combustion engine and an FC

The orange and blue bars represent utilization through combustion engine and FC, respectively. As can be seen, utilization through an FC instead of a combustion engine causes smallest potential environmental impact for all of the alternative fuels. However, utilization of LNG through a combustion engine causes less environmental impact than methanol utilized in an FC.

7.5 Production Comparison

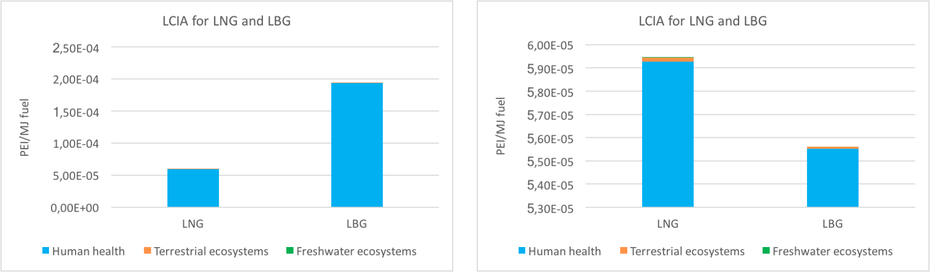
In the study developed by Gilbert et al. (2018), two production methods of hydrogen were analysed; hydrogen produced from LNG and hydrogen produced from renewable wind power. As can be seen in the section above, choice of production method has a huge impact on the environmental footprint from the fuel. In the study developed by Gilbert et al. (2018), both methanol and LNG were produced from NG. Though, both of them may be produced from biomass as well. Methanol and LNG produced from biomass is usually referred to as bio-methanol and LBG, respectively.

Brynolf, Fridell, and Andersson (2014) implemented an LCI comparing the production methods of LNG and methanol. Concrete values for the LCI can be found in Appendix D.6. The result from the study developed by Brynolf, Fridell, and Andersson (2014) has been used as input in an LCIA to compare the fuels potential environmental impact. As earlier, ReCiPe 2016 is used as weighting method. As mentioned in Chapter 3.2, there is disagreement regarding the environmental impact from biomass-CO_2. If assuming CO_2 with biomass origin has the same environmental impact as CO_2 with fossil origin, production from LNG is the best alternative. On the other hand, if CO_2 emissions with biomass origin can be neglected, production from biomass is preferable. The LCIA for methanol and LNG can be seen in Figure 7.6 and 7.7, respectively. While Figure 7.6a and 7.7a take all CO_2 emissions with biomass origin into consideration, Figure 7.6b and 7.7b neglect all CO_2 emissions with biomass origin.



(a) 100 % impact from biomass-CO_2 **(b)** 0 % impact from biomass-CO_2

Figure 7.6: LCIA for methanol and bio-methanol



(a) 100 % impact from biomass-CO_2 **(b)** 0 % impact from biomass-CO_2

Figure 7.7: LCIA for LNG and LBG

There are big variations on the environmental impact based on whether CO_2 from biomass is included or not. Anyway, according to the study developed by Cherubini et al. (2011), there are uncertainties of how much impact biomass-CO_2 has. Therefore, a sensitivity analysis has been developed for both methanol, bio-methanol, LNG and LBG. The sensitivity analysis, which can be seen in Figure 7.8, illustrates how much impact bio-CO_2 can have before it is not preferable to produce the fuels from biomass, where the x-axis represent the percentage of CO_2 emissions from biomass origin included in the LCIA. Table 7.2 present the percentage of included CO_2 emissions from biomass origin at the intersections.

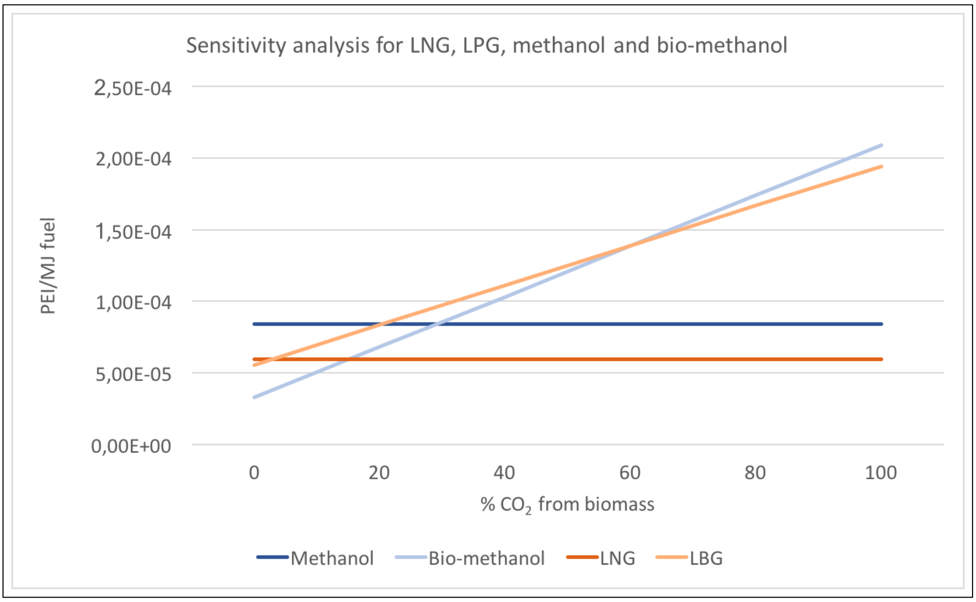


Figure 7.8: Sensitivity analysis for LNG, LBG, methanol and bio-methanol

Table 7.2: Intersection for fuels in sensitivity analysis

Fuels			Percentage of CO_2 emissions from biomass origin at intersection
LNG	and	LBG	3 %
LNG	and	bio-methanol	15 %
Methanol	and	LBG	21 %
Methanol	and	bio-methanol	29 %
LBG	and	bio-methanol	60 %

As can be seen from the figure and table above, if CO_2 with biomass origin has more than 15 % impact, it will in any cases be preferable to use LNG instead of LBG, methanol and bio-methanol.

Chapter 8

Economical Estimation

This chapter will present an LCC estimation for the cruise vessel, comparing prices for hydrogen, LNG and methanol as fuel utilized through an FC. HFO utilized through a combustion engine is used as benchmark.

Both OPEX and VOYEX should be calculated as present value, P. Values needed to calculate present value are listed in Table 8.1.

Table 8.1: Values needed to calculate present value

Expression	Symbol	Value	Unit
Market rate	p	7	%
Estimated inflation	f	3	%
Number of years/periods	n	30	years
Real interest rate	p′	0.0388	

Based on information in the table above, net present value factor, P′, can be calculated. P′ is the factor to be multiplied with future amount, F, to obtain the net present value, P.

$$P' = \left[\frac{(1+p)^n - 1}{p \times (1+p)^n} \right] \tag{8.1}$$

$$P' = \left[\frac{(1+0.07)^{30} - 1}{0.07 \times (1+0.07)^{30}} \right] = 17.54 \tag{8.2}$$

All calculations necessary to determine LCC for the various fuels can be found in Appendix E.

8.1 Capital Expenditures

CAPEX consist of building costs and administration costs. The building cost estimation is based on values given in Levander (2006), where only machinery- and accommodation costs is changed.

Obtaining prices for FCs have been hard. Anyway, from private communication with both Prasad Rohit, sales manager in Proton Motor Fuel Cell GmbH, and Mark Kammerer, business development manager in Hydrogenics GmbH, there has been received information which makes it reasonable to assume FC prices of 10 000-20 000 NOK/kW. The concrete price is determined by the distributor's availability of mass production and automation. Since the vessel will need a total power of almost 11.5 MW, it is rational to assume a FC price of 10 000 NOK/kW. Furthermore, there will be need of a reformer when utilization of LNG or methanol in a PEMFC. As well as for the FC prices, it has been hard to find reliable prices for reformers. Nevertheless, according to Battelle Memorial Institute (2016), a reformer for a 100 kW PEMFC costs approximately 40 000 NOK, which equals to 400 NOK/kW. Furthermore, a price of 2 000 NOK/kW is set for cooling system, ventilation etc.

Estimates used for calculation of extra costs during the building process can be seen in Table 8.2 and are found from Amdahl, Endal, et al. (2014). Table 8.3 presents the CAPEX values, all given in NOK.

Table 8.2: Additional costs during building process

Costs	Percentage of building costs
Administration costs	10%
Engineering costs	10%
Financing	5%
Yard profit	10%

Table 8.3: CAPEX

	Hydrogen	LNG	Methanol	HFO
Building costs	1 007 904 609	1 012 475 859	1 012 475 859	899 337 422
Administration costs	100 790 461	101 247 586	101 247 586	89 933 742
Engineering costs	100 790 461	101 247 586	101 247 586	89 933 742
Financing	50 395 230	50 623 793	50 623 793	44 966 871
Yard profit	100 790 461	101 247 586	101 247 586	89 933 742
Total	1 360 671 223	1 366 842 410	1 366 842 410	1 214 105 520

8.2 Operational Expenditures

8.2.1 Fuel Cell Replacement

One of the main OPEX for a vessel powered by FCs is the change of them. According to Mr. Rohit and Mr. Kammerer, the lifetime of an FC is approximately 20 000-25 000 hours, and the FC must be replaced when it has reached its lifetime. Originally, the price for FC replacement will be equal the price of new FC, i.e. about 10 000 NOK/kW. There is reason to believe that when mass production is beneficial for FC distributors, the FC prices will decrease. Mr. Kammerer estimates that in only few years, the FC price can be decreased to about half of today's price. Hence, the FC price for replacement is set to be 5 000 NOK/kW.

8.2.2 Annual Operational Expenditures

Estimates used for calculation other OPEX can be seen in Table 8.4.

Table 8.4: Estimates for annual OPEX

Costs	Estimate
Maintenance costs	5% of building cost
Administration costs	5% of building cost
Insurance costs	5% of building cost
Classing costs	5 MNOK/5 years
Crew wages	600 000 NOK/person annual

8.2.3 Summary

Table 8.5 presents a summary of annual OPEX for the vessel, where all values are given in NOK.

Table 8.5: Annual Operational Expenditures

	Hydrogen	LNG	Methanol	HFO
Change of FCs	11 842 700	11 842 700	11 842 700	-
Maintenance	50 395 230	50 623 793	50 623 793	44 966 871
Spare parts	100 200 000	100 200 000	100 200 000	100 200 000
Administration	50 395 230	50 623 793	50 623 793	44 966 871
Insurance	2 519 762	3 123 325	3 123 325	2 24 344
Classification	1 000 000	1 000 000	1 000 000	1 000 000
Sum	215 452 922	116 314 217	116 314 217	193 382 086
Present value 30 years	2 686 975 858	2 700 119 980	2 700 119 980	2 401 911 799

8.3 Voyage Related Expenditures

8.3.1 Fuel Costs

All of the compared fuels have different energy density, which means that comparing the fuels' price based on price per kg is not a good estimation. Therefore, the fuel prices are compared based on price per kWh.

There are naturally variations in fuel prices, and it is hard to predict how the prices will be in for instance 25 years. Fuel prices are therefore compared based on today's prices. Furthermore, fuel prices depend on the way the fuel is produced. Among others, hydrogen can be produced from NG or from renewable sources, where production from NG is cheaper than from the latter one.

Hydrogen prices are found for hydrogen produced from renewable sources. Furthermore, liquid hydrogen is more expensive than compressed hydrogen. Bjørn Gregert Halvorsen, technology specialist in NEL ASA, assume that liquefaction of hydrogen requires approximately 10 kWh/kg hydrogen, which cause extra costs. It has not been successful finding concrete values for liquid hydrogen, so the fuel price for hydrogen is for compressed hydrogen.

Fuel prices can be seen in Table 8.6. Conversion of the values can be found in Appendix E.1.

Table 8.6: Fuel prices for HFO, hydrogen, LNG and methanol

Fuel	Cost [kr/kWh]	Source
Hydrogen	0.51	GREENSTAT (2018)
LNG	0.18	ICE (2018)
Methanol	0.50	Methanol (2018)
HFO	0.25	Methanol (2018)

8.3.2 Port Costs

As described in Chapter 4.2, the vessel will dock in Bergen, Geiranger, Tromsø, Hammerfest and Bodø. Port charges for the various places are found from Port of Bergen (2018), Geirangerfjord Cruise Port (2018), Hammerfest Havn KF (2018) and Bodø Havn KF (2018).

8.3.3 Summary

Table 8.7 presents a summary of annual VOYEX.

Table 8.7: Annual voyage related expenditures

	Hydrogen	LNG	Methanol	HFO
Fuel	24 008 114	8 473 452	23 537 366	11 768 683
Port costs	25 298 256	25 275 181	25 289 250	25 459 785
Sum	49 306 370	33 748 633	48 826 617	37 228 468
Present value 30 years	611 844 776	418 788 174	605 891 497	461 969 593

8.4 Life Cycle Costs

A summary of LCC can be seen in Table 8.8, all values given in NOK. LCC are found from the formula:

$$LCC = CAPEX + \left[\frac{(1+p)^n - 1}{p \times (1+p)^n} \right] \times (OPEX + VOYEX) \tag{8.3}$$

Table 8.8: LCC

	Hydrogen	LNG	Methanol	HFO
CAPEX	1 360 671 223	1 366 842 410	1 366 842 410	1 214 105 520
OPEX	2 686 957 828	2 700 119 980	2 700 119 980	2 401 911 799
VOYEX	611 844 776	418 788 174	605 891 497	461 969 593
LCC	4 659 473 856	4 485 750 564	4 672 853 997	4 077 986 911

The distribution of CAPEX, OPEX and VOYEX for the LCC can be seen graphically in Figure 8.1.

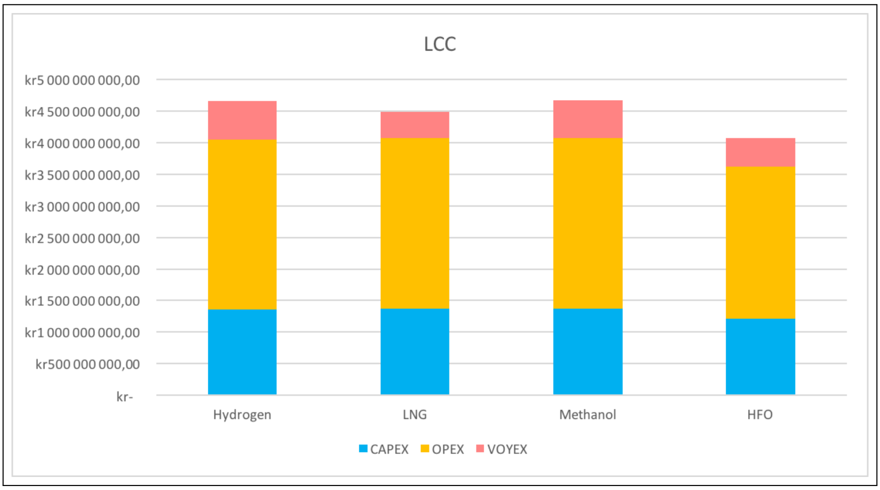


Figure 8.1: Distribution of CAPEX, OPEX and VOYEX

8.5 Required Freight Rate

Assuming the cruise on average will transport 70% of the passenger capacity, annual number of passengers can be found as:

$$C = \text{number of passengers} \times \text{trips/year} = 500 \times 0.7 \times 19 = 6650 \text{ passengers} \quad (8.4)$$

RFR can be calculated from:

$$RFR = \frac{LCC}{\left[\frac{(1+p)^n - 1}{p \times (1+p)^n}\right] \times C} \quad (8.5)$$

RFR for the various fuels can be seen in Table 8.9, given as NOK/PAX per round trip and NOK/PAX per day.

Table 8.9: RFR

RFR per	Hydrogen	LNG	Methanol	HFO
PAX/trip [NOK]	56 465	54 359	56 627	49 418
PAX/day [NOK]	3 137	3 020	3 146	2 745

Chapter 9

Discussion

This chapter discusses the results and the various aspects in the thesis.

Regard to the fact that there is not much available documentation, it was challenging to gather the required information. FCs used for ship propulsion are relatively new technology, and has never been used for big vessels, including cruise vessels.

A challenge regarding the alternative fuels, and especially hydrogen, is to produce them in an environmental friendly way. As can be seen in Figure 7.5 in Chapter 7.4, hydrogen produced by renewable hydropower is the best solution, while hydrogen produced by LNG is the worst, excluding HFO. Though, 48 % of produced hydrogen has its origin from LNG, while only 4 % is from renewable energy sources. Unfortunately, there is lack of focus on emissions during production, as emissions during operation and *zero emission operation* often are main focus.

The Norwegian government is developing a supply chain for CO_2 capture, which can be stored under the seabed. As can be seen in the LCI in Chapter 7.2, during a life cycle, CO_2 emissions are of most significance, which applies for all of the fuels. Capture of CO_2 will reduce GHGs, and by then also the potential environmental impact. Additionally, CO_2 capture may cause a different outcome in the environmental assessment.

The vessel's main dimensions are not considered in the environmental evaluation. This is because the main dimensions for a vessel fuelled by hydrogen, LNG or methanol are not of significance. If there were bigger variations in the main dimensions, this should be considered by taking resistance calculations into account. In this case, it was random that the main dimensions were so equal for both hydrogen, LNG and methanol, and were a result of the chosen tank size. When a PEMFC is used, LNG and methanol as fuel require more machinery space than hydrogen as fuel. Though, hydrogen has smaller specific energy per volume than both LNG and methanol.

For the LCIA, 100 years ionizing radiation, referred to as Hierarchist, were assumed. Anyway, both Individualist, 20 years, and Egalitarian, 1 000 years, could also have been considered, which may influence the result. While Hierarchist is assumed to be on the baseline, Individualist and Egalitarian are optimistic and pessimistic, respectively.

In this thesis, among other things, the environmental footprint from hydrogen produced from LNG and LNG reformed to hydrogen aboard the vessel is considered. According to the result obtained in Chapter 7.3, hydrogen produced from LNG causes more than 45 % higher environmental impact than LNG reformed to hydrogen aboard the vessel. Though there may be some differences in emissions, it is not reasonable that they are this big. It has not succeeded finding these difference's origin.

There is a lot of focus on the Paris agreement, which is a driving force for climate change. Several Governments have ratified to the Convention, and many resources are being used to reach the goals set. It is not necessarily only financial requirements that determine which solution is chosen, but also requirements related to the Paris Agreement. One cannot rely on what is profitable in the short-therm, but also consider the environmental impact. The maritime industry is a strong and global industry driven by competition, which may be challenging in order to obtain contracts. Additionally, passengers on expedition cruise vessels have become more concerned with the environment, and want to explore areas which are unaffected by humans. A low environmental impact from cruise ships is also a costumer requirement in this context.

MARPOL claims requirements regarding emissions from ships in operation, but it has not been found any regulations regarding emissions during production of fuels. Among the evaluated fuels, hydrogen produced from renewable sources has the lowest environmental impact, while hydrogen produced from LNG has the highest impact. Anyway, emissions during operation are the same whether hydrogen is produced from renewable sources or LNG. The environmental impact from shipping could be decreased by international requirements regarding emissions during fuel's life cycle.

As presented in Chapter 7.2, all of the fuels fulfill MARPOL's Regulation 14, while only hydrogen and LNG fulfill Regulation 13. There are uncertainties related to the actual emissions of NOx, as it has not succeeded finding any source stating the emissions. NOx emissions from LNG and methanol during operation in an FC is assume to be equal as NOx emission during operation in a combustion engine, though it is a conservative approach. Furthermore, the allowable limit of NOx emissions is based on rotation per minute for a combustion engine. As there are no rotation per minute in an FC, the strictest requirement was assumed.

In Chapter 7.4, a comparison of the alternative fuels in an FC and a combustion engine is developed. Emissions from the fuels utilized through a combustion engine had already been developed by Gilbert et al. (2018). However, it would be of interest to compare all the aspects with FCs against combustion engines. While a combustion engine normally has a lifetime equal to the ship's lifetime, an FC has a lifetime of approximately 20 000-25 000 hours. Having a lifetime of 30 years cause about 6 replacements of the FCs. LCA for the FCs is not included in this thesis. Considering an FC has a lifetime of approximately five years, the environmental impact from production, maintenance and disposal should be evaluated.

As the situation is today, PEMFC is considered as the best FC alternative. This is mainly caused by the fact that it is most commercial available. Though, it is of interest to find which FC is the best solution for the future, taking both environment, economics and technical feasibility into account. As times goes by, it is reasonable to assume that both HT-PEMFC and SOFC will be more utilized. HT-FCs have several advantages versus LT-FCs, among other things increased overall efficiency.

The final result would probably have been different if another FC had been chosen. The need of an external reformer when utilization of other fuels than hydrogen in PEMFC, causes both increased machinery size and costs. For an SOFC, the reformation of fuels occurs within the FC, which means there will be no need of an external reformer. Experts within this field have different opinions regarding HT-FCs. Some claims they are most suitable as source for auxiliary power delivering constant power to a system that not will be switched off. On the other hand, other means they should be used for propulsion power for other fuels than hydrogen, due to their internal reformation of fuels. It is crucial to increase their flexibility regarding start-up and change of power demand in order to make them competitive for propulsion.

Car ferries and fast ferries are often first to use new technology regarding alternative energy sources for propulsion. A reason may be that the sailing route for ferries normally goes between two base stations, and the infrastructure is therefore easier to develop. A cruise vessel, on the other hand, will be dependent on bunkering- or charging stations several places on their sailing route. The infrastructure and availability of alternative and environmental friendly fuels are a reoccurring challenge. The development of infrastructure for LNG has expanded rapidly. Bunker facilities are dependent on global demand, and it is reasonable to assume that the infrastructure will increase when the global demand increase. An alternative regarding infrastructure is use of bunkering vessels, which is a flexible solution. It is important to be aware of emissions from these bunkering vessels, and take emission during the whole life cycle into consideration. The aim of utilizing environmental friendly fuels may be decreased if bunkering vessels use for instance HFO or MDO.

