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Alternative fuels on board of carbon-neutral cruise vessels

Delft University of Technology

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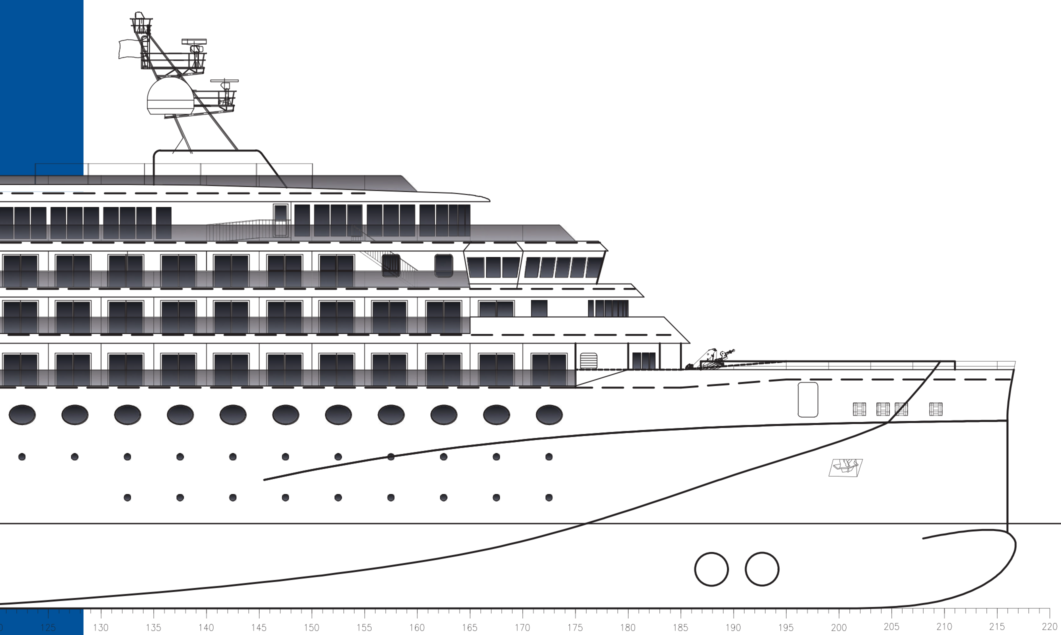

DAMEN

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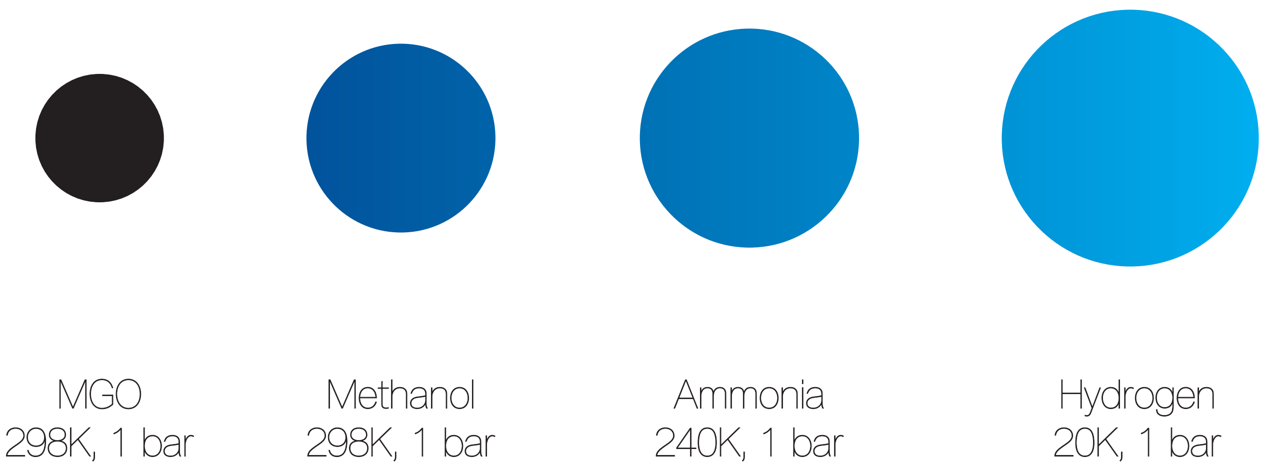
A visual representation of energy:

The cross section of the spheres which volumetric energy content is equal to charging your mobile phone approximately 20 times



Alternative fuels on board of carbon-neutral cruise vessels

The selection, implementation and design impact of alternative fuels on board of carbon-neutral cruise vessels

by

Casper Louis Volger

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at the Delft University of Technology,
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Preface

In 1838 the English artist J.M.W. Turner painted the artwork "The Fighting Temeraire, tugged to her last berth to be broken up". This majestic painting shows the HMS Temeraire, a 56 meter long British Royal Navy sailing vessel, which served the navy for many years and played a crucial role in the Battle of Trafalgar in 1805. In this painting, the impressive ship is seen being tugged away to a scrapyard by a paddle steam ship of which the first models were constructed in the early 1800s. In my opinion the painting shows the impermanence of technology. Moreover, in the near future, conventional marine propulsion methods and fuels will be replaced and former state-of-the-art technology will become obsolete. This raises the notion that solutions that "we" as marine engineers construct are merely temporary and we should thus always keep innovating.

As a future marine engineer, I therefore chose to study a field in which innovation and change is needed now more than ever. In front of you lies my final deliverable of my Marine Technology degree. Over the last 10 months I investigated the use of alternative fuels on board of carbon-neutral cruise vessels. This thesis could not have been completed without the support of several people, who I would like to thank beforehand.

Firstly, I would like to express my gratitude to my supervisor Peter de Vos. Several meetings, interesting discussions and cups of coffee led to the attainment of knowledge and insights which proved invaluable to this thesis. Equally unmissable in this process was Klaas Visser, who not only helped me during the process of writing my thesis, but also motivated me to choose the subject of marine engineering during his inspiring lectures on WVA and Diesel Engines.

A very special thank you to my colleagues at Damen Shipyards. My supervisors Erik-Jan Boonen and Robin Brouwer who provided me with valuable insights and supported me throughout the whole process. And to Federico for the help, critical feedback this thesis needed and above all, the enjoyable moments at the office.

Thanks for the support I received from my dear friends Pieter, Ruben and Roel, without whom marine engineering wouldn't have been the same. My girlfriend who was there for me during this research. Lastly, my parents for supporting me and my three sisters for being there. Everything begins and ends with family.

Casper Volger
Amsterdam, August 2019

The Fighting Temeraire, tugged to her last berth to be broken up, Joseph M.W. Turner, 1838

Definitions

Fuel:
In this report, the term *fuel* is considered to be associated with a specific primary energy source and processing options. An *energy carrier* only represents the compound or phenomenon that carries the energy. Desribed in subsection 1.1.2

Alternative fuel:
In this report, the term *alternative fuel* refers to fuels that are alternatives to marine fossil fuel oils like HFO, MDO or MGO in shipping. Described in subsection 1.1.2

Carbon neutral:
In this report the term *carbon neutral* will be used to describe all processes where there is a net-zero carbon emission. This can be achieved either by emitting no carbon at all i.e. *zero-carbon emission* or through CO_2 compensation. Described in subsection 1.1.3.

Feasible or feasibility study:
The term *feasible* in this report will be used to address the ability a process, solution or concept has to be made, done or achieved. Consequently, the term *feasibility study* will be used to describe the examination of a process, solution or concept to decide if a suggested method or plan is possible, achievable or reasonable. Described in subsection 1.4.

Electrofuel:
In this report the term *electrofuel* will be used to describe fuels produced with renewable electric energy. Desribed in section 2.1.

Prime mover:
In this report,the term *prime mover* is used to describe the system on board of a ship that converts chemical energy from a fuel into useful energy on board of a ship.

Nomenclature

Abbreviations

FC	-	Fuel Cell
GHS	-	Glocal Harmonized System of classification and labelling chemicals
HFO	-	Heavy Fuel Oil
ICE	-	Internal Combustion Engine
LHV	-	Lower Heating Value
MGO	-	Marine Gas Oil
PEMFC	-	Proton Exchange Membrane Fuel Cell
SATP	-	Standard Ambient Temperature and Pressure
SCR	-	Selective Catalytic Reduction
sfc	-	Specific fuel consumption
SOFC	-	Solid Oxid Fuel Cell
TRL	-	Technical Readiness Level

Symbols

η		Efficiency
∇		Displacement
B_{wl}	[m]	Beam at waterline
C_b	[-]	Block Coefficient
GT		Gross Tonnage
L_{oa}	[m]	Length over all
L_{pp}	[m]	Length between perpendiculars
L_{wl}	[m]	Length over waterline
P_b	[kW]	Brake power
P_e	[kW]	Effective Power
R	[N]	Resistance
T	[m]	Draft

Abstract

The growth of the cruise industry throughout recent years and the changing public opinion on cruise ships has led to increasing concerns regarding the impact cruise vessels have on the world's climate and environment. Cruise passengers prefer not to be related with heavy polluting vessels. In fact, trends like responsible tourism and sustainable travel are increasing, especially among younger generations. In order to maintain a viable business model, cruise operators are compelled to consider exploring new energy sources and energy carriers to power their cruise vessels. Alternative carbon-neutral fuels are found to be a potential solution. As such, this research aims to evaluate the viability of possible alternative carbon-neutral fuels on board cruise ships.

First, a literature review was performed in order to find feasible carbon-neutral alternatives for conventional fuel oil. In doing so, it was found that biofuels cannot be classified as alternative fuels in the maritime industry. Moreover, current and future supplies of biofuels do not meet the demand the maritime industry will have. When considering electrofuels, however, more feasible alternatives were found. Hydrogen, ammonia and methanol made with renewable energy as a primary feedstock and water and ambient air as a secondary feedstock were thus considered as possible alternative fuels to be implemented on board a cruise vessel.

When analysing the viability of implementing the selected alternative fuels, several aspects had to be taken into consideration. One such aspect was the storage of the fuel on board, as this may be challenging. More specifically, liquid hydrogen has to be stored at cryogenic conditions, requiring a lot of storage space, for example. Next, the power conversion systems had to be examined. Here it became clear that hydrogen and ammonia can be used in a fuel cell and methanol can be used in both a fuel cell and an internal combustion engine. Lastly, cost considerations had to be analysed. This was done by creating a cost prediction that considers the operating expenditures (OPEX) and capital expenditures (CAPEX) of the selected alternative fuels.

In order to then analyse the environmental impact of the selected alternative fuels, a design impact tool was made. First, a parametric study on cruise ship dimensions was performed. Here a database of 26 cruise vessels within a range of 15,000 to 90,000 GT was examined in order to find relations between the number of passengers, ship speed and ship dimension. Consequently, a dimension prediction model was created based on the number of passengers, the level of luxury and the maximum speed of the vessel. With these dimensions, a ship resistance estimation was established based on the prediction model of Holtrop Mennen. The resistance figures of the vessel then allowed for the calculation of the required installed propulsion power. These results were validated by using the data from the database as input. An AIS data analysis was then performed in order to predict ship speed over different types of operation. This information in combination with the power consumed by passengers led to a load balance and energy consumption prediction of the selected alternative fuels. These predicted values were taken into account when analysing the environmental impact of the selected alternative fuels.

Next, the impact of selected alternative fuels on the design of a cruise vessel was analysed through a developed design impact tool. The impact of a fuel was examined based on ship dimension, endurance and costs. Several concept ships were tested in order to analyse the impact of the selected fuels. After the impact tool was used for different scenarios it was concluded that hydrogen will have the largest impact on ship design, followed by ammonia. Methanol will have the smallest impact on ship design of the selected alternative fuels. Methanol used in a fuel cell configuration has the smallest impact on a large cruise vessel (>2000 pax) resulting in an increase in GT of around 4%. When considering TRL and the implementation on board, methanol in an ICE is considered most feasible.

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1
Introduction

In 2015, the *United Nations Climate Change Conference*, or COP21, took place in Paris, France. During this conference nations from around the world gathered to discuss climate change and more specially, how to decelerate global warming, which led to the establishment of the Paris Climate Agreement. The Paris Agreement aims to tackle global warming by setting targets in terms of greenhouse gas emissions, mitigation, adaption and finance. The long-term goal of the agreement is to keep the global average temperature under 2 degrees Celsius above pre-industrial levels. As a result of the Paris Agreement, the International Maritime Organization (IMO) adopted an initial strategy to reduce and ultimately eliminate GHG emissions from ships in April 2018. Moreover, all members of the IMO came to the agreement to cut CO_2 emissions from ships by at least 50% by 2050 compared to levels of 2008. The strategy implies that the maritime industry would consume between 3.8% and 5.8% of the remaining carbon-budget under the Paris Agreement, up from 2.3% in 2015. Meeting these goals will require fast implementation of policies that improve fuel efficiency of the global fleet and moreover, the promotion of the development and the deployment of low- and zero carbon fuels and propulsion technologies. Whilst the majority of ships are currently fossil-fuel powered, new, alternative and carbon-neutral fuels are emerging to become new energy sources and carriers for the future fleet. The shift towards these new alternative fuels will also be of relevance to the cruise ship industry and its cruise vessels, as cruise vessels are one of the most fuel-demanding ship types.

In this report a study on alternative, carbon-free energy sources and carriers for cruise vessels is presented, which is the result of a project carried out at Damen Shipyards Gorinchem and supervised by the Delft University of Technology. In this first chapter, an introduction to the research is given. In section 1.1 the problem is stated and background information on the problem is presented. Next, the research objective is outlined in section 1.2. In section 1.4 the scope of the research is defined. Finally, the research approach will be described in section 1.3.

1.1. Problem background

The problem as introduced above can be summarised as the following problem statement:

Problem statement:
It is unknown which carbon-neutral alternative energy sources and carries are most suitable for the wide range of marine propulsion and power systems on board of cruise vessels.

In order to fully understand the problem statement some aspects, keywords and definitions should be elaborated to the aformentioned problem statement. In addition, the stakeholder of the problem should be determined. In the following sections the keywords of the problem statement and stakeholders of this problem will be explained in detail.

1.1.1. Stakeholders

Several stakeholders might be affected, interested or play a role in providing the solution to the problem. In the sections below, possible stakeholders of the problem are described.

Cruise vessel owners and operators

The modern cruise industry originated in the 1960's in North America [24]. As a result of the fast developing aviation technology, North Atlantic passenger traffic declined significantly throughout the 1950's and 1960's. In order to remain a relevant player in the tourism industry, several Atlantic ship liners came up with a new business model; Cruise vacations as we know it nowadays. Ever since, cruise shipping has developed into an extensive tourism product that provide passengers not only accommodation but also entertainment, shopping, dining and fitness facilities, changing cruise vessels into floating resorts.

The number of cruise passengers worldwide has increased considerably, doubling from 13.2 to 26.6 million passengers between 2005 and 2017. The cruise ship order book contains 120 new ships as of November 2018 with ship deliveries scheduled through 2027 [6]. Cruise vessels are one of the most fuel demanding ship types due to their high propulsion and hotel energy requirements [26]. Opposed to cargo vessels or platform supply vessels, cruise ships have to produce adequate power at a constant level to comply with the constant high energy demand for the hotelling services, entertainment and amenities. Moreover, when berthed in port, cruise ships prefer self-reliance to cover power needs.

The growth of the cruise industry over the recent years and the changing public opinion about cruise ships has led to increasing concerns about the environmental impact cruise vessels have. Cruise passengers prefer not to be related with heavy polluting vessels. Trends like responsible tourism and sustainable travel are increasing, especially among younger generations [21]. Cruise vacations tend to be more polluting than travelling to tourist destinations by airplane, making cruise vacations one of the most polluting forms of tourism [26]. Furthermore, citizens and local governments living around popular cruise destinations have growing concerns about the consequences of emissions of cruise vessels on their cities. The high levels of particular matter (PM), SO_x and NO_x raise questions about public health as well as the visible pollution of smoke plumes, that are considered to have a negative impact on people's experience of the city or natural site. The decision to ban all air-polluting ships from fjords by 2026, made by Norwegian Authorities in May 2018 [66], is an example of how governments are also playing an increasingly influential role in cruise ship operations.

In order to maintain a viable business model, cruise operators have to consider exploring new energy sources and energy carriers to power their cruise vessels. Alternative carbon-neutral fuels could be the solution. To date, limited research has been performed in the field of propulsion systems and emissions of cruise vessels. Students and researchers primarily concentrate on other marine sectors like freight transport and offshore support vessels. It is unknown what alternative fuels are suitable for the wide range of marine propulsion and power systems on board of cruise vessels.

International Maritime Organization

As a specialised agency of the United Nations, the IMO is the global standard-setting authority for the safety, security and environmental performance of international shipping. Its main role is to create a regulatory framework for the shipping industry that is fair and effective, universally adopted and universally implemented [50].

Within the IMO, the Marine Environment Protection Committee (MEPC) addresses environmental issues. The committee is empowered to consider any matter within the scope of the IMO concerned with the prevention and control of pollution from ships. The MARine POLlution convention (MARPOL) is the main international convention covering prevention of pollution of the marine environment by ships from operational or accidental causes. In 2005 Annex VI was added to the MARPOL convention. This annex sets limits on sulphur oxide and nitrogen oxide emissions from ship exhausts and prohibits deliberate emissions of ozone depleting substances; designated emission control areas set more stringent standards for SO_x, NO_x and particulate matter. A chapter adopted in 2011 covers mandatory technical and operational energy efficiency measures aimed at reducing greenhouse gas emissions from ships [52].

Section 1.1.3, provides more detail regarding the IMO's initial Greenhouse Gas Strategy.

Shipbuilders and marine propulsor manufacturers
In order to cope with the future, shipbuilders and marine propulsor manufactures around the world are searching for future-ready ship designs and propulsion systems. At this moment it is not known what alternative fuel will power the next generation of ships. On average, a ships' lifespan is approximately 25 years, this means that a significant amount of ships sailing at this moment will still be in operation by 2035. Decarbonization of the maritime industry will depend on the rate of fleet renewal and on the technologies available for shipbuilders and marine propulsor manufactures to design and build carbon-neutral vessels.

One such shipbuilder is Damen Shipyards. Damen Shipyards is an international group of shipyards doing business in more than 120 countries. Damen operates globally over 50 shipyards, repair yards, and related companies as well as numerous partner yards that can build Damen vessels locally. Damen Shipyards is involved in ship design, construction, maintenance and repair activities within a wide range of products including patrol vessels, cargo vessels, ferries, tugs and work boats. In 2016, Damen Shipyards unveiled a new design for a 115 passenger capacity expedition cruise vessel [44] for the first time. In 2018, this design was revised resulting in a 200 to 250-passenger vessel in the high-end, luxury segment including polar class, helicopter decks and swimming pools. In February 2019 Damen announced the signing of the first cruise vessel to be build by Damen Shipyards. The vessel, called SeaDream Innovation and owned by SeaDream Cruises. The 15,000GT vessel can carry up to 220 passengers and has the highest standards of luxury. A picture is shown in figure 1.1.

Figure 1.1: SeaDream Innovation

In the future, Damen has the ambition to built more cruise vessels in the range from 15,000 to 90,000 GT.

Classification society
Classification societies are non-governmental organisations that establish and maintain technical standards for the construction and operation of ships. Classification societies issue classification certificates which provide ship owners a classification to register the ship and to obtain insurance. In addition, ships may be required to have certain classification certificates to enter ports or waterways. Classification certificates are a verification that the vessel is in compliance with the classification standards of the society issuing the classification certificate. Large classification societies are DNV GL, Lloyd's Register and Bureau Veritas.

If solutions and new techniques in respect to carbon-neutral propulsion would be found and implemented on a large scale on ships it is up to classification societies to adapt rules and set new regulations.
Having defined the various stakeholders involved in identifying alternative energy sources for cruise vessels, the following section will proceed by deconstructing the concept of alternative fuels.

1.1.2. Alternative fuels, energy carriers, energy sources and energy conversion

Over the course of history, marine propulsion has changed a few times, as can be seen in figure 1.2. Human power was replaced by wind power, wind power was succeeded by steam engines in the nineteenth century and over the course of the last century the steam engine was replaced by the diesel engine. HFO, or residual fuel oil, is at this moment the dominant shipping fuel and is used in the majority of marine engines. In 2015, HFO accounted for 84% of the total international shipping energy mix [4].

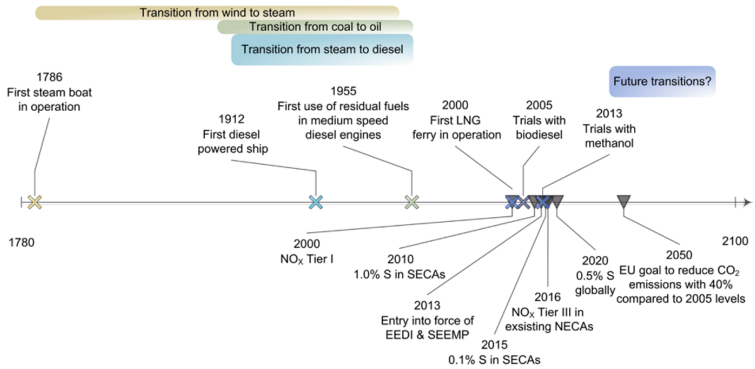


Figure 1.2: Time line for the transitions of marine fuels from 1780 to 2100 with selected events in history and environmental regulations

Over the past few decades alternative fuels have arisen within the maritime industry. Throughout this report the term *alternative fuels* is used to describe fuels that are alternatives to marine fossil fuel oils like HFO, MDO or MGO in shipping. Examples of these alternative fuels are liquified natural gas (LNG), biodiesel and methanol.