Whether hydrogen, LNG or methanol is the best fuel for utilization in an FC depends on the stakeholders' values. Though, methanol is not an appropriate fuel for FCs, as it requires more space and causes higher potential environmental impact than both hydrogen and LNG. It can be questioned whether it is beneficial to spend so much money on installing an FC for use of LNG, as it respectively has 1.5 times higher potential environmental impact than hydrogen produced from renewables.

Requiring a fuel tank capacity for sailing in 100 hours, HFO obtained higher GV than both hydrogen, LNG and methanol. Though the fuel tank is smaller than for the other fuels, the machinery size was found as bigger for a combustion engine than FCs. There has not been found values for size of cooling system and ventilation for FCs, which may be a source of error. However, it is assumed that the machinery size for the FCs is conservative.

Regarding hydrogen and LNG, the fuel tanks should be placed with a minimum distance of $^B/_5$ from ship side. In which extent the area between the fuel tanks and ship side is utilized will depend the main dimensions of the vessel. In this thesis, it is assumed that this area can be utilized. If this is not the case, it should be taken into consideration.

There is not developed any general arrangement in this thesis. It would be of interest to see how the FCs and tanks had been integrated in a general arrangement, which probably would have been affected.

A method in SBSD could have been utilized for stability calculations, but has not been implemented due to lack of time. Stability is crucial for a vessel, and is highly relevant to control.

The technology is developing all the time, and challenges today will probably be solved within a few years.

Chapter 10

Conclusion

The evaluation of whether hydrogen, LNG or methanol is most suitable in an FC on a cruise vessel, is based on how much machinery- and tank space they require, their environmental impact and their costs.

PEMFC was considered as the most suitable FC. PEMFC requires an external reformer for reformation of LNG and methanol to hydrogen. Water and electricity is the only outcome when hydrogen is utilized through and PEMFC, while utilization of LNG and methanol cause emissions of CO_2 and some NOx as well.

Considering GT and fuel tanks accommodating fuel for 100 hours sailing, LNG is the best alternative. Methanol and hydrogen received the same GT, though it was only 1.01 times bigger than for LNG, which in practice can be considered as equal. If the tank size is increased even more, hydrogen will obtain the highest GT, while methanol will obtain the second highest.

Regarding the environmental aspect, hydrogen produced from renewable hydrogen is the best option. It should be noted that hydrogen produced from LNG has highest potential environmental impact, and it is therefore important to distinguish between these two ways of production. Both methanol and LNG have less emissions by utilization in FC than combustion engine. Furthermore, is has been found that LNG in a combustion engine is a better alternative than methanol in an FC. All of the fuels utilized through FCs will cause less environmental impact than HFO utilized in a combustion engine.

Among the three evaluated fuels, LNG obtained the lowest LCC. LCC for LNG is 1.10 times higher than the LCC for HFO. Hydrogen and methanol are 1.14 and 1.15 times more expensive than HFO during a life cycle.

10.1 Further Work

Further work recommended to obtain a more thorough result are listed below:

- Regarding choice of FCs, a more thorough study of HT-FCs' feasibility could be analysed. Use of HT-FCs would probably affect both costs and main dimensions.
- More detailed costs- and area information regarding the machinery system needed for FCs, including both ventilation and cooling system.
- An adequate comparison of an LCA for FCs and combustion engine.
- It is preferable to develop a general arrangement in order to investigate the technical feasibility, and an accurate determination of placement of both fuel tanks and FCs. Additionally, both weight- and stability calculations should be developed.

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Appendices

Appendix A

Fuel Cell Projects

A.1 Maritime Fuel Cell Projects

Information about FC projects in the maritime sector found by Tronstad et al. (2017) can be seen in Table A.1.

Table A.1: FC projects in shipping

Project	Main partners	Year	Fuel Cell	Capacity	Fuel
FellowSHIP	Eidesvik Offshore, Wärtsilä	2003-2011	MCFC	320 kW	LNG
Viking Lady METHAPU Undline	Wallenius Maritime, Wärtsilä, DNV	2006-2010	SOFC	20 kW	Methanol
E4Ships-Pa-X-ell MS Mariella	Meyer Werft, DNV GL, Lürssen Werft, etc	Phase 1: 2009-2017 Phase 2: 2017-2022	HT-PEMFC	60 kW	Methanol
E4Ships-SchlBZ MS Forester	Thyssen Krupp Marine System, DNV GL, Leibniz University Hannover, OWI, Reederei Rörd Braren, Sunfire	Phase 1: 2009-2017 Phase 2: 2017-2022	SOFC	100 kW	Diesel

E4Ships - Toplanterne	DNV GL, Meyer Werft, Thyssen Krupp Maritime Systems, Lürssen Werft, Flensburger Schiffbaugesellschaft, VSM	Phase 1: 2009-2017 Phase 2: 2012-2022	-	-	-
RiverCell	Meyer Werft, DNV GL, Neptun Werft, Viking Cruises	Phase 1: 2015-2017 Phase 2: 2017-2022	HT-PEMFC	250 kW	Methanol
RiverCell-Elektra	TU Berlin, BEHALA, DNV GL, etc	2015-2016	HT-PEMFC	-	Hydrogen
ZemShip - Alsterwasser	Proton Motors, GL, Alster Touristik GmbH, Linde Group, etc	2006-2013	PEMFC	96 kW	Hydrogen
FCSHIP	DNV, GL, LR, RINA, EU GROWTH program	2002-2004	MCFC SOFC PEMFC	-	Various
New-H-Ship	INE (Icelandic New Energy), GL, DNV, etc	2004-2006	-	-	-
NEMO H2	Rederij Lovers etc	2012-present	PEMFC	60 kW	Hydrogen
Hornblower Hybrid	Hornblower	2012-present	PEMFC	32 kW	Hydrogen
Hydrogenesis	Bristol Boat Trips etc	2012-present	PEMFC	12 kW	Hydrogen
MF Vågen	CMR Protech, ARENA-Project	2010	HT-PEMFC	12 kW	Hydrogen
Vlass 212A/212 Submarines	CMR Prototech, ARENA-Project, ThyssenKrupp Marine Systems, Siemens	2000-1011	PEMFC	306 kW	Hydrogen

US SSFC	U.S. Department of Defens, Office of Naval Research	2000-2011	PEMFC MCFC	500 kW (PEM) 625 kW (MCFC)	Diesel
SF-BREEZE	Sandia National Lab. Red and White Fleet	2015-Present	PEMFC	120 kW per module. Total power 2.5 MW	Hydrogen
MC-WAP	FINCANTIERI, Cetana, OWI, TÜBITAK, RINA, NTUA, Techip, KTI, etc	2005-2010	MCFC	150 kW	Diesel
FELICITAS - subproject 1	Lürssen, FhG, IVI, AVL, HAW, Rolls-Royce, INRETS, VUZ	2005-2008	-	-	-
FELICITAS - subproject 2	Rolls-Royce, Uni Genoa, Lürssen, HAW, Uni Eindhoven	2005-2008	SOFC	250 kW	LNG
FELICITAS - subproject 3	NuCellsys, FhG IVI, CCM	2005-2008	PEMFC	Cluster system	Hydrocarbon fuels and hydrogen
FELICITAS - subproject 4	FhG IVI, Lürssen, NTUA, NuCellSys, CCM, Uni Belfort, AVL, CDL	2005-2008	PEMFC	-	-
Cobalt 233 Zet	Zebotec, Brunnert-Grimm	2007-present	PEMFC	50 kW	Hydrogen

A.2 Overall Fuel Cell Shipments In 2017

Concrete values for overall shipped FCs and shipped MWs per FC type can be seen in Table A.2 and A.3, respectively (*The Fuel cell Industry Review 2017* 2018).

Table A.2: Shipments by FC type 2015-2017

Fuel cell type	Shipments by FC (1,000 units)		
	2015	2016	2017
PEMFC	53.5	44.5	45.5
SOFC	5.2	16.2	24
DMFC	2.1	2.3	2.8
PAFC	0.1	0.1	0.2
AFC	0.0	0.1	0.1
MCFC	0.0	0.0	0.0

Table A.3: Shipped megawatts by FC type 2015-2017

Fuel cell type	Shipped MWs per FC type		
	2015	2016	2017
PEMFC	151.8	341.0	486.8
PAFC	24.0	56.2	81.0
SOFC	53.3	62.9	76.4
MCFC	68.6	55.7	24.7
AFC	0.2	0.5	0.5
DMFC	0.2	0.2	0.3

Appendix B

Machinery

B.1 Specific Fuel Consumption

Calculation of the fuels' SFC, given as [g/kWh] can be seen below.

$$1kWh = \frac{kJ}{3600s} \tag{B.1}$$

$$\frac{kJ}{kg} = \frac{kJ}{3600s \times kg} = \frac{kWh}{kg} \tag{B.2}$$

$$\text{Fuel consumption} = \frac{kg}{kWh} = \frac{1}{\frac{kWh}{kg}} \tag{B.3}$$

In order to find SPC, the fuel consumption should be divided on the power generator's efficiency. These can be seen in Table B.1.

Table B.1: Efficiencies during power generation

Fuel	Efficiency [%]
HFO	45
Hydrogen	55
LNG	40
Methanol	40

SFC for hydrogen, LNG and methanol utilized in an FC and HFO utilized in a combustion engine are calculated below.

$$\text{Fuel consumption HFO} = \frac{43000kJ}{kg} = 11.94{}^{kWh}/_{kg} = 84{}^{g}/_{kWh} \tag{B.4}$$

$$\text{SFC HFO} = \frac{84{}^{g}/_{kWh}}{0.45} = 186{}^{g}/_{kWh} \tag{B.5}$$

$$\text{Fuel consumption hydrogen} = \frac{142000kJ}{kg} = 39.44{}^{kWh}/_{kg} = 25{}^{g}/_{kWh} \tag{B.6}$$

$$\text{SFC hydrogen} = \frac{25{}^{g}/_{kWh}}{0.55} = 46{}^{g}/_{kWh} \tag{B.7}$$

$$\text{Fuel consumption LNG} = \frac{52000kJ}{kg} = 14.44{}^{kWh}/_{kg} = 69{}^{g}/_{kWh} \tag{B.8}$$

$$\text{SFC LNG} = \frac{69{}^{g}/_{kWh}}{0.40} = 173{}^{g}/_{kWh} \tag{B.9}$$

$$\text{Fuel consumption methanol} = \frac{21000kJ}{kg} = 5.83{}^{kWh}/_{kg} = 171{}^{g}/_{kWh} \tag{B.10}$$

$$\text{SFC methanol} = \frac{171{}^{g}/_{kWh}}{0.40} = 429{}^{g}/_{kWh} \tag{B.11}$$

SFC for HFO and hydrogen can be compared with the SFC found by Gilbert et al. (2018), and the comparison can be seen in Table B.2. The differences are not of any significance, and may be related to different efficiencies during power generation.

Table B.2: Comparison of fuel consumption [g/kWh]

Fuel	Obtain in this work	Obtained by Gilbert et al. (2018)
HFO	186	179
Hydrogen	46	57

B.2 Boil-Off

According to Andreas Züttel (2003), the boil-off for a tank having a storage volume of 100 m ^{3} and 20 000 m ^{3}is 0.2 % and 0.06 % per day, respectively. By interpolation, the boil-off for a hydrogen- and LNG tank with a storage volume of 1 307 m ^{3} and 772 m ^{3}, respectively, can be found.

B.2.1 Boil-Off for Hydrogen

$$f(x) \approx f(x_1) + \frac{x - x_1}{x_2 - x_1}(f(x_2) - f(x_1)) \tag{B.12}$$

where

f(x)= Boil-off for tank volume = 1 307 m^3

x = 1 307

f(x_1) = 0.2

x_1 = 100

f(x_2) = 0.06

x_2 = 20 000

By this, the boil-off for the tank with a storage volume of 1 307 m ^{3} can be found as:

$$f(1307) = 0.2 + \frac{1307 - 100}{20000 - 100} \times (0.06 - 0.2) = 0.19\% \tag{B.13}$$

The volume of the boil off can then be found as:

$$1307m^3 \times 0.19\% = 2.5m^3 \tag{B.14}$$

Total energy which can be received by a given volume fuel can be found as:

$$\text{Energy} = \frac{\text{Volume} \times \text{Specific energy} \times \text{Volume density} \times \text{Efficiency}}{\text{Safety factor}} \tag{B.15}$$

The total energy is:

$$\frac{2.5 \times 142000 \times 70.8 \times 0.55 \times 0.55}{1.2} = 6335863kJ = 1759kWh \tag{B.16}$$

B.2.2 Boil-Off for LNG

$$f(x) \approx f(x_1) + \frac{x - x_1}{x_2 - x_1}(f(x_2) - f(x_1)) \tag{B.17}$$

where

f(x)= Boil-off for tank volume = 772 m^3

x = 772

$f(x_1)$ = 0.2

x_1 = 100

$f(x_2)$ = 0.06

x_2 = 20 000

By this, the boil-off for the tank with a storage volume of 1 307 m ^{3} can be found as:

$$f(1307) = 0.2 + \frac{772 - 100}{20000 - 100} \times (0.06 - 0.2) = 0.19\% \tag{B.18}$$

The volume of the boil off can then be found as:

$$772m^3 \times 0.19\% = 1.5m^3 \tag{B.19}$$

The total energy is:

$$\frac{1.5 \times 52000 \times 450 \times 0.40 \times 0.55}{1.2} = 5850000kJ = 1625kkWh \tag{B.20}$$

B.2.3 Summary

During 24 hours, total energy demand in port can be found as:

$$\text{Power needed in port} \times \text{Time in port} = \text{Total energy demand} \tag{B.21}$$

$$1984 \times 24 = 47616kWh \tag{B.22}$$

The boil-off rate for hydrogen and LNG is equal to 1 759 kWh per day and 1 625 kWh per day, respectively, while the power demand in port is equal to 47 616 kWh per day. Hence, the boil-off rate is not of significance, and shore power will be utilized when the vessel is docked.

Appendix C

Required Spaces

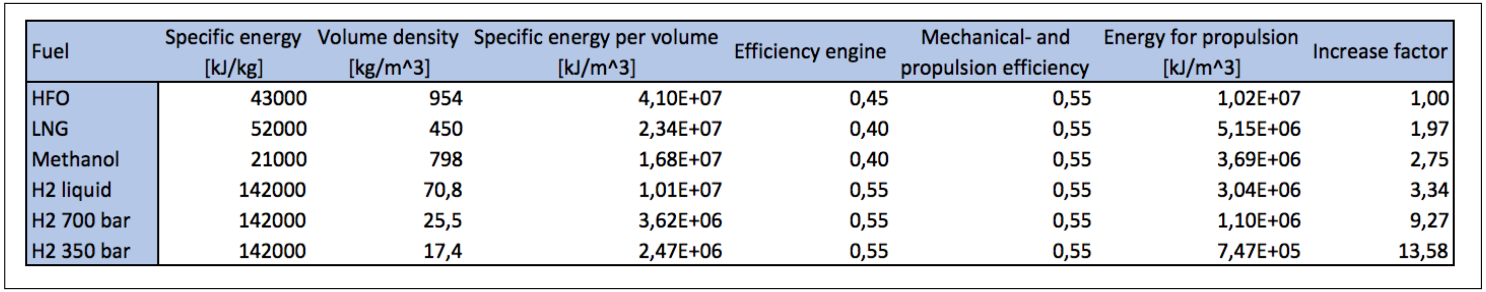
Data for calculation of necessary tank sizes can be seen in the following pages.

Table C.1: Specifications

Specifications		
Endurance power	9 200	kW
Power in port	1 984	kW
Speed	15	knots
Duration	100	hours
Safety factor	1.2	-
Tank breadth	9.2	m
Tank height	3	m
Electrical efficiency		
HFO	0.45	
Hydrogen	0.55	
Methanol	0.4	
LNG	0.4	
Mechanical- and propulsion efficiency		
All	0.55	

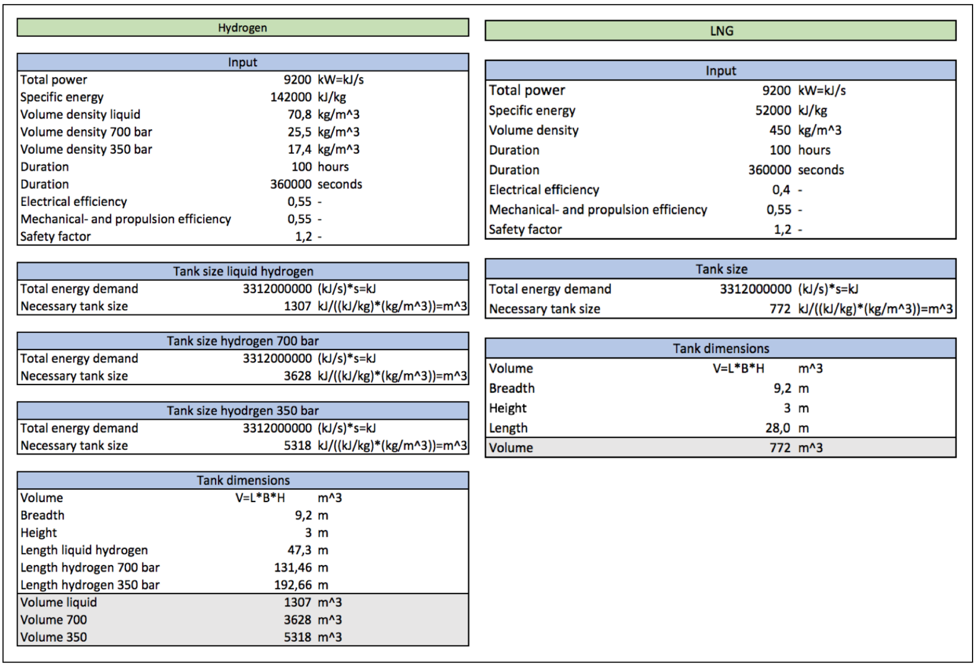
Table C.2: Sailing route

Sailing route				Time at sea	
Hamburg	Bergen	870	km	31	hours
Bergen	Geiranger	370	km	13	hours
Geiranger	Tromsø	1 160	km	42	hours
Tromsø	Honningsvåg	380	km	14	hours
Honningsvåg	Svolvær	2 660	km	96	hours
Svolvær	Hamburg	1 860	km	67	hours
Total		7 300	km	263	hours



Fuel	Specific energy [kJ/kg]	Volume density [kg/m^3]	Specific energy per volume [kJ/m^3]	Efficiency engine	Mechanical- and propulsion efficiency	Energy for propulsion [kJ/m^3]	Increase factor
HFO	43000	954	4,10E+07	0,45	0,55	1,02E+07	1,00
LNG	52000	450	2,34E+07	0,40	0,55	5,15E+06	1,97
Methanol	21000	798	1,68E+07	0,40	0,55	3,69E+06	2,75
H2 liquid	142000	70,8	1,01E+07	0,55	0,55	3,04E+06	3,34
H2 700 bar	142000	25,5	3,62E+06	0,55	0,55	1,10E+06	9,27
H2 350 bar	142000	17,4	2,47E+06	0,55	0,55	7,47E+05	13,58

Figure C.1: Fuel properties



Hydrogen

Input		
Total power	9200	kW=kJ/s
Specific energy	142000	kJ/kg
Volume density liquid	70,8	kg/m^3
Volume density 700 bar	25,5	kg/m^3
Volume density 350 bar	17,4	kg/m^3
Duration	100	hours
Duration	360000	seconds
Electrical efficiency	0,55	-
Mechanical- and propulsion efficiency	0,55	-
Safety factor	1,2	-

Tank size liquid hydrogen		
Total energy demand	3312000000	(kJ/s)*s=kJ
Necessary tank size	1307	kJ/((kJ/kg)*(kg/m^3))=m^3

Tank size hydrogen 700 bar		
Total energy demand	3312000000	(kJ/s)*s=kJ
Necessary tank size	3628	kJ/((kJ/kg)*(kg/m^3))=m^3

Tank size hyodrgen 350 bar		
Total energy demand	3312000000	(kJ/s)*s=kJ
Necessary tank size	5318	kJ/((kJ/kg)*(kg/m^3))=m^3

Tank dimensions		
Volume	V=L*B*H	m^3
Breadth	9,2	m
Height	3	m
Length liquid hydrogen	47,3	m
Length hydrogen 700 bar	131,46	m
Length hydrogen 350 bar	192,66	m
Volume liquid	1307	m^3
Volume 700	3628	m^3
Volume 350	5318	m^3

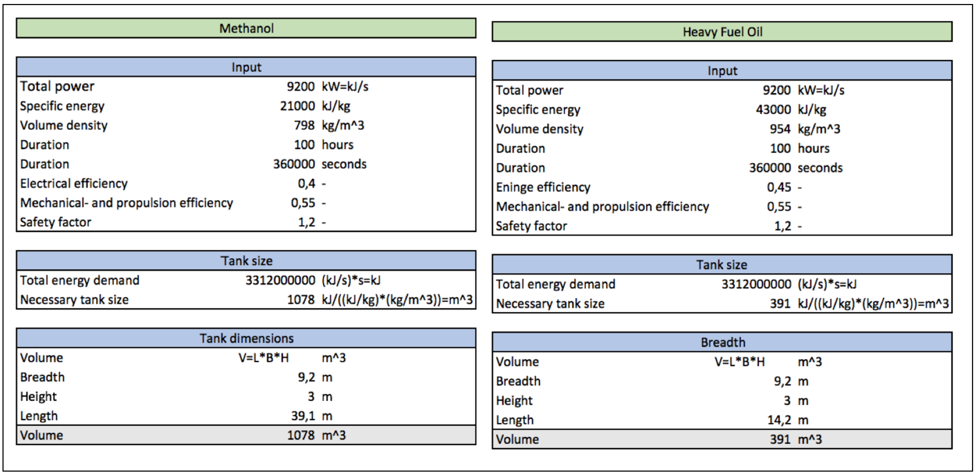
LNG

Input		
Total power	9200	kW=kJ/s
Specific energy	52000	kJ/kg
Volume density	450	kg/m^3
Duration	100	hours
Duration	360000	seconds
Electrical efficiency	0,4	-
Mechanical- and propulsion efficiency	0,55	-
Safety factor	1,2	-

Tank size		
Total energy demand	3312000000	(kJ/s)*s=kJ
Necessary tank size	772	kJ/((kJ/kg)*(kg/m^3))=m^3

Tank dimensions		
Volume	V=L*B*H	m^3
Breadth	9,2	m
Height	3	m
Length	28,0	m
Volume	772	m^3

Figure C.2: Tank size for hydrogen and LNG



Methanol

Input		
Total power	9200	kW=kJ/s
Specific energy	21000	kJ/kg
Volume density	798	kg/m^3
Duration	100	hours
Duration	360000	seconds
Electrical efficiency	0,4	-
Mechanical- and propulsion efficiency	0,55	-
Safety factor	1,2	-

Tank size		
Total energy demand	3312000000	(kJ/s)*s=kJ
Necessary tank size	1078	kJ/((kJ/kg)*(kg/m^3))=m^3

Tank dimensions		
Volume	V=L*B*H	m^3
Breadth	9,2	m
Height	3	m
Length	39,1	m
Volume	1078	m^3

Heavy Fuel Oil

Input		
Total power	9200	kW=kJ/s
Specific energy	43000	kJ/kg
Volume density	954	kg/m^3
Duration	100	hours
Duration	360000	seconds
Eninge efficiency	0,45	-
Mechanical- and propulsion efficiency	0,55	-
Safety factor	1,2	-

Tank size		
Total energy demand	3312000000	(kJ/s)*s=kJ
Necessary tank size	391	kJ/((kJ/kg)*(kg/m^3))=m^3

Breadth		
Volume	V=L*B*H	m^3
Breadth	9,2	m
Height	3	m
Length	14,2	m
Volume	391	m^3

Figure C.3: Tank size for methanol and HFO

Appendix D

Environmental Evaluation

D.1 System Boundaries

The system boundaries from the LCAs developed by Gilbert et al. (2018) and Brynolf, Fridell, and Andersson (2014) can be seen in Figure D.1 and D.2, respectively.

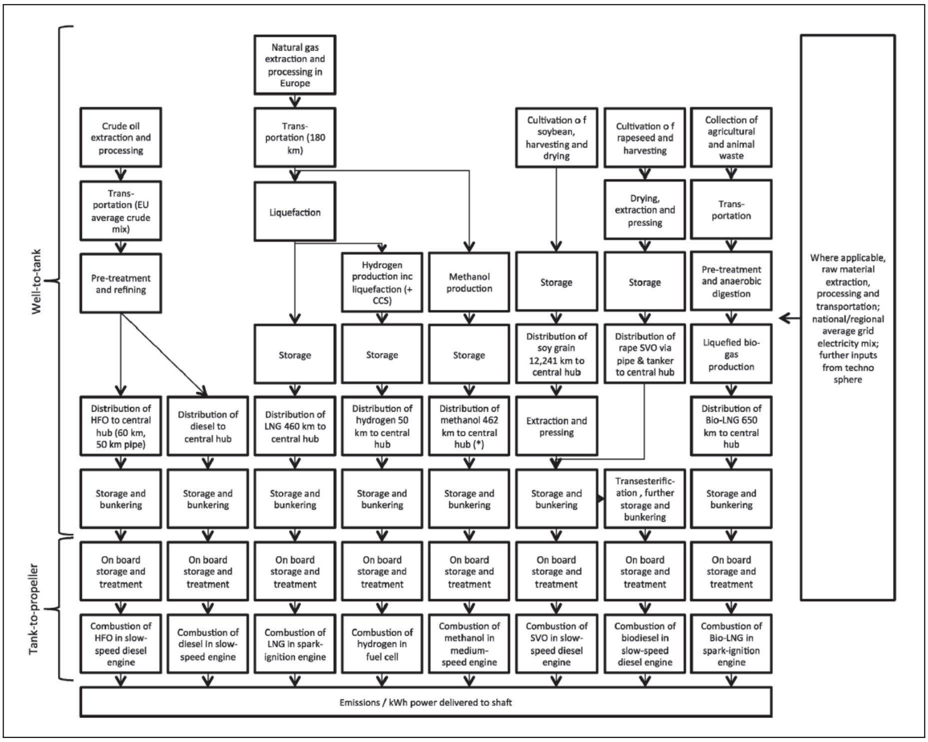


Figure D.1: System boundaries for the LCA developed by Gilbert et al. (2018)

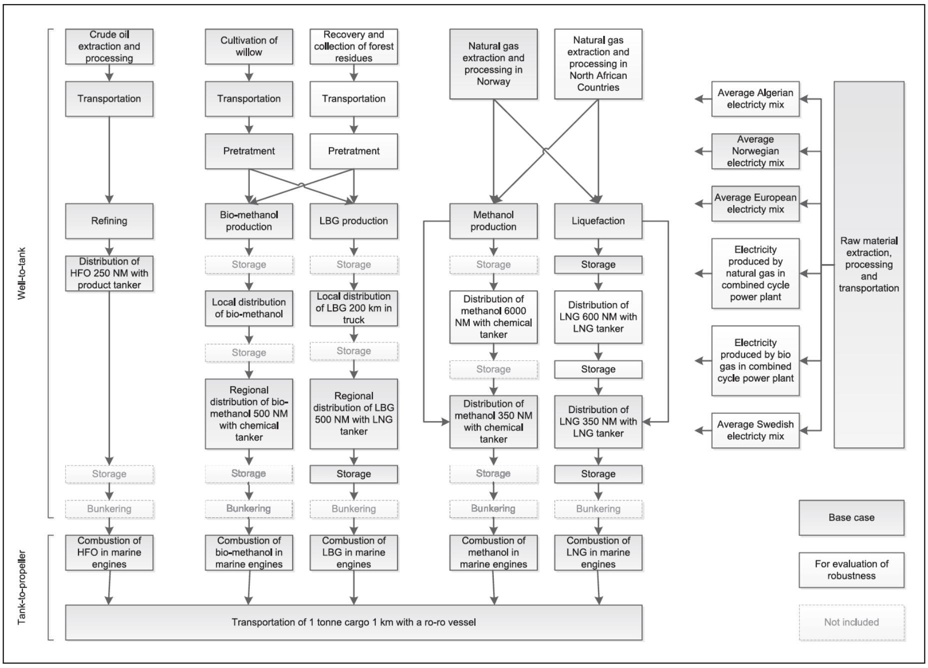


Figure D.2: System boundaries for the LCA developed by Brynolf, Fridell, and Andersson (2014)

D.2 Midpoint- and Endpoint Indicators

The midpoint- and endpoint indicators for ReCiPe 2016 can be seen in Figure D.3.

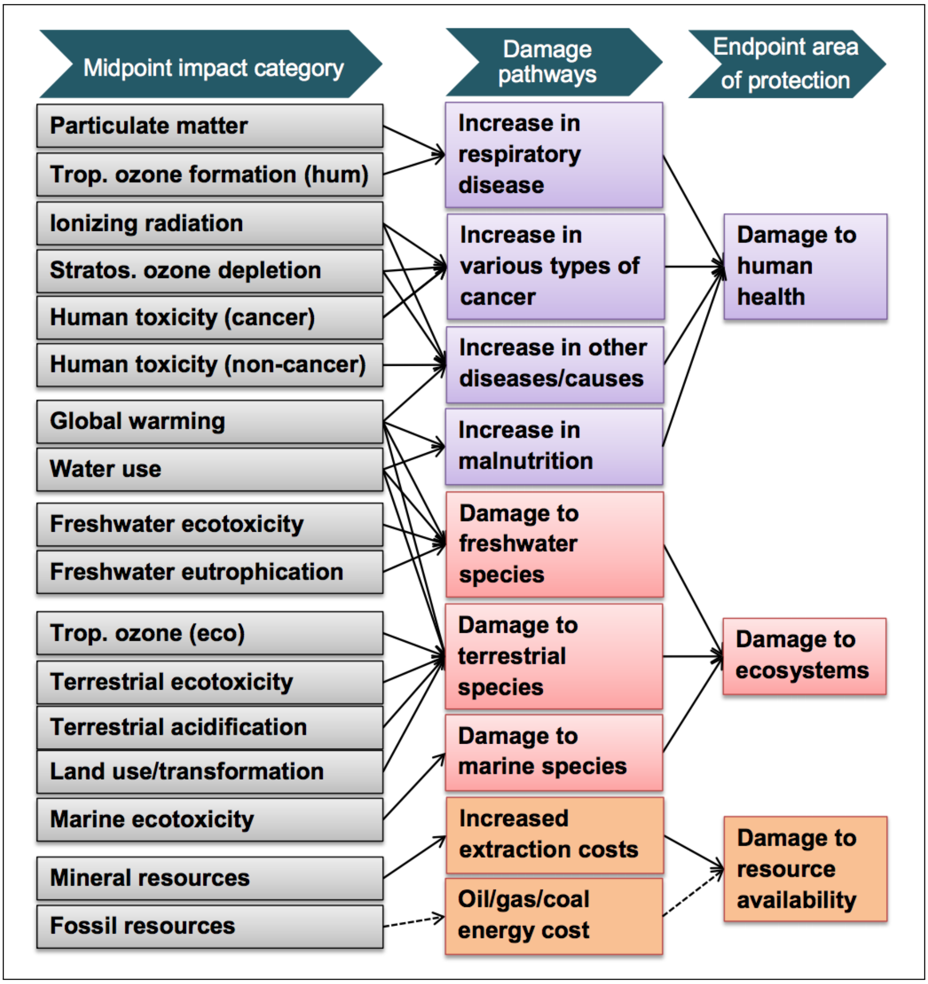


Figure D.3: Midpoint- and endpoint indicators for ReCiPe 2016. Source: Huijbregts et al. (2016)

D.3 Life Cycle Inventory Analysis

Table D.1 presents the concrete values of the LCI for hydrogen produced from wind power, hydrogen produced from LNG, LNG and methanol produced from LNG developed by Gilbert et al. (2018). All these fuels are utilized through an FC. HFO utilized in a combustion engine is used as a benchmark. All values are given in [g/kWh].

Table D.1: LCI for hydrogen, LNG and methanol [g/kWh]

Emission	HFO	Methanol	LNG	Hydrogen LNG	Hydrogen Renewable
During production [g/kWh]					
CO_2	59.00	402.75	51.75	926.00	98.00
CH_4	0.58	0.60	0.39	1.76	0.41
N_2O	0,00	0.02	0.02	0.04	0.01
NOx	0.20	0.44	0.12	0.96	0.98
PM	0.02	0.00	0.00	0.14	0.06
SOx	0.35	0.00	0.18	0.87	1.15
During operation [g/kWh]					
CO_2	541.00	587.25	470.25	0.00	0.00
CH_4	0.01	0.00	0.00	0.00	0.00
N_2O	0.03	0.00	0.00	0.00	0.00
NOx	16.60	3.43	1.34	0.00	0.00
PM	0.76	0.00	0.00	0.00	0.00
SOx	3.40	0.00	0.00	0.00	0.00
Total [g/kWh]					
CO_2	600.00	990.00	522.00	926.00	98.00
CH_4	0.59	0.60	0.39	1.76	0.41
N_2O	0.03	0.02	0.02	0.04	0.01
NOx	16.80	3.87	1.46	0.96	0.98
PM	0.78	0.00	0.00	0.14	0.06
SOx	3.75	0.00	0.18	0.87	1.15

Calculations to convert these values from [g/kWh] to the functional unit, [kg/PAX per round trip], can be seen in Table D.2 below.

Table D.2: Conversion of LCI values to functional unit

Per round trip		
Time in port	146	h
Time maneuvering	8	h
Total time	154	h
Endurance power	91 425	kW
Power per round trip	14 079 450	kWh
PAX per round trip	350	PAX
Power per PAX/round trip	40 227	kWh/PAX per round trip
$^{g}/_{kWh} \times {}^{kWh}/_{PAX}$ per round trip $= {}^{g}/_{PAX}$ per round trip		

From the calculation, total emissions given as [$^{kg}/_{PAX}$ per round trip] and [$^{kg}/_{PAX}$ per day] can be seen in Table D.3 and D.4.

Table D.3: LCI for hydrogen, LNG and methanol [kg/PAX per round trip]

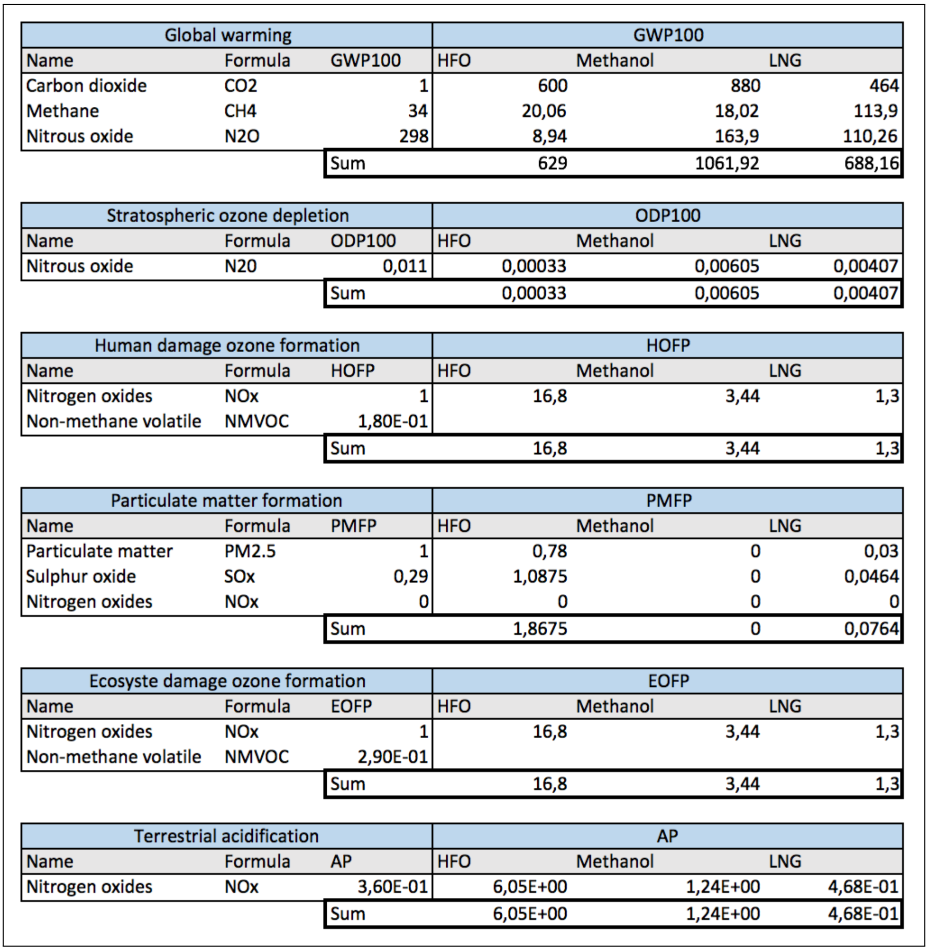
Emission	HFO	Methanol	LNG	Hydrogen LNG	Hydrogen Renewable
CO_2	24 136	39 825	20 998	37 250	3 942
CH_4	24	24	16	71	16
N_2O	1	1	1	2	0
NOx	676	156	59	39	39
PM	31	0	0	6	2
SOx	151	0	7	35	46

Table D.4: LCI for hydrogen, LNG and methanol [kg/PAX per day]

Emission	HFO	Methanol	LNG	Hydrogen LNG	Hydrogen Renewable
CO_2	1 341	2 212	1 167	2 069	219
CH_4	1	1	1	4	1
N_2O	0	0	0	0	0
NOx	38	9	3	2	2
PM	2	0	0	0	0
SOx	8	0	0	2	3

D.4 Life Cycle Impact Assessment

Relevant values and calculations for obtaining impact factors can be seen in Figure D.4 and D.5.



Global warming			GWP100		
Name	Formula	GWP100	HFO	Methanol	LNG
Carbon dioxide	CO2	1	600	880	464
Methane	CH4	34	20,06	18,02	113,9
Nitrous oxide	N2O	298	8,94	163,9	110,26
		Sum	629	1061,92	688,16

Stratospheric ozone depletion			ODP100		
Name	Formula	ODP100	HFO	Methanol	LNG
Nitrous oxide	N20	0,011	0,00033	0,00605	0,00407
		Sum	0,00033	0,00605	0,00407

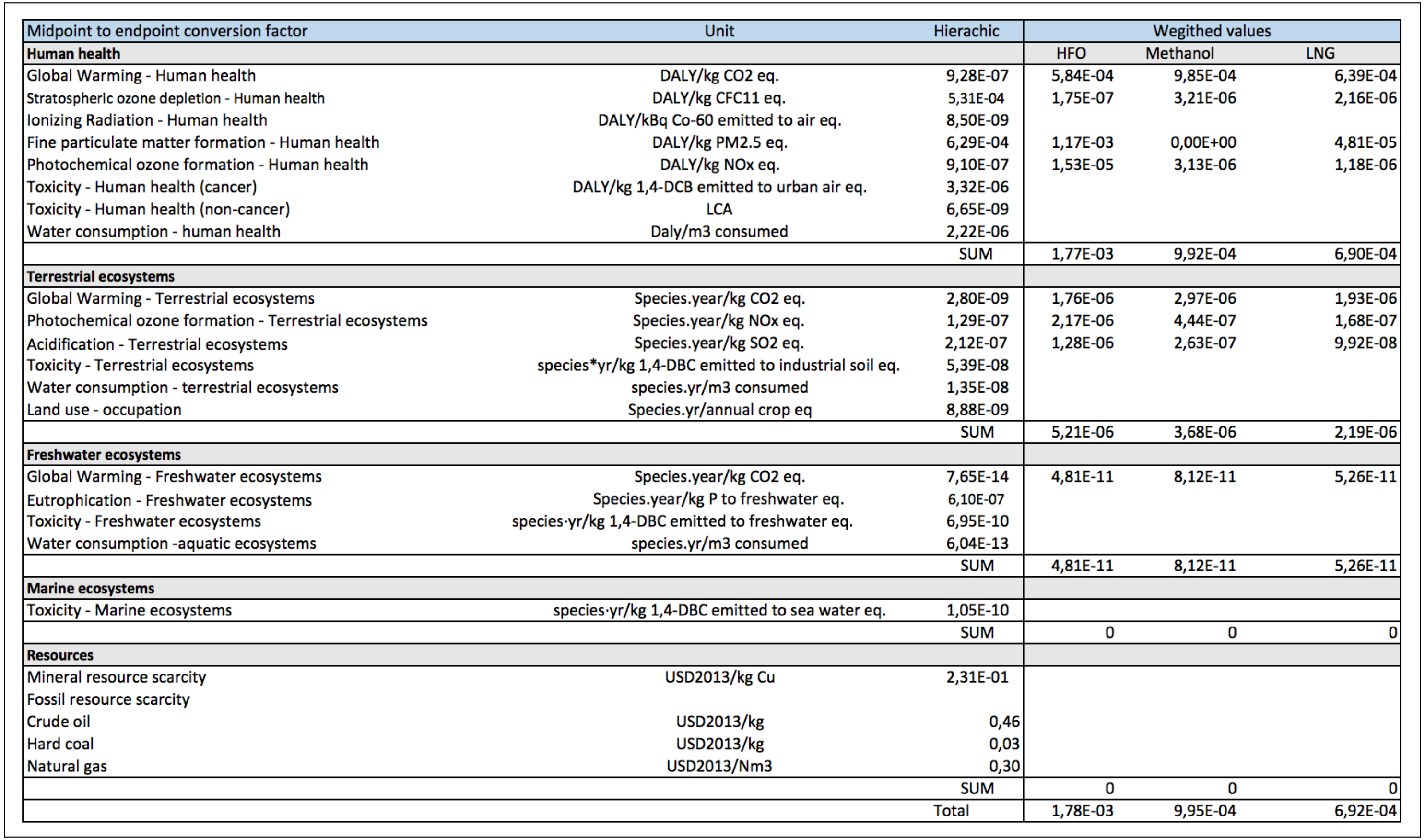
Human damage ozone formation			HOFP		
Name	Formula	HOFP	HFO	Methanol	LNG
Nitrogen oxides	NOx	1	16,8	3,44	1,3
Non-methane volatile	NMVOC	1,80E-01			
		Sum	16,8	3,44	1,3

Particulate matter formation			PMFP		
Name	Formula	PMFP	HFO	Methanol	LNG
Particulate matter	PM2.5	1	0,78	0	0,03
Sulphur oxide	SOx	0,29	1,0875	0	0,0464
Nitrogen oxides	NOx	0	0	0	0
		Sum	1,8675	0	0,0764

Ecosyste damage ozone formation			EOFP		
Name	Formula	EOFP	HFO	Methanol	LNG
Nitrogen oxides	NOx	1	16,8	3,44	1,3
Non-methane volatile	NMVOC	2,90E-01			
		Sum	16,8	3,44	1,3