When looking at marine fuels the following simplified energy chain applies, as can be found in figure 1.3:

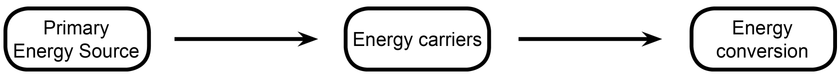


Figure 1.3: Simplified energy chain

For example, when looking at the use of HFO as a marine fuel the following simplified energy chain is found:

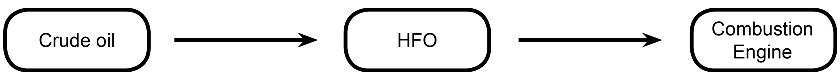


Figure 1.4: Energy chain for the use of HFO

As shown in figure 1.4, when using HFO/MDO/MGO as a marine fuel, crude oil acts as the primary energy source, HFO as the energy carrier and an internal combustion engine as the energy converter producing mechanical energy to propel the ship.
To get a better and a more broad overview of the energy chain, other aspects of the energy chain should also be taken into account. This is done in the following figure :

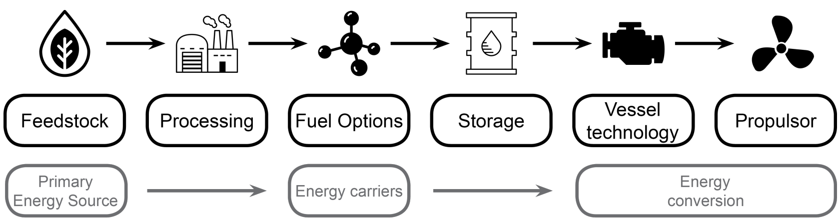


Figure 1.5: Energy chain from feedstock to propulsor

As can be seen in figure1.5, the steps of processing, transport and propulsor are added to the energy chain, these steps are important in the complete chain to assess alternative fuels since numerous possibilities are available within the industry. In the example shown in figure 1.6 the chain of HFO is described in black. In blue and green, the alternative fuel hydrogen can be found. Although the energy carrier for the blue and the green chain is the same, other steps are different, making it a different type of fuel.

In this report, the term *fuel* is considered to be associated with a specific primary energy source and processing options. An *energy carrier* only represents the compound or phenomenon that carries the energy. The type of energy carrier in the fuel will determine the possible prime movers used in the energy chain that convert the chemical energy into the ship's propulsion [5].

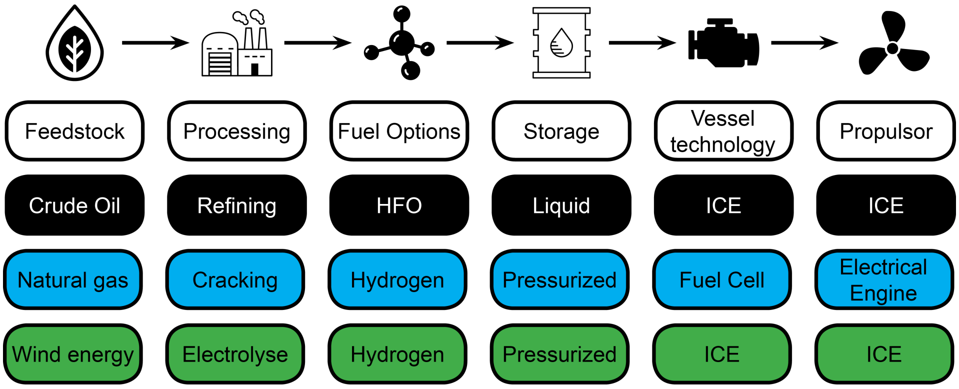


Figure 1.6: Energy chain from feedstock to propulsor with examples of HFO (black), hydrogen made from natural gas (blue) and hydrogen made from renewable energy (green)

Based on the research of Brynolf [13], DNV GL has mapped the most potential feedstock (energy source), fuel options (energy carries) and vessel technology (energy conversion) [1]. This is shown in the following figure:

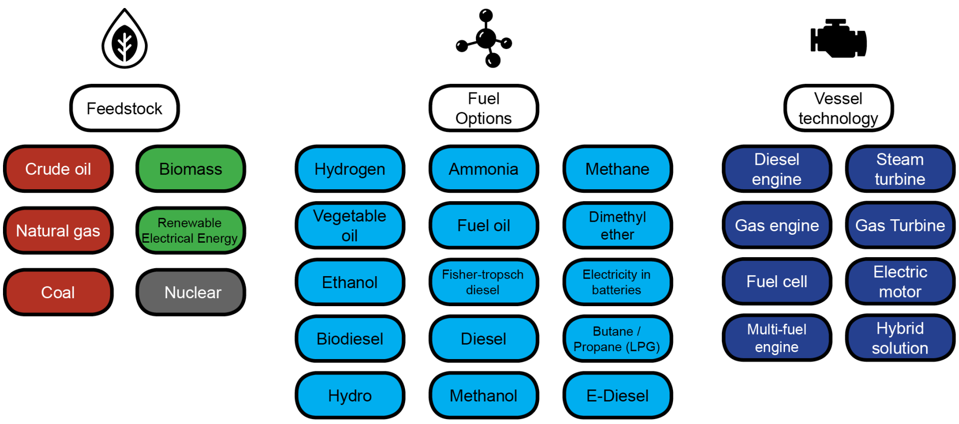


Figure 1.7: Simplified illustration of feedstock (energy source), fuel options (energy carries) and vessel technology (energy conversion) based on DNV [1] and Brynolf [13]

This also explains the essence of the larger problem that arises when doing research in the field of alternative carbon-neutral fuels. In fact, there are so many possible alternative energy sources, carrier options and corresponding conversion types to consider, that finding a single best solution is close to impossible. When considering energy sources, the potential types of biomass already include numerous different types of feedstock. And when adding renewable electric energy as an energy source, there are over 100 different types of possible feedstock to consider. With these various possible feedstock solutions, multiple energy carriers can be produced through different types of production methods. The energy from the energy carrier can also be converted into useful energy in numerous vastly different ways. And in turn, for every particular solution different efficiencies, boundary conditions, limits, materials, geographic constraints and economic constraints apply.

Thus, the aim of this investigation into alternative carbon-neutral fuels for the cruise ship industry is not to find a single, best solution. Instead, it aims to produce reliable results that analyse possible alternatives that can be further investigated in the future. The scope of this research (section 1.4) therefore funnels and narrows down the methods and assumptions made. In Chapter 2 a selection of feasible carbon-neutral fuels are made based on the energy chain, as described in figure 1.5. Only this selection of fuels will be considered in this research.

1.1.3. Carbon emissions

Marine fuel currently contributes approximately 3% to global man-made CO_2 emissions [1]. CO_2 is a greenhouse gas contributing to global warming. In order to stop global warming, CO_2 emissions have to be reduced.

In Figure 1.8 an overview of fuel categories is made. The triangle illustrates all marine fuels, divided in net carbon-emissions. When beginning at the top, all fuels are considered. Next are *alternative fuels* which represents all fuels except for conventional marine fuel oil products. The next category is *Low-carbon fuels*. Low-carbon fuels are alternative fuels that have lower carbon emissions, such as LNG, methanol or bio-mass based alternatives. The last two categories are described in the following paragraph.

Carbon neutrality and carbon-free

To operate a carbon neutral vessel, the propulsion and power system of the vessel should not produce any net CO_2 emissions. This can be achieved either by emitting no carbon at all i.e. the use of *carbon-free fuels* or through CO_2 compensation through the use of bio- or renewable synthetic fuels. These two categories are the bottom two categories in Figure 1.8.

In order to operate a carbon-neutral ship all the carbon emissions of the ship operations have to be compensated elsewhere. Carbon neutrality can be achieved via two different types of carbon-neutral fuels. The first type is biofuel. Biofuels are fuels derived from biological material. Plants, crops and other vegetation are the feedstock for biofuel. In the process of growing, the vegetation has captured an equivalent amount of CO_2 through photosynthesis resulting in a net zero carbon emission of the fuel. First-generation biofuels are made from sugars and vegetable oil, second-generation biofuels are manufactured from various types of non-food biomass.

The second type of carbon-neutral fuel is synthetic fuel produced from renewable energy that is used to hydrogenate carbon dioxide, creating a fuel for combustion engines or fuel cells. In this process CO_2 is captured from the air or from industrial processes creating a net zero carbon emission of the fuel.

As seen in figure 1.8, the last category are carbon-free fuels. When operating carbon-free, a ship runs on anything not emitting any carbon emissions, this can be electricity or hydrogen but also sails or a nuclear reactor.

In this report the term *carbon-neutral* will be used to describe all processes where there is a net-zero carbon emission.

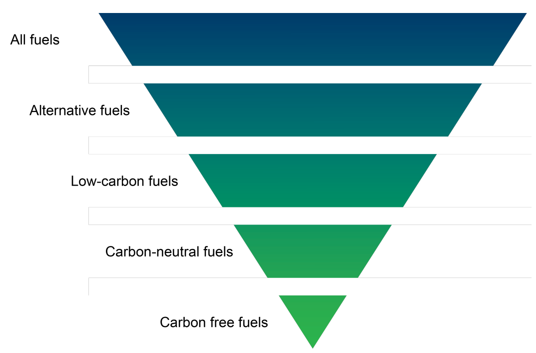


Figure 1.8: Overview of marine fuels used in shipping sorted on carbon net-emissions

Paris Climate Agreement
The Paris Climate Agreement was established in 2015 at the United Nations Climate Change Conference, or COP21, in Paris, France. The aim of this agreement is to strengthen the global response to climate change by keeping the global temperature rise in this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius. Additionally, the agreement aims to strengthen the ability of countries to deal with the impacts of climate change. Although the Paris Agreement is a binding agreement, detailed consequences nor legislation were set for the shipping and aviation industry. This leaves it to governments and regulators like the IMO to use the Paris Agreement as a framework and to set new goals and regulations concerning the effect shipping has on global warming.

IMO's initial GHG strategy
As described above, the maritime industry is expected to take measures to reduce the emission of greenhouse gasses (GHG) and to diminish the impact ships have on the environment. In 2015, reduction targets for international transport over sea and through air were left out of the Paris Climate Agreement. IMO's sister agency governing aviation, the International Civil Aviation Organization (ICAO), adopted a global climate agreement aimed at carbon-neutral growth from 2020. To stay in line with the ICAO, the IMO took steps to take actions and started with an initial GHG strategy.

The strategy includes an overall vision regarding decarbonization, GHG reduction target through 2050 with accompanied short-,mid- and long-term measures and criteria for future review. The stated vision of the strategy is a qualitative description of IMO's ambition. It is stated as follows:

"IMO remains committed to reducing GHG emissions from international shipping and, as a matter of urgency, aims to phase them out as soon as possible in this century" [51].

In order to reach this vision a range of emission pathways are possible under IMO's initial strategy as shown in figure 1.9.

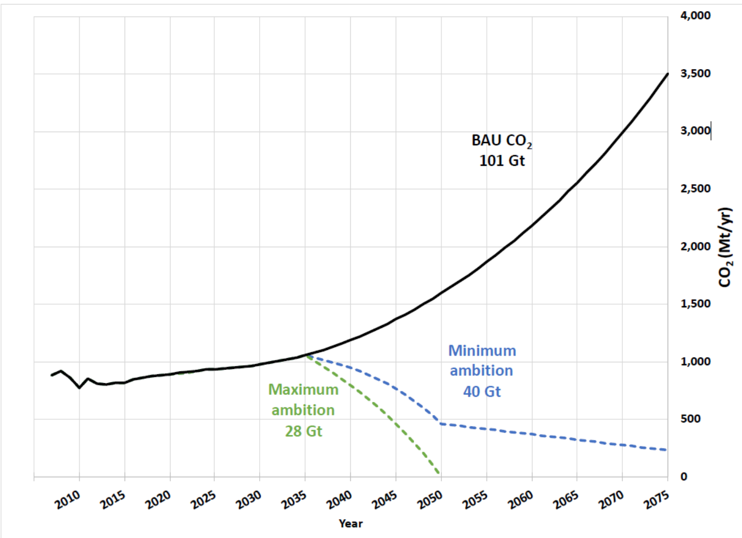


Figure 1.9: CO_2 emissions from international shipping under IMO's initial GHG strategy (blue and green) vs. BAU (black), with cumulative emissions 2017 throughout 2075

In figure 1.9 three possible pathways of CO_2 emissions from international shipping are outlined [48]. The black line is the "Business As Usual" (BAU) scenario. the blue line reflects the minimum ambition within the initial strategy, it reflects a 40% carbon intensity reduction by 2030 and an absolute emissions reduction of 50% by 2050, with full decarbonization by 2100. The green line projects the maximum ambition of the strategy; full decarbonization by 2050. The green line reflects the pace that is consistent with the Paris Climate Agreement.

In order to reduce carbon emissions from ships and reach the goals set out in the strategy, several measures are drawn up to meet the emission targets. The measures are distinguished in short-term measures, implemented from 2018 to 2023; mid-term measures for the period between 2023 and 2030 and finally long-term measures for the years after 2030. The measures are shown in table 1.1. It should be noted that the measures drawn up in the table are concepts and still need to be made mandatory under an IMO convention like the MARPOL before they are legally binding.

Type	**Years**	**Measure**	**Target**
Short-term	2018 - 2023	New Energy Efficiency Design Index (EEDI) phases	New vessels
		Operational efficiency measures (e.g. SEEMP, operational efficiency standard)	In-service vessels
		Existing fleet improvement program	In-service vessels
		Speed reduction	In-service vessels
		Measures to address methane and VOC emissions	Engines and fugitive emissions
Mid-term	2023 - 2030	Alternative low-carbon and zero-carbon fuels implementation program	In-service vessels / Fuels / New vessels
		Further operational efficiency measures (e.g. SEEMP, operational efficiency standard)	In-service vessels
		Market-based Measures (MBMs)	In-service vessels / Fuels
Long-term	2030 +	Development and provision of zerocarbon or fossil-free fuels	In-service vessels / Fuels / New vessels

Table 1.1: Candidate measure included in IMO's initial GHG strategy

This research will focus on the long-term measurements set by the IMO; The development and provision of zero-carbon or fossil-free fuels. The IMO has stated the following on long-term measurements during the Marine Environment Protection Conference on 13 April 2018:

All the following candidate measures represent possible long-term further action of the Organization on matters related to the reduction of GHG emissions from ships:

1. *to pursue the development and provision of zero-carbon or fossil-free fuels to enable the shipping sector to assess and consider decarbonization in the second half of the century;*
2. *to encourage and facilitate the general adoption of other possible new / innovative emission reduction mechanism(s).*

This section has provided background information to the problem statement, which focuses on the suitability of carbon-neutral alternative fuels on board of cruise vessels. The next section will proceed to outline the research objective and the scope of the research.

1.2. Research objective

Combining the problem statement and problem background presented in this chapter, the objective of this thesis can be stated as follows:

Thesis objective:
Evaluate possible alternative power sources and carriers that can power carbon-neutral cruise vessels

The sub-research objectives are formulated as follows:

i *Identify and evaluate different types of carbon-neutral energy sources and carriers and select the most feasible;*

ii *Identify and analyse necessary measures and requirements for implementing selected carbon-neutral fuels on board of a cruise vessel;*

iii *Analyse the impact selected carbon-neutral fuels have on the cruise vessels' design and operation;*

iv *Provide an outline for future developments and research of alternative carbon-neutral fuels in the cruise ship industry.*

The report is structured in such a way that sub-objectives are dedicated to specific chapters as explained in the following section (1.3) where the approach of this research is given.

1.3. Research approach

In order to investigate the research problem it first has to be determined how to examine the functionality and feasibility of alternative fuels. At current day, several CO2 reducing techniques as well as lower and non-CO_2 emitting fuels are in development. Some fuels are in an advanced stage of development whereas others are in an early stage of development or even still in a conceptual stage. In order to attain an overview of the available fuels and techniques a literature study has to be performed. The goal of the literature study is to map alternative, carbon-neutral fuels which can be used in the shipping industry. The fuels found in the literature study will be examined on the basis of the feedstock of the fuel, the production process and the thermo-chemical properties of the fuel. Based on these premises, a selection of the most feasible fuels will be made. The literature study and fuel assessment can be found in Chapter 2 where sub objective i is answered.

Next, in Chapter 3, an analysis of the impact of the selected alternative fuels will be provided. More specifically, storage methods and required equipment are considered and reviewed. The possible energy conversion techniques are examined and only feasible energy systems are selected to take into consideration for implementation. Cost predictions regarding the capital costs (CAPEX) and operational costs (OPEX) are also made. Finally, class rules of selected fuels and corresponding storage methods and energy systems are reviewed. The work of this chapter results in the answer to sub objective ii.

Subsequently, design parameters of cruise vessels will be discussed in Chapter 4. In this chapter, design parameters of a cruise ship will be determined based on a database consisting cruise vessels. The goal is to provide techniques to estimate physical dimensions and power characteristics of a cruise vessel in a preliminary design phase. This includes the dimensions, resistance, installed power, level of luxury etc. This data will be used in the design-impact analysis of a carbon-neutral cruise vessel.

With information gathered about the selected alternative fuels, the corresponding storage and conversion techniques as well as cruise vessel design, a design impact analysis is made in Chapter 5. The design impact analysis is established in the form of an interactive tool where input parameters are 'number of passengers', the level of luxury and design speed. The model will be based on the characteristics of the fuels, required machinery as well as the design parameters from the previous chapters. The output of the model will give an overview of the impact the implementation of a selected fuel will have on the design of the cruise vessel. With the knowledge of Chapter 4 and Chapter 5 sub objective iii can be answered.

Finally, results, conclusions and recommendations are provided in Chapter 6, where the last sub objective and the main thesis objective of this research will be answered.

1.4. Scope of the research

In order to fulfil the objective of the research and ensure the quality, validity and reliability of the findings within the limited time available, the scope of the research will have to be determined in advance. The scope of this research is based on the first three sub-objectives as in section 1.2.

Sub objective i:

- **Nuclear solutions** will not be considered due to the high investment cost and high complexity of nuclear propulsion systems. Moreover, partly unknown safety risks and a relative negative public opinion make nuclear energy an unfavourable propulsion method for cruise vessels.
- **CO_2-negative solutions** will not be considered. In recent years, CO_2-negative solutions,such as under water exhaust release under the ship's hull in combination with ocean afforestation [47]. Due to the conceptual phase carbon-negative solutions are still in and the limited scientific research and literature available, carbon-negative solutions will be excluded from this research.
- **On-board CO_2-capture** will not be considered. Although CO_2-capture results in carbon-neutral operations of a (cruise) vessel, CO_2-capture is not a sustainable solution to the problem statement.
- **Availability** of alternative fuels is assumed plentiful worldwide. A geographical analysis of the availability of alternative fuels is not in the scope of this research.

Sub objective ii:

- **Storage** of the selected fuels will be in enclosed tanks, the storage of fuels in other chemical compounds is not considered.
- **Efficiencies** of power conversion and distribution systems are given and assumed to be constant within the complete range of speed and power consumption
- **Estimated costs** of production, OPEX, machinery and CAPEX are indications based on assumptions and have not been validated.

Sub objective iii:

- **Impact** of a selected alternative fuel will be an approximation based on a dimension and power prediction model for vessels from 15,000 to 90,000 GT only.
- **Occupancy rate** of a cruise vessel is 100%. Meaning the maximum number of passengers is on board during operation.
- **Classification rules** will not be considered in this research. This is due to the fact that only limited classification rules are determined by classification societies.

The term *feasible* in this report will be used to address the ability a process, solution or concept has to be made, done or achieved. Consequently, the term *feasibility study* will be used to describe the examination of a process, solution or concept to decide if a proposed method or plan is possible, achievable or reasonable.

2
Analysis of alternative carbon-neutral fuels in the maritime industry

Emissions from shipping can be directly related to a ship's fuel consumption. In the case of emissions to air this is particularly true since emissions to air are a product of fuel combustion. In order to reduce and ultimately eliminate carbon emissions from ships it is of great importance to analyse different types of alternative carbon-neutral fuels. However, choosing an appropriate fuel is not an easy process. Factors like the feedstock, fuel production and processing, energy content, and the type of energy a fuel can produce will have a significant impact on the ship's emissions, especially emissions to the air.

In this chapter different types of alternative fuels will be considered for maritime use. The goal of this chapter is to select viable carbon-neutral alternative fuels that can be considered for the propulsion and power systems on board of a cruise vessel. This goal will be obtained through analysing the energy chain of the fuel. The energy chain is explained in Chapter 1 (Figure 1.5) and will be divided in different steps in this chapter. In section 2.1, the possible feedstock of carbon-neutral fuels are discussed. In section 2.2 the production and processing of the fuels will be considered. Next, the chemical and thermophysical properties of the carbon-neutral alternative fuels will be discussed in section 2.3. Finally, conclusions will be drawn and a selection of carbon-neutral alternative fuels will be made in section 2.5.

Based on literature a selection of alternative carbon-neutral fuels have been selected to be analysed in this chapter. In Appendix A.1 all fuels that were taken into account are listed with corresponding possible feedstock and available literature. A first selection of alternative fuels is made based on the available literature, the technical readiness level and thermo-chemical properties.

Within different groups of fuels, literature review was conducted. Mechanical stored energy types like flying wheels and compressed air have an energy density that is too low to be a potential fuel for cruise vessels. Thermal energy stored in cryogens or molton salts face the same challenge and are rather solutions for local and short-term applications. In the last decade the place of batteries within the energy transition grew significantly. The chemical storage of electricity in batteries is a solution for smaller scale applications like automotive vehicles or smaller vessels such as tugs. But power density is too low in order to be used to power larger equipment, such as trucks, trains, heavy machinery, and ships, where the low power/energy densities of batteries cannot meet the power and range demands of these systems.

Energy carriers for shipping industry in solid or powder state are limited. Research shows that it is possible to use metal powder as a fuel in a combustion engine. However, literature on this subject is very limited and the technical readiness level is very low. The same goes for solid hydrides. A hydride is a compound where a hydrogen atom is bonded to a more electropositive element or group. This compound can act like a hydrogen carrier and thus can be used as a fuel in a combustion engine or fuel cell. Literature is limited and reveals technical challenges which are not in favor of solid hydrides [55] [42].

Of the remaining fuel categories (hydrogen, hydrides, alcohols, ethers, alkane and diesel) the most feasible fuels were selected. In this Chapter, seven different alternative fuels will be analysed from different feedstocks and in variable physical conditions.In table 2.1 all alternative fuels are specified with their corresponding group and renewable feedstock.

Group	Fuel	Renewable feedstock
Hydrogen	Hydrogen	Renewable energy
Hydride	Ammonia	Renewable energy
Alcohols	Methanol	Renewable energy, biomass
	Ethanol	Renewable energy, biomass
Alkane	Methane	Renewable energy, biomass
Ether	Dimethyl ether	Renewable energy, biomass
Diesel	Diesel	Renewable energy, biomass

Table 2.1: Alternative fuels and corresponding renewable feedstock reviewed in this section

Alternative fuels will be analysed and compared with MGO as a marine fuel, since this is the most conventional marine oil which is currently used on board of cruise vessels. The properties of MGO can be found in table 2.2.