Terrestrial acidification			AP		
Name	Formula	AP	HFO	Methanol	LNG
Nitrogen oxides	NOx	3,60E-01	6,05E+00	1,24E+00	4,68E-01
		Sum	6,05E+00	1,24E+00	4,68E-01

Figure D.4: Calculation of fuels' potential environmental impact



Midpoint to endpoint conversion factor	Unit	Hierachic	Wegithed values		
Human health			HFO	Methanol	LNG
Global Warming - Human health	DALY/kg CO2 eq.	9,28E-07	5,84E-04	9,85E-04	6,39E-04
Stratospheric ozone depletion - Human health	DALY/kg CFC11 eq.	5,31E-04	1,75E-07	3,21E-06	2,16E-06
Ionizing Radiation - Human health	DALY/kBq Co-60 emitted to air eq.	8,50E-09			
Fine particulate matter formation - Human health	DALY/kg PM2.5 eq.	6,29E-04	1,17E-03	0,00E+00	4,81E-05
Photochemical ozone formation - Human health	DALY/kg NOx eq.	9,10E-07	1,53E-05	3,13E-06	1,18E-06
Toxicity - Human health (cancer)	DALY/kg 1,4-DCB emitted to urban air eq.	3,32E-06			
Toxicity - Human health (non-cancer)	LCA	6,65E-09			
Water consumption - human health	Daly/m3 consumed	2,22E-06			
		SUM	1,77E-03	9,92E-04	6,90E-04
Terrestrial ecosystems					
Global Warming - Terrestrial ecosystems	Species.year/kg CO2 eq.	2,80E-09	1,76E-06	2,97E-06	1,93E-06
Photochemical ozone formation - Terrestrial ecosystems	Species.year/kg NOx eq.	1,29E-07	2,17E-06	4,44E-07	1,68E-07
Acidification - Terrestrial ecosystems	Species.year/kg SO2 eq.	2,12E-07	1,28E-06	2,63E-07	9,92E-08
Toxicity - Terrestrial ecosystems	species*yr/kg 1,4-DBC emitted to industrial soil eq.	5,39E-08			
Water consumption - terrestrial ecosystems	species.yr/m3 consumed	1,35E-08			
Land use - occupation	Species.yr/annual crop eq	8,88E-09			
		SUM	5,21E-06	3,68E-06	2,19E-06
Freshwater ecosystems					
Global Warming - Freshwater ecosystems	Species.year/kg CO2 eq.	7,65E-14	4,81E-11	8,12E-11	5,26E-11
Eutrophication - Freshwater ecosystems	Species.year/kg P to freshwater eq.	6,10E-07			
Toxicity - Freshwater ecosystems	species·yr/kg 1,4-DBC emitted to freshwater eq.	6,95E-10			
Water consumption -aquatic ecosystems	species.yr/m3 consumed	6,04E-13			
		SUM	4,81E-11	8,12E-11	5,26E-11
Marine ecosystems					
Toxicity - Marine ecosystems	species·yr/kg 1,4-DBC emitted to sea water eq.	1,05E-10			
		SUM	0	0	0
Resources					
Mineral resource scarcity	USD2013/kg Cu	2,31E-01			
Fossil resource scarcity					
Crude oil	USD2013/kg	0,46			
Hard coal	USD2013/kg	0,03			
Natural gas	USD2013/Nm3	0,30			
		SUM	0	0	0
		Total	1,78E-03	9,95E-04	6,92E-04

Figure D.5: Calculation of fuels' potential environmental impact

The result from the LCIA can be seen in Table D.5.

Table D.5: LCIA

Impact	HFO	Methanol	LNG	Hydrogen LNG	Hydrogen Renewable
Human health	1.77×10^{-4}	9.47×10^{-4}	5.37×10^{-4}	1.17×10^{-3}	3.55×10^{-4}
Terrestrial ecosystems	5.21×10^{-6}	3.64×10^{-6}	1.82×10^{-6}	2.99×10^{-6}	5.23×10^{-7}
Freshwater ecosystems	4.81×10^{-11}	7.78×10^{-11}	4.15×10^{-11}	7.63×10^{-11}	8.79×10^{-12}
Total	1.78×10^{-3}	9.15×10^{-4}	5.39×10^{-4}	1.18×10^{-3}	3.56×10^{-4}

D.5 Emissions by Utilization of Combustion Engine

LCI for methanol and LNG utilized in a combustion engine can be seen in Table D.6.

Table D.6: LCI analysis for methanol and LNG utilized in a combustion engine

Emission	HFO	Methanol	LNG
During production [g/kWh]			
CO_2	59.00	358.00	46.00
CH_4	0.58	0.53	0.35
N_2O	0.00	0.02	0.02
NOx	0.20	0.39	0.11
PM	0.02	0.00	0.00
SOx	0.35	0.00	0.16
During operation [g/kWh]			
CO_2	541.00	522.00	412.00
CH_4	0.01	0.00	3.00
N_2O	0.03	0.53	0.02
NOx	16.60	3.05	1.19
PM	0.76	0.00	0.03
SOx	3.40	0.00	0.00
Total [g/kWh]			
CO_2	600.00	880.00	458.00
CH_4	0.59	0.53	3.35
N_2O	0.03	0.55	0.04
NOx	16.80	3.44	1.30
PM	0.78	0.00	0.03
SOx	3.75	0.00	0.16

LCIA for methanol and LNG can be seen in Table D.7.

Table D.7: LCIA for methanol and LNG utilized in a combustion engine

Impact	HFO	Methanol	LNG
Human health	1.77×10^{-4}	9.92×10^{-4}	5.91×10^{-4}
Terrestrial ecosystems	5.21×10^{-6}	3.68×10^{-6}	1.90×10^{-6}
Freshwater ecosystems	4.81×10^{-11}	8.12×10^{-11}	4.47×10^{-11}
Total	1.78×10^{-3}	9.95×10^{-4}	5.93×10^{-4}

D.6 Production Comparison for LNG and Methanol

A comparison of the LCI for production of methanol and bio-methanol can be seen in Table D.8, while Table D.9 presents the LCI values for production of LNG and LBG. Both of the LCIs are developed by Brynolf, Fridell, and Andersson (2014), and the values are given in [g/MJ fuel]. Additionally, it is assumed that the fuels are utilized through an FC.

Table D.8: LCI for methanol and bio-methanol utilized through an FC

Emission	Methanol	Bio-methanol
During production [g/MJ fuel]		
CO_2 fossil origin	20	17
CO_2 biomass origin	0	120
CH_4	0.011	0.042
N2O	0.00029	0.00022
NOx	0.046	0.056
PM	0.00057	0.011
SOx	0.0021	0.048
NMVOC	0.011	0.014
During operation [g/MJ fuel]		
CO_2 fossil origin	69	0
CO_2 biomass origin	0	69
CH_4	0	0
N2O	0	0
NOx	0	0
PM	0	0
SOx	0	0
NMVOC	0	0
Total [g/MJ fuel]		
CO_2 fossil origin	89	17
CO_2 biomass origin	0	189
CH_4	0.011	0.042
N2O	0.00029	0.00022
NOx	0.046	0.056
PM	0.00057	0.011
SOx	0.0021	0.048
NMVOC	0.011	0.014

Table D.9: LCI for LNG and LBG utilized through an FC

Emission	LNG	LBG
During production [g/MJ fuel]		
CO_2 fossil origin	8.3	27
CO_2 biomass origin	0	97
CH_4	0.033	0.18
N2O	0.00017	0.00033
NOx	0.0095	0.053
PM	0.00032	0.018
SOx	0.00083	0.073
NMVOC	0.00069	0.0087
During operation [g/MJ fuel]		
CO_2 fossil origin	54	0
CO_2 biomass origin	0	52
CH_4	0	0
N2O	0	0
NOx	0	0
PM	0	0
SOx	0	0
NMVOC	0	0
Total [g/MJ fuel]		
CO_2 fossil origin	62.3	27
CO_2 biomass origin	0	149
CH_4	0.033	0.18
N2O	0.00017	0.00033
NOx	0.0095	0.053
PM	0.00032	0.018
SOx	0.00083	0.073
NMVOC	0.00069	0.0087

Appendix E

Economical Estimation

E.1 Fuel Costs

Conversion of fuel costs can be seen in Table E.1.

Table E.1: Conversion of fuel costs

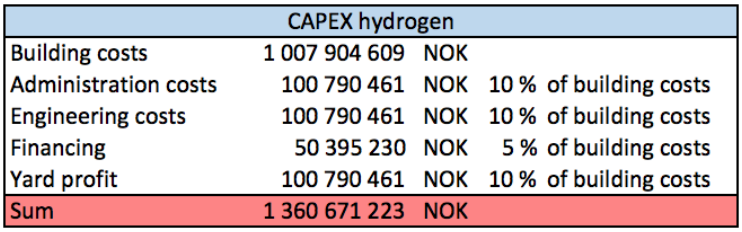
Fuel	Calculation
Hydrogen	$\frac{142000kJ}{3600s} = 39.44kWh$ $\frac{20kr}{kg} : \frac{39.44kWh}{kg} = 0.51{}^{kr}/_{kWh}$
LNG	$18€/_{MWh} = 0.18{}^{kr}/_{kWh}$
Methanol	$500€/_{MWh} = 0.5{}^{kr}/_{kWh}$
HFO	$25€/_{MWh} = 0.25{}^{kr}/_{kWh}$

E.2 Life Cycle Cost Calculation

All information needed to calculate LCC for the various fuels can be seen in the following pages.

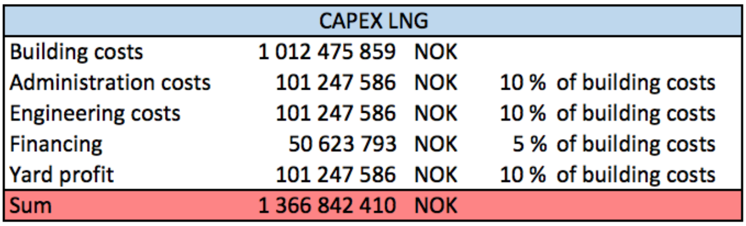
Table E.2: System information needed for LCC calculation

System information		
Lifetime	30	years
Endurance	13	days
Range	7 300	km
Average speed	15	knots
Number of trips	19	trips/year
Time at sea	271	hours/leg
Operation during lifetime	154 470	hours
PAX capacity	500	passengers
Average rate of passengers	70	%
Crew	167	persons



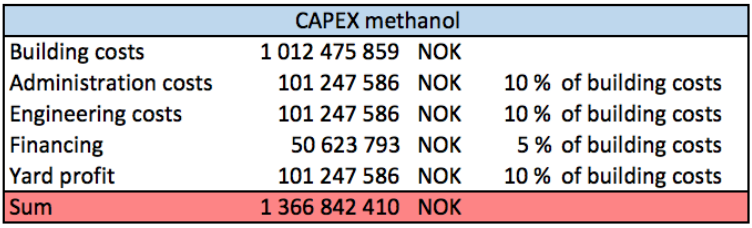
CAPEX hydrogen				
Building costs	1 007 904 609	NOK		
Administration costs	100 790 461	NOK	10 %	of building costs
Engineering costs	100 790 461	NOK	10 %	of building costs
Financing	50 395 230	NOK	5 %	of building costs
Yard profit	100 790 461	NOK	10 %	of building costs
Sum	1 360 671 223	NOK		

Figure E.1: CAPEX hydrogen



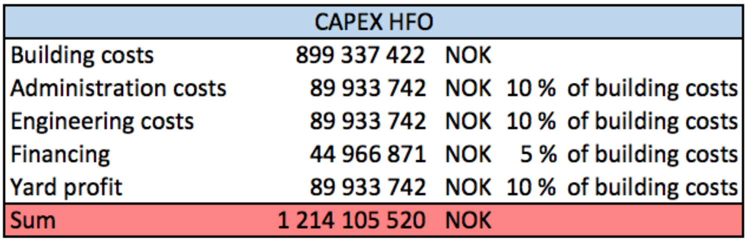
CAPEX LNG				
Building costs	1 012 475 859	NOK		
Administration costs	101 247 586	NOK	10 %	of building costs
Engineering costs	101 247 586	NOK	10 %	of building costs
Financing	50 623 793	NOK	5 %	of building costs
Yard profit	101 247 586	NOK	10 %	of building costs
Sum	1 366 842 410	NOK		

Figure E.2: CAPEX LNG



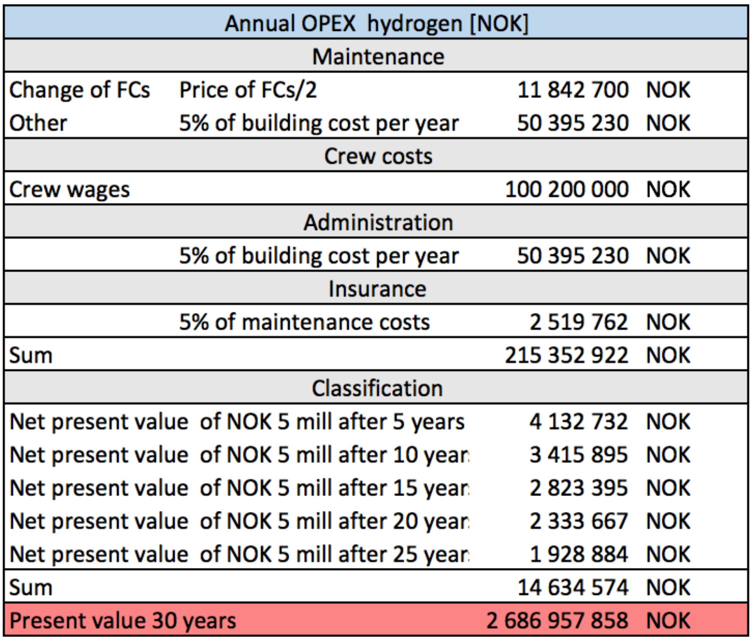
CAPEX methanol				
Building costs	1 012 475 859	NOK		
Administration costs	101 247 586	NOK	10 %	of building costs
Engineering costs	101 247 586	NOK	10 %	of building costs
Financing	50 623 793	NOK	5 %	of building costs
Yard profit	101 247 586	NOK	10 %	of building costs
Sum	1 366 842 410	NOK		

Figure E.3: CAPEX methanol



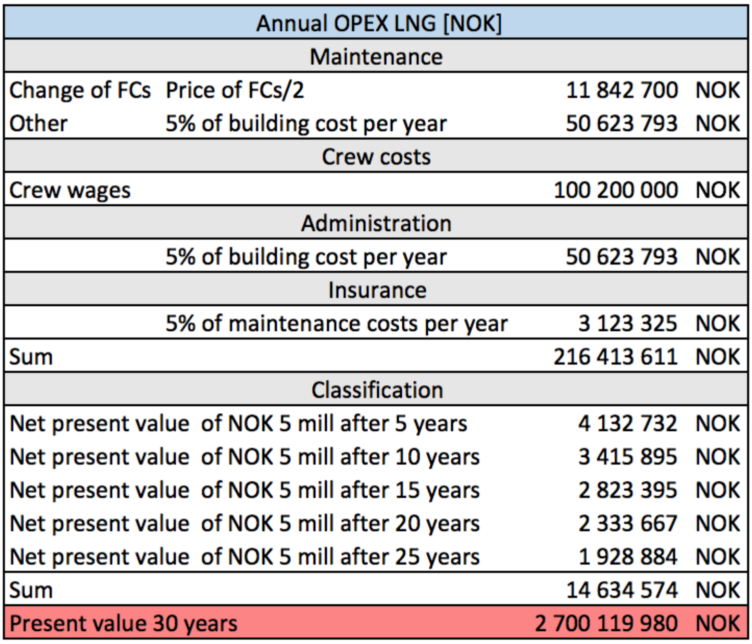
CAPEX HFO				
Building costs	899 337 422	NOK		
Administration costs	89 933 742	NOK	10 %	of building costs
Engineering costs	89 933 742	NOK	10 %	of building costs
Financing	44 966 871	NOK	5 %	of building costs
Yard profit	89 933 742	NOK	10 %	of building costs
Sum	1 214 105 520	NOK		

Figure E.4: CAPEX HFO



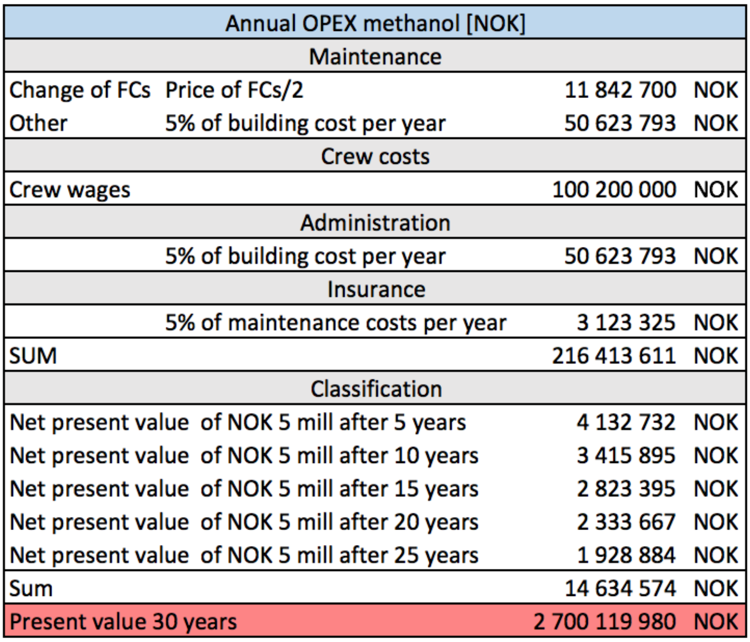
Annual OPEX hydrogen [NOK]			
Maintenance			
Change of FCs	Price of FCs/2	11 842 700	NOK
Other	5% of building cost per year	50 395 230	NOK
Crew costs			
Crew wages		100 200 000	NOK
Administration			
	5% of building cost per year	50 395 230	NOK
Insurance			
	5% of maintenance costs	2 519 762	NOK
Sum		215 352 922	NOK
Classification			
Net present value	of NOK 5 mill after 5 years	4 132 732	NOK
Net present value	of NOK 5 mill after 10 year	3 415 895	NOK
Net present value	of NOK 5 mill after 15 year	2 823 395	NOK
Net present value	of NOK 5 mill after 20 year	2 333 667	NOK
Net present value	of NOK 5 mill after 25 year	1 928 884	NOK
Sum		14 634 574	NOK
Present value 30 years		2 686 957 858	NOK

Figure E.5: Annual OPEX hydrogen



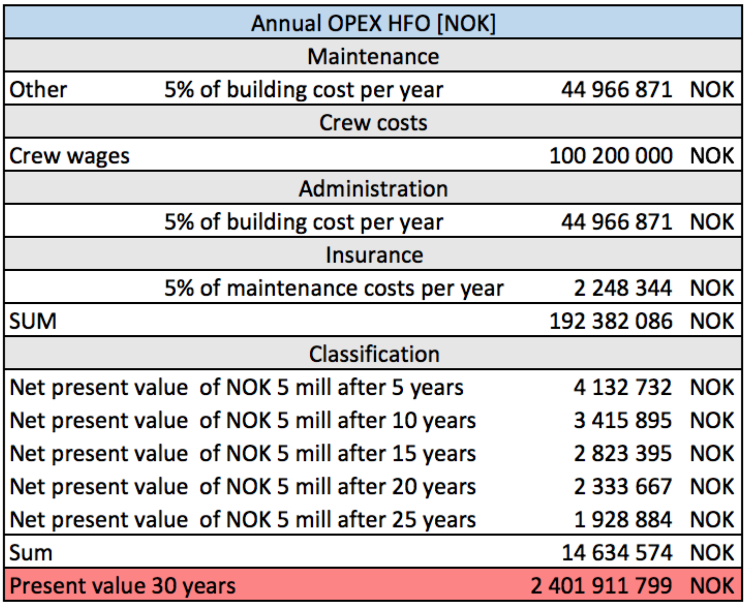
Annual OPEX LNG [NOK]			
Maintenance			
Change of FCs	Price of FCs/2	11 842 700	NOK
Other	5% of building cost per year	50 623 793	NOK
Crew costs			
Crew wages		100 200 000	NOK
Administration			
	5% of building cost per year	50 623 793	NOK
Insurance			
	5% of maintenance costs per year	3 123 325	NOK
Sum		216 413 611	NOK
Classification			
Net present value	of NOK 5 mill after 5 years	4 132 732	NOK
Net present value	of NOK 5 mill after 10 years	3 415 895	NOK
Net present value	of NOK 5 mill after 15 years	2 823 395	NOK
Net present value	of NOK 5 mill after 20 years	2 333 667	NOK
Net present value	of NOK 5 mill after 25 years	1 928 884	NOK
Sum		14 634 574	NOK
Present value 30 years		2 700 119 980	NOK