Name	Feedstock	Density [tonnes /m3]	LHV [MJ / kg]	Energy density [MJ / l]	Storage
MGO	Crude oil	0.85	42.7	36.3	Liquid at SATP

Table 2.2: Properties of Marine Gas Oil / MGO

2.1. Renewable feedstock

Renewable feedstock for alternative marine fuels consist of 2 possible types of energy sources. The first one is biomass, the second is renewable electric energy. In this section both biomass (subsection 2.1.1) and renewable electric energy (subsection 2.1.2) will be analysed.

2.1.1. Biomass

Biomass is biological material derived from living, or recently living organisms. Biomass as an energy resource can be derived from various organisms such as agricultural crops, forest products, aquatic plants, crop residues, animal manures, and wastes, such as municipal solid waste (MSW). Biomass' primary growing process is photosynthesis, where organisms use solar energy to produce energy rich organic material from inorganic input like CO_2, H_2O and plant nutrients like nitrogen and phosphorous. This process can make biofuels a carbon-neutral energy resource, meaning all CO_2 that is emitted to air during combustion is already absorbed by the feedstock in the growing stage of the biomass. The biofuels found in literature that will be analysed in this report are:

1. Bio Methanol
2. Bio Ethanol
3. Bio Dimethyl ether (Bio DME)
4. Bio Gas
5. Bio Diesel

Biofuels derived from biomass can be classified in two major categories based on the feedstock; First-generation biofuels and second-generation biofuels.

First-generation biofuels are developed from sugars and vegetable oils found in food crops and processed with standard technologies. First-generation biofuels are in essence edible for human or animals and are grown on agricultural land. *Second-generation* biofuels are derived from feedstock that is not edible for human consumption or are not grown on agricultural land suitable for food production. Second generation biofuels include specifically grown inedible energy crops, cultivated inedible oils, agricultural and municipal wastes, waste oils, and algae. At present, the production of second-generation biofuels are not cost productive because of a number of technical barriers [43]. The most commonly used feedstock for biofuels within the scope of this research are displayed in table 2.3.

Bio Fuel	Feedstock	Conversion
Bio Methanol	Wheat / Corn	Fermentation
Bio Ethanol	Sugarcrane / Corn	Fermentation
Bio DME	Wood / Pulpwood	Gasification
Bio Gas	Straw from cereals / Category 3 fats	Anaerobic digestion
Bio Diesel	Soybean / Rapeseed	Pyrolysis

Table 2.3: Feedstock of selected biofuels [43][33][18]

Biomass can be processed in multiple ways to become a biofuel. Four different conversions are used at this moment; Thermo-chemical conversion, biological conversion, chemical conversion and physical conversion. Since both chemical and physical conversion of biomass do not result in any of the biofuels within the scope of this research these conversions will not be taken into account. In section 2.2, biofuel production technologies will be explained further.

Biofuel production has gained serious attention as a sustainable substitute for crude oil based fuels in recent decades. This has led to a discussion on the issue of land use for biofuels instead of food. In order to obtain a sustainable biofuel, two principles must be used to guide production [64]. First, biofuels must be produced from feedstock with a much lower life cycle greenhouse gas emission compared to fossil fuels. Secondly there must be no competition with food production for humans and animals. The first principle will be feasible and with increasing growing and harvest technologies carbon-neutral biofuels will be achievable.

However, when looking at the second principle, challenges arise. Growing enough biomass to produce biofuels requires land and resources and since second generation biofuels are still not cost productive nor scalable, arable land has to be used for biomass to grow. In order to meet shipping energy demand, an area as large as India should be dedicated to biomass cultivation by 2030 and should have the potential to grow up to an area as large as twice the size of Australia by 2050 [35]. This makes biofuel an unlikely long-term replacement of fossil fuels. It is for that reason that biofuels will not be taken into the design and implementation phase of this research.

However, biofuels can play a big role during the transition towards carbon-neutral future. Biofuels have similarities when looking at combustion characteristics and thermo-chemical properties making it possible to implement biofuels in existing marine infrastructure.

2.1.2. Renewable Electric Energy

Another carbon-neutral energy source is renewable electric energy. In this report *Renewable Electric Energy* is a term used for electricity generated by solar-, wind-, hydro-, ocean or geothermal energy. In the scope (Chapter 1 section 1.4) it was determined that nuclear energy will not be taken into account as an onboard power source, nuclear energy will also not be seen as a renewable electric energy source in this report. In 2016, renewable electric energy was responsible for 4.1% of the total world electricity supply with a gross value of 24.1 Exajoule (EJ) [4]. The total supply is only a small fraction of the total potential renewable electric energy available in the world as can be seen in table 2.4

Renewable Feedstock	Production in 2016 [EJ] [4]	Technical potential [EJ/year] [54]
Solar Energy	2.60	62,000-280,000
Wind Energy	3.47	1250-2250
Geothermal Energy	3.39	810-1545
Hydro energy	14.66	50-60
Ocean Energy [a]	0.00	3240-10,500

[a] Ocean energy refers to the potential kinetic energy present in waves, currents and tides.

Table 2.4: Potential and production of various renewable energy sources

Renewable electric energy can be used to produce renewable electrofuels. In this report the term *electrofuels* will be used to describe fuels produced by renewable electric energy. Renewable electric energy is used to convert, store and reconvert electric energy into energy carriers. In literature this is often referred to as "Power-to-X". The X can refer to multiple energy carriers such as: *Power-to-Hydrogen* (PTH), *Power-to-Liquid* (PTL) and *Power-to-Gas* (PTG).

In this report the following electrofuels will be analysed:

1. Hydrogen (PTH)
2. Dimethyl Ether (PTL)
3. Methanol (PTL)
4. Ethanol (PTL)
5. Methane (PTG)
6. Fischer-Tropsch Diesel (PTL)
7. Ammonia (PTL)

Note that hydrogen can be used as a fuel for fuel cells or combustion engines but can also be used as a feedstock in the production of the other electrofuels mentioned above. The different production methods of the electrofuels mentioned above will be explained in section 2.2.

Over the past decades prices of renewable energy and specifically prices of solar- and wind energy have decreased significantly. Electricity costs are often expressed in the "Levelized cost of electricity" (LCOE). This value represents the net value of the unit-cost of electricity over the lifetime of a generating asset. LCOE is the sum of costs over lifetime divided by the sum of electrical energy produced over lifetime. Renewable sources often tend to have high capital costs due to expensive technologies applied in wind turbines and solar cells. However, there are no more fuel costs for many renewable electric energy sources. LCOE of photovoltaics (PV) solar energy in the USA has fallen from $75 / kWh in the end of the 1970's to $0.25 / kWh in 2017 [65]. Windenergy LCOE experienced a similar decline with the rise of large offshore wind farms and the improvement of wind turbine technology. In 2015, LCOE of dutch windfarms was $0.15 / kWh. Due to increasing wind farms and fast growing technologies it is expected that LCOE of offshore wind will decrease to $0.033 / kWh by 2025. [68].

In this report the price of renewable electric energy used as feedstock is $0.09 per kWh at current day and a projected price of $0.04 per kWh in 2050 unless mentioned otherwise.

2.1.3. Sub-conclusion

In this section the feedstock of alternative carbon-neutral fuels were discussed. Either biomass or renewable electric energy can be used to produce biofuels or electrofuels. Biofuels can be derived into first and second generation biofuels. At present, first generation biofuels are already produced on large scale where second generation biofuels are not cost productive and have a relatively low technical readiness level. The limited arable land available and the lack of mature technology for second generation biofuels makes it impossible to produce enough biofuel for the maritime industry. For that reason, biofuels will not be taken into account in the design and implementation phase of this research.

Renewable energy production is increasing and only a limited amount of the total available renewable energy is being converted at the moment. The increasing grow of wind and solar energy can create enough energy to produce electrofuels for the maritime industry. In section 2.2, production processes of the following fuels will be examined:

- Hydrogen
- Dimethyl Ether
- Methanol
- Ethanol
- Methane
- Fischer-Tropsch Diesel
- Ammonia

2.2. Fuel production

2.2.1. Hydrogen production

Hydrogen can be produced through various technologies. The most common is through the reforming of hydrocarbons such as natural gas and coals. At present, 95% of the total world hydrogen production is done though steam reforming of natural gas. As can be seen in formula 2.1 steam reforming of natural gas has CO as a side product making it a non-carbon-neutral process.

$$CH_4 + H_2O \rightleftharpoons CO + 3\,H_2 \tag{2.1}$$

Another principle is the electrolysis of water. This process transforms electricity into hydrogen using solely electric energy and clean water as the feed. Carbon-free hydrogen can be produced by using renewable energy in this process. Electrolysis works on the principle of electricity splits water into hydrogen and oxygen. An electric DC power source is connected to two electrodes acting as a cathode and an anode placed in water. The cathode and anode are separated by a electrolyte, which conducts only one kind of ion and thereby splitting the water into hydrogen and oxygen. This process is shown in figure 2.1 and can be written in the following formulas where formula 2.2 is the reaction at the cathode, formula 2.3 is the reaction at the anode and formula 2.4 is the total reaction.

$$4\,H_2O + 4\,e^- \longrightarrow 2\,H_2 + 4\,OH^- \tag{2.2}$$

$$4\,OH^- \longrightarrow O_2 + 2\,H_2O + 4\,e^- \tag{2.3}$$

$$2\,H_2O \longrightarrow 2\,H_2 + O_2 \tag{2.4}$$

The electrolyte used in the elektrolyser can either be a liquid, for example sodium sulphate, as well as a physical membrane. Electrolysers are therefore differentiated by the electrolyte materials used and the temperature under which they operate. The most common electrolysis methods are shown in table 2.5.

	AE	PEM	AEM	SOE
Full name	Alkaline Electrolysis	Proton Exchange Membrane Electrolysis	Anion Exchange Membrane Electrolysis	Solid Oxide Electrolysis
Electrolyte	Potassiumhydroxid	Solid state membrane	Polymer membrane	Oxide ceramic
Electrode material	Nickel	Noble metals	Nickel	Yttria-stabilized zirconia
Temperature	60 - 80 °C	60 - 80 °C	60 - 80 °C	700- 900 °C
Pressure	Ambient	Up to 85 bar	Ambient	1 - 10 bar
Efficiency	65 - 82 %	65 - 78 %	N/A	85 % (lab)
System costs	1,000 - 1,200 €/kW	1,900 – 2,300 €/kW	N/A	N/A
Maturity level	Commercial	Demonstration	Demonstration	R&D

Table 2.5: Available electrolyzers and their main characteristics, based on [3] and [10]

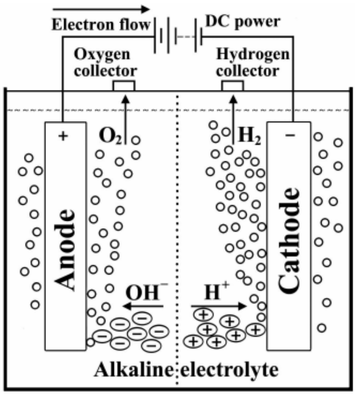


Figure 2.1: Schematic overview of electrolysis

Low-temperature electrolysers are currently available on the market, and AE is the clear market leader, accounting for most of the installed capacity worldwide. PEM electrolysis has been commercially available since the beginning of the 21st century and is still in demonstration phase. SOE and AEM have only just appeared on the market and have to prove to be reliable, scalable and profitable ways of producing hydrogen. The increasing need for clean energy carriers and power storage during peak hours of renewable energy have led to an acceleration with regards to electrolysis techniques. The economic attractiveness of hydrogen production by electrolysis is very much dependent on electricity prices. At today's energy prices, electrolysis is more expensive than steam reforming (Schiller 2012). Ultimately, producing hydrogen by electrolysis requires an inexpensive electricity supply, and in particular surplus renewable electricity.

In this report, an electrolysis efficiency of 75% will be used.

Besides being a fuel, hydrogen can also be a feedstock for other electrofuels. In this report it is assumed that all hydrogen used as a feedstock for the production of electrofuels is a product of electrolysis from renewable energy.

2.2.2. Hydrocarbon production

In this subsection, the production of methanol, ethanol, DME, methane and Fischer-Tropsch Diesel will be discussed. The secondary feedstock for these fuels are hydrogen and CO_2. Hydrogen is, as described before, produced by electrolysis. CO_2 is either captured from ambient air or captured from industrial processes.

The first step in producing hydrocarbon electrofuels is the production of syngas. Syngas is a gaseous mixture of hydrogen, carbon monoxide and carbon dioxide. Syngas can be used to produce multiple hydrocarbon electrofuels through various technologies and processes. In figure 2.2 all hydrocarbon electrofuels and corresponding processes within the scope of this report are displayed.

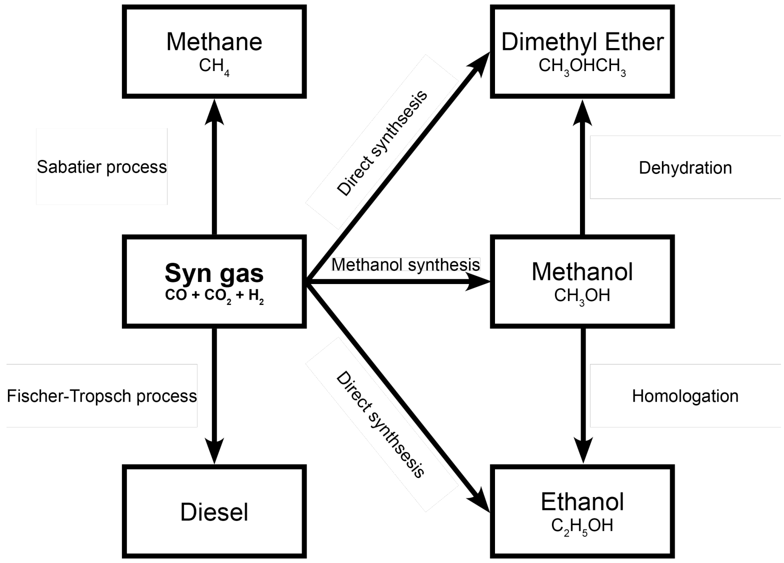


Figure 2.2: Diagram of syngas conversion processes covered in this report, own diagram based on [60]

Methanol
Methanol is the simplest alcohol with the chemical formula CH_3OH and can be produced according the following reactions:

$$CO + 2\,H_2 \longleftrightarrow CH_3OH \tag{2.5}$$

This reaction takes place at 5 to 10 MPa and 250 degrees Celcius and is promoted by the use of catalysts which are often a mixture of copper and zinc oxides supported on alumina. The process occures via the initial conversion of CO into CO_2, which is then hydrogenated.

$$CO_2 + 3\,H_2 \longleftrightarrow CH_3OH + H_2O \tag{2.6}$$

Subsequently, the H_2O is recycled via the water-gas shift reaction according to the following formula

$$CO + H_2O \longleftrightarrow CO_2 + H_2 \tag{2.7}$$

This results in the overall reaction, which is the same as listed above.

$$CO_2 + 3\,H_2 \longrightarrow CH_3OH + H_2O \tag{2.8}$$

The process is characterized by the high selectivity of the total reaction (>99.8%). Although thermodynamic considerations suggest operating at temperatures as low as possible, the process of methanol synthesis is carried out at about 200–300 °C because the catalyst is active only inside this temperature range. Thermodynamic equilibrium limitations and catalyst deactivation seriously affect methanol production. In particular, the decay in catalyst activity results in an unavoidable unsteady process of operation. A good catalyst should remain active for several years (up to 4) [12].

Methanol can be used as a fuel in an internal combustion engine or fuel cell but can also be used as a feedstock to produce ethanol or DME.

Ethanol
Ethanol is a simple alcohol with the chemical formula C_2H_5OH. Ethanol can be produced either directly from syngas or from methanol. When produced directly from syngas the following reaction applies:

$$2\,CO + 4\,H_2 \longrightarrow C_2H_5OH + H_2O \tag{2.9}$$

This reaction is thermodynamically favorable and highly exothermic and ideally occurs below 300 °C. The reaction is promoted by the use of Cobalt and Rhodium as catalysts. To date, this process has not been proven commercially attractive and reliable efficiencies and production data is not available.

Ethanol can also be produced via homologation of methanol according the following reaction:

$$CH_3OH + CO + 2\,H_2 \longrightarrow C_2H_5OH + H_2O \tag{2.10}$$

The reaction is supported by the use of copper and cobalt as catalyst.

At present, most ethanol is produced from either petrochemical feedstock or biomass. This results in limited data and literature available concerning the production of ethanol with hydrogen and CO_2 as a feedstock. Although from a thermodynamic point of view, calculations show high selectivity, no large-scale production facilities produce ethanol via this way. [20]

Dimethyl ether (DME)

Dimethyl ether or DME, is a the simplest ether and has the chemical formula of CH_3OCH_3. DME has an identical molecule formula to that of ethanol, however, the chemical structure is different, making DME an isomer of ethanol. Over the past two decades, DME has gained attention as a fuel [**?**]. DME can be produced by the dehydration of methanol. The following reaction applies:

$$2\,CH_3OH \longrightarrow C_2H_5OH + H_2O \tag{2.11}$$

In this process, methanol is dehydrated over a copper-based acid catalyst. Research shows that DME could also be produced directly from syngas through the use of copper, zinc or zirconium as catalyst, although thermodynamics are in favour of this one-step production of DME from syngas, this process is still in its development phase and no large production is available to date.

Methane

Methane gas is the simplest alkane and consist of 4 hydrogen atoms bonded to one carbon atom and can be writen as CH_4. Methane gas can be produced by applying the Sabatier reaction on syngas according the following formulas:

$$CO + 3\,H_2 \longrightarrow CH_4 + H_2O \tag{2.12}$$

$$CO_2 + 4\,H_2 \longrightarrow CH_4 + 2\,H_2O \tag{2.13}$$

Ideally, the process occurs at a temperature between 200 and 400 °C, a pressure between 4 and 12 bar and in presence of a nickel catalyst. Alternatively, ruthenium and alumina could improve the catalyst efficiency. The production of methane from renewable energy has a very low efficiency of well below 50%. This is partly due to the absence of an efficient catalyst. Also the investments in the "Power-to-Gas" production facilities have been very low since natural gas is still significantly cheaper and available in large quantities.

Fischer-Tropsch Diesel

Diesel produced through the Fischer-Tropsch process, also called FT Diesel is a mixture of several hydrocarbons within the range from $C_{10}H_{20}$ to $C_{15}H_{28}$. FT Diesel has been available since the 1920's and used on large scale during World War II and after that in South Africa. The Fischer-Tropsch process involves a series of chemical reactions that produce different types of hydrocarbons including diesel. The reaction can be approached as follows:

$$(2n+1)H_2 + nCO \longrightarrow C_nH_{2n+2} + nH_2O \tag{2.14}$$

The reaction takes place between 200 and 240 °C at 7 to 12 bar and with cobalt, iron or ruthenium as a catalyst. Although the Fischer-Tropsch process has a long history and has improved over the decades, it remains a rather inefficient production method. Total selectivity lies between the 15% and 40%.

2.2.3. Ammonia production

Ammonia is a hydride consisting of 3 hydrogen atoms and one nitrogen atom (NH_3). Ammonia can be produced through the Haber-Bosch process where H_2 reacts with N_2 under an elevated temperature of 450 °C and at high pressure of 100 bar according to the following reaction:

$$3\,H_2 + N_2 \longrightarrow 2\,NH_3 \tag{2.15}$$

Worldwide production of ammonia was 175 million tonnes in 2016 making it one of the most produced inorganic chemicals. Ammonia is mainly used for fertilising agricultural crops but is also used for the production of plastics. Most of the ammonia is produced through the Haber-Bosch process. However, natural gas is also often used as feedstock. In order to produce ammonia in a carbon-neutral manner, hydrogen from renewable energy has to be used. Nitrogen can be obtained by air separation. Atmospheric air consist out of 78% nitrogen making nitrogen widely available.

2.2.4. Sub-conclusion

In this section various electrofuels were discussed based on production methods of the fuels. Hydrogen is a fuel that can produced through electrolysis of water with renewable electric energy and water as feedstock. There are different types of electrolyzers available at this moment using different techniques. At the moment Solid Oxide Electrolysis (SOE) shows to be the most promising technology with a efficiency of 85%. However, since this technique is still in developing phase, assumed is that hydrogen production is done through PEM electrolysis. Hydrogen production has gained growing attention over the recent years which has resulted in an acceleration in available technologies and growing R&D budget. Multiple big companies like Shell, Equinor (former Statoil), Bosch and Toyota are interested in the production or the use of hydrogen. It is highly likely hydrogen will introduce itself at one point in the maritime industry.

Next to hydrogen several hydrocarbons were analysed in this chapter. Carbon-neutral hydrocarbons are made from hydrogen and captured carbon, with both processes using solely renewable electric energy. The first step is to make syngas which can later be transformed into methanol, ethanol, DME, methane or diesel. Although specific large-scale production data is not available, an estimation of production energy and efficiency can be made for the different types of fuels. In table 2.6 estimations are given.

Electrofuel	**Production efficiency** (η_{prod})
Hydrogen	75%
Ammonia	62%
Methanol	56%
Ethanol	50-60%
DME	50-60%
Methane	40-50%
FT Diesel	15-40%

Table 2.6: Production efficiency of selected electrofuels

The estimated efficiency is either based on literature or calculated by dividing lower heating value (LHV) of the fuel by the total sum of electricity used in the production process, as can be seen in formula 2.16. For all fuels except hydrogen this includes hydrogen production and nitrogen / carbon capture.

$$\eta_{prod} = \frac{\text{LHV}_{\text{fuel}}}{\text{Electricity}_{\text{production}}} \times 100\% \quad (2.16)$$

As can be seen in table 2.6, production efficiency of different electrofuels differ 15% (FT Diesel) to 75% (hydrogen). It should be noted that the efficiency of ethanol, DME and methane mostly rely on lab results and pilot projects found in literature.