Figure E.6: Annual OPEX LNG



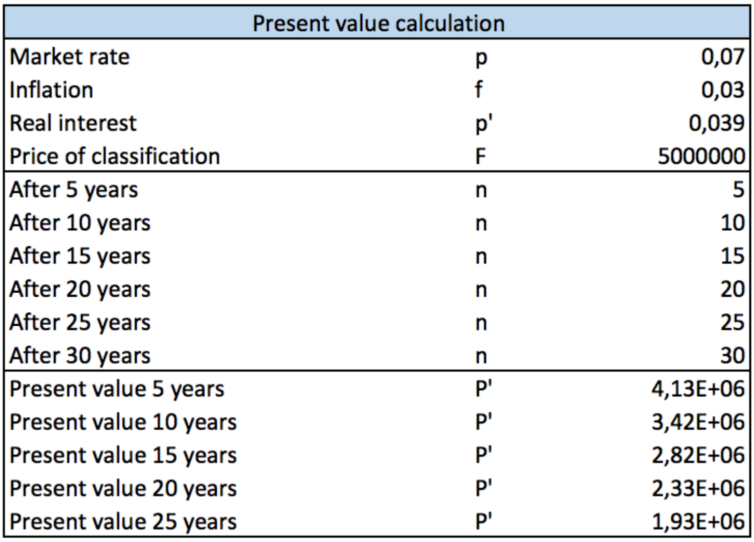
Annual OPEX methanol [NOK]			
Maintenance			
Change of FCs	Price of FCs/2	11 842 700	NOK
Other	5% of building cost per year	50 623 793	NOK
Crew costs			
Crew wages		100 200 000	NOK
Administration			
	5% of building cost per year	50 623 793	NOK
Insurance			
	5% of maintenance costs per year	3 123 325	NOK
SUM		216 413 611	NOK
Classification			
Net present value	of NOK 5 mill after 5 years	4 132 732	NOK
Net present value	of NOK 5 mill after 10 years	3 415 895	NOK
Net present value	of NOK 5 mill after 15 years	2 823 395	NOK
Net present value	of NOK 5 mill after 20 years	2 333 667	NOK
Net present value	of NOK 5 mill after 25 years	1 928 884	NOK
Sum		14 634 574	NOK
Present value 30 years		2 700 119 980	NOK

Figure E.7: Annual OPEX methanol



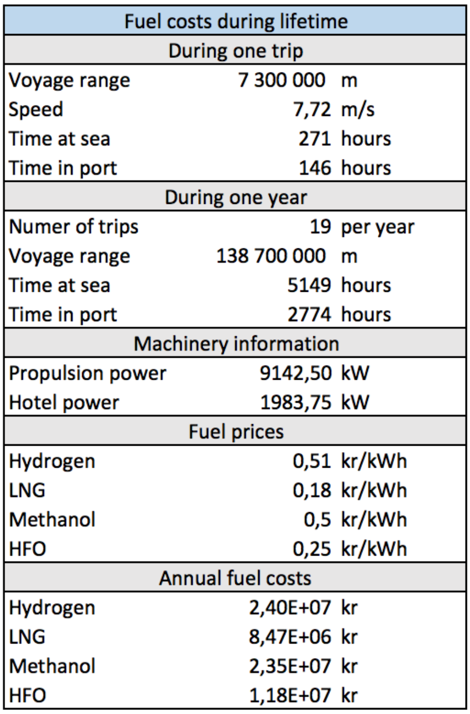
Annual OPEX HFO [NOK]			
Maintenance			
Other	5% of building cost per year	44 966 871	NOK
Crew costs			
Crew wages		100 200 000	NOK
Administration			
	5% of building cost per year	44 966 871	NOK
Insurance			
	5% of maintenance costs per year	2 248 344	NOK
SUM		192 382 086	NOK
Classification			
Net present value	of NOK 5 mill after 5 years	4 132 732	NOK
Net present value	of NOK 5 mill after 10 years	3 415 895	NOK
Net present value	of NOK 5 mill after 15 years	2 823 395	NOK
Net present value	of NOK 5 mill after 20 years	2 333 667	NOK
Net present value	of NOK 5 mill after 25 years	1 928 884	NOK
Sum		14 634 574	NOK
Present value 30 years		2 401 911 799	NOK

Figure E.8: Annual OPEX HFO



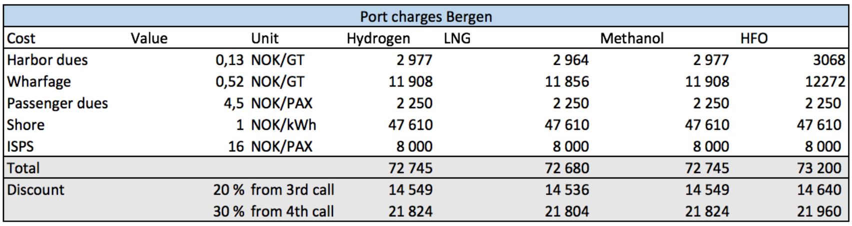
Present value calculation		
Market rate	p	0,07
Inflation	f	0,03
Real interest	p'	0,039
Price of classification	F	5000000
After 5 years	n	5
After 10 years	n	10
After 15 years	n	15
After 20 years	n	20
After 25 years	n	25
After 30 years	n	30
Present value 5 years	P'	4,13E+06
Present value 10 years	P'	3,42E+06
Present value 15 years	P'	2,82E+06
Present value 20 years	P'	2,33E+06
Present value 25 years	P'	1,93E+06

Figure E.9: Present value calculation for classification



Fuel costs during lifetime		
During one trip		
Voyage range	7 300 000	m
Speed	7,72	m/s
Time at sea	271	hours
Time in port	146	hours
During one year		
Numer of trips	19	per year
Voyage range	138 700 000	m
Time at sea	5149	hours
Time in port	2774	hours
Machinery information		
Propulsion power	9142,50	kW
Hotel power	1983,75	kW
Fuel prices		
Hydrogen	0,51	kr/kWh
LNG	0,18	kr/kWh
Methanol	0,5	kr/kWh
HFO	0,25	kr/kWh
Annual fuel costs		
Hydrogen	2,40E+07	kr
LNG	8,47E+06	kr
Methanol	2,35E+07	kr
HFO	1,18E+07	kr

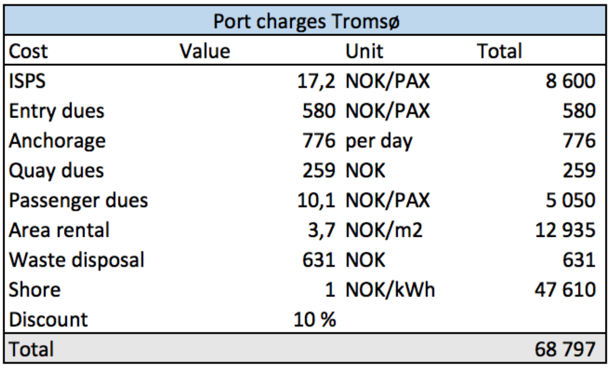
Figure E.10: Fuel costs during lifetime



Port charges Bergen

Cost	Value	Unit	Hydrogen	LNG	Methanol	HFO
Harbor dues	0,13	NOK/GT	2 977	2 964	2 977	3068
Wharfage	0,52	NOK/GT	11 908	11 856	11 908	12272
Passenger dues	4,5	NOK/PAX	2 250	2 250	2 250	2 250
Shore	1	NOK/kWh	47 610	47 610	47 610	47 610
ISPS	16	NOK/PAX	8 000	8 000	8 000	8 000
Total			72 745	72 680	72 745	73 200
Discount	20 %	from 3rd call	14 549	14 536	14 549	14 640
	30 %	from 4th call	21 824	21 804	21 824	21 960

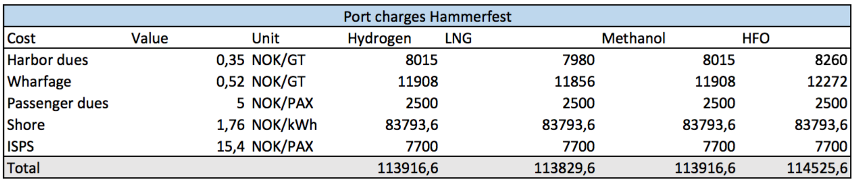
Figure E.11: Port charges in Bergen



Port charges Tromsø

Cost	Value	Unit	Total
ISPS	17,2	NOK/PAX	8 600
Entry dues	580	NOK/PAX	580
Anchorage	776	per day	776
Quay dues	259	NOK	259
Passenger dues	10,1	NOK/PAX	5 050
Area rental	3,7	NOK/m2	12 935
Waste disposal	631	NOK	631
Shore	1	NOK/kWh	47 610
Discount	10 %		
Total			68 797

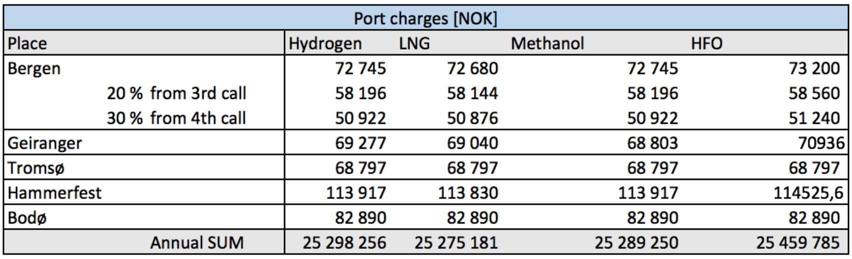
Figure E.12: Port charges in Tromsø



Port charges Hammerfest

Cost	Value	Unit	Hydrogen	LNG	Methanol	HFO
Harbor dues	0,35	NOK/GT	8015	7980	8015	8260
Wharfage	0,52	NOK/GT	11908	11856	11908	12272
Passenger dues	5	NOK/PAX	2500	2500	2500	2500
Shore	1,76	NOK/kWh	83793,6	83793,6	83793,6	83793,6
ISPS	15,4	NOK/PAX	7700	7700	7700	7700
Total			113916,6	113829,6	113916,6	114525,6

Figure E.13: Port charges in Hammerfest



Port charges [NOK]

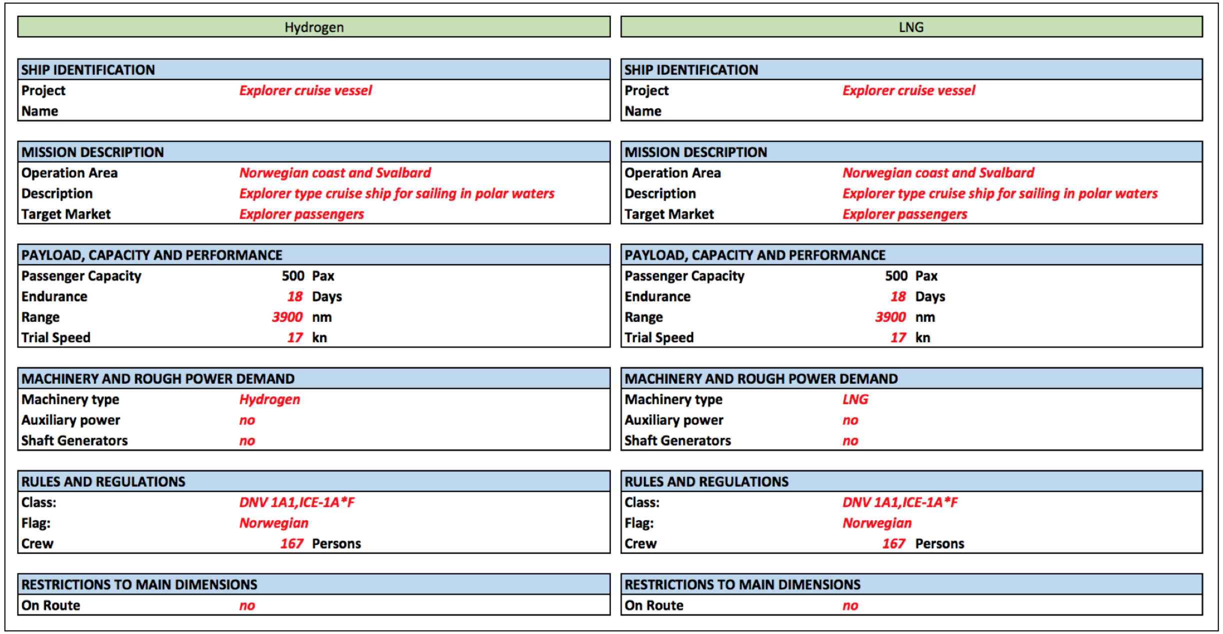
Place	Hydrogen	LNG	Methanol	HFO
Bergen	72 745	72 680	72 745	73 200
20 % from 3rd call	58 196	58 144	58 196	58 560
30 % from 4th call	50 922	50 876	50 922	51 240
Geiranger	69 277	69 040	68 803	70936
Tromsø	68 797	68 797	68 797	68 797
Hammerfest	113 917	113 830	113 917	114525,6
Bodø	82 890	82 890	82 890	82 890
Annual SUM	25 298 256	25 275 181	25 289 250	25 459 785

Figure E.14: Annual port charges

Appendix F

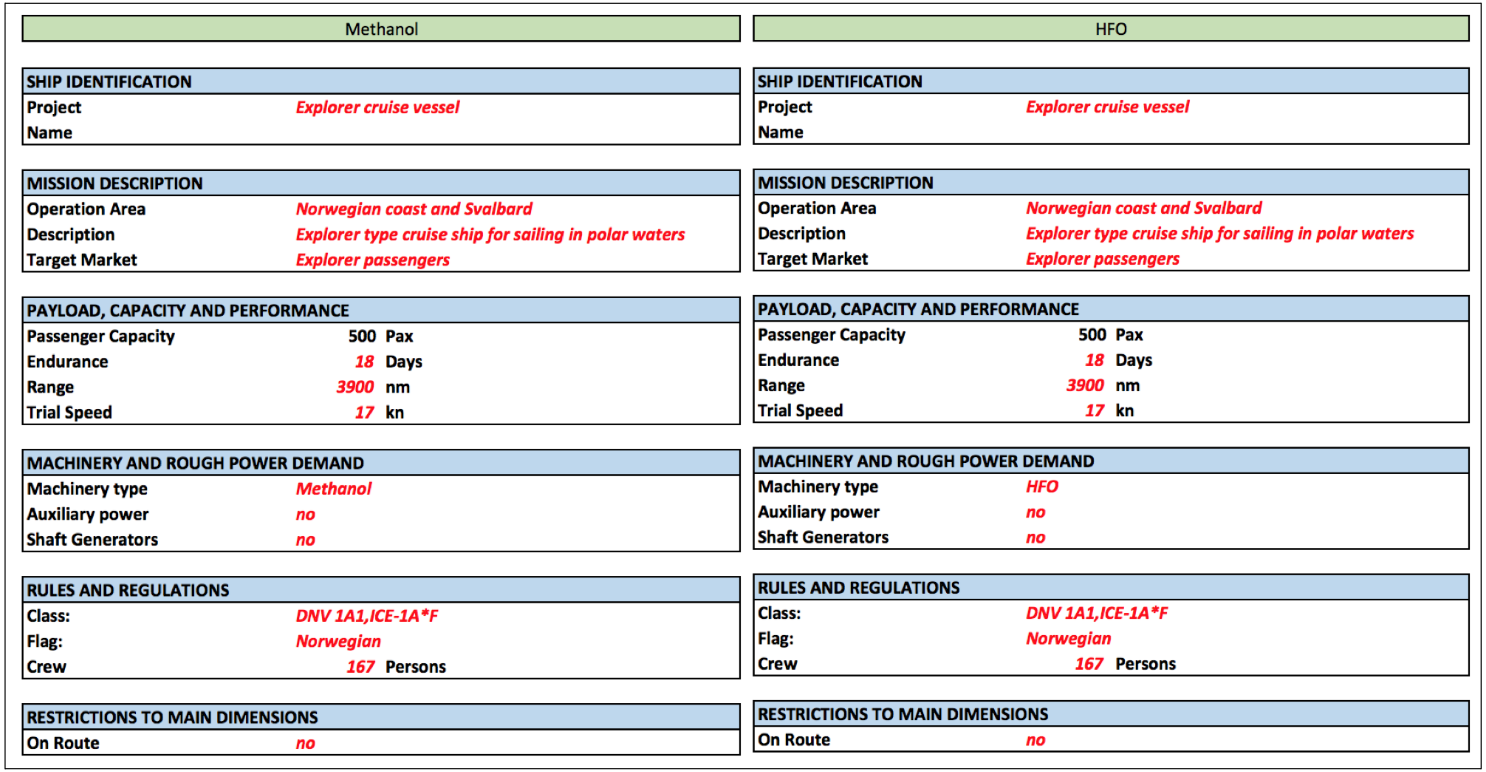
System Based Ship Design

All information used for SBSD can be seen in the following figures.



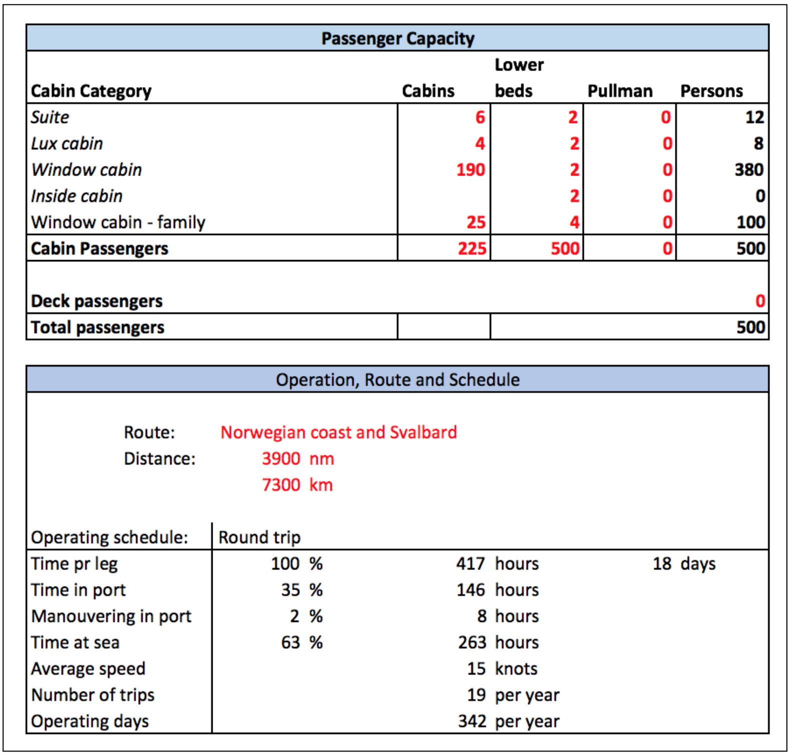
	Hydrogen	LNG
SHIP IDENTIFICATION		
Project	*Explorer cruise vessel*	*Explorer cruise vessel*
Name		
MISSION DESCRIPTION		
Operation Area	*Norwegian coast and Svalbard*	*Norwegian coast and Svalbard*
Description	*Explorer type cruise ship for sailing in polar waters*	*Explorer type cruise ship for sailing in polar waters*
Target Market	*Explorer passengers*	*Explorer passengers*
PAYLOAD, CAPACITY AND PERFORMANCE		
Passenger Capacity	500 Pax	500 Pax
Endurance	*18* Days	*18* Days
Range	*3900* nm	*3900* nm
Trial Speed	*17* kn	*17* kn
MACHINERY AND ROUGH POWER DEMAND		
Machinery type	*Hydrogen*	*LNG*
Auxiliary power	*no*	*no*
Shaft Generators	*no*	*no*
RULES AND REGULATIONS		
Class:	*DNV 1A1,ICE-1A*F*	*DNV 1A1,ICE-1A*F*
Flag:	*Norwegian*	*Norwegian*
Crew	*167* Persons	*167* Persons
RESTRICTIONS TO MAIN DIMENSIONS		
On Route	*no*	*no*

Figure F.1: Summary for hydrogen and LNG



	Methanol	HFO
SHIP IDENTIFICATION		
Project	*Explorer cruise vessel*	*Explorer cruise vessel*
Name		
MISSION DESCRIPTION		
Operation Area	*Norwegian coast and Svalbard*	*Norwegian coast and Svalbard*
Description	*Explorer type cruise ship for sailing in polar waters*	*Explorer type cruise ship for sailing in polar waters*
Target Market	*Explorer passengers*	*Explorer passengers*
PAYLOAD, CAPACITY AND PERFORMANCE		
Passenger Capacity	500 Pax	500 Pax
Endurance	*18* Days	*18* Days
Range	*3900* nm	*3900* nm
Trial Speed	*17* kn	*17* kn
MACHINERY AND ROUGH POWER DEMAND		
Machinery type	*Methanol*	*HFO*
Auxiliary power	*no*	*no*
Shaft Generators	*no*	*no*
RULES AND REGULATIONS		
Class:	*DNV 1A1,ICE-1A*F*	*DNV 1A1,ICE-1A*F*
Flag:	*Norwegian*	*Norwegian*
Crew	*167* Persons	*167* Persons
RESTRICTIONS TO MAIN DIMENSIONS		
On Route	*no*	*no*

Figure F.2: Summary for methanol and HFO



Passenger Capacity

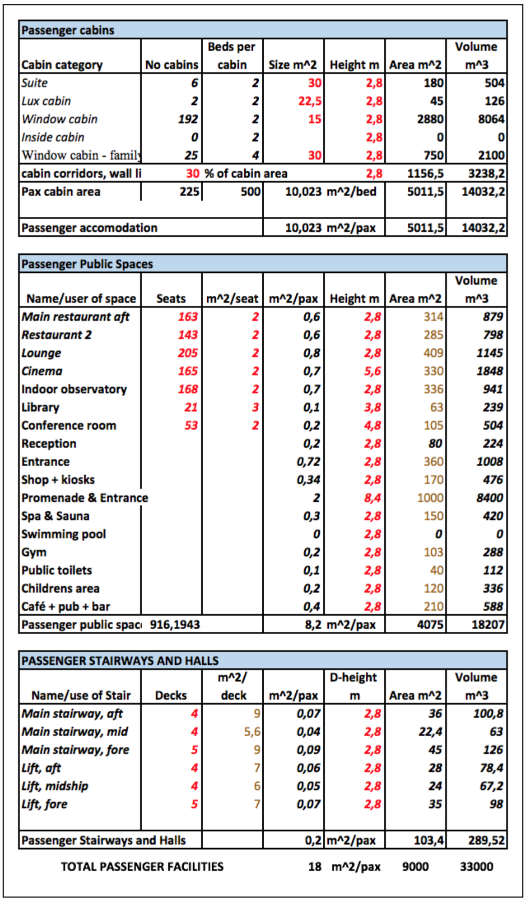
Cabin Category	**Cabins**	**Lower beds**	**Pullman**	**Persons**
Suite	6	2	0	12
Lux cabin	4	2	0	8
Window cabin	190	2	0	380
Inside cabin		2	0	0
Window cabin - family	25	4	0	100
Cabin Passengers	225	500	0	500
Deck passengers				0
Total passengers				500