From this subsection it can be concluded that the production of FT Diesel is too inefficient and energy consuming to be a potential fuel that can be used in large scale like in the maritime industry. Methane production is also characterised by a low production efficiency. Although, methane produced through renewable energy has shown improvement in production scale and efficiency over the last years it has unfavourable process characteristics as it is bounded to the Sabatier process which has a maximum selectivity of 80%. Ethanol, DME and Methane have a relative low production efficiency and proven large scale technologies are currently not available. Methanol , ethanol and DME production efficiency lie in the same range. For both DME and ethanol produced with electrical energy, no large scale production technologies have been proven. Although first results are promising, the TRL is still low. In literature, methanol shows more promising results than ethanol and DME.

Because of the reasons mentioned above, FT Diesel, methane, ethanol and DME will not be taken into consideration for the next phase of this research. In the next section (2.3), the properties of hydrogen, ammonia and methanol will be investigated.

2.3. Fuel options and properties

After selecting fuels based on feedstock (2.1) and production (2.2), in this section properties of the different fuels will be analysed.
In this section hydrogen, methanol and ammonia are compared based on the following properties:

- **Physical state:**, under Standard Ambient Temperature and Pressure (SATP, 298 K and 101.325 kPa) not all fuels have the same physical state. Per fuel the physical state is determined by what temperature phases change at and what the corresponding density is based on the boiling point and by critical point. The critical point is a temperature and pressure under which a gas can no longer be liquefied.
- **Energy content:** the energy content in a specific fuel is dependent on the density of the fuel and the Lower Heating Value (LHV), which is defined as the amount of energy or heat that is released in a theoretical complete combustion minus the heat of the vaporisation of water during combustion. When multiplying the LHV and density, the volumetric energy density can be determined, which is the amount of energy per unit of volume.
- **Flash point:** this is the lowest temperature at which vapours of the material will ignite, when given an ignition source. Fuels which have a flashpoint under 311 K are called flammable and fuels with a flashpoint above 311 K are called combustible.
- **Auto-ignition temperature:** this is the lowest temperature at which fuels spontaneously ignite under ASTP and without any source of combustion such as a flame or spark.
- **Explosive limits:** these apply to the combustible characteristics of fuels. The explosive limits are defined as the boundaries between which the fuel, in combination with air, will combust. The lower flammibility limit (LFL) is the lowest concentration of the fuel in air capable of producing a flash in the presence of an ignition source. The upper flammability limit (UFL) is the highest concentration of the fuel in air capable of producing a ignition in the presence of an ignition source. When a fuel is below LFL it is called "too lean", when concentration are above UFL it is called "too rich".
- **Safety:** in this section, fuels are assessed by the potential hazards they could cause. This is done based on the "Globally Harmonized System of Classification and Labelling of Chemicals" or GHS, which is an internationally agreed upon standard managed by the UN.

All chemical and physical data in this section is based on the GESTIS substance database [28] and the NSIT Chemistry WebBook of the National Institute of Standards and Technology of the United States of America [45] unless referred otherwise.

2.3.1. Hydrogen

Hydrogen is a compound which consist out of two hydrogen atoms and has the chemical formula of H_2. At standard temperature and pressure hydrogen is at a gaseous state. Hydrogen gas doesn't exist in large quantities in nature. However, in most cases hydrogen can be found in a chemically bonded form such as in water and natural gas. Hydrogen was used as a fuel for the first time in the first generation jet engines prior to World War II. Developments in hydrogen technologies continued in the 1960s and 1970 as a result of space travel and the oil price crises. In the last two decades, hydrogen has gained momentum as a carbon-free alternative energy carrier in the energy transition.

Name	**Hydrogen**
Chemical formula	H_2
Chemical structure	H — H
Physical state at SATP	Gas
Boiling point [K]	20
Critical point	33 Kelvin, 13 bar
Density [tonnes / m^3]	8.99×10^{-5}
Lower Heating Value (LHV) [kJ / tonnes]	120.21
Flash point [K]	-
Auto-ignition temperature [K]	833
Lower Explosive Limit	4.0%
Upper Explosive Limit	77.0%

Table 2.7: Physical and thermo-physical properties of hydrogen

At ambient pressure and room temperature hydrogen is a gas. Hydrogen has an extremely low boiling point of 20 Kelvin. The critical temperature of hydrogen is 33 Kelvin, meaning hydrogen can no longer be liquefied once the temperature is above 33 Kelvin. The critical pressure is 13.1 bar, meaning hydrogen can no longer be liquefied when the gas exceeds this pressure. This can be seen in figure 2.3.

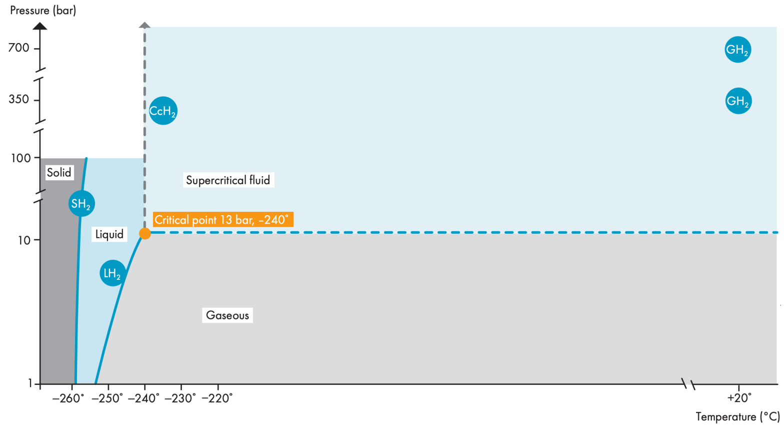


Figure 2.3: Phase diagram of hydrogen [3]

Hydrogen has a lower heating value of 120.21 MJ / kg which is the highest of all fuels analysed in this report. However, since the density of hydrogen is relatively low volumetric energy content is very low. At STAP, hydrogen has a density of 8×10^{-5} tonnes / m^3. So in order to use hydrogen as a fuel and to store it in an efficient way it has to be either compressed or liquefied. When compressed at 298 Kelvin and 700 bar the density of hydrogen is 39 kg / m^3 resulting in a volumetric energy content of 4.72 MJ / L. In Figure 2.4 the density and volumetric energy content of hydrogen can be found at different pressures. When hydrogen is cooled below 20 Kelvin it liquefies. Liquefied hydrogen has a density of 71 kg / m^3 resulting in a volumetric energy content of 8.51 MJ / L.

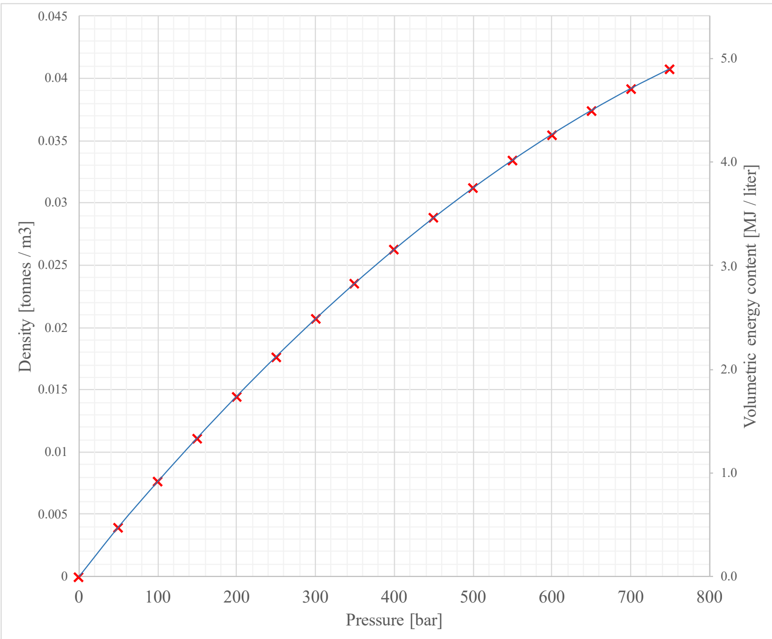


Figure 2.4: The density and volumetric energy content of hydrogen versus the pressure

Hydrogen is an extremely flammable gas. The storage and usage of hydrogen on board of a ship should thus be done with great caution. When liquefied, hydrogen can cause severe damage and burns to the body. Hydrogen has the GHS labels GHS01 (flammable) and GHS04 (compressed gas) where the latter means the gas is either compressed or liquefied and therefore can explode if heated and can cause cryogenic burns or injuries.

2.3.2. Methanol

Methanol, also known as methyl alcohol, is the simplest alcohol. Methanol consists out of a methyl group linked to a hydroxyl group and has the chemical formula of $CH_{30}H$. Methanol has been used as a fuel since the 17th century when it was first used to burn stoves. Methanol is a basic component for hundreds of essential chemical products such as plastic and paint.

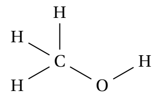
Name	Methanol
Chemical formula	CH_3OH
Chemical structure	
Physical state at SATP	Liquid
Density at SATP [kg / m^3]	682
Boiling Point [K]	338
Critical point	513 K, 80 bar
Lower Heating Value (LHV) [MJ / kg]	19.9
Flash point [K]	282
Auto-ignition temperature [K]	713
Lower Explosive Limit	6.0%
Upper Explosive Limit	36.0%

Table 2.8: Physical and thermo-physical properties of methanol

Methanol's physical and chemical properties are favourable when looking at the possibilities of being an alternative fuel. It has a boiling point of 338 Kelvin meaning it behaves like a liquid fuel and can be stored in standard fuel tanks for liquid fuels. The lower heating value and volumetric energy content of methanol are respectively 19.55 kJ/tonnes and 15.46 kJ/m^3, meaning methanol has half the energy content per volume and per mass compared to conventional Diesel. The ignition range of methanol lies between 6.0% and 36.0%. The high auto-ignition temperature or 713 Kelvin makes methanol suitable for spark-ignition engines as well as compression-ignition engines [70].

Methanol has multiple hazards which should be taken into account when using methanol as a fuel. More specifically, it is a highly toxic chemical and even small amounts can cause blindness and damage to liver, kidney and heart and can have an affect on the human central nervous system of the human. In addition, methanol has a flash point of 282 Kelvin making methanol a highly flammable fuel, meaning that extra attention is required in order to guarantee safe usage on board. Methanol has GHS labels GHS02 (flammable), GHS06 (toxic) and GHS08 (health hazard).

2.3.3. Ammonia

Ammonia is a compound of nitrogen and hydrogen with the formula NH_3. Ammonia is the simplest pnictogen hydride, which are binary compounds of hydrogen with pnictogen atoms (nitrogen, phosphorus, arsenic, antimony and bismuth). Ammonia is the only pnictogen hydride that has the chemical and physical characteristics to be considered as an alternative fuel. It is a compound that can be found in nature in very small quantities. The majority of ammonia is industrially produced by mankind. From the 19th century onward, ammonia has been experimentally used as fuel for combustion engines and in recent years, it has been tested successfully as a fuel cell in multiple experiments. However, ammonia only gained traction as a fuel in the last few years.

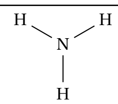
Name	Ammonia
Chemical formula	NH_3
Chemical structure	
Physical state at SATP	Gas
Density at SATP [kg / m^3]	0.792
Boiling Point [K]	240
Critical point	405 Kelvin, 11.3 bar
Lower Heating Value (LHV) [MJ / kg]	18.60
Flash point [K]	405
Auto-ignition temperature [K]	903
Lower Explosive Limit	15.4%
Upper Explosive Limit	28.0%

Table 2.9: Physical and thermo-physical properties of Ammonia

At SATP, ammonia is a gas. With a boiling temperature of 240 Kelvin, ammonia is easy to liquefy or cool and transport. The density of liquid ammonia is 0.72 tonnes per m^3 and the corresponding lower heating value and volumetric energy content of DME are 18.60 kJ/tonnes and 13.34 kJ/m^3 respectively which is approximately twice as low as conventional diesel. Ammonia has a relative high auto-ignition temperature of 903 Kelvin.

Ammonia has GHS labels GHS05 (corrosive), GHS06 (toxic) and GHS09 (environmental hazard). In small concentrations it is not toxic to humans. However, large concentrations of gaseous ammonia can result in lung damage and death. Ammonia is highly corrosive which should be taken into account in the next phase of this research. Additionally, when using ammonia in a combustion engine, NO_x can be formed, which is a greenhouse gas.

2.3.4. Sub-conclusion

In this section, three different types of fuel were analysed. Based on the properties of the fuels the following conclusions can be drawn.

When looking at boiling temperatures, critical points and density of the different fuels it can be concluded that both hydrogen and ammonia have to be kept under lower temperatures and pressures to become liquid. Methanol is the only fuel that is already in liquid phase under SATP. When looking from an energy density perspective it will always be favourable to store fuel on board with the highest density possible. For ammonia this will require a relatively small decrease in temperature. For hydrogen it will require a decrease in temperature to 20 Kelvin. Although this will require a complex cooling system consuming extra energy it is a proven technology which is available.

The energy content of fuels differ significantly. Both ammonia and methanol have lower heating values around 20 MJ/kg. Hydrogen on the other hand has a considerably large lower heating value of 120 MJ/kg. However, due to the very low density of hydrogen, the volumetric energy content of hydrogen is very low. In figure 2.5 the area required for the same amount of energy normalised to MGO is illustrated.

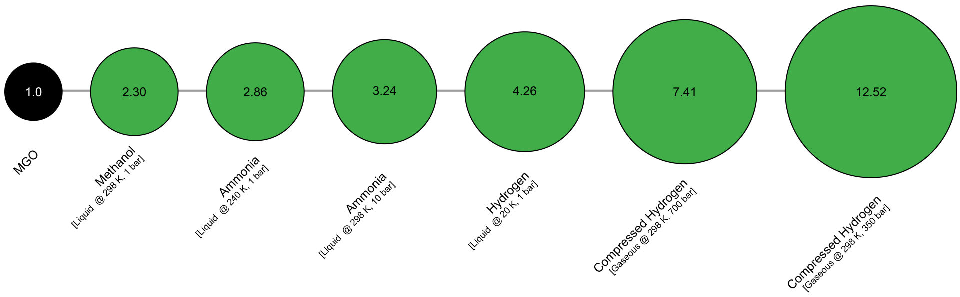


Figure 2.5: Volumetric energy content normalised for MGO

As can be seen, methanol requires 2.6 times the space MGO needs. Ammonia kept under 240 Kelvin requires 3.2 times more space than MGO due to the lower LHV compared to methanol. When looking at hydrogen, the pressure and temperature under which hydrogen is stored has a big influence on the required space. When cooled to 20 Kelvin and thus in liquid phase, hydrogen requires 4.8 times the space MGO needs. When looking at compressed hydrogen, factors increase significantly to factor 8.7 when compressed to 700 bar and a factor 14.6 when compressed to 350 bar. Due to these high factors, implications on ship design will be too large. It is for this reason that only liquid hydrogen will be considered as a potential alternative fuel in this report. Note that this data and figure 2.5 is based only on the thermophysical data and not on the space needed for implementation of the fuel on the ship such as tank insolation, coolers or conversion machinery such as fuel cells or combustion engines which will be further discussed in Chapter 3.

When analysing explosive characteristics it can be concluded that all fuels analysed in this section have favourable explosive characteristics compared to MGO. Ammonia has a relatively high auto-ignition and flash point, which can be challenging when looking at the fuel from a combustion engine design perspective. Despite the fact that explosive limits are smaller compared to methanol and hydrogen, ammonia still has a wider explosive range than MGO. It should be noted that literature on ammonia as an combustible fuel is limited and feasibility still has to be proven. Methanol has the lowest flashpoint, this means extra care has to be taken when using methanol on board of ships. In figure 2.6 all ignition ranges are displayed.

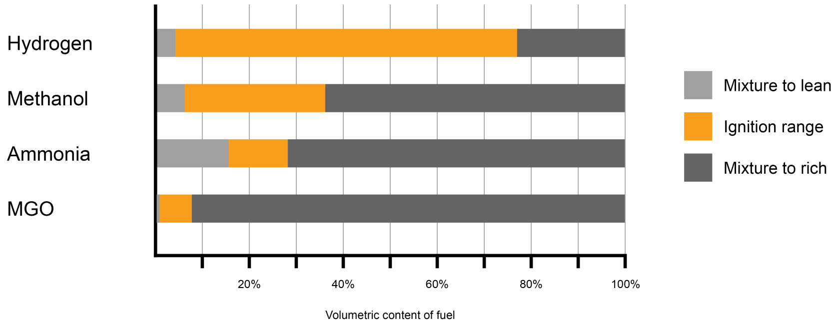


Figure 2.6: The ignition range of selected alternative fuels

When taking safety of the fuel storage and usage into account the following can be concluded. Methanol is the fuel that has the most impact on the human body and should be handled with care. Ammonia has a high corrosive effect, meaning the effect on the storage and machinery installed to use ammonia should be chosen carefully. As determined, hydrogen will only be assessed when in liquid phase, so called cryogenic hydrogen. Cryogenic material should always be handled with care. Cryogenic hydrogen has been used in several industries for decades and a lot of experience can be found in, for example the aerospace industry. Although all fuels have multiple safety risks and hazards, all the risks and hazard can be minimised by using the right equipment and following certain guidelines.

Based on the properties of the different materials, hydrogen, ammonia and methanol are all selected to be taken into the next phase of this research. All three fuels are considered most feasible when in liquid state due to the high volumetric energy density. This means that hydrogen is stored at 20 Kand 1 bar, ammonia at 240 K and 1 bar and methanol at SATP. Liquefied hydrogen will be written as LH_2, ammonia as NH_3 and methanol as MeOH.

2.4. Price of selected alternative fuels

Since the commodity market for electrofuels is not yet as established as for other chemicals and fuels, price prediction has to be made based on estimations of the price of the price of renewable energy, the efficiency of the production process of the fuel and the price of the feedstock materials needed to produce the fuels.

As defined earlier the price of renewable energy is estimated at 90$ / MWh in 2020 and the projected price of renewable energy in 2050 is 40$ / MWh.

For all fuels, hydrogen is required and thus the electrolysis process will be an important factor for the total fuel production efficiency and consequently the production price of a fuel. Secondary feedstock for methanol will be CO2 which has to be captured from air and N_2 for the production of ammonia which also can be captured from air.

The estimation made in this research are based on the following prices and assumptions:

Year	2020	2050
Electricity price	90 $ / MWh	40 $ /MWh
Electrolysis efficiency	60%	80%
Methanol synthesis efficiency	99.8%	99.8%
Haber-Bosch efficiency	95%	99%
CO2 capture	40 $ / tn	10 $ / tn
N2 Capture	8% of energy consumption production	8% of energy consumption production
Liquefaction NH3 efficiency	99%	99%
Liquefaction H2 efficiency	90%	90%
Distribution prices	4 $ / MWh	2 $ / MWh
Capital and O&M costs	10 $ / MWh	2 $ / MWh

Table 2.10: Feedstock prices and production assumptions of selected alternative fuels

This concludes into the following price estimations:

	Liquid Hydrogen (LH2)	Methanol (MeOH)	Ammonia (NH3)
Price estimations 2020	200 $ / MWh	225 $ / MWh	225 $ / MW
Projected price 2050	80 $ / MWh	90 $ / MWh	90 $ / MWh

Table 2.11: Price estimations of selected alternative fuels

Prices estimated in this research are within the range of price estimation found in various literature studies on the prices of alternative fuels like Brynolf [13], Lyubovsky [36], Valera-Media [67] and Verhelst [70].

In this research the prices of production for 2020 will be used to make the OPEX analysis in Chapter 5.

2.5. Conclusion and selection of fuels

In this chapter different types of alternative fuels for the maritime industry were analysed. When looking at feedstock, carbon-neutral fuels can either be produced from biomass, called biofuels, or renewable electric energy, called electrofuels. Limited availability for big scale use and immature technologies concerning second generation biofuels make biofuels an unsuitable replacement for conventional fuels. However, it should be noted that biofuels can play a big role as carbon-neutral fuel for the transition period between 2020 and 2030 when carbon-neutral fuels are introduced in the martime industry.

Electrofuels that were considered have been categorized into hydrogen, hydrocarbons and ammonia. The production of these fuels are not all the same. Fischer-Tropsch diesel and methane show very low production efficiencies which has a negative effect on the overall efficiency. DME and ethanol both show moderate production efficincies between 50% and 60%. However, these results are based on calculations and small scale production pilots. It is therefore that only hydrogen, ammonia and methanol will be considered as possible alternative fuels.

Hydrogen has a high lower heating value, however, the low density of hydrogen results in a low volumetric energy content. When liquefied, hydrogen has the highest energy content and thus is the most feasible phase for storage on board of a ship. Ammonia is kept under a relatively small lowered temperature of 240 Kelvin.

The goal of this chapter was to select viable carbon-neutral alternative fuels that can be considered for the propulsion and power systems on board of a cruise vessel. The sub-objective as determined in Chapter 1.2 was as follows:

i *"Identify and evaluate different types of carbon-neutral energy sources and carriers and select the most feasible"*

This chapter showed that the following carbon-neutral alternative fuels are most feasible to use:

- Hydrogen
- Ammonia
- Methanol

In table 2.12 the three selected fuels and corresponding properties can be found. In the remainder of this research the properties and physical states as shown in the table will be used unless mentioned otherwise.

	Liquefied Hydrogen	Ammonia	Methanol
Energy carrier	LH_2	NH_3	CH_3OH
Temperature [Kelvin]	20	240	298
Pressure [bar]	1.0	1.0	1.0
Physical state	Cryogenic liquid	Liquid	Liquid
Feedstock	RE, water	RE, Hydrogen, CO2	RE, Hydrogen, N2
Production	Electrolysis	Haber-Bosch process	Methanol Synthesis
Density [kg / m3]	70.9	792.0	682.3
Boiling point [Kelvin]	20.0	240.0	338.0
LHV [MJ / kg]	120.1	18.6	19.9
Volumetric energy content [MJ / m3]	8515.1	14731.2	13577.8
Flash point [Kelvin]	-	405	282
Auto-ignition point [Kelvin]	833	903	713
Explosive range	4 - 77 %	15.4 - 28 %	6 - 36 %
Toxic	No	No	Yes
Hazards	GHS02: Flammable GHS04: Compressed gas	GHS05: Corrosive GHS06: Toxic GHS09: Environmental hazard	GHS05: Flammable GHS06: Toxic GHS08: Health hazard

Table 2.12: Selected alternative fuels and corresponding properties

3

Impact on ship design and operation of selected alternative fuels

In order to determine which of the selected alternative fuels can best be used on board a cruise vessel several aspects have to be taken into consideration. In this chapter, the implementation of alternative fuels on board of a cruise vessel will be discussed. Moreover, section 3.1 will focus on the storage of selected alternative fuels. In section 3.2 power conversion and propulsion systems possibilities will be explained. Next, in section 3.3 the costs of the implementation and the use of alternative fuels on board of the ship will be reviewed. In section 3.4 conclusions are drawn and a clear overview regarding the selected systems, subsystems and assumptions is given, which will be used together with data from the design impact analysis in chapter 4 to make the design of a carbon-neutral cruise vessel in Chapter 5.

3.1. Storage of selected alternative fuels

Alternative fuels selected in the previous chapter are not all in liquid state at standard ambient temperature and pressure (SATP). However, as it is favourable to store the fuels in liquid form, as this is often the most energy dense way to store and transport fuels, several aspects have to be taken into account when storage tanks are selected.

3.1.1. Cryogenic storage of liquid hydrogen

Of all selected fuels, liquid hydrogen is the most challenging fuel to store due to its extremely low boiling temperature of 20 Kelvin (-253 °C). Cryogenic storage of hydrogen can only be achieved in tanks where the temperature can be kept below 20 Kelvin and the pressure between 1 and 10 MPa. This means several design aspects have to be taken into account.

The challenges of storing liquid hydrogen are not new phenomena. In the aerospace industry liquid hydrogen has been used for rocket propulsion for decades and thus these challenges have been encountered before. A big difference with the use of liquid hydrogen as a rocket fuel, however, is the discharge time, which is considerably less for a rocket that uses the largest part of its fuel during take-off than it is for a cruise vessel. However, this does not change the geometry, thermo-physical or structural design parameters of the storage requirements for liquid hydrogen on board a cruise vessel.

More specifically, in order to keep hydrogen in liquid state the tank has to be outfitted with insulated walls. Insulation of the tank is done by installing a double tank wall with multiple layers of insulation material and a vacuum space between both walls. This tank-design prevents heat transfer to a certain level but is not able to prevent hydrogen from heating up and evaporating. This evaporation is known as the boil-off rate of the tank and can be used to fuel the prime mover. When the boil-off rate exceeds the specific fuel consumption, the gaseous hydrogen has to be captured and refrigerated and can then be returned to the tank. Insulation layers are available and researched in various forms and materials. Depending on price and volume available many possibilities can be implemented. Since hydrogen is much lighter in mass than conventional MDO, there are no weight restrictions to be considered in this research as the mass of insulation will not exceed the difference in the mass of the MDO. The many possibilities in the type of insulation and the materials used in the tank make it hard to predict what the thickness of the insulation will be compared to that of the total volume. After numerous discussions and interviews with cryogenic tank suppliers it has become clear that an increase of 20% of the radius would be a fair assumption to make regarding the thickness of the tank. One important aspect to take into consideration in the design of a liquid hydrogen propulsion system is to make the tank as large as possible as the loss of useful space will be larger when multiple tanks are installed.

Due to the vacuum space between tank walls and the extremely low temperature within the tank there are limited geometric shapes possible. Only spherical, cylindrical, ellipsoid or a combination of these forms are able to be designed in such a way that stress and temperature, which will result in deformation of the tank, are distributed evenly over the tank wall. Due to the limited height available to use within the ship, which is often limited by one or two times the deck height, a spherical tank will never satisfy the volume requirements. Ellipsoid storage tanks have rarely been used in practice until this date and are unlikely to be cheaper and easier to construct than cylindrical tanks. For this reason, cylindrical shaped tanks will be the only storage tank of LH_2 considered in this research.

When selecting materials for storage and piping equipment extra attention is required. The low temperature conditions will make the material of the tank wall brittle, for example. However, a strong stainless steel of higher quality will satisfy the requirements and endure the conditions. Moreover, the material will deform when temperature changes. This means that the tank will inevitably deform when all liquid hydrogen is out of the tank and consequently temperature rises. This results in an undesirable deformation and stress in the tank. Although this effect is known, a solution has yet to be found. Studies and companies claim different rates of liquid hydrogen that should be constant in the tank to maintain the temperature. Rates vary from 10% to 30% of the total tank volume. In this report 25% of the total volume will be used as the volume that has to be present at a constant rate in the tank.

When exiting the tank, LH_2 has to be heated up significantly in order to be used in a fuel cell or combustion engine. Here lies a possible advantage since the energy used in this process can be used as a refrigerator for the air conditioning system, which is known to be a large energy consumer on board of a cruise vessel as discussed in the next chapter.

3.1.2. Cooled storage of liquid ammonia

When it comes to the storage of liquid ammonia a lot of literature is available. Ammonia is widely used within the chemical industry and is already transported on a large scale in tanks. To keep ammonia in a liquid state, a temperature of 240 Kelvin is required. The temperature requirement means insulation and a double walled tank have to be installed.

Another challenge will be the selection of materials for the tank wall. Ammonia in a pure liquid state will have a corrosive effect on many materials due to its high acidity constant and low pH value. This means only stainless steel can be used in the storage and piping of ammonia. Additionally, the low temperature conditions within the tank will cause deformation of the inner tank walls. The deformation will be smaller compared to liquid hydrogen, making it possible to completely empty the tank although it will be more time efficient to keep the tank at a constant temperature when considering bunkering time. The boil-off will be used as the fuel flow and when the boil-off rate exceeds the specific fuel consumption, the gaseous ammonia has to be captured and refrigerated and can then be returned to the tank.

It is evident that, considering the double wall tank, insulation and temperature requirements, a cylindrical tank would be the most efficient storage method. Moreover,it would result in a minimal thermal loss. Just like liquid hydrogen, ammonia has to be heated up in order to be used in a combustion engine or fuel cell. The energy used to heat up the fuel can be recovered and used for cooling i.e. cooled storage and air-conditioning.

In this research, a wall thickness of 5% of the radius is assumed. In order to prevent the power system from running dry and keep a small amount for high emergency cases, it is assumed 5% of the total volume of the tank remains filled with ammonia.

3.1.3. Storage of methanol

Of all selected alternative fuels, methanol will be the least challenging to implement in terms of storage. Methanol is in liquid state at SATP, meaning that tanks do not have to be insulated nor do they have to be cooled. This also means that it is a more flexible fuel when considering location of storage. No losses of volume will occur when tanks are divided around the ship design. The only limitation of methanol storage is the dimensions of the watertight section in which a methanol tank is situated. Due to the corrosive nature of methanol, extra attention has to be paid when selecting the tank wall material. Methanol tanks can be constructed of either carbon steel or stainless steel. Carbon steel has the advantage of lower capital cost, but the disadvantage of higher life cycle cost due to increased maintenance and costs associated with corrosion protection [39].

In order to prevent the power system from running dry and keep a small amount for high emergency cases, it is assumed 5% of the total volume of the tank remains filled with methanol.

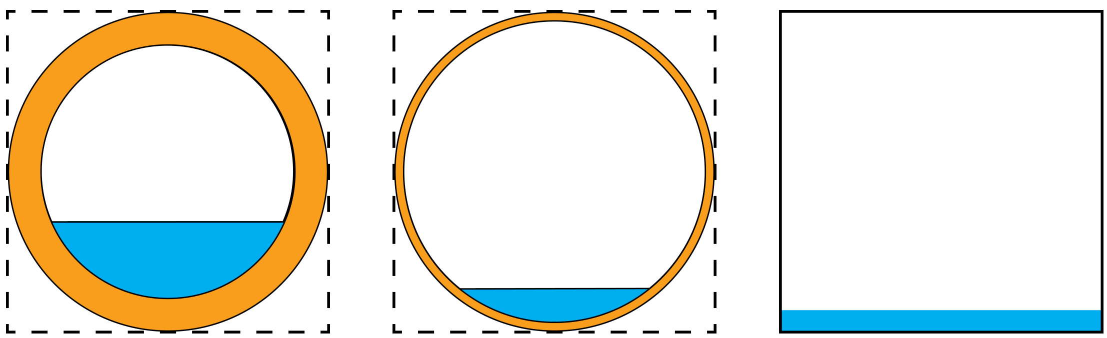
3.1.4. Sub-conclusion

The storage of the selected alternative fuels will come with a volume expansion in comparison to conventional MDO. From this section it can be concluded that liquid hydrogen will be the most challenging fuel to store due to its cryogenic conditions. An overview of the storage parameters used in the next chapter can be found in the following table:

	Liquid hydrogen (LH_2)	**Liquid ammonia (NH_3)**	**Methanol**
Temperature	20 Kelvin	240 Kelvin	293 Kelvin
Pressure	1-3 bar	1-3 bar	1 bar
Boil-off	Yes	Yes	No
Secondary machinery	Compressors Coolers Heaters	Compressors Coolers Heaters	-
Shape	Cylindrical	Cylindrical	-
Max length	Compartment length	Compartment length	Compartment length
Max height	Deck height	Deck height	Deck height
Material	Stainless steel	Stainless steel	Stainless steel
Kind insulation	Double wall vacuum	Double wall insulated	Single wall
Thickness insulation	20% radius	5% radius	neglectable
Minimum fill	25% volume	5% volume	5% volume

Table 3.1: Overview of storage tanks for selected fuels

The storage challenge becomes more visible in the following figure where the schematic overview of the cross section of the selected tanks are given. For liquid hydrogen, only 38% of the volume can be used for storage, for ammonia this is 67% and methanol has the most favourable tank design with 95% useful volume. Here it is assumed that the space between the cylinder and the box around it (diameter of the tank) can not effectively be used.



(a) Hydrogen (b) Ammonia (c) Methanol

Figure 3.1: Cross section of selected storage tanks

3.2. Power Conversion

The next subsystem is the energy conversion system. Here, chemical energy from a fuel is converted into useful energy for energy consumers on board of the ship. The energy conversion system consists out of 3 parts as schematically described in the following figure:

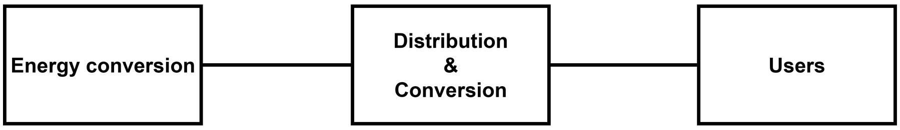


Figure 3.2: Schematic overview of a main components of a energy conversion system [72]

The *energy conversion* is the system where energy from the fuel is transformed into energy which can be used on a ship. This energy is transferred through *distribution and transmission* systems to the *users* of the energy on board of the ship.

The energy conversion system (first block in figure) on board of a ship is the system where chemical energy is converted into energy that can be used on board of the ship. In most literature, this is called the *prime mover*. In this thesis, the term *prime mover* is used to describe the system on board of a ship that converts chemical energy from a fuel into useful energy on board of a ship.

The energy of prime movers are rated in kilowatt ([kW]) and the size of prime movers in ([m^3/kW]). The efficiency of a prime mover is described with η_E. The prime mover efficiency is described as the ratio of prime mover power (P_B) and the heat input from the selected fuel ($\dot{Q}_F$):

$$\eta_E = \frac{P_B}{\dot{Q}_F} \tag{3.1}$$

The P_B installed generally depends on the operation of the vessel and the speed at which it is sailing, the heat input $\dot{Q}_F$ depends on the mass flow of the fuel and the heating value of the selected fuel. Consequently, the efficiency of the prime mover will differ over the range of operations and speed the ship is sailing due to the varying load and prime mover output. The prime mover efficiencies used in this research are assumed to be constant over the range of operations. So called 'part-load' conditions do not have effect on the efficiency of the prime mover. The efficiency of the total power system is explained in Chapter 4 and the efficiency of selected prime movers and fuels can be found in Chapter 5

Energy from the prime mover has to be transmitted to the users of the ship. This can either be through mechanical energy of electric energy. When energy is transferred to for example a propulsor, mechanical energy by means of a rotating shaft can be used to drive the propeller. On the other hand, when the user is for example the air conditioning system, electric energy is required. As mentioned earlier is the energy consumption on board of a cruise vessel very variable. When looking at the end users on board of a cruise vessel a majority requires electric energy. One of the main users of energy, the propulsion system, is required to be flexible and has to operate efficiently in all conditions. Moreover, the large variety of passenger services such as restaurants, entertainment facilities and hotelling services require a high amount of electric energy. For these reasons, diesel-electric propulsion systems have been installed on a majority of the cruise vessels active at present day.

The propulsor is one of the main energy users on board of the vessel. When selecting propulsors, important requirements are the sound and vibration levels of the system, the manoeuvrability and the space the propulsor requires. Considering these requirements, podded propulsors are the most optimal solution compared to other propulsors. This is also what can be seen in existing cruise vessels within the scope of this research, explained in Chapter 4. It is for this reason that in this report, only podded propulsors will be considered in the total propulsion system.

This automatically means that transmission of energy from prime mover to propulsor requires the energy to be electric and the prime mover to generate electricity. In this report the power conversion systems of selected alternative fuels will be compared to a power system where MDO is used as a fuel in an internal combustion engine which drives a generator. Electric energy is used to transfer energy from prime mover (ICE + generator) to energy users. Among which is the propulsion system.

As determined in the previous section, the prime mover has to generate electricity. It is therefore that only a combustion engine combined with a generator or a fuel cell will be considered as prime movers in this research.

3.2.1. Internal combustion engine (ICE) with generator

Combustion engines in combination with a generator have been known in the maritime industry for several decades both as auxiliary engines and as prime movers, for example, for podded propulsors and other electrical propulsion engines. The principle of this type of engine is that the output shaft drives a multi-poled magnet into a coil which generates electricity. This electricity can subsequently be transformed by means of a frequency drive and switch board to the end users. This process is further explained in the subsection 3.2.3 where secondary machinery of the propulsion system is covered.

H_2 in ICE

The combustion process of hydrogen can be written in the following formula:

$$\text{Combustion reaction: } 2H_2 + O_2 \longrightarrow 2H_2O \tag{3.2}$$

However, since air is used in the engine that will contain nitrogen, NO_x, a harmful emission, will be formed under the high temperatures in the engine. This means that the exhaust gas has to be conducted to an exhaust gas treatment in order to scrub out the NO_x. Scrubbing NO_x is done through the use of a selective catalytic reduction system (SCR), this is further explained in Chapter 5

The favourable combustion characteristics of hydrogen make hydrogen an interesting combustion fuel. The wide ignition range of hydrogen lies between 4% and 77% of the volume. This means that hydrogen is able to be used in a combustion engine running on extremely lean air/hydrogen mixtures. This makes it easy to start a hydrogen fuel combustion engine. Lean combustion is more efficient and minimises fuel consumption. However, this comes at the cost of a reduction in power of the engine. Since the volumetric energy density of hydrogen is already very low, this will only enlarge the volume challenge hydrogen has.

The auto ignition temperature of hydrogen is 833 Kelvin, which is higher than most other fuels. The auto ignition energy is 0.02 MJ, which is very low. This means extra caution has to be paid to misfiring and wrong timing, especially since the fuel will ignite at a very lean mixture. It is therefore that hydrogen combustion engines run most reliably and efficiently when an ignition source is used in the engine. This ignition source should ideally be a spark since it is easy to time.

The flame velocity of hydrogen is around 3.5 m/s, which is very high. This is very favourable in a combustion engine where ideally all fuel in the cylinder burns at the same time. This means that maximum pressure is created when the piston is in a high position at the ignition. The piston is therefore exposed to the pressure created with the ignition in a small time step, pushing the piston down with more power. The drawback is that this only occurs when hydrogen is added in the engine at a rich mixture. Since this will increase fuel consumption, a trade-off between fuel consumption and power will occur results in a prime mover efficiency in the range of 15% to 40% [69] [17] [61].

Overall the uncertainty of the efficiency under which the engine will operate is a major drawback when considering an internal combustion engine fuelled by hydrogen. Since hydrogen already takes up most volume per energy unit, it is not favourable that due to its low efficiency even more volume has to be brought on board of the vessel.

NH_3 in ICE

Although scientific research is plentiful, limited results have been shown. No internal combustion engines are available yet and fuel cell technology is not yet at the level where pure ammonia can be used as a fuel. The main advantage of ammonia is the lack of carbon atoms, which results in a carbon free emission. Disadvantages are within the thermo-chemical properties of ammonia as can be found in the previous chapter

Due to the high ignition energy characteristics of ammonia, it is impossible to use solely ammonia as a fuel in an internal combustion engine. This means an additive fuel has to be mixed with ammonia to burn it in a combustion engine. Since carbon-neutral operations are required in this research, this has to be either hydrogen or e-methanol. No research has been found on the development or operation of ammonia-methanol. For this reason only ammonia hydrogen mixtures will be considered in this research.

The high auto-ignition temperature, narrow explosive limits and high latent heat of vaporisation limit the use of ammonia in a combustion ignition engine. The use of ammonia in a spark ignited engine is limited by incomplete combustion as a result of the low flame speed and the explosive limits. The low flame speed of ammonia makes it a more suitable fuel for low-speed engines. Which is not favourable for a generator.

At this moment, several engine manufacturers are researching ammonia fuelled combustion engines. Until current day this is limited to two-stroke spark ignition engines. The used volume ratio is 70% ammonia and 30% hydrogen. Estimated efficiency of this engine lies within the range of 30% to 50%. In this concept the waste heat of the engine is used in the cracker where ammonia is cracked and the hydrogen produced in the cracker is used as additive fuel.

One disadvantage of using ammonia in an combustion engine is the emission of NO_x. This is partly due to the standard reaction where nitrogen and oxygen from the intake air will form NO_x under the high temperature conditions in the engine. The other reason is so called ammonia-slip. This is the unburned ammonia in the engine which is emitted in the air.

Overall it can be concluded that the use of ammonia in a combustion engine will be challenging and ammonia has not yet proven itself as a feasible fuel for combustion engines.

MeOH in ICE

Of the selected alternative fuels, methanol has the most favourable thermo-physical properties when looking at combustion. The wide explosive range, the low auto-ignition point and low flash point make methanol an easy to use fuel in a combustion engine.

Methanol can be used in both spark ignited (SI) engines as well as in compression ignition (CI) engines. In terms of efficiency, SI engines have favourable characteristics with an efficiency in the range of 30% to 50%. In addition, CI engines are still in a developing phase and reliable data of CI engines running solely on methanol has not yet been found.

Just like any other fuel that is burned at high temperature in a combustion engine, NO_x will form and will be emitted. It is therefore that an exhaust gas cleaner (scrubber) has to be installed in order to guarantee NO_x-free operations.

3.2.2. Fuel cell

Fuel cells are a relatively new technology in the maritime industry and have until current day not been used apart from during pilot projects and as prototypes. A fuel cell works on the principle of an electrochemical reaction where chemical energy in the form of a fuel is converted into electric energy. The electrochemical reaction can be subdivided in multiple reactions where on one side of the fuel cell (anode) electrons are removed from a compound and on the other side of the fuel cell (cathode) electrons are added to a compound. Between the anode and the cathode, an electrolyte is placed which only lets ions through. The remaining electrons want to flow from the anode to the cathode. When connecting the anode and the cathode this results in an electrical energy flow. This process can be seen in figure 3.3 where a schematic overview of a fuel cell is given. Consequently, corresponding formulas (3.3,3.4,3.5), are given when pure hydrogen is used as a fuel.

$$\text{Anode reaction: } 2H_2 \longrightarrow 4H^+ + 4e^- \tag{3.3}$$

$$\text{Cathode reaction: } O_2 + 4H^+ + 4e^- \longrightarrow 2H_2O \tag{3.4}$$

$$\text{Overall reaction: } 2H_2 + O_2 \longrightarrow 2H_2O \tag{3.5}$$

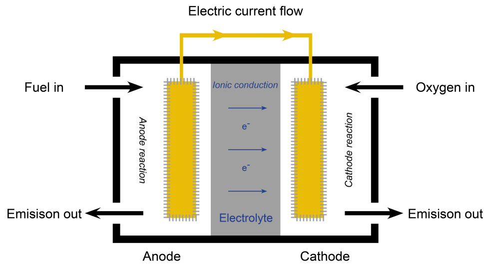


Figure 3.3: Schematic overview of a fuel cell

As can be seen, the fuel cell process is exactly the reverse process and reaction of a electrolyzer, which produces hydrogen, as discussed in chapter 2 in subsection 2.3.1.

Currently two types of fuel cells are available on the market that can be used for maritime purposes. The first one is a Proton Exchange Membrane Fuel Cell (PEMFC) and the second one is the Solid Oxide Fuel Cell (SOFC).

The PEMFC can be operated at low temperature (LT-PEMFC) and at high temperature (HT-PEMFC). LT-PEMFC are commercially developed types of fuel cells. The LT-PEMFC consist of a porous platinum-based anode and cathode. The high cost of platinum is a disadvantage of the LT-PEMFC. Due to the low operating temperature the LT-PEMFC is sensitive to impurities like carbon monoxide. A high purity of oxygen is required in order to ensure stable operation, this results in a high complexity of the system since secondary equipment like purifiers has to be installed. The efficiency of a LT-PEMFC is around 70% at current day. Expected is that in the future this could increase to a maximum of 80%.

The HT-PEMFC operates at higher temperatures between the 373 and 473 Kelvin. This partly compensates for the disadvantages of LT-PEMFC with the main advantage being easier fuel handling and thus a higher tolerance regarding impurities of the fuel. The efficiency of an HT-PEMFC lies between 35% and 45% at current day.

The Solid Oxide Fuel Cell (SOFC) is a fuel cell which operates at temperatures between 737 and 1273 Kelvin. Due to this high temperature, steam will form at the anode side of the fuel cell, which means water is formed at the cathode side. The advantage of a SOFC is that it is suitable for all alternative fuels selected in this research due to the high temperatures and steam formations at the anode side. The efficiency of the SOFC is around 60% and could be increased to 75% by making use of waste heat recovery which can be used for heating of the fuel or in an auxiliary system.

Based on the data shown in table 3.2, it was decided to solely consider LT-PEMFC for this research. The main reason is the high TRL score. This results in the fact that a lot of information about LT-PEM fuel cells is available from suppliers.