Operation, Route and Schedule

Route: Norwegian coast and Svalbard
Distance: 3900 nm
7300 km

Operating schedule:	Round trip		
Time pr leg	100 %	417 hours	18 days
Time in port	35 %	146 hours	
Manouvering in port	2 %	8 hours	
Time at sea	63 %	263 hours	
Average speed		15 knots	
Number of trips		19 per year	
Operating days		342 per year	

Figure F.3: Mission



Passenger cabins

Cabin category	No cabins	Beds per cabin	Size m^2	Height m	Area m^2	Volume m^3
Suite	6	2	30	2,8	180	504
Lux cabin	2	2	22,5	2,8	45	126
Window cabin	192	2	15	2,8	2880	8064
Inside cabin	0	2		2,8	0	0
Window cabin - family	25	4	30	2,8	750	2100
cabin corridors, wall li	30	% of cabin area		2,8	1156,5	3238,2
Pax cabin area	225	500	10,023	m^2/bed	5011,5	14032,2
Passenger accomodation			10,023	m^2/pax	5011,5	14032,2

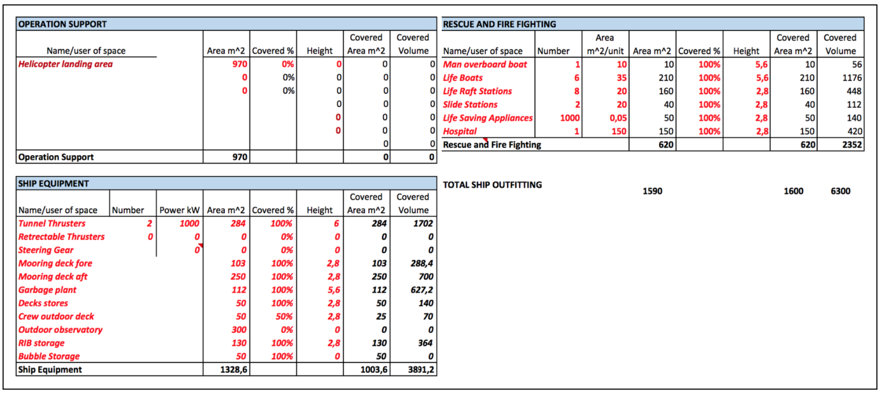
Passenger Public Spaces

Name/user of space	Seats	m^2/seat	m^2/pax	Height m	Area m^2	Volume m^3
Main restaurant aft	163	2	0,6	2,8	314	879
Restaurant 2	143	2	0,6	2,8	285	798
Lounge	205	2	0,8	2,8	409	1145
Cinema	165	2	0,7	5,6	330	1848
Indoor observatory	168	2	0,7	2,8	336	941
Library	21	3	0,1	3,8	63	239
Conference room	53	2	0,2	4,8	105	504
Reception			0,2	2,8	80	224
Entrance			0,72	2,8	360	1008
Shop + kiosks			0,34	2,8	170	476
Promenade & Entrance			2	8,4	1000	8400
Spa & Sauna			0,3	2,8	150	420
Swimming pool			0	2,8	0	0
Gym			0,2	2,8	103	288
Public toilets			0,1	2,8	40	112
Childrens area			0,2	2,8	120	336
Café + pub + bar			0,4	2,8	210	588
Passenger public spac	916,1943		8,2	m^2/pax	4075	18207

PASSENGER STAIRWAYS AND HALLS

Name/use of Stair	Decks	m^2/ deck	m^2/pax	D-height m	Area m^2	Volume m^3
Main stairway, aft	4	9	0,07	2,8	36	100,8
Main stairway, mid	4	5,6	0,04	2,8	22,4	63
Main stairway, fore	5	9	0,09	2,8	45	126
Lift, aft	4	7	0,06	2,8	28	78,4
Lift, midship	4	6	0,05	2,8	24	67,2
Lift, fore	5	7	0,07	2,8	35	98
Passenger Stairways and Halls			0,2	m^2/pax	103,4	289,52
TOTAL PASSENGER FACILITIES			18	m^2/pax	9000	33000

Figure F.4: Passenger spaces



OPERATION SUPPORT

Name/user of space	Area m^2	Covered %	Height	Covered Area m^2	Covered Volume
Helicopter landing area	970	0%	0	0	0
	0	0%	0	0	0
	0	0%	0	0	0
			0	0	0
			0	0	0
			0	0	0
				0	0
Operation Support	970			0	0

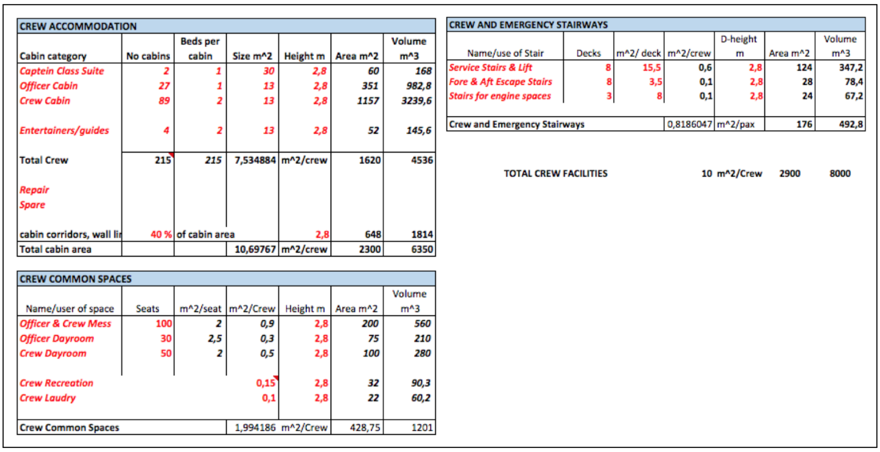
RESCUE AND FIRE FIGHTING

Name/user of space	Number	Area m^2/unit	Area m^2	Covered %	Height	Covered Area m^2	Covered Volume
Man overboard boat	1	10	10	100%	5,6	10	56
Life Boats	6	35	210	100%	5,6	210	1176
Life Raft Stations	8	20	160	100%	2,8	160	448
Slide Stations	2	20	40	100%	2,8	40	112
Life Saving Appliances	1000	0,05	50	100%	2,8	50	140
Hospital	1	150	150	100%	2,8	150	420
Rescue and Fire Fighting			620			620	2352
TOTAL SHIP OUTFITTING			1590			1600	6300

SHIP EQUIPMENT

Name/user of space	Number	Power kW	Area m^2	Covered %	Height	Covered Area m^2	Covered Volume
Tunnel Thrusters	2	1000	284	100%	6	284	1702
Retrectable Thrusters	0	0	0	0%	0	0	0
Steering Gear		0	0	0%	0	0	0
Mooring deck fore			103	100%	2,8	103	288,4
Mooring deck aft			250	100%	2,8	250	700
Garbage plant			112	100%	5,6	112	627,2
Decks stores			50	100%	2,8	50	140
Crew outdoor deck			50	50%	2,8	25	70
Outdoor observatory			300	0%	0	0	0
RIB storage			130	100%	2,8	130	364
Bubble Storage			50	100%	0	50	0
Ship Equipment			1328,6			1003,6	3891,2

Figure F.5: Ship outfitting



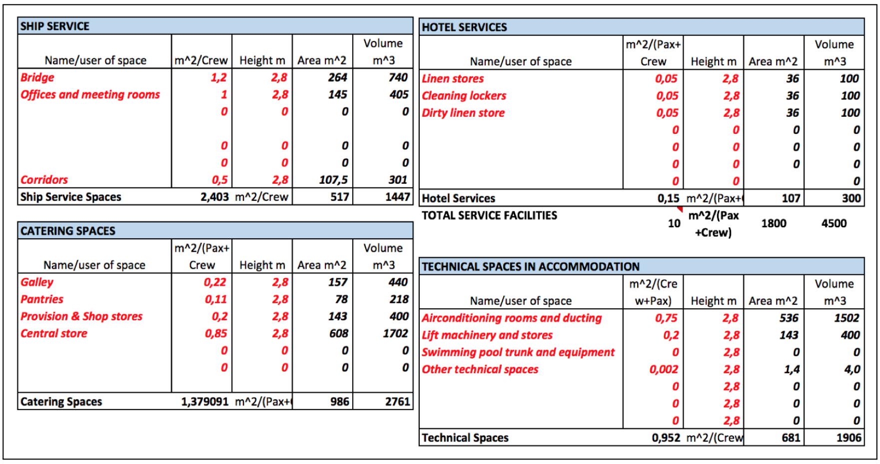
CREW ACCOMMODATION						
Cabin category	No cabins	Beds per cabin	Size m^2	Height m	Area m^2	Volume m^3
Captein Class Suite	2	1	30	2,8	60	168
Officer Cabin	27	1	13	2,8	351	982,8
Crew Cabin	89	2	13	2,8	1157	3239,6
Entertainers/guides	4	2	13	2,8	52	145,6
Total Crew	215	215	7,534884	m^2/crew	1620	4536
Repair						
Spare						
cabin corridors, wall li	40 %	of cabin area		2,8	648	1814
Total cabin area			10,69767	m^2/crew	2300	6350

CREW COMMON SPACES						
Name/user of space	Seats	m^2/seat	m^2/Crew	Height m	Area m^2	Volume m^3
Officer & Crew Mess	100	2	0,9	2,8	200	560
Officer Dayroom	30	2,5	0,3	2,8	75	210
Crew Dayroom	50	2	0,5	2,8	100	280
Crew Recreation			0,15	2,8	32	90,3
Crew Laudry			0,1	2,8	22	60,2
Crew Common Spaces			1,994186	m^2/Crew	428,75	1201

CREW AND EMERGENCY STAIRWAYS						
Name/use of Stair	Decks	m^2/ deck	m^2/crew	D-height m	Area m^2	Volume m^3
Service Stairs & Lift	8	15,5	0,6	2,8	124	347,2
Fore & Aft Escape Stairs	8	3,5	0,1	2,8	28	78,4
Stairs for engine spaces	3	8	0,1	2,8	24	67,2
Crew and Emergency Stairways			0,8186047	m^2/pax	176	492,8

TOTAL CREW FACILITIES	10	m^2/Crew	2900	8000

Figure F.6: Crew



SHIP SERVICE				
Name/user of space	m^2/Crew	Height m	Area m^2	Volume m^3
Bridge	1,2	2,8	264	740
Offices and meeting rooms	1	2,8	145	405
	0	0	0	0
	0	0	0	0
	0	0	0	0
Corridors	0,5	2,8	107,5	301
Ship Service Spaces	2,403	m^2/Crew	517	1447

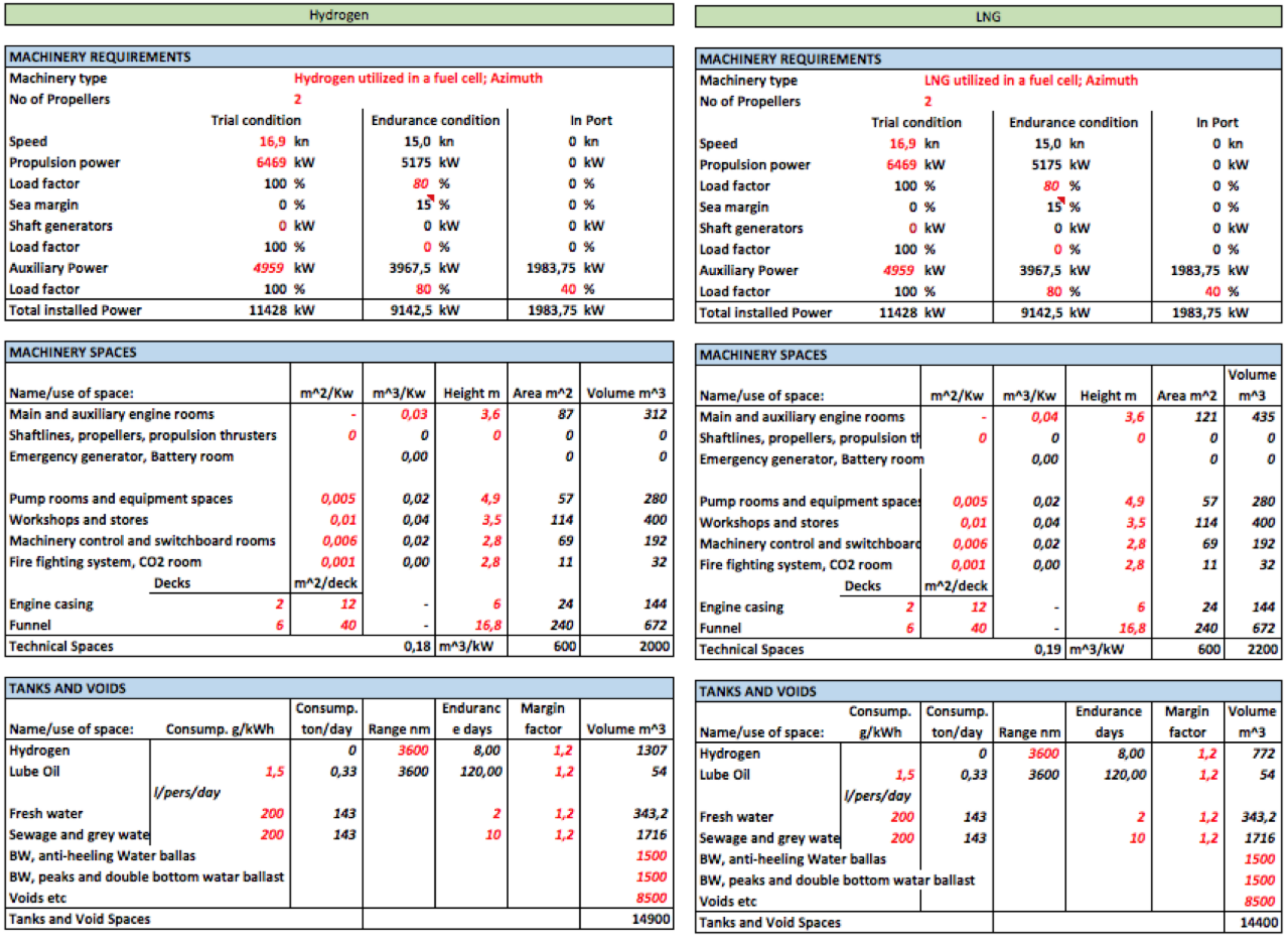
CATERING SPACES				
Name/user of space	m^2/(Pax+ Crew	Height m	Area m^2	Volume m^3
Galley	0,22	2,8	157	440
Pantries	0,11	2,8	78	218
Provision & Shop stores	0,2	2,8	143	400
Central store	0,85	2,8	608	1702
	0	0	0	0
	0	0	0	0
Catering Spaces	1,379091	m^2/(Pax+	986	2761

HOTEL SERVICES				
Name/user of space	m^2/(Pax+ Crew	Height m	Area m^2	Volume m^3
Linen stores	0,05	2,8	36	100
Cleaning lockers	0,05	2,8	36	100
Dirty linen store	0,05	2,8	36	100
	0	0	0	0
	0	0	0	0
	0	0	0	0
	0	0		0
Hotel Services	0,15	m^2/(Pax+	107	300

TOTAL SERVICE FACILITIES	10	m^2/(Pax +Crew)	1800	4500

TECHNICAL SPACES IN ACCOMMODATION				
Name/user of space	m^2/(Cre w+Pax)	Height m	Area m^2	Volume m^3
Airconditioning rooms and ducting	0,75	2,8	536	1502
Lift machinery and stores	0,2	2,8	143	400
Swimming pool trunk and equipment	0	2,8	0	0
Other technical spaces	0,002	2,8	1,4	4,0
	0	2,8	0	0
	0	2,8	0	0
	0	2,8	0	0
Technical Spaces	0,952	m^2/(Crew	681	1906

Figure F.7: Service



Hydrogen

MACHINERY REQUIREMENTS						
Machinery type	Hydrogen utilized in a fuel cell; Azimuth					
No of Propellers	2					
	Trial condition		Endurance condition		In Port	
Speed	16,9	kn	15,0	kn	0	kn
Propulsion power	6469	kW	5175	kW	0	kW
Load factor	100	%	80	%	0	%
Sea margin	0	%	15	%	0	%
Shaft generators	0	kW	0	kW	0	kW
Load factor	100	%	0	%	0	%
Auxiliary Power	4959	kW	3967,5	kW	1983,75	kW
Load factor	100	%	80	%	40	%
Total installed Power	11428	kW	9142,5	kW	1983,75	kW

MACHINERY SPACES						
Name/use of space:		m^2/Kw	m^3/Kw	Height m	Area m^2	Volume m^3
Main and auxiliary engine rooms		-	0,03	3,6	87	312
Shaftlines, propellers, propulsion thrusters		0	0	0	0	0
Emergency generator, Battery room			0,00		0	0
Pump rooms and equipment spaces		0,005	0,02	4,9	57	280
Workshops and stores		0,01	0,04	3,5	114	400
Machinery control and switchboard rooms		0,006	0,02	2,8	69	192
Fire fighting system, CO2 room		0,001	0,00	2,8	11	32
	Decks	m^2/deck				
Engine casing	2	12	-	6	24	144
Funnel	6	40	-	16,8	240	672
Technical Spaces			0,18	m^3/kW	600	2000

TANKS AND VOIDS						
Name/use of space:	Consump. g/kWh	Consump. ton/day	Range nm	Endurance days	Margin factor	Volume m^3
Hydrogen		0	3600	8,00	1,2	1307
Lube Oil	1,5	0,33	3600	120,00	1,2	54
	l/pers/day					
Fresh water	200	143		2	1,2	343,2
Sewage and grey wate	200	143		10	1,2	1716
BW, anti-heeling Water ballas						1500
BW, peaks and double bottom watar ballast						1500
Voids etc						8500
Tanks and Void Spaces						14900

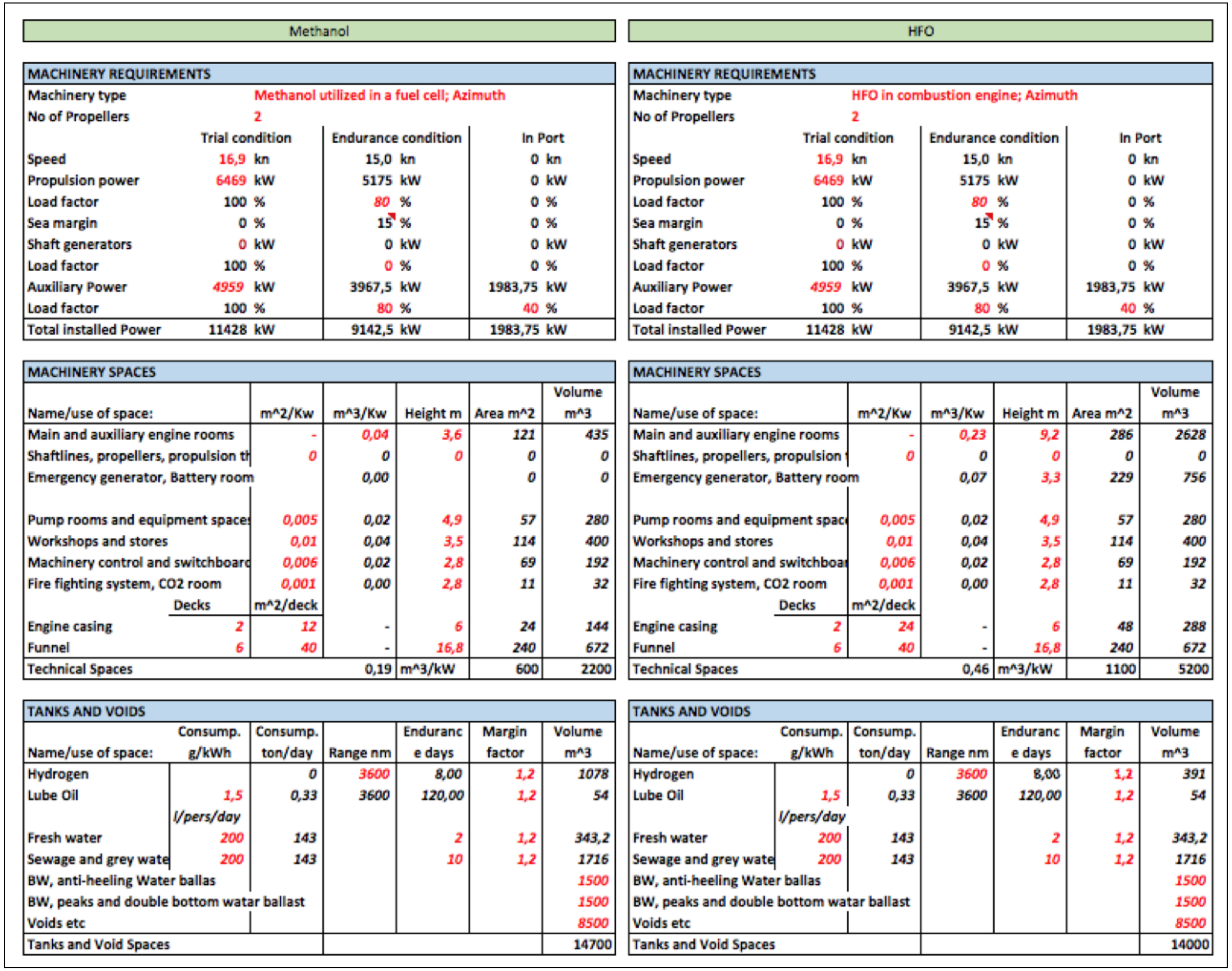
LNG

MACHINERY REQUIREMENTS						
Machinery type	LNG utilized in a fuel cell; Azimuth					
No of Propellers	2					
	Trial condition		Endurance condition		In Port	
Speed	16,9	kn	15,0	kn	0	kn
Propulsion power	6469	kW	5175	kW	0	kW
Load factor	100	%	80	%	0	%
Sea margin	0	%	15	%	0	%
Shaft generators	0	kW	0	kW	0	kW
Load factor	100	%	0	%	0	%
Auxiliary Power	4959	kW	3967,5	kW	1983,75	kW
Load factor	100	%	80	%	40	%
Total installed Power	11428	kW	9142,5	kW	1983,75	kW