	LT-PEMFC	**HT-PEMFC**	**SOFC**
Operating temperature [Kelvin]	313 -353	373 - 473	737 - 1273
Electrical efficiency [%]	60	35 - 45	60
Fuel purity required	99.99% H2	CO <3%	Light hydrocarbons
Life time	5k to 20k hours	10k to 60k hours	10k to 40k hours
Start-up time	<10 seconds	10 - 60 minutes	>30 minutes
Load transients (0 to 100%)	<5 seconds	2 - 5 minutes	<15 minutes
Technology Readiness Level (TRL)	8	7 - 8	5 - 7
Cooling	Water cooling	Water cooling	Air cooling
Waste heat recovery	-	- / +	++
Volumetric power [kW/m^3]	100	100	10

Table 3.2: Properties of fuel cells analysed in this research

H_2 in a fuel cell
The use of hydrogen in a fuel cell is a proven technology which has gained a lot of support from science and the industry over the past decades. Hydrogen can either be used in a PEMFC or SOFC. Hydrogen gas can be used directly in both fuel cells without any treatement. When storing liquid, hydrogen has to be heated, as explained in previous section.

NH_3 in a fuel cell
Ammonia can be used in a fuel cell. In order to do this, ammonia has to be cracked into hydrogen and nitrogen.

Besides the fuel cells already analysed, the Direct Ammonia Fuel Cell (DAFC) is a fuel cell under development which can be fed directly with ammonia. Since limited data is available about these fuel cells and their technical readiness level is very low, these type of fuel cells will not be considered in this report.

MeOH in a fuel cell
Methanol can be used in a fuel cell. In order to do this, methanol has to be reformed into hydrogen and carbon mono- and di- oxide. Reforming is done by steamreformin the methanol.

Besides the fuel cells already analysed, the Direct methanol fuel cell is a fuel cell under development which can be fed by an aqueous methanol mix of 25% methanol dissolved in water. The fuel cell operates between 323 and 393 Kelvin. Although the DMFC has an efficiency of around 40%, which is still within the range of other fuel cells considered in this research, the DMFC tends to produce only very low voltage over a long time period. It is for this reason that the DMFC will not be considered as a feasible prime mover in this report.

It should be noted that since methanol contains carbon, carbon-dioxide is still emitted when the methanol is reformed before using it in the fuel cell. It will not emit any NO_x since methanol is not combusted.

3.2.3. Secondary machinery
When selecting propulsion systems, it is very important to take required secondary machinery into account. Secondary machinery is any machinery or subsystems which is not the prime mover, transmission or propulsor in the propulsion system but is nevertheless an essential component to guarantee constant operations.

For both hydrogen and ammonia heaters for the fuel are required, as explained in section A.2. The heaters will heat the fuel up after the cryogenic and cooled storage before it enters the prime mover. An advantage of this subsystem is that the waste heat can be used for cooling like the AC system and refrigeration.

Next to heaters, also compressors have to be installed that will keep the storage tank at the right pressure and can re-liquefy hydrogen gas in the re-circulation loop of surplus boil-off gas which cannot be used for power generation.

Inert gas has to be stored on board to fill the storage tanks to keep them filled and cooled. Inert gas is often pure nitrogen. When fuel cells are used as prime mover, inert gas is also used to dispose all unwanted hydrogen gas in the piping system when operation is halted. In that case, nitrogen is pumped into the complete system in order to prevent hydrogen leaks or unwanted accumulation of hydrogen in the piping and fuel cell system. In methanol combustion engine system inert gas is used to remove all methanol from piping system when engines are not operating. This is mainly due to the corrosive effect methanol can have one the (stainless) steel of the piping system and engine.

When using fuel cells, batteries have to be installed. This is mainly due to the fact that fuel cell only operates when the flow of fuel is constant resulting in a constant power output. When power demand is lower than power output, energy has to be stored in batteries. Stored energy can be used in later stage when power demand is higher than power supply or when fuel cells are not operating. Batteries will be the most important aspect when considering secondary machinery. Depending on the load profile of the vessel and design of the ship the number of batteries can be calculated. Batteries often are heavy components; this means extra attention has to be paid to the location of batteries in the design phase of a cruise vessel due to the stability of the ship. The amount of batteries against the installed power and consumed energy is a trade-off with many factors including the load profile of the vessel, the volume available and the amount of fuel cells installed. Since this trade-off is too complex and time consuming to cover in this research, batteries will not be taken into account in volume calculations.

Lastly, a reformer has to be installed in the fuel cell configurations when ammonia or methanol are used. The reformer converts ammonia and methanol into hydrogen. In Chapter 5, reformer devices for both ammonia and methnol are selected.

3.3. Costs of selected alternative fuels on board of a cruise vessel

The costs of alternative fuels on board a cruise vessel are divided in Capital Expenditures (CAPEX) and in Operating Expenses (OPEX). OPEX price estimations are based on the production prices found in Chapter 2.4. CAPEX predictions are difficult to make. Therefore it should be noted that all estimated CAPEX costs in the following section are based on literature, information retrieved from the internet and internal discussions with experts within the industry and partners of Damen Shipyards and have relative high uncertainty levels. It is for that reasons that CAPEX and OPEX are not taken into account when selecting a fuel. The information on the CAPEX and OPEX is used as input data for the design model in Chapter 5.

3.3.1. CAPEX

The CAPEX are the costs a ship owner/ operator has to make in order to implement alternative fuels on board a ship. CAPEX are divided in costs for the prime mover, the secondary machinery and fuel storage tank of a vessel. This includes the costs of the complete propulsion system, the storage system and all secondary systems required to operate a vessel using alternative fuels. The costs of the podded propulsion system is not included in this research, however, as it is assumed that this subsystem is already present in conventional cruise ship design. As limited data is available regarding storage systems and secondary machinery, alternative price predictions have to be made. In the price prediction presented in this research, it is assumed that the price is correlated with the complexity of the total propulsion system and accompanying secondary machinery, resulting in a complexity factor per propulsion system. This factor, which is based on internal discussions, information retrieved from the internet and product information received from suppliers within the maritime industry, is multiplied by the CAPEX of the prime mover.

The results found are displayed in the following table:

	Hydrogen		Ammonia		Methanol	
Prime mover	Fuel cell (LT-PEM)	Combustion engine	Fuel cell (LT-PEM)	Combustion engine	Fuel cell (LT$_PEM$)	Combustion engine
Price	3000 $ / kW	375 $ / kW	3000 $ / kW	375 $ / kW	3500 $ / kW	375 $ / kW

Table 3.3: Price estimations CAPEX of selected prime movers

3.3.2. OPEX

The OPEX are the costs a ship owner/ operator has to make in order to use alternative fuels while sailing/ operating. The OPEX in this case are the costs of the fuel itself. For the OPEX costs, the prices of alternative fuels estimated for 2020, as calculated in Chapter 2.4, are used.

	Liquid Hydrogen (LH2)	Methanol (MeOH)	Ammonia (NH3)	MGO
Price 2020	200 $ / MWh	225 $ / MWh	225 $ / MWh	51 $ / MWh

Table 3.4: Price estimations of selected alternative fuels and MGO

3.4. Conclusion

In this chapter, the implementation of the selected alternative fuels has been reviewed.

First, a review on storage systems for the selected fuels was performed. Hydrogen is stored cryogenic at a temperature of 20 Kelvin, this results in a relative complex and volume consuming storage system. Assumed was that liquid hydrogen on board is stored in cylindrical tanks, where 20% of the radius is used for the double wall structure filled with vacuum space and insulation material. The tank can never be used optimally since 25% of the volume of the tank has to be filled with liquid hydrogen to keep constant conditions within the tank. Ammonia storage is less volume consuming due to the higher temperature it is stored at and consequently, less insulation material is needed. It is assumed that 5% of the radius of the tank is used for the double wall and insulation material. Extra attention has to be paid when selecting materials for the tank due to the corrosive nature of ammonia. Methanol storage will have the least impact on the ship design relative to ammonia and liquid hydrogen. Methanol can be stored under SATP conditions and does not require a double wall structure.

Next, propulsion systems have been discussed. The use of podded propulsion will suit the cruise vessel operational profile and therefor it was assumed only podded propulsion was considered. This automatically led to an electric transmission from prime mover to propulsor and other users. Two different types of prime movers were considered; the combustion engine and the fuel cell. This led into the following results.

	Hydrogen		**Ammonia**		**Methanol**	
Prime mover	Fuel Cell	ICE	Fuel Cell	ICE	Fuel Cell	ICE
Type	LT-PEMFC	Spark Ignition	LT-PEMFC	Spark Ignition	LT-PEMFC	Spark Ignition
Fuel treatment	Heating	Heating	Cracking	Heating and cracking	Cracking	-
Efficiency 2020	55%	25%	55%	35%	55%	40%
Efficiency 2050	80%	35%	75%	50%	75%	50%
Selected for design	Yes	No	Yes	No	Yes	Yes

Table 3.5: Selected fuels with corresponding power systems and efficiencies

As can be seen in table 3.5, four of the six prime movers have been selected to implement in the design phase. Hydrogen in a fuel cell shows promising efficiencies if expected scientific progression is made. When looking at a combustion engine, hydrogen has unfavourable characteristics, efficiency are low and operations will require very specific settings and adjustments. Since hydrogen is already the selected fuel with the lowest volumetric energy content, it would mean only more hydrogen has to be stored in order to satisfy the energy requirements of the vessel. It was therefor decided that a combustion engine was not selected as a possible prime mover. When considering ammonia, the same decision was made to drop the combustion engine as a possible prime mover. Reasons were primarily the fact that ammonia in pure form cannot be used as a fuel in a combustion engine. This means ammonia has to be cracked in order to use it in a combustion engine, this will result in a lower overall efficiency and more over will increase the complexity of the total propulsion system. Of methanol both propulsion systems are considered feasible and will be taken into the next phase of designing. In Appendix A.2 a systematical lay out of the power systems of the four selected configurations can be found.

When looking at CAPEX and OPEX limited reliable price estimations can be made. This has a couple of reasons. When estimating CAPEX, assumptions had to be made regarding machinery which are not produced at large scale at current day. CAPEX estimations are done based on literature and information from suppliers. For the CAPEX, an complexity factor is added which is multiplied with the CAPEX of the prime mover. The OPEX is based on the prices of the selected fuels as determined in Chapter 2. The CAPEX and OPEX have not been used to select a specific fuel nor prime mover. Nevertheless, the values are used in the design model in Chaper 5.

With the information gathered in this chapter, the second sub-objective as described in section 1.2 can be answered. The second sub objective was stated as follows:

ii *Analyse the impact selected carbon-neutral fuels have on the cruise vessels' design and operation*

From this research it was concluded that:

- Considering the storage of the selected alternative fuels, storing liquid hydrogen will be very challenging. The volume of the tank per volumetric energy content is very high due to the insulation and cylindrical shape of the tank. When comparing methanol and ammonia storage, methanol has the advantage of being liquid at SATP making it possible to store the liquid without insulation and in square shaped tanks. The cooled storage of both hydrogen and methanol also results in extra machinery on board to keep the liquid at temperatures below boiling point and to reliquify boil-off gases.
- When selecting a power conversion system, either internal combustion engine or fuel cells are available for selected alternative fuels. The use of ammonia in a combustion engine is still in the development phase and limited research is available. In order to use ammonia in a combustion engine, it has to be cracked in to at least 30% volume hydrogen. Fuel cell technology is relative new and still developing resulting in high prices per kW. However, fuel cells have an advantage over combustion engines when looking at efficiency and the volumetric power content (kW / m^3). The combustion engine efficiency and TRL for hydrogen and ammonia are not high enough to consider these power systems as feasible to use on board of a cruise vessel.
- The costs of the implementation of selected alternative fuels is estimated. Clear is that replacing internal combustion engine for fuel cell technology will result in a large price increment which lies in the order of 12. The increase in operational expenses of liquid hydrogen, ammonia and methanol lies in the order of 5 when compared to MGO. The production process of all selected fuels required a lot of energy, resulting in high production prices. Moreover, the uncertainty about the technologies of both renewable fuel production and fuel cells and the price of renewable energy are very hard to predict. At this point in time it is hard to make price estimation about current and future technologies. Therefore, it is decided to not examine the selected fuels and technologies based on the CAPEX and OPEX.

4

Cruise ship design parameters

In this chapter, the primary objective is to create a reliable prediction model of vessel dimensions, design parameters and power consumption based on the profile and operation of cruise ships
Firstly, in section 4.1, a database is presented in which the data of 26 cruise vessels between 15,000 GT and 90,000 GT are listed, none of which are older than 25 years. This database is then used to find correlations between the number of passengers, ship dimensions, ship resistance and installed power. In section 4.2, the dimensions of a cruise vessel are predicted based on the number of passengers and the level of luxury. Next, in section 4.3, the ship resistance and corresponding required propulsion power needed on board are estimated based on the dimensions of the ship and its design speed. In section 4.4 other energy consumers on board a vessel, next to propulsion power, are described. The power consumption of the vessel is then discussed in section 4.5 where a closer look is taken at the effect of speed, endurance and range on the design of a vessel. Finally, findings and conclusions regarding the design of a carbon-neutral cruise vessel are presented in section 4.6.

The generated data and prediction model, together with data on design implementation of alternative fuels from Chapter 3, will be used in the design analysis of a carbon-neutral cruise vessel in the next chapter.

4.1. Parent cruise ship data

In order to make a good estimate of cruise ship dimensions and performance existing cruise vessels were analysed. In table 1, a database of cruise vessels is presented, which has been selected to be used as a reference when making estimations. Cruise vessels between 10,000 and 90,000 gross tonnage (GT) were chosen, where 10,000 GT is the lower limit of oceangoing cruise vessels with more than 100 passengers, and 90,000GT is the upper limit of what Damen Shipyards can produce at this moment. None of the listed ships are older than 25 years and all are equipped with diesel-electric propulsion. The table below lists the cruise vessel, the cruise operator, the year launched, the gross tonnage (GT), the number of passengers (N_{Pax}), the length over all (L_{OA}), the beam at water line (B_{WL}), the draft of the vessel (T) and the maximum design speed (v_s)

Vessel name	**Operator**	**Year launched**	***GT***	N_{Pax}	L_{OA} *[m]*	B_{WL} *[m]*	*T [m]*	v_s *[kn]*
Le Lyrial	Ponant	2015	10700	264	142.0	18.0	4.8	16.0
Seadream	Seadream	2021	15000	220	155.1	21.4	5.2	17.0
Seabourn Odyssey	Seabourn	2009	23346	450	197.0	26.0	6.4	21.0
Silver Whisper	Silversea	2000	28258	382	190.0	24.9	6.0	21.0
Seven Seas Navigator	RSS	1999	28550	490	170.7	24.8	7.3	20.0
Azamara Journey	Azmara	2000	30277	694	181.0	25.5	5.8	21.0
Silver Spirit	Silversea	2009	39519	540	196.0	26.0	6.2	21.0
Silver Muse	Silversea	2017	40700	596	212.8	27.0	6.6	21.0
Seabourn Encore	Seabourn	2016	41865	635	210.5	28.0	6.5	18.6
AidaAura	Aida	2003	42289	1300	202.8	28.1	6.2	20.0
Seven Seas Voyager	RSS	2001	42363	706	206.5	28.8	7.1	20.0
Viking Sky	Viking	2016	47842	930	228.2	28.2	6.5	20.0
Seven Seas Mariner	RSS	2001	48075	700	216.1	28.3	6.4	20.0
Seven Seas Explorer	RSS	2015	54000	750	224.0	31.1	7.1	21.0
Veendam	HAL	1996	57092	1350	218.0	31.0	7.5	20.9
Amsterdam	HAL	2000	62735	1380	237.0	32.3	8.1	23.9
Marina	HAL	2010	66084	1250	238.4	32.3	7.3	20.0
Crystal Serenity	Crystal	2003	68870	980	250.0	32.3	8.0	23.0
Grandeur of the Seas	RCI	1996	73817	2446	279.0	32.3	7.8	23.5
Norwegian Spirit	NCL	1998	75400	1996	267.9	32.3	7.9	25.5
Aurora	P&O	2000	76152	1950	270.0	32.3	7.9	24.0
Oceana	P&O	2000	77499	2272	261.3	32.3	8.1	22.4
Pride of America	NCL	2005	80439	2186	280.6	32.3	8.0	22.2
Noordam	HAL	2006	82318	1916	285.3	32.3	7.9	24.0
Carnival Miracle	Carnival	2003	85942	2124	294.0	32.3	8.0	24.0
Nieuw Amsterdam	HAL	2009	86700	2106	285.3	32.3	7.9	23.9

Table 4.1: The parent cruise ship data set

An analysis of the above data set was conducted to develop a method to estimate ship dimensions and installed power. A model based on two variables is schematically given in the following figure:

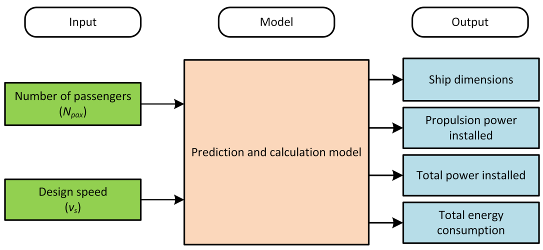


Figure 4.1: Schematic overview of the predicition model

Assumed is that with the number of passengers an estimation of the dimensions of the ship can be made. A resistance prediction can be made with data on vessel dimensions and design speed, resulting in the propulsion power required. The total installed power on board can be calculated when propulsion power, auxiliary service power and power used for passenger services are summed up.

When plotting the number of passengers against the dimension (GT, L_{oa}, B_{wl}, T) no correlation can be found, the same conclusion can be drawn when plotting the design speed (v_s) against these dimensions. This can be seen in the data plots of the data set in Appendix B.3. However, a strong correlation between the length of the vessel and the gross tonnage can be found. Since the number of passengers and design speed will be used to estimate ship dimension, this correlation is not applicable to the model as an input. When looking for other correlations, it is safe to assume that a relation between GT and the volume per passenger can be found as the GT describes the volume of all enclosed spaces in a ship.

From several travel agencies and cruise vessel websites, data can be found regarding the type of accommodation on board of the selected cruise vessels and in particular, the floor area for the different types of rooms and suites on board of the ship. By dividing the total sum of floor area of accommodations by the number of passengers, the average hotel floor area per passenger, $A_{Hotel,pax}$, is calculated. Assumed is an average floor-to-ceiling height of 2.8 meters for all passenger accommodation. With this value the average hotel volume per passenger, $V_{Hotel,pax}$, can be calculated. The values found are shown in table 4.3.

As can be seen, average hotel area per passenger differs significantly within a range of 6.6 m^2 to 26.2 m^2 which shows roughly a factor 4 increase. Passenger accommodation size is often categorised in different types varying between luxurious (suite level, large area per passenger) to standard (cabin level, small area per passenger). When plotting the total passenger hotel area ($A_{Hotel,total}$) versus the GT a correlation can be found with a R^2 value of 0.87 as can be seen in figure 4.2. The R^2 implies that a reliable correlation could be found. However, making a fair estimation of the hotel area per passenger will be challenging since the range of the found values are is large. By taking the average of all hotel volume per passenger reliable results are not guaranteed.

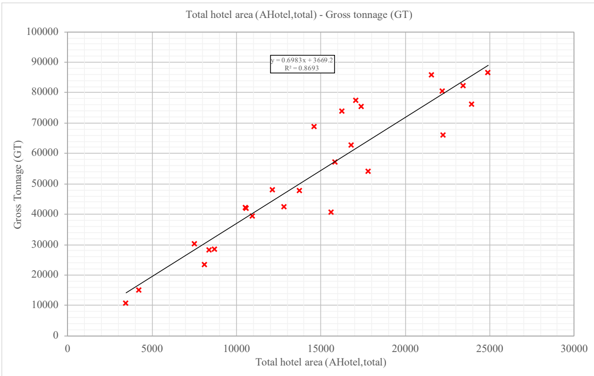


Figure 4.2: The correlation between total passenger hotel area ($A_{Hotel,total}$) and gross tonnage (GT) of the 26 cruise vessels from parent data set

In order to make more accurate estimations, the level of luxury on board of a ship is determined which will be described as Luxury Level or LL in this thesis. It is assumed that the luxury level can be based upon the passenger hotel area per person. When analysing the parent cruise ships, the following division is made:

- Luxury Level 1 (LL1): the highest level of luxury where accommodation area per passenger is larger than 17 m^2
- Luxury Level 2 (LL2): the second level of luxury where accommodation area per passenger is between the 11 m^2 and 17 m^2
- Luxury Level 1 (LL1): the lowest level of luxury where accommodation area per passenger is less than 11 m^2

When validating the assumption mentioned above, one can look at the number of passengers per crew member, representing the level and intensity of service a passenger could expect during a journey. In table 4.3, all pax/crew ratios are shown. As can be seen, this assumption seems representative. For the vessels which are classified luxury level 1, the pax/crew ratio is less then 1.5. In the luxury level 1 range, the only vessel showing a different value is the Marine which has a pax/crew ratio of 1.56. After analysing the vessel's destinations, prices and reviews online it was decided to classify the Marina as LL1.

Luxury level 2 has a pax/crew ratio which lies generally between the 1.5 and 2.0. In the luxury level 2 range, larger inconsistencies were found. The vessels of Holland America Line (HAL) and the Aurora owned by P&O-cruises have a hotel area per passenger of LL2 but a pax/crew ratio of over 2.0. After reviewing the vessel's destinations, prices and reviews online it was decided to classify the vessels of HAL and the Aurora as LL2.

Luxury level 3 cruise vessels have a pax/crew ratio greater than 2.0.

After categorizing the cruise vessels from the database into 3 different luxury levels, new estimations of the GT based on the hotel area can be made. When plotting the data, the following relations are found:

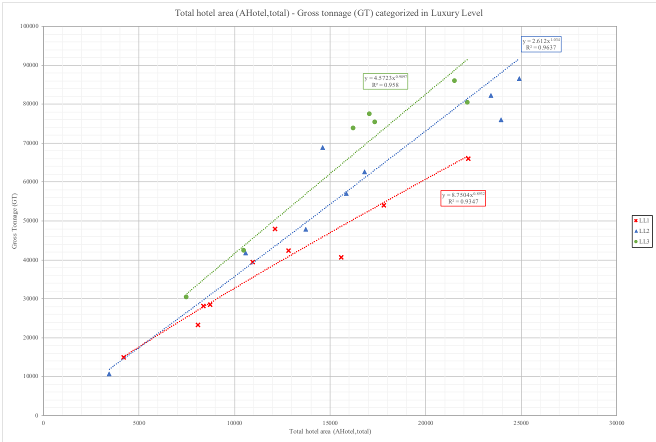


Figure 4.3: Total hotel area on board of a cruise vessel against the GT sorted on Luxury Level

In this figure the total hotel area is plotted against the GT of the parent cruise vessels. The data points are divided based on the 3 levels of luxury. As predicted in the previous subsection, more accurate correlations can be found when taking a luxury level into consideration. The luxury level will therefore be used as an input in the estimation model. The selected luxury level will give an index for the hotel area per passenger. According the following formula:

$$A_{Hotel,total} = N_{pax} * A_{LLx,pax} \tag{4.1}$$

The area per passenger per luxury level is calculated by taking the average value of the parent data set. Values that are found are as follows:

Luxury Level	**Hotel area per pax ($A_{LLx,pax}$)**
LL1	20.0 m^2
LL2	13.3 m^2
LL3	8.9 m^2

Table 4.2: Hotel area per passenger per luxury level

When include the luxury level, the following schematic overview of the prediction model can be given:

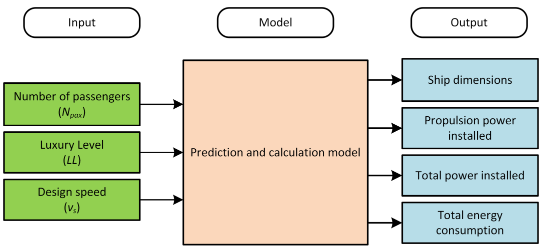


Figure 4.4: Schematic overview of the predicition model including Luxury Level

Example 4.1

Consider 3 different cruise vessels with the same amount of passengers of $N_{Pax} = 1000$ but a different level of luxury. Cruise vessel A has the highest level of luxury, LL1. Cruise vessel B is LL2 rated and lastly Cruise Vessel C which has LL3. This leads to the following results:

Cruise ship	Luxury level	N_{Pax}	$A_{Hotel,total}$	Estimated GT
Cruise Ship A	1	1000	19900 m^2	GT
Cruise Ship B	2	1000	13290 m^2	GT
Cruise Ship C	3	1000	8870 m^2	GT

Firstly, this example shows that although the number of passengers is constant, the hotel area differs very much. Consequently, the correlation between total hotel area and the GT per luxury level leads to an estimation of the GT.

Vessel name	**Operator**	N_{Pax}	$A_{Hotel,pax}$ [m^2/pax]	$V_{Hotel,pax}$ [m^3/pax]	*LL*	N_{Crew}	***Pax per crew***
Silver Muse	Silversea	596	26.1	73.21	1	411	1.5
Seven Seas Explorer	RSS	750	23.8	66.52	1	552	1.4
Silver Whisper	Silversea	382	21.9	61.40	1	295	1.3
Silver Spirit	Silversea	540	20.3	56.81	1	376	1.4
Seadream	Seadream	220	19.1	53.47	1	182	1.2
Seabourn Quest	Seabourn	450	18.7	52.25	1	335	1.3
Seven Seas Voyager	RSS	706	18.2	50.85	1	460	1.5
Seabourn Odyssey	Seabourn	450	18.0	50.41	1	330	1.4
Seven Seas Navigator	RSS	490	17.8	49.82	1	340	1.4
Marina	Oceania	1250	17.8	49.80	1	800	1.6
Seven Seas Mariner	RSS	700	17.3	48.45	1	460	1.5
Seabourn Encore	Seabourn	635	16.7	46.69	2	330	1.9
Crystal Serenity	Crystal	980	14.9	41.72	2	600	1.6
Viking Sky	Viking	930	14.8	41.32	2	550	1.7
Le Lyrial	Ponant	264	13.1	36.55	2	139	1.9
Aurora	P&O	1950	12.3	34.38	2	850	2.3
Noordam	HAL	1916	12.2	34.24	2	800	2.4
Amsterdam	HAL	1380	12.2	34.07	2	647	2.1
Nieuw Amsterdam	HAL	2106	11.8	33.10	2	929	2.3
Veendam	HAL	1350	11.7	32.88	2	568	2.4
Azamara Journey	Azmara	694	10.8	30.34	3	350	2.0
Pride of America	NCL	2186	10.2	28.44	3	927	2.4
Carnival Miracle	Carnival	2124	10.1	28.39	3	930	2.3
Norwegian Spirit	NCL	1996	8.7	24.37	3	965	2.1
AidaAura	Aida	1300	8.1	22.67	3	418	3.1
Oceana	P&O	2272	7.5	21.05	3	889	2.6
Grandeur of the Seas	RCI	2446	6.6	18.60	3	760	3.2

Table 4.3: Parent cruise ship data with corresponding accommodation area, volume per passenger, luxury level and pax/crew ratio

4.2. Dimension estimations parameters of cruise vessels

The dimensions which are relevant for ship design for a preliminary concept design and resistance and power prediction of a cruise vessel are:

- Gross Tonnage (GT)
- Length over all (L_{oa})
- Length between perpendiculars (L_{pp})
- Length at waterline (L_{wl})
- beam at waterline(B_{wl})
- Draft (D)
- Displacement (∇)

Two different methods have been considered for estimating dimensions. In "Method A" the beam and draft are determined based on the length and GT of the vessel. In "method B", the beam and draft are determined based on a prediction of the displacement. Both methods are schematically given in the following figures where the green boxes are the input variables.

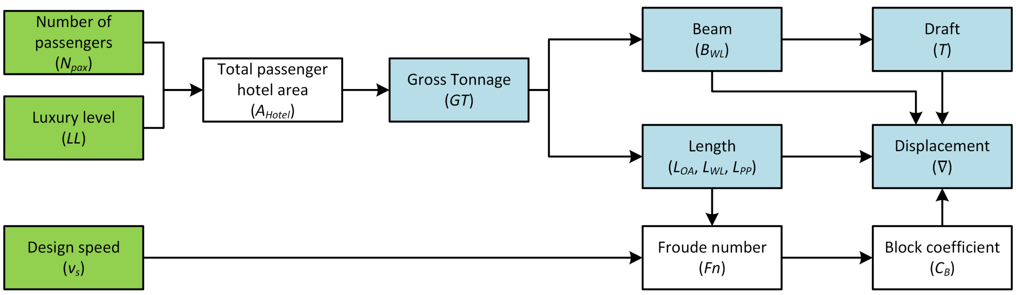


Figure 4.5: Systematic overview of prediction method A

Method A relies on the correlations between dimensions found in the parent data base as shown in plots in Appendix B.3.

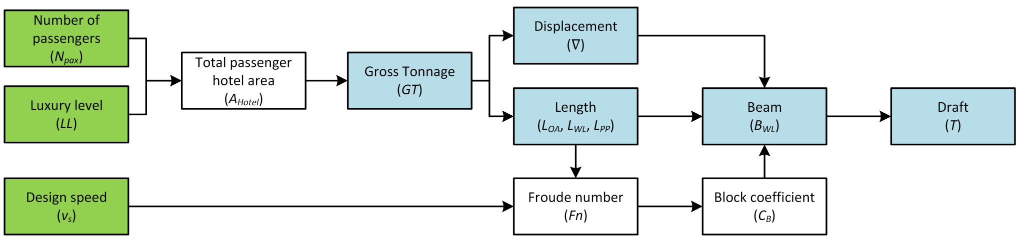


Figure 4.6: Systematic overview of prediction method B

Method B is based on the prediction of the displacement of the vessel, which leads to the beam and draft prediction.

As can be seen, both methods use the given design speed as an input for the estimation of the block coefficient, C_B. This estimation is based on the method of Townsin which uses the Froude number in order to predict the C_B. The Froude number can be written as:

$$Fn = \frac{v_s}{\sqrt{g * L_{wl}}} \tag{4.2}$$

Consequently, the C_B is described by Townsin as:

$$C_B = 0.7 + 0.125 \tan^{-1} \frac{23 - 100 * Fn}{4} \tag{4.3}$$

As can be seen in Appendix A.3, the method of Townsin has a larger variability at higher Froude numbers. After discussion with MARIN, it was concluded that for Froude numbers of cruise vessels up to and 0.40, Townsins' predictions can be assumed as reliable and thus to be reliable for the parent cruise ships since Froude numbers are between the 0.22 and 0.27.

Method A and Method B are both used in this section, at the end of this section, a data validation and comparison of results is done.

4.2.1. Gross Tonnage

As explained in the previous section, the GT will be predicted based on the passenger hotel area. The total passenger hotel area is calculated using equation 4.1. Consequently, the correlations found in the previous section the GT can be calculated based on the following equations:

$$GT = 8.750 * {A_{LL1}}^{0.893} \tag{4.4}$$

$$GT = 2.612 * {A_{LL2}}^{1.034} \tag{4.5}$$

$$GT = 4.5723 * {A_{LL3}}^{0.990} \tag{4.6}$$

The GT is estimated following the same calculations for both method A and method B

4.2.2. Length

With the GT estimated, the overall length of the vessel can be estimated. When looking at the database, the following linear relation can be found:

$$L_{oa} = 0.0018 * GT + 130.17 \tag{4.7}$$

Given the overall length of the vessel, the length between perpendiculars and the length on waterline of the vessel can be estimated. Since limited data is available considering the length between perpendiculars and the length onwaterline of selected cruise vessels, the following assumptions are made based on internal discussion at Damen Shipyards and a hand-out of the MARIN ship design workshop 2019:

$$L_{pp} = 0.9 * L_{oa} \tag{4.8}$$

$$L_{wl} = 1.02 * L_{pp} \tag{4.9}$$

The L_{OA}, L_{pp} and L_{wl} is estimated following the same calculations for both method A and method B.

4.2.3. Beam

The next dimension that has to be found is the beam of the vessel. The beam is calculated differently in method A and method B. Interesting in the parent data set is the number of ships that have a beam with values that are or just below 32.3 meters.This value corresponds to the Panamax value, which represents the limitations of the locks of the Panama canal.

Method A

When method A is followed, the B_{WL} is calculated based on the correlation between the GT and the B_{WL} . In figure 4.7 the GT against the B_{WL} is plotted.

When analysing the data points it can be concluded that often ships over 60,000 GT are limited by the Panamax dimension.Equation 4.10 is based on the correlation between beam and GT of the 16 cruise vessels with a beam smaller than 32.3 meter. For the data points below 60,000 GT the following linear correlation was found:

$$B_{wl} = 0.0002 * GT + 17.777 \qquad \text{for } GT < 60,000 \tag{4.10}$$

$$B_{wl} = 32.3 \qquad \text{for } GT > 60,000$$

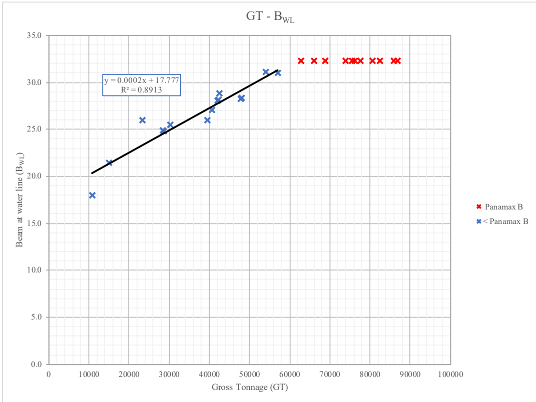


Figure 4.7: The correlation between the Gross Tonnage (GT) and beam (B_{WL}) of parent cruise vessels

Method B

When using method B, the B_{WL} is calculated from the estimated displacement. Here, the displacement is first calculated as described in the subsection 4.2.5. Next, the B/D ratio as determined in subsection 4.2.4. Consequently, these equations are combined as follows:

$$\nabla = L_{wl} * B_{wl} * \frac{B_{wl}}{4.13} * C_B \tag{4.11}$$

$$B_{wl} = \sqrt{\frac{\nabla * 4.14}{L_{WL} * C_B}}$$

4.2.4. Draft (T)

Correlations between both length and draft and GT and draft have not been found reliable. When looking at the relation between beam and draft, results seem most reliable. The average relation found at the data base is:

$$T = \frac{B_{wl}}{4.13} \tag{4.12}$$

In Appendix B.2 the B/T ratios off all parent cruise ships can be found. Both method A and method B use the B/T ratio as described to estimate the draft of the vessel.

4.2.5. Displacement

The displacement of the vessel depends on the hull form and describes the volume of water the hull of the ship displaces. The ship's displacement is calculated through the following formula:

$$\nabla = L_{wl} * B_{wl} * T * C_B \tag{4.13}$$

Method A

Method A is based on the dimension found by correlations described above and the C_B given in equation 4.3. Consequently the displacement can be calculated following equation 4.13 above.

Method B

Method B relies on a predicted displacement based on the GT of the vessel. The displacement for the parent cruise vessels is predicted using the vessel dimension and a predicted C_B. The predicted displacement is plotted against the GT of the vessel in order to find a correlation in figure 4.8.

With the results found above the following correlation can be made:

$$\nabla = 0.5122 * GT + 2317.7 \tag{4.14}$$

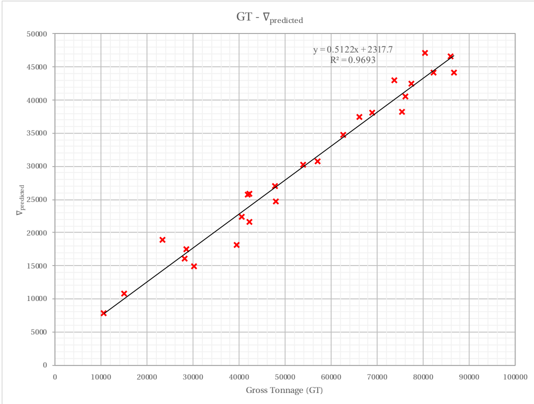


Figure 4.8: The correlation between the GT and the calculated ∇ of the parent cruise vessels.

4.2.6. Data validation and method selection

In order to have a reliable prediction values, the methods used in this section are validated. This is done based on the data set of the parent cruise vessels. Moreover, it is determined which method will be used to predict dimension of the beam and the draft of the vessel. The GT and length prediction is the same for both methods.

The GT calculated based on the number of passengers and luxury level of the parent cruise date ships has an average error of 1.9%, a average error deviation of 12.9% and a R^2 value of 94.3%. This implies a plausible method. One reason some vessel have large deviation is the results of using a constant value for hotel area per passenger per luxury level. The GT predictions are the least accurate predictions when looking at the errors. However, since results based on the estimated GT, which are described below, show high accuracy, the GT prediction as described is used in the design model.

The length of the vessel is based on the GT and calculating though te linear correlation found in the parent cruise data set. The results show that the predicted length over all is close to the values of the data set. The average error is 0.7% and has a relatively small average error deviation of 6.8%. The largest absolute deviation found is 14.1%. The length calculations are considered reliable.

When analysing the estimated beam and draft from both estimation methods it is clear that method B has the most reliable outcome. The average error and error deviation is considerably lower when using method B compared to method A. Therefore it is decided to use method B in the prediction model.

It should be noted that dimension estimations are based on the parent data base of cruise ships as determined in section 4.1. There is thus no guarantee that reliable data can be found if cruise vessels outside the range of 15,000 t0 90,000 GT or older than 25 years are considered.

	Method A			
	Length (L_{oa})	**Gross Tonnage**	**Beam**	**Draft**
Average error	1.9%	0.7%	-2.7%	-2.7%
Average error deviation	12.9%	6.8%	3.4%	3.6%
R2-value	94.3%	92.3%	96.1%	91.7%

Table 4.4: Results of predictions using method A for the parent cruise ship data set

	Method B			
	Length (L_{oa})	**Gross Tonnage**	**Beam**	**Draft**
Average error	1.9%	0.7%	-0.1%	-0.27%
Average error deviation	12.9%	6.8%	1.4%	2.3%
R2-value	94.3%	92.3%	98.4%	95.8%

Table 4.5: Results of predictions using method B for the parent cruise ship data set

4.3. Ship resistance and propulsion power prediction

4.3.1. Ship resistance

Vessel dimensions are predicted using the estimations based on the number of passengers on board of the vessel. With these dimensions the total ship resistance, RT, is estimated. This is represented by the following formula:

$$R_t = C_T * \frac{1}{2} * \rho_{sw} * v^2 * S) \tag{4.15}$$

In this equation, C_T is the total ship resistant coefficient, ρ_{sw} is the density of seawater, v is the ship speed and S is the total whetted surface of the ship. In this thesis, the power prediction method of Holtrop and Mennen is used as described in “An approximate power prediction method” [25]. The total resistance is subdivided into:

$$R_T = R_F(1+k) + R_{app} + R_W + R_B + R_{TR} + R_A \tag{4.16}$$

Where:

R_F	The frictional resistance according to the ITTC-1957 friction formula
$(1+k)$	Form factor describing the viscous resistance of the hull form in relation to RF
R_{App}	Resistance of appendages
R_W	Wave-making and wave-breaking resistance
R_B	Additional pressure resistance of a bulbous bow near the water surface
R_{TR}	Additional pressure resistance of immersed transom stern
R_A	Model-ship correlation resistance

In Appendix A.4 the complete calculation and resistance prediction with corresponding formulas and assumptions can be found.

4.3.2. Propulsion Power

After calculating the total ship resistance, one can calculate the power that is needed to move a ship through the water, defined as the effective power or P_E. P_E can be estimated by the following equation that relates total ship resistance to the ship's speed:

$$P_E = R_T * v \tag{4.17}$$

Given the effective power, the brake power needed to propel a ship can be calculated according to the following formula:

$$P_B = \frac{P_E}{\eta_D * \eta_{TRM}} \tag{4.18}$$

Here, η_D is the propulsive efficiency and η_{TRM} is the efficiency of all the subsystems transferring energy from the output of the prime mover to the propulsor.

Propulsive efficiency

It is common practice to define the *total propulsive efficiency* as all effects concerning the hull and propeller [72]. The propulsive efficiency is the quotient of the effective power, calculated as above, and the power delivered to all propellers, or P_D. This leads to the following equation:

$$\eta_D = \frac{P_E}{P_D} \tag{4.19}$$

The propulsive efficiency is the product of three efficiencies; the hull efficiency (η_H), the open water propeller efficiency (η_O) and the relative rotative efficiency (η_R).

$$\eta_D = \eta_H * \eta_O * \eta_R \tag{4.20}$$

The open water propeller efficiency is by far the most influential factor in this equation. The hull efficiency and the relative rotative efficiency are in most cases both between a range of 0.95 and 1.05. The open water propeller efficiency depends on many factors, amongst others the design and the loading of the propeller. Since it is deemed unnecessary and too time-consuming to perform a study on the type of propellers, it is assumed that the propeller efficiency is set at 70%.

Transmission efficiency

In this report the transmission efficiency, or η_{TRM}, is the combined efficiency of all the subsystems transferring energy from the prime mover to the propeller of the vessel. As determined in chapter 3.2 it is assumed that the cruise vessel will be equipped with thrusters and that energy is transmitted from prime mover to propeller through electric energy. In order to calculate the brake power of the prime mover the efficiency of the propulsion system has to be determined. To do this, the efficiencies of the various subsystems of the propulsion systems have to be determined first. In the following figures, the power train from prime mover to propeller with sub-systems and efficiencies is described:

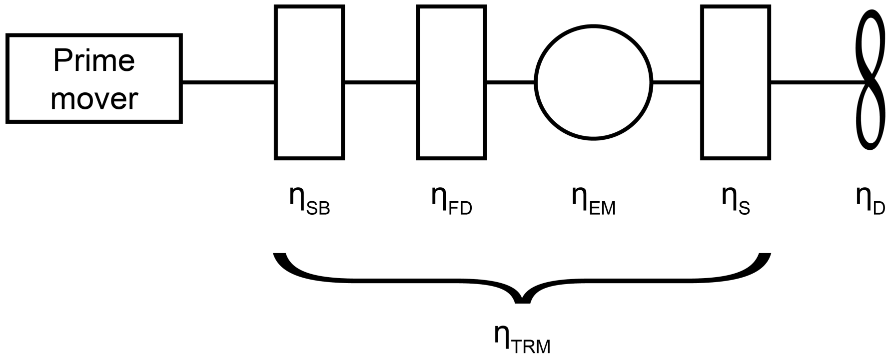


Figure 4.9: Propulsion power train sub-systems

The transmission efficiency is broken up into different aspects:

Subsystem	Symbol	Efficiency
Switch board	η_{SB}	0.991
Frequency drive	η_{FD}	1.00
Electric motor	η_{EM}	0.97
Propeller shaft	η_S	0.963

This means the total efficiency of the transmission from prime mover to propeller can be calculated in the following way:

$$\eta_{TRM} = \eta_{SB} * \eta_{FD} * \eta_{EM} * \eta_S \tag{4.21}$$

$$\eta_{TRM} = 0.991 * 1.00 * 0.97 * 0.963 = 92.57\%$$

This means that the total brake power required from prime move to propeller can be calculated as follows:

$$P_B = \frac{P_E}{\eta_D * \eta_{TRM}} \tag{4.22}$$

$$P_B = \frac{P_E}{0.70 * 0.9257}$$

$$P_B = \frac{P_E}{0.65}$$

In the next chapter, the efficiencies estimated in this section are used in the propulsion model.