MACHINERY SPACES						
Name/use of space:		m^2/Kw	m^3/Kw	Height m	Area m^2	Volume m^3
Main and auxiliary engine rooms		-	0,04	3,6	121	435
Shaftlines, propellers, propulsion th		0	0	0	0	0
Emergency generator, Battery room			0,00		0	0
Pump rooms and equipment space		0,005	0,02	4,9	57	280
Workshops and stores		0,01	0,04	3,5	114	400
Machinery control and switchboard		0,006	0,02	2,8	69	192
Fire fighting system, CO2 room		0,001	0,00	2,8	11	32
	Decks	m^2/deck				
Engine casing	2	12	-	6	24	144
Funnel	6	40	-	16,8	240	672
Technical Spaces			0,19	m^3/kW	600	2200

TANKS AND VOIDS						
Name/use of space:	Consump. g/kWh	Consump. ton/day	Range nm	Endurance days	Margin factor	Volume m^3
Hydrogen		0	3600	8,00	1,2	772
Lube Oil	1,5	0,33	3600	120,00	1,2	54
	l/pers/day					
Fresh water	200	143		2	1,2	343,2
Sewage and grey wate	200	143		10	1,2	1716
BW, anti-heeling Water ballas						1500
BW, peaks and double bottom watar ballast						1500
Voids etc						8500
Tanks and Void Spaces						14400

Figure F.8: Machinery & ship system for hydrogen and LNG



Methanol

MACHINERY REQUIREMENTS			
Machinery type	Methanol utilized in a fuel cell; Azimuth		
No of Propellers	2		
	Trial condition	Endurance condition	In Port
Speed	16,9 kn	15,0 kn	0 kn
Propulsion power	6469 kW	5175 kW	0 kW
Load factor	100 %	80 %	0 %
Sea margin	0 %	15 %	0 %
Shaft generators	0 kW	0 kW	0 kW
Load factor	100 %	0 %	0 %
Auxiliary Power	4959 kW	3967,5 kW	1983,75 kW
Load factor	100 %	80 %	40 %
Total installed Power	11428 kW	9142,5 kW	1983,75 kW

MACHINERY SPACES						
Name/use of space:		m^2/Kw	m^3/Kw	Height m	Area m^2	Volume m^3
Main and auxiliary engine rooms		-	0,04	3,6	121	435
Shaftlines, propellers, propulsion th		0	0	0	0	0
Emergency generator, Battery room			0,00		0	0
Pump rooms and equipment space		0,005	0,02	4,9	57	280
Workshops and stores		0,01	0,04	3,5	114	400
Machinery control and switchboard		0,006	0,02	2,8	69	192
Fire fighting system, CO2 room		0,001	0,00	2,8	11	32
	Decks	m^2/deck				
Engine casing	2	12	-	6	24	144
Funnel	6	40	-	16,8	240	672
Technical Spaces			0,19	m^3/kW	600	2200

TANKS AND VOIDS						
Name/use of space:	Consump. g/kWh	Consump. ton/day	Range nm	Endurance days	Margin factor	Volume m^3
Hydrogen		0	3600	8,00	1,2	1078
Lube Oil	1,5	0,33	3600	120,00	1,2	54
	l/pers/day					
Fresh water	200	143		2	1,2	343,2
Sewage and grey wate	200	143		10	1,2	1716
BW, anti-heeling Water ballas						1500
BW, peaks and double bottom watar ballast						1500
Voids etc						8500
Tanks and Void Spaces						14700

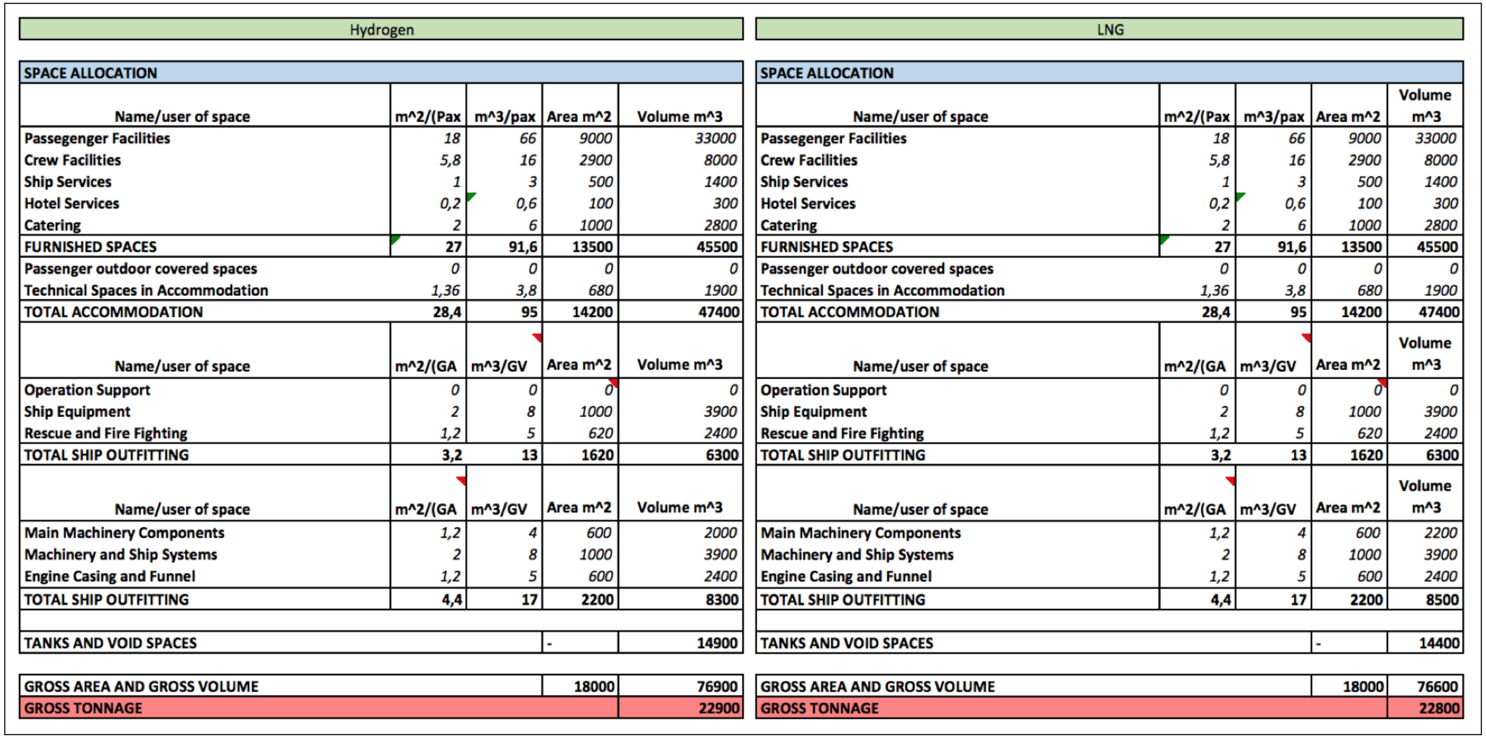
HFO

MACHINERY REQUIREMENTS			
Machinery type	HFO in combustion engine; Azimuth		
No of Propellers	2		
	Trial condition	Endurance condition	In Port
Speed	16,9 kn	15,0 kn	0 kn
Propulsion power	6469 kW	5175 kW	0 kW
Load factor	100 %	80 %	0 %
Sea margin	0 %	15 %	0 %
Shaft generators	0 kW	0 kW	0 kW
Load factor	100 %	0 %	0 %
Auxiliary Power	4959 kW	3967,5 kW	1983,75 kW
Load factor	100 %	80 %	40 %
Total installed Power	11428 kW	9142,5 kW	1983,75 kW

MACHINERY SPACES						
Name/use of space:		m^2/Kw	m^3/Kw	Height m	Area m^2	Volume m^3
Main and auxiliary engine rooms		-	0,23	9,2	286	2628
Shaftlines, propellers, propulsion		0	0	0	0	0
Emergency generator, Battery room			0,07	3,3	229	756
Pump rooms and equipment spac		0,005	0,02	4,9	57	280
Workshops and stores		0,01	0,04	3,5	114	400
Machinery control and switchboar		0,006	0,02	2,8	69	192
Fire fighting system, CO2 room		0,001	0,00	2,8	11	32
	Decks	m^2/deck				
Engine casing	2	24	-	6	48	288
Funnel	6	40	-	16,8	240	672
Technical Spaces			0,46	m^3/kW	1100	5200

TANKS AND VOIDS						
Name/use of space:	Consump. g/kWh	Consump. ton/day	Range nm	Endurance days	Margin factor	Volume m^3
Hydrogen		0	3600	8,00	1,2	391
Lube Oil	1,5	0,33	3600	120,00	1,2	54
	l/pers/day					
Fresh water	200	143		2	1,2	343,2
Sewage and grey wate	200	143		10	1,2	1716
BW, anti-heeling Water ballas						1500
BW, peaks and double bottom watar ballast						1500
Voids etc						8500
Tanks and Void Spaces						14000

Figure F.9: Machinery & ship system for methanol and HFO



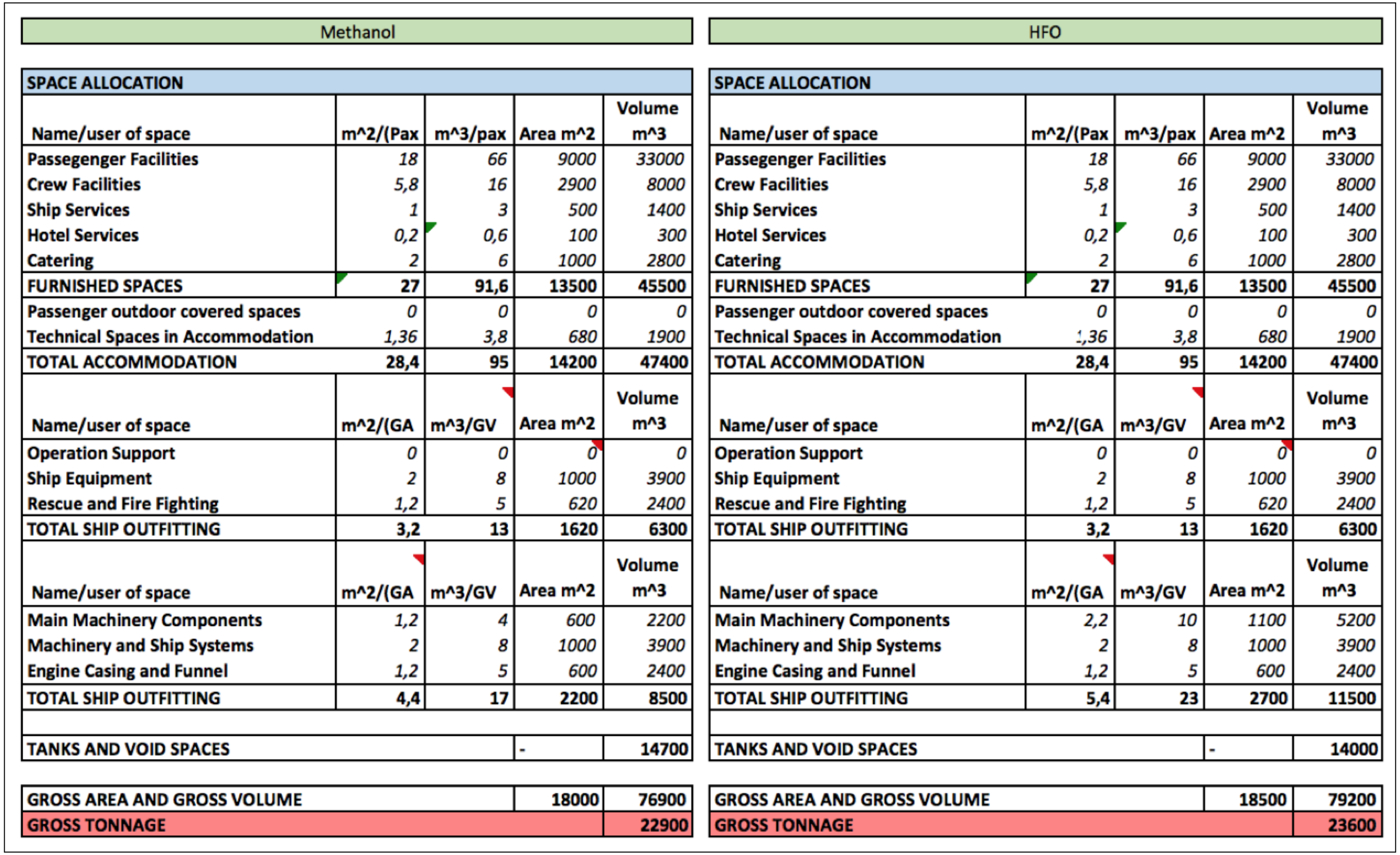
Hydrogen

SPACE ALLOCATION				
Name/user of space	m^2/(Pax	m^3/pax	Area m^2	Volume m^3
Passegenger Facilities	18	66	9000	33000
Crew Facilities	5,8	16	2900	8000
Ship Services	1	3	500	1400
Hotel Services	0,2	0,6	100	300
Catering	2	6	1000	2800
FURNISHED SPACES	**27**	**91,6**	**13500**	**45500**
Passenger outdoor covered spaces	0	0	0	0
Technical Spaces in Accommodation	1,36	3,8	680	1900
TOTAL ACCOMMODATION	**28,4**	**95**	**14200**	**47400**
Name/user of space	m^2/(GA	m^3/GV	Area m^2	Volume m^3
Operation Support	0	0	0	0
Ship Equipment	2	8	1000	3900
Rescue and Fire Fighting	1,2	5	620	2400
TOTAL SHIP OUTFITTING	**3,2**	**13**	**1620**	**6300**
Name/user of space	m^2/(GA	m^3/GV	Area m^2	Volume m^3
Main Machinery Components	1,2	4	600	2000
Machinery and Ship Systems	2	8	1000	3900
Engine Casing and Funnel	1,2	5	600	2400
TOTAL SHIP OUTFITTING	**4,4**	**17**	**2200**	**8300**
TANKS AND VOID SPACES			-	**14900**
GROSS AREA AND GROSS VOLUME			**18000**	**76900**
GROSS TONNAGE				**22900**

LNG

SPACE ALLOCATION				
Name/user of space	m^2/(Pax	m^3/pax	Area m^2	Volume m^3
Passegenger Facilities	18	66	9000	33000
Crew Facilities	5,8	16	2900	8000
Ship Services	1	3	500	1400
Hotel Services	0,2	0,6	100	300
Catering	2	6	1000	2800
FURNISHED SPACES	**27**	**91,6**	**13500**	**45500**
Passenger outdoor covered spaces	0	0	0	0
Technical Spaces in Accommodation	1,36	3,8	680	1900
TOTAL ACCOMMODATION	**28,4**	**95**	**14200**	**47400**
Name/user of space	m^2/(GA	m^3/GV	Area m^2	Volume m^3
Operation Support	0	0	0	0
Ship Equipment	2	8	1000	3900
Rescue and Fire Fighting	1,2	5	620	2400
TOTAL SHIP OUTFITTING	**3,2**	**13**	**1620**	**6300**
Name/user of space	m^2/(GA	m^3/GV	Area m^2	Volume m^3
Main Machinery Components	1,2	4	600	2200
Machinery and Ship Systems	2	8	1000	3900
Engine Casing and Funnel	1,2	5	600	2400
TOTAL SHIP OUTFITTING	**4,4**	**17**	**2200**	**8500**
TANKS AND VOID SPACES			-	**14400**
GROSS AREA AND GROSS VOLUME			**18000**	**76600**
GROSS TONNAGE				**22800**

Figure F.10: System summary for hydrogen and LNG



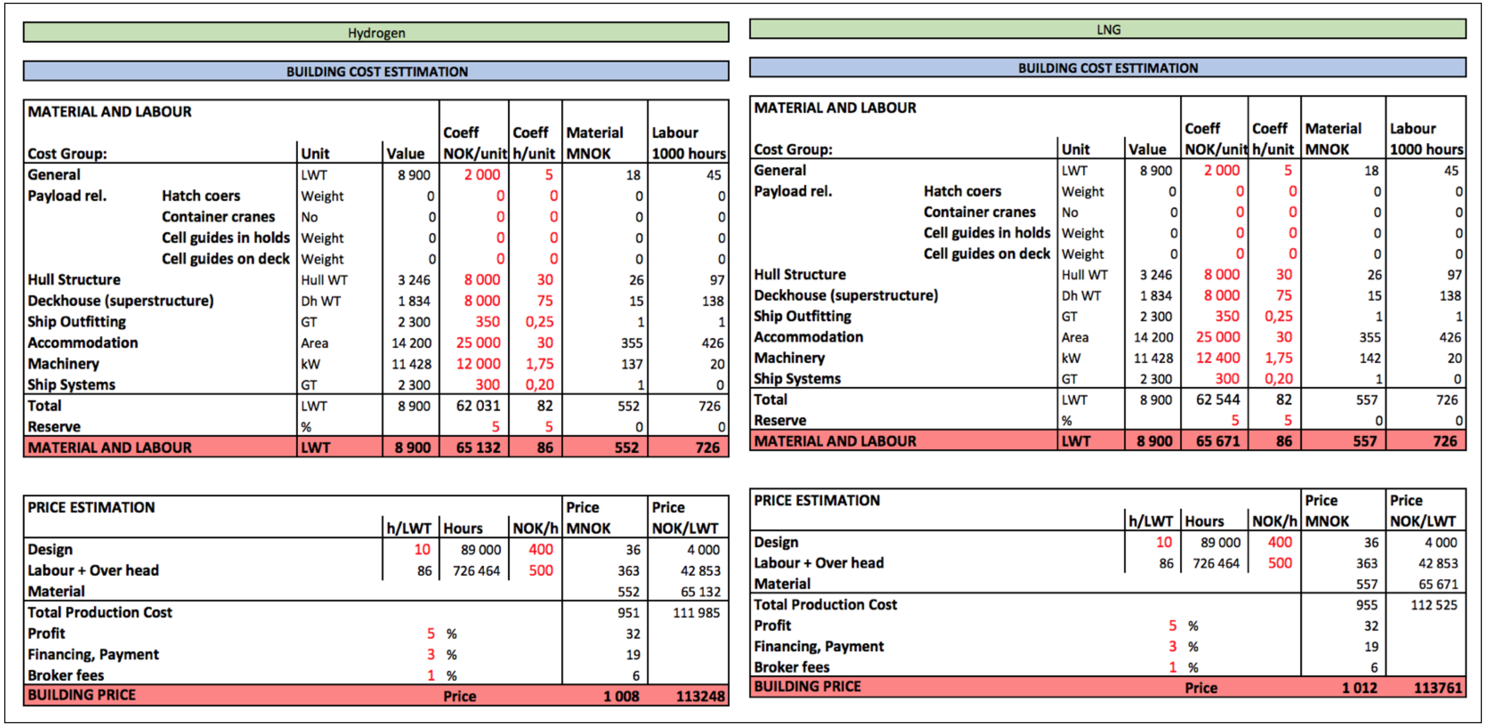
Methanol

SPACE ALLOCATION				
Name/user of space	m^2/(Pax	m^3/pax	Area m^2	Volume m^3
Passegenger Facilities	18	66	9000	33000
Crew Facilities	5,8	16	2900	8000
Ship Services	1	3	500	1400
Hotel Services	0,2	0,6	100	300
Catering	2	6	1000	2800
FURNISHED SPACES	27	91,6	13500	45500
Passenger outdoor covered spaces	0	0	0	0
Technical Spaces in Accommodation	1,36	3,8	680	1900
TOTAL ACCOMMODATION	28,4	95	14200	47400
Name/user of space	m^2/(GA	m^3/GV	Area m^2	Volume m^3
Operation Support	0	0	0	0
Ship Equipment	2	8	1000	3900
Rescue and Fire Fighting	1,2	5	620	2400
TOTAL SHIP OUTFITTING	3,2	13	1620	6300
Name/user of space	m^2/(GA	m^3/GV	Area m^2	Volume m^3
Main Machinery Components	1,2	4	600	2200
Machinery and Ship Systems	2	8	1000	3900
Engine Casing and Funnel	1,2	5	600	2400
TOTAL SHIP OUTFITTING	4,4	17	2200	8500
TANKS AND VOID SPACES			-	14700
GROSS AREA AND GROSS VOLUME			18000	76900
GROSS TONNAGE				22900

HFO

SPACE ALLOCATION				
Name/user of space	m^2/(Pax	m^3/pax	Area m^2	Volume m^3
Passegenger Facilities	18	66	9000	33000
Crew Facilities	5,8	16	2900	8000
Ship Services	1	3	500	1400
Hotel Services	0,2	0,6	100	300
Catering	2	6	1000	2800
FURNISHED SPACES	27	91,6	13500	45500
Passenger outdoor covered spaces	0	0	0	0
Technical Spaces in Accommodation	1,36	3,8	680	1900
TOTAL ACCOMMODATION	28,4	95	14200	47400
Name/user of space	m^2/(GA	m^3/GV	Area m^2	Volume m^3
Operation Support	0	0	0	0
Ship Equipment	2	8	1000	3900
Rescue and Fire Fighting	1,2	5	620	2400
TOTAL SHIP OUTFITTING	3,2	13	1620	6300
Name/user of space	m^2/(GA	m^3/GV	Area m^2	Volume m^3
Main Machinery Components	2,2	10	1100	5200
Machinery and Ship Systems	2	8	1000	3900
Engine Casing and Funnel	1,2	5	600	2400
TOTAL SHIP OUTFITTING	5,4	23	2700	11500
TANKS AND VOID SPACES			-	14000
GROSS AREA AND GROSS VOLUME			18500	79200
GROSS TONNAGE				23600

Figure F.11: System summary for methanol and HFO



Hydrogen

BUILDING COST ESTTIMATION

MATERIAL AND LABOUR Cost Group:		Unit	Value	Coeff NOK/unit	Coeff h/unit	Material MNOK	Labour 1000 hours
General		LWT	8 900	2 000	5	18	45
Payload rel.	Hatch coers	Weight	0	0	0	0	0
	Container cranes	No	0	0	0	0	0
	Cell guides in holds	Weight	0	0	0	0	0
	Cell guides on deck	Weight	0	0	0	0	0
Hull Structure		Hull WT	3 246	8 000	30	26	97
Deckhouse (superstructure)		Dh WT	1 834	8 000	75	15	138
Ship Outfitting		GT	2 300	350	0,25	1	1
Accommodation		Area	14 200	25 000	30	355	426
Machinery		kW	11 428	12 000	1,75	137	20
Ship Systems		GT	2 300	300	0,20	1	0
Total		LWT	8 900	62 031	82	552	726
Reserve		%		5	5	0	0
MATERIAL AND LABOUR		LWT	8 900	65 132	86	552	726

PRICE ESTIMATION	h/LWT	Hours	NOK/h	Price MNOK	Price NOK/LWT
Design	10	89 000	400	36	4 000
Labour + Over head	86	726 464	500	363	42 853
Material				552	65 132
Total Production Cost				951	111 985
Profit	5 %			32	
Financing, Payment	3 %			19	
Broker fees	1 %			6	
BUILDING PRICE		Price		1 008	113248

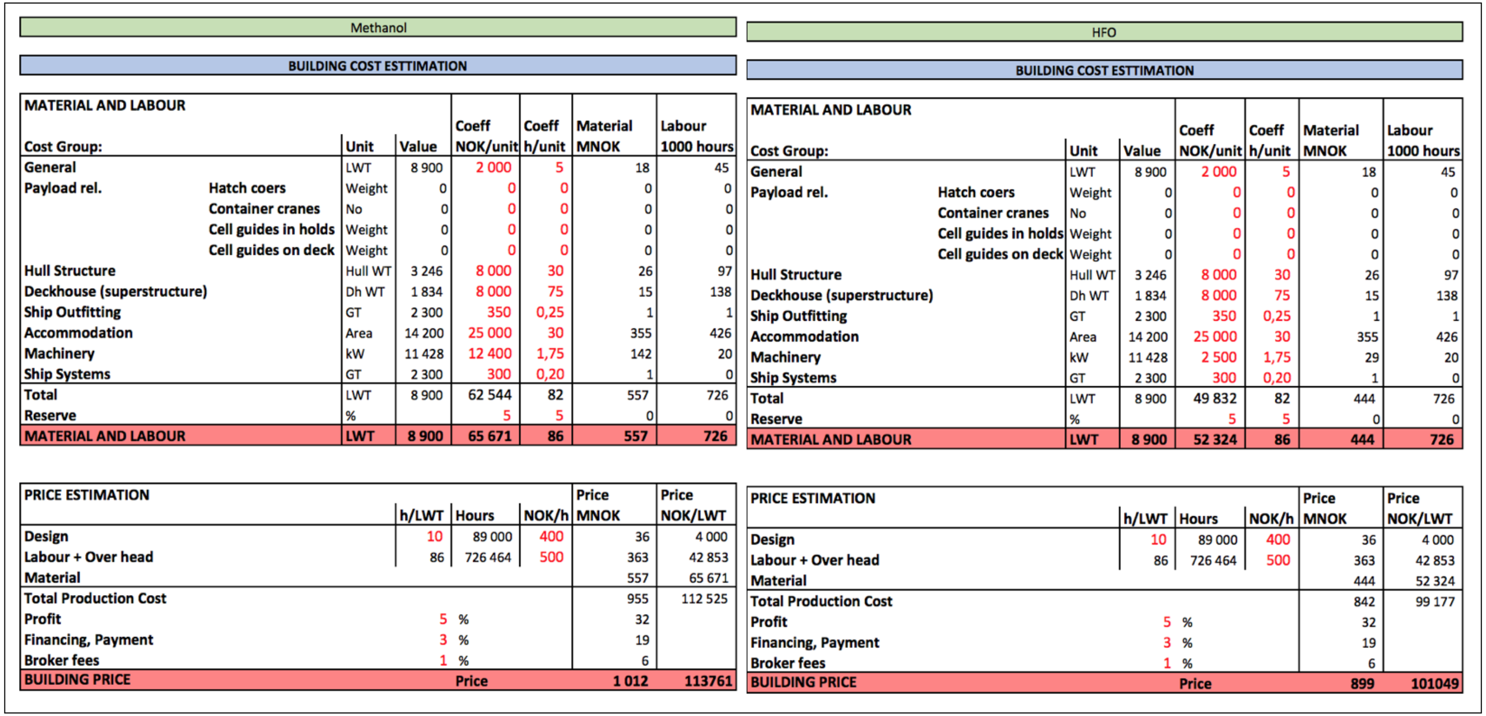
LNG

BUILDING COST ESTTIMATION

MATERIAL AND LABOUR Cost Group:		Unit	Value	Coeff NOK/unit	Coeff h/unit	Material MNOK	Labour 1000 hours
General		LWT	8 900	2 000	5	18	45
Payload rel.	Hatch coers	Weight	0	0	0	0	0
	Container cranes	No	0	0	0	0	0
	Cell guides in holds	Weight	0	0	0	0	0
	Cell guides on deck	Weight	0	0	0	0	0
Hull Structure		Hull WT	3 246	8 000	30	26	97
Deckhouse (superstructure)		Dh WT	1 834	8 000	75	15	138
Ship Outfitting		GT	2 300	350	0,25	1	1
Accommodation		Area	14 200	25 000	30	355	426
Machinery		kW	11 428	12 400	1,75	142	20
Ship Systems		GT	2 300	300	0,20	1	0
Total		LWT	8 900	62 544	82	557	726
Reserve		%		5	5	0	0
MATERIAL AND LABOUR		LWT	8 900	65 671	86	557	726

PRICE ESTIMATION	h/LWT	Hours	NOK/h	Price MNOK	Price NOK/LWT
Design	10	89 000	400	36	4 000
Labour + Over head	86	726 464	500	363	42 853
Material				557	65 671
Total Production Cost				955	112 525
Profit	5 %			32	
Financing, Payment	3 %			19	
Broker fees	1 %			6	
BUILDING PRICE		Price		1 012	113761

Figure F.12: Building cost for hydrogen and LNG



Methanol

BUILDING COST ESTTIMATION

MATERIAL AND LABOUR Cost Group:		Unit	Value	Coeff NOK/unit	Coeff h/unit	Material MNOK	Labour 1000 hours
General		LWT	8 900	2 000	5	18	45
Payload rel.	Hatch coers	Weight	0	0	0	0	0
	Container cranes	No	0	0	0	0	0
	Cell guides in holds	Weight	0	0	0	0	0
	Cell guides on deck	Weight	0	0	0	0	0
Hull Structure		Hull WT	3 246	8 000	30	26	97
Deckhouse (superstructure)		Dh WT	1 834	8 000	75	15	138
Ship Outfitting		GT	2 300	350	0,25	1	1
Accommodation		Area	14 200	25 000	30	355	426
Machinery		kW	11 428	12 400	1,75	142	20
Ship Systems		GT	2 300	300	0,20	1	0
Total		LWT	8 900	62 544	82	557	726
Reserve		%		5	5	0	0
MATERIAL AND LABOUR		LWT	8 900	65 671	86	557	726

PRICE ESTIMATION		h/LWT	Hours	NOK/h	Price MNOK	Price NOK/LWT
Design		10	89 000	400	36	4 000
Labour + Over head		86	726 464	500	363	42 853
Material					557	65 671
Total Production Cost					955	112 525
Profit		5	%		32	
Financing, Payment		3	%		19	
Broker fees		1	%		6	
BUILDING PRICE			Price		1 012	113761

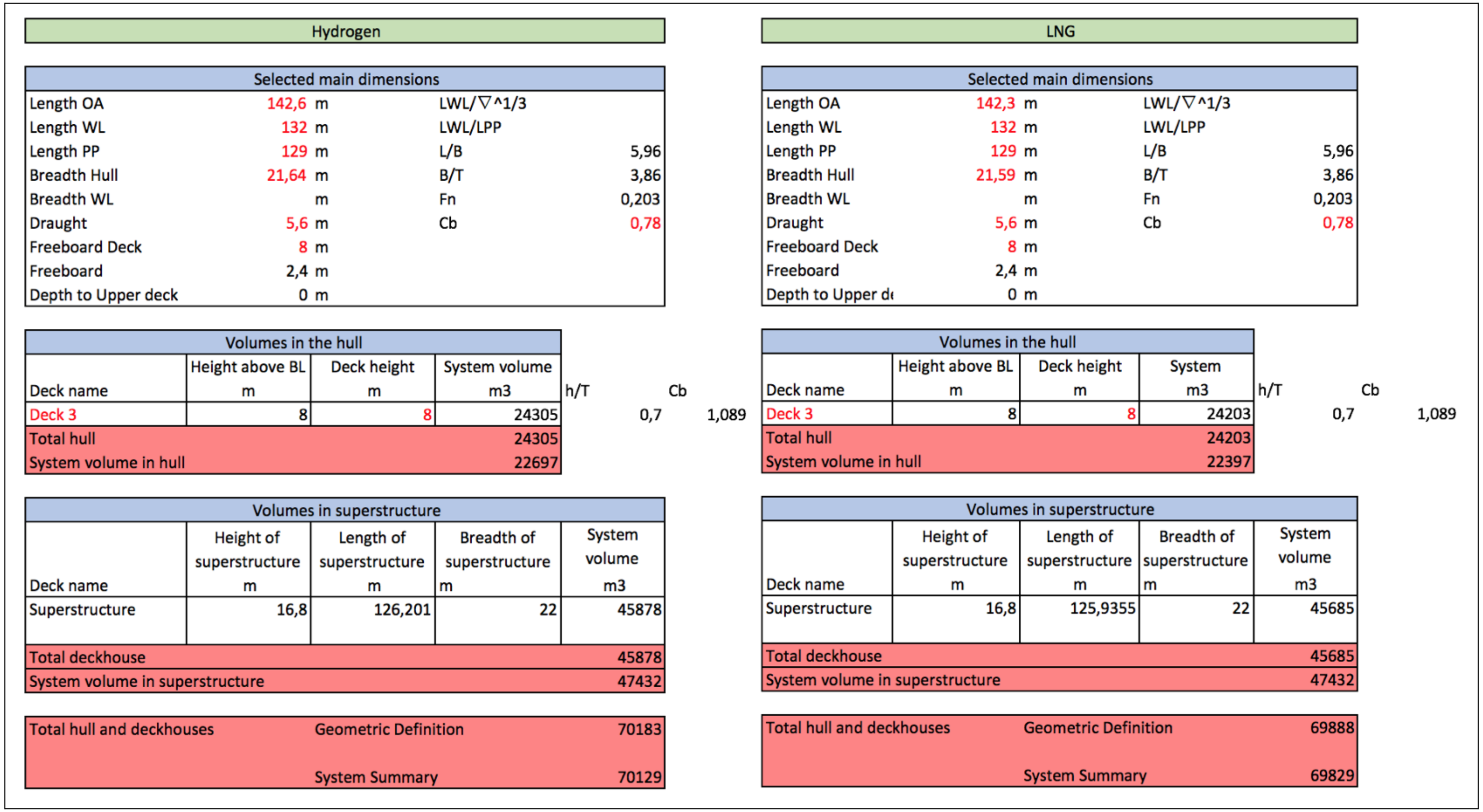
HFO

BUILDING COST ESTTIMATION

MATERIAL AND LABOUR Cost Group:		Unit	Value	Coeff NOK/unit	Coeff h/unit	Material MNOK	Labour 1000 hours
General		LWT	8 900	2 000	5	18	45
Payload rel.	Hatch coers	Weight	0	0	0	0	0
	Container cranes	No	0	0	0	0	0
	Cell guides in holds	Weight	0	0	0	0	0
	Cell guides on deck	Weight	0	0	0	0	0
Hull Structure		Hull WT	3 246	8 000	30	26	97
Deckhouse (superstructure)		Dh WT	1 834	8 000	75	15	138
Ship Outfitting		GT	2 300	350	0,25	1	1
Accommodation		Area	14 200	25 000	30	355	426
Machinery		kW	11 428	2 500	1,75	29	20
Ship Systems		GT	2 300	300	0,20	1	0
Total		LWT	8 900	49 832	82	444	726
Reserve		%		5	5	0	0
MATERIAL AND LABOUR		LWT	8 900	52 324	86	444	726

PRICE ESTIMATION		h/LWT	Hours	NOK/h	Price MNOK	Price NOK/LWT
Design		10	89 000	400	36	4 000
Labour + Over head		86	726 464	500	363	42 853
Material					444	52 324
Total Production Cost					842	99 177
Profit		5	%		32	
Financing, Payment		3	%		19	
Broker fees		1	%		6	
BUILDING PRICE			Price		899	101049

Figure F.13: Building cost for methanol and HFO



Hydrogen

Selected main dimensions

Length OA	142,6	m	LWL/∇^1/3	
Length WL	132	m	LWL/LPP	
Length PP	129	m	L/B	5,96
Breadth Hull	21,64	m	B/T	3,86
Breadth WL		m	Fn	0,203
Draught	5,6	m	Cb	0,78
Freeboard Deck	8	m		
Freeboard	2,4	m		
Depth to Upper deck	0	m		

Volumes in the hull

Deck name	Height above BL m	Deck height m	System volume m3	h/T	Cb
Deck 3	8	8	24305	0,7	1,089
Total hull			24305		
System volume in hull			22697		

Volumes in superstructure

Deck name	Height of superstructure m	Length of superstructure m	Breadth of superstructure m	System volume m3
Superstructure	16,8	126,201	22	45878
Total deckhouse				45878
System volume in superstructure				47432

Total hull and deckhouses	Geometric Definition	70183
	System Summary	70129

LNG

Selected main dimensions

Length OA	142,3	m	LWL/∇^1/3	
Length WL	132	m	LWL/LPP	
Length PP	129	m	L/B	5,96
Breadth Hull	21,59	m	B/T	3,86
Breadth WL		m	Fn	0,203
Draught	5,6	m	Cb	0,78
Freeboard Deck	8	m		
Freeboard	2,4	m		
Depth to Upper de	0	m		

Volumes in the hull

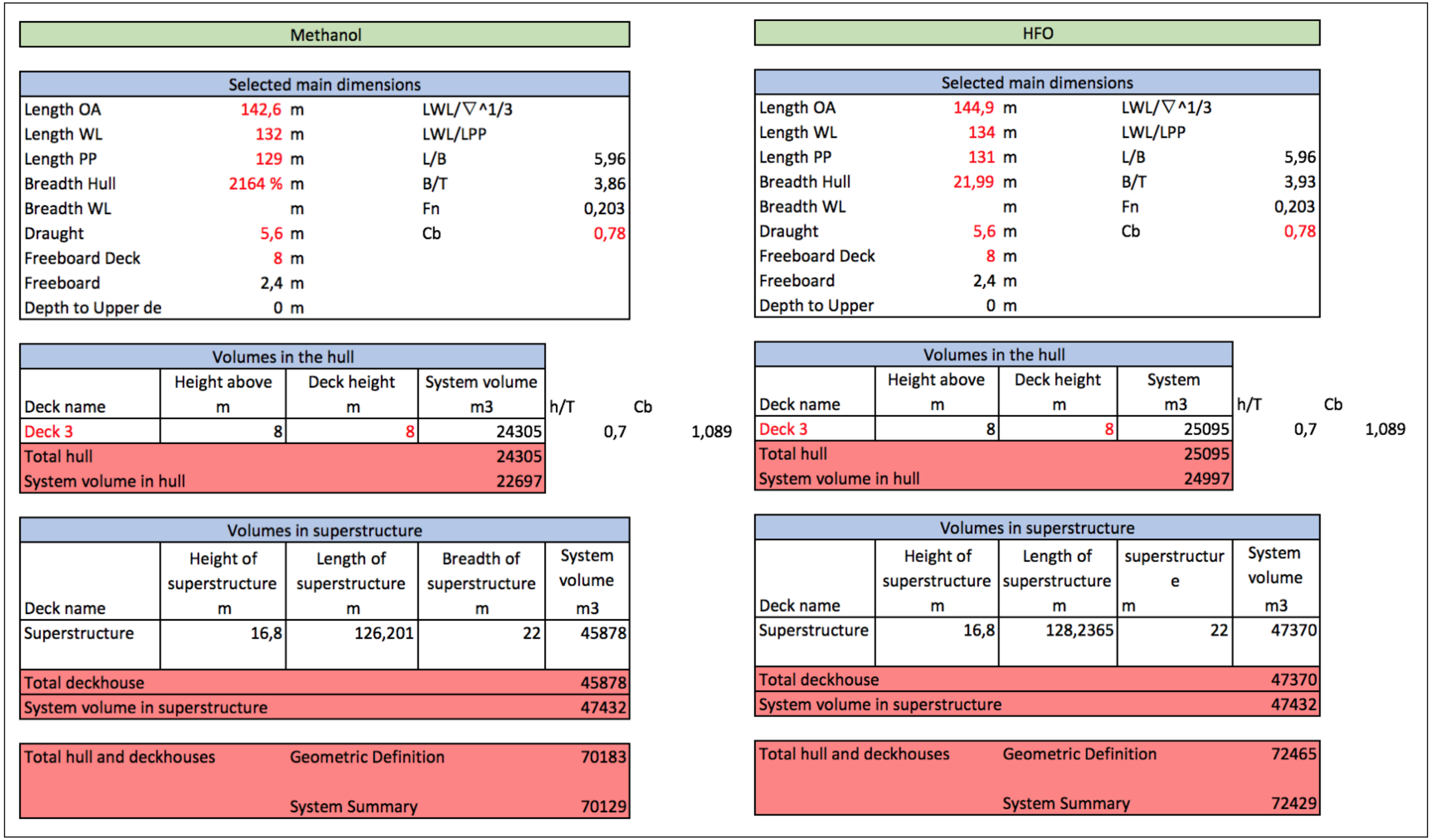
Deck name	Height above BL m	Deck height m	System m3	h/T	Cb
Deck 3	8	8	24203	0,7	1,089
Total hull			24203		
System volume in hull			22397		

Volumes in superstructure

Deck name	Height of superstructure m	Length of superstructure m	Breadth of superstructure m	System volume m3
Superstructure	16,8	125,9355	22	45685
Total deckhouse				45685
System volume in superstructure				47432

Total hull and deckhouses	Geometric Definition	69888
	System Summary	69829

Figure F.14: Geometry for hydrogen and LNG



Methanol

Selected main dimensions				
Length OA	142,6	m	LWL/∇^1/3	
Length WL	132	m	LWL/LPP	
Length PP	129	m	L/B	5,96
Breadth Hull	2164 %	m	B/T	3,86
Breadth WL		m	Fn	0,203
Draught	5,6	m	Cb	0,78
Freeboard Deck	8	m		
Freeboard	2,4	m		
Depth to Upper de	0	m		

Volumes in the hull						
Deck name	Height above m	Deck height m	System volume m3	h/T	Cb	
Deck 3	8	8	24305		0,7	1,089
Total hull			24305			
System volume in hull			22697			

Volumes in superstructure				
Deck name	Height of superstructure m	Length of superstructure m	Breadth of superstructure m	System volume m3
Superstructure	16,8	126,201	22	45878
Total deckhouse				45878
System volume in superstructure				47432

Total hull and deckhouses	Geometric Definition	70183
	System Summary	70129

HFO

Selected main dimensions				
Length OA	144,9	m	LWL/∇^1/3	
Length WL	134	m	LWL/LPP	
Length PP	131	m	L/B	5,96
Breadth Hull	21,99	m	B/T	3,93
Breadth WL		m	Fn	0,203
Draught	5,6	m	Cb	0,78
Freeboard Deck	8	m		
Freeboard	2,4	m		
Depth to Upper	0	m		

Volumes in the hull						
Deck name	Height above m	Deck height m	System m3	h/T	Cb	
Deck 3	8	8	25095		0,7	1,089
Total hull			25095			
System volume in hull			24997			

Volumes in superstructure				
Deck name	Height of superstructure m	Length of superstructure m	superstructure m	System volume m3
Superstructure	16,8	128,2365	22	47370
Total deckhouse				47370
System volume in superstructure				47432

Total hull and deckhouses	Geometric Definition	72465
	System Summary	72429

Figure F.15: Geometry for methanol and HFO