4.3.3. Data validation

The data calculated with the assumptions made in this chapter and the Holtrop-Mennen Prediction is validated in order to check whether the basics of the power prediction model can be used in the next chapter. Data is validated by comparing the values of the power prediction model with the installed power on board of the vessel as registered on the ship specifics. In this model the input parameters are:

- Number of passengers N_{Pax}
- Luxury Level LL
- Maximum design speed v_s

The dimensions are estimated using the method discussed in the previous section (4.2). In the data validation was assumed that diesel-electric propulsion has a propulsive efficiency (η_D) of 0.7 and a transmission efficiency (η_{TRM}) of efficiency of 0.9257 as calculated in this section. The following results were founded:

Vessel name	N_{Pax}	Luxury Level	v_s [kn]	$P_{Prop,installed}$[kW]	$P_{Prop,estimated}$[kW]	Error
Marina	1250	1	20.0	24000	26437	10.2%
Seabourn Odyssey	450	1	21.0	15000	14815	-1.2%
Seadream	220	1	17.0	5600	6904	23.3%
Seven Seas Explorer	750	1	21.0	18000	20076	11.5%
Seven Seas Mariner	700	1	20.0	17000	17813	4.8%
Seven Seas Navigator	490	1	20.0	15536	14503	-6.6%
Seven Seas Voyager	706	1	20.0	17000	17900	5.3%
Silver Muse	596	1	21.0	17000	17571	3.4%
Silver Spirit	540	1	21.0	17000	16566	-2.6%
Silver Whisper	382	1	21.0	15700	13362	-14.9%
Amsterdam	1380	2	23.9	31000	29993	-3.2%
Aurora	1950	2	24.0	40000	36937	-7.7%
Crystal Serenity	980	2	23.0	27000	22760	-15.7%
Le Lyrial	264	2	16.0	4600	5304	15.3%
Nieuw Amsterdam	2106	2	23.9	35200	36858	4.7%
Noordam	1916	2	24.0	35200	36491	3.7%
Seabourn Encore	635	2	18.6	12000	12268	2.2%
Veendam	1350	2	20.9	24000	26645	11.0%
Viking Sky	930	2	20.0	14500	16972	17.0%
AidaAura	1300	3	20.0	18800	18673	-0.7%
Azamara Journey	694	3	21.0	13500	13310	-1.4%
Carnival Miracle	2124	3	24.0	35200	32332	-8.1%
Grandeur of the Seas	2446	3	23.5	34000	34590	1.7%
Norwegian Spirit	1996	3	25.5	40000	34724	-13.2%
Oceana	2272	3	22.4	28000	29505	5.4%
Pride of America	2186	3	22.2	25000	28478	13.9%

Average error	**2.2%**
Average error deviation	**7.7%**
R^2-value	**97.7%**

Table 4.6: Propulsion power installed and predicted of the parent cruise data set

The estimated values of propulsion power that are calculated with the described prediction method are within the range of -15.7% to 23.2% of the value that is installed on actual vessels. The average error is 2.2% with an average error deviation of 7.7%. The R^2 value is 97.7%.

Overall it can be stated that this method of power prediction leads to reliable results. The values of the installed power and estimated power will always deviate from one another. Reasons for this are the chosen engine manufacturer and corresponding engines available, the sea margin which is required by the client or the redundancy of the total propulsion system. Moreover, as can be seen in Appendix A.4, several assumption in the Holtrop Mennen prediction have been made regarding the hull form, bulb of the vessel and resistance of for example appendages. This can lead to inconsistencies. However, the majority of the data shows only a small error between predicted and installed propulsion power. It is for this reason that the prediction model will be used as a basis for the design model in the next chapter.

4.4. Power consumers

As explained in Chapter 3.2, power conversion on board of a vessel serves the purpose to propel the ship as well as supplying energy to all other users on board of the vessel. This is schematically described in figure 3.2. This model could be expanded into the following overview:

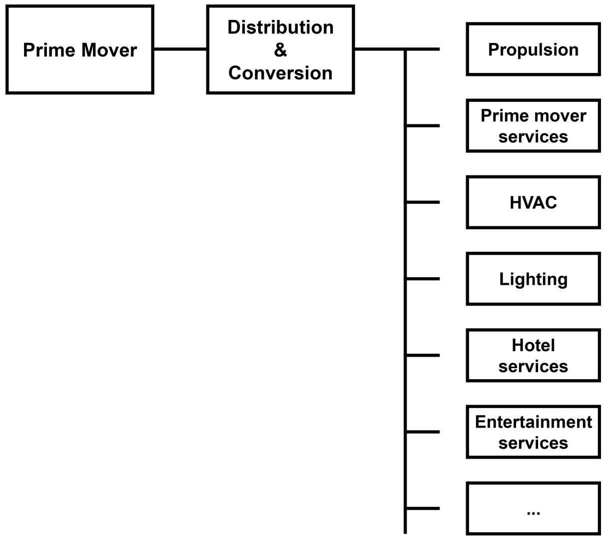


Figure 4.10: Overview of energy distribution to a selection of energy users on board of a cruise vessel

In order to make a fair estimations of fuel consumption, installed power and subsystems, more information has to be gathered regarding the energy users. When considering a cruise vessel, multiple energy users have to be considered. In this research, the power consumers will be divided into 3 different categories:

1. Propulsion power consumption
2. Auxiliary power consumption
3. Passenger & crew power consumption

4.4.1. Propulsion power consumption

The first category is the power consumed by the propulsion of the ship. This is calculated in the model through the Holtrop-Mennen prediction method as explained in section 4.3. This category is only the power used by the propulsion system of the ship and does not include auxiliary power consumption of for example engine room ventilation or engine support systems.

4.4.2. Auxiliary power consumption

The second category contains all the power consumed by machinery and (sub)-systems which are not part of the propulsion system but are necessary in order for the vessel to maintain operations. This includes machinery like engine room ventilation, which keeps the propulsion system operational. In addition, it includes energy consumption of navigation systems, stabilizers and communication systems.

It can be assumed that the auxiliary power consumption is related to the size of the ship and thus the total installed propulsion power on board of the vessel. This assumption was confirmed as acceptable during internal discussions with numerous design and proposal engineers within Damen. From these discussions it was advised to use 10% of the used propulsion power as the auxiliary power consumption. A study on the total energy balance of cruise vessels would be too time consuming and will not contribute significantly to the estimations since auxiliary systems as determined in this research will have a minor impact on the total energy consumption.

4.4.3. Passenger and passenger services consumption

The last category is passenger and passenger services. This includes all the power that is consumed in systems and services in order to provide a comfortable stay for passengers during their time on board. Since the role of crew members is to serve all passengers on board, the power that is consumed by the crew is included in this category. The power consumption also includes services for passengers like laundry equipment, galleys of restaurants and the light and sound systems which are installed for entertainment purposes. The biggest consumer in this category, however, is clearly the heating, ventilation and air conditioning (HVAC) system, which often consumes around 33% of the of the total passenger & crew power consumption.

When predicting the power consumption of this category, one could look at the installed power on board of the parent database cruise vessel. The installed power minus the propulsion power and the share of auxiliary power as determined above should give the installed power assigned for passenger services. This calculation, however, shows no clear correlation (Appendix B.4). In fact, installed power per passenger differs widely. And even taking the levels of luxury into account, no correlation was found, which implies no clear relation between the installed power and the number of passengers.

Alternative methods have to be found in order to make predictions regarding the power consumption for passengers. When looking at literature a handful of reports and studies can be found where assumptions have been made in order to predict passenger power consumption. In a study performed by the Danish port authorities [16] a value between 2.5 and 3.9 kWh per passenger per hour is suggested. In the master thesis of Nurmi [46] and Korhonen[31], values of 2.2 and 2.8 kWh per passenger per hour were used respectively.

Within Damen, reference data of 3 ships was available showing the following results:

Ship	N_{pax}	Power consumption
Ship 1*	220	3.5 kWh per pax per hour
Ship 2*	906	5 kWh per pax per hour
Ship 3*	1500	3.1 kWh per pax per hour

*Due to disclosure agreements, ships have been given an anynomous name.

Table 4.7: Passenger and passenger services power consumption of reference vessels

Since an in depth review of the power consumption is not within the scope of this research the data mentioned is used to make a prediction. When making this prediction it was found that reference Ship 2 of table 4.7 was a so called resident-cruise vessel where passengers live on board of the ship in fully furbished apartments. For this reason, this data was not taken into account. When reviewing the remaining values of both studies mentioned and the two reference vessels, the average value is 3.0 kWh per passenger per hour. Note that it can be expected that a correlation could be found between the level of luxury and the energy consumption per passenger. Since creating a detailed load balance is not within the scope of this research a constant energy consumption is assumed.

It was concluded that a value of 3 kW per passenger per hour was assumed plausible and will be used in the load balance prediction and design model.

4.5. Energy consumption

In order to predict the total energy consumption on board of a ship, a load balance of the cruise vessel has to be specified. For this one has to look at the operational profile of the cruise vessel. As described by Stapersma [72], the starting point for an analysis of the operational profile is the main goal or purpose of a ship: the mission. A mission specifies which tasks a vessel has to fulfil. Together with other specification such as the area of operation, speed and period of time at sea, the mission specification is established. In this section an estimation of the total energy consumption and operational profile is made based on the mission of the ship. The mission of a cruise vessel is to bring passengers to multiple vacation destination while providing a comfortable stay on board of the vessel. It is assumed that a cruise vessel has an occupancy rate of 100% meaning that the maximum number of passengers is onboard during operation.

4.5.1. Ship speed

An input of the model is the design speed of the vessel. With the design speed as an input, the required installed propulsion power is calculated in section 4.3. However, the cruise vessel will sail at multiple speeds during its trips.

The various speeds are adjusted to the operational profile a cruise ship has and the specific trip it is making. As specified above, the mission of the cruise vessel is to bring passengers to multiple vacation destination while providing a comfortable stay on board of the vessel. This means often ships will sail during night hours in order to allow passengers to disembark the ship at destination during day time.

In order to make an estimation regarding the speed profile of the vessel, AIS data of selected vessels from the parent cruise ship data base was used.

AIS data analysis

The Automtic Identification System, or AIS, is an automatic tracking systems used for marine traffic. Each vessel has a transceiver, which broadcast information regarding the ships status such as their position, speed and heading. This data can be received by an AIS antenna or can be downloaded from an AIS database. AIS data can only be received when a vessel is within the range of an AIS antenna. When a vessel is outside this range, satellites could receive this information calles AIS-S data. In this research no AIS-S data was used.

AIS data of the parent cruise ships from 05-05-2018 and 20-06-2019 has been used in order to create a speed profile. AIS data was downloaded from an AIS data server. The data has an interval of 1 hour between every update. When the vessel is outside the range of an AIS antenna no information was received. The speed profile is based on the GPS coordinates of the vessel and the time step between both data point. The average speed was calculated per time step. In total 14 vessels showed reliable AIS data which was analysed. All data can be found in appendix B.5. At average, the following speed profile was found:

Speed range [%]	Average speed [%]	Time period [%]
0% - 20%	6.4%	48.4%
20% - 40%	32%	15.7%
40% - 60%	51%	19.2%
60% - 90%	73%	16.0%
90% - 100%	93%	0.6%

Table 4.8: The average speed profile based on AIS data from 14 cruise vessel of parent database

In the analysis a speed of 0 knots (0% - 20% of design speed) was assigned to the operation "In port". After reviewing the AIS data results internal with Design & Proposal engineers it was brought to attention that when in port, ships are also manoeuvring, one of the reasons for the relative high average speed, which is still 6.4% of the design speed. When manoeuvring, power consumption of propulsors is very high due to the impulsive use of thrusters and thrust force, including the bowthruster. Therefore. it is assumed that during manoeuvring operations in port, the cruise vessel uses 90% of the total installed propulsion power which is equal to the power consumption of reference ships in dynamic positioning operations. It is assumed these operations take approximately 4% of the total time. After the analysis of the AIS data the following speed profile was determined for a cruise vessel and will be used in the design model.

Operation	Speed [% v_s]	Time period
In port - Quayside	35%	45%
In port - Manoeuvring	5%	4%
Sailing	30%	15%
Sailing	50%	20%
Sailing	75%	15%
Sailing	95%	1%

Table 4.9: Assumed speed profile as used in the model

The corresponding propulsive power is calculated by means of the propeller law. This given by the MAN basics of ship propulsion guidelines for medium-sized, medium-speed ships like feeder container ships,reefers, RoRo ships, etc [**?**]

$$P_B = c * {v_s}^{3.5} \tag{4.23}$$

In this equation, P_B is the required break power, c is a constant which can be determined from the design point and v_s is ship speed. When multiplying the time of the operations with the brake power required for this specific operation the power consumption of propulsion is calculated.

4.5.2. Range

The range of the cruise vessel is the maximum distance the vessel can sail. The range of the vessel is correlated to the speed at which the vessel is sailing. At high speed, ship resistance will increase, and following the propeller law, the required propeller power will increase by the power of 3. This results in a higher specific fuel consumption and thus range will decrease when a fixed amount of fuel is assumed.

At low speeds the energy per mile will increase meaning the range will decrease. This is mainly due to the constant load the system has to give to auxiliary systems and the passenger energy consumption. In adition, the idle fuel flow, or the flow that is required to keep engines and fuel cells running at stationary level, causes the specific fuel flow to increase steeply at low speeds as speed is zero, but fuel is still consumed.

In this report and in the design model a minimum range of a cruise vessel is assumed to be 6000 nautical miles. This distance is equal to the distance from Auckland, New Zealand to to Buenos Aires, Argentina. This route represents the maximum route a cruise vessel can sail over open ocean and is often used as a criteria set by cruise operators.

The range of the vessel will be described as R.

4.5.3. Endurance

The definition of endurance is given by Stapersma [72] as the time the ship can sail as a function of speed. As determined in the previous subsection, the minimum range is 6000 nautical miles. In the endurance calculation it is assumed that the ship will sail at constant speed of 75% v_s, max and will not stop. The ship will have a full occupancy. This assumption differs from the standard load profile that was determined in table 4.9. The endurance of the vessel is the number of days a specific vessel can sail when a fixed amount of fuel is assumed. The endurance is described with T and can be calculated as follows:

$$T_{days} = \frac{R}{75\% v_s} / 24 \tag{4.24}$$

Since the endurance is a function of both the speed and the range of the vessel, endurance will be added to the input in the design model where the minimum endurance is determined by the minimum range of 3500 nautical miles. The endurance will be an input where the number of days the vessel has to operate independently has to be selected. The minimum is equal to the number of days which it takes to make an Atlantic crossing as described in equation 4.24.

Example 4.2

Consider a cruise vessel with 1000 passengers which has luxury level 2 and a maximum design speed v_s of 20 knots. With this information, the dimensions of the ship can be estimated as follows:

GT	47940
L_{wl}	199.6 meter
B_{wl}	28.3 meter
T	6.86 meter
P_B	18500 kW
P_{aux}	1850 kW
P_{pax}	3000 kW

With the installed power the corresponding speed profile and load balance can be made:

Operation	Speed [% v_s]	Speed [kn]	P_B [kW]
In port - Quayside	0%	0	0
In port - Manoeuvring	0%	0	21600
Sailing	30%	6	277
Sailing	50%	10	1657
Sailing	75%	15	6850
Sailing	95%	19	15665

The minimum endurance can be determined from equation 4.24 by dividing the range of 6000 nm by a ship speed of 15 knots. Following the minimum endurance of 17 days when sailing at 75% of the maximum speed. The energy consumed with this trip is equal to 55815 MWh. This is equal to 45 days of operations when operating following the standard load balance without bunkering new fuel.

4.6. Conclusion

The primary objective of this chapter was to create a reliable prediction model of cruise ship dimensions, design parameters and power consumption based on their profile and operation.

First, a data base of 26 reference cruise ships was established, this is the so-called parent cruise ship database. Using the database, correlations based on the number of passengers and ship dimension were analysed. Concluded was that taking a level of luxury into account, accurate predictions of ship dimensions can be made based on the number of passengers. With the predicted dimensions, a resistance prediction can be made with the Holtrop-Mennen method leading to the needed propulsive power one has to install on board of a cruise vessel. With the found correlations a first model was made where input was the number of passengers and design speed. Ship dimensions and ship propulsion power was the output. This model was tested and generated data was validated based on the parent cruise ship data.

Next, a further investigation into power consumers on board of the cruise vessel was conducted. Here, it was found that next to the propulsion power, auxiliary systems also consume another 10% of the propulsion power. Moreover, the power consumption of passengers and for passenger services was analysed. It was concluded that a power consumption of 3 kWh per passenger per hour was a fair assumption. This data will be integrated in the model as parameters in order to generate the output where not only propulsive power but total installed power is considered.

In order to create insights and reliable results considering the power consumption on board of a cruise vessel, a closer look was taken at the load balance and operational profile of the vessel. The speed of the vessel was analysed based on AIS data in order to create a speed profile. The propulsion power for different speeds is estimated with the propeller law. The range of the vessel determines the minimum energy stored on board of the vessel. The minimum range of a cruise vessel is set at 6000 nautical miles. The endurance of the ship is the number of days a cruise ship operates on the energy stored on board. The endurance of the vessel is therefore the last input parameter in order to calculate the stored energy required for a cruise vessel.

With all input, design parameters and calculations, the first part of the design model is established. The model is schematically given in the following figure:

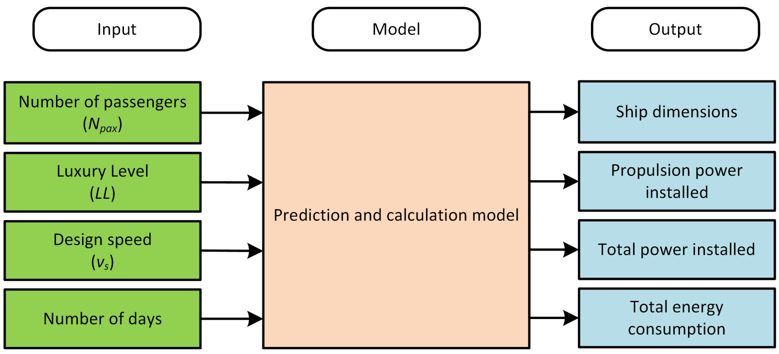


Figure 4.11: Revised model including luxury level and endurance

In the next chapter, this model will be used and developed further by integrating alternative fuels in order to analyse the impact on the design and operation of a vessel.

5 The design of a carbon-neutral cruise vessel

In this chapter, the primary objective is to approach the impact of selected alternative fuels on the design and operation of the vessel. In this chapter the information about implementation of selected alternative fuels from Chapter 3 and the dimension and power prediction from Chapter 4 are combined in order to create an overview on the effect on cruise ship design and operation.

In section 5.1 the design model will be explained. The test scenario's which will be used as an input are described in section 5.2. The results from the tool and the corresponding impact analysis is given in 5.3. Conclusions can be found in the last section of this chapter, section 5.4.

As decided in chapter 4, three different types of fuels in four different configurations will be analysed in this Chapter:

- Hydrogen in a fuel cell (H_2-FC)
- Ammonia in a fuel cell (NH_3-FC)
- Methanol in a fuel cell (MeOH-FC)
- Methanol in an internal combustion engine (MeOH-ICE)

The selected alternative fuels will be compared to the conventional power system on board of cruise ship where MGO used in an internal combustion engine. The properties of MGO can be found in Chapter 2, table 2.2. The properties of the internal combustion engine and power system can be found in section 3.2.

This impact model is only applicable for cruise vessels between the 15,000 and 90,000 GT since the parametric analysis and dimension and power predictions have been based on a data base with ships of this size as can be read in Chapter 4.

5.1. Design impact model

The goal of the design impact model is to estimate the impact the implementation of a selected alternative fuel has on the design and the operation of a ship. In this model, the input consist out of three input variables:

- Number of passengers (N_{Pax})
- Luxury level (LL)
- Design speed (v_s)

The power consumed is calculated following the method explained in Chapter 4. Consequently the following model will lead to the impact on the ship design:

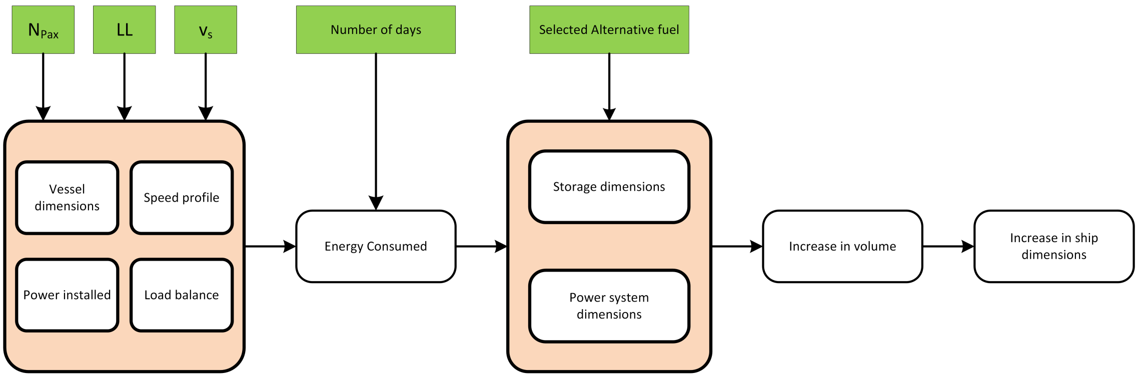


Figure 5.1: Schematic overview of the design impact tool

5.1.1. Energy consumption and storage dimensions

With the number of days the vessel operates and the load balance of the cruise vessel the amount of energy required can be calculated. Next, the volume needed of selected alternative fuels has to be determined.

For all alternative fuels selected, the specific fuel consumption is calculated following equation 5.1.

$$\text{sfc} = \frac{3600}{\eta_E * \text{LHV}} \tag{5.1}$$

In this equation, η_E is the efficiency of the prime mover as described in section 3.2, equation 3.1. The LHV is the lower heating value of the selected fuel as stated in table 2.12. The specific fuel consumption as shown in 5.1 is calculated in kilogram per kilowatt hour [kg/kWh]. When dividing the sfc with the density of the fuel the volumetric specific fuel consumption in [m^3/kWh] can be calculated. The following results were found:

	H_2-FC	NH_3-FC	MeOH-FC	MeOH-ICE	MGO-ICE
η_E	70%	70%	70%	50%	50%
LHV [kj/kg]	120100	18600	19900	19900	42700
sfc [kg/MWh]	43.2	279.0	260.8	365.1	170.1
sfc [m3/MWh]	0.61	0.41	0.33	0.46	0.20

Table 5.1: Specific energy consumption of selected alternative fuels and power systems

The sfc and the energy required consequently lead to the volume of the fuel needed on board of the vessel for a specific time unit.

As discussed in section 3.1, the storage methods for selected alternative fuels differs. Hydrogen is kept in liquid state at cryogenic temperature in a cylindrical tank. Ammonia is also stored in cylindrical tanks but at a temperature of 240 Kelvin. Methanol can be stored in square tanks at SATP. Hence, the volume of the storage systems required can be calculated.

Here, the following assumptions are made:

- The maximum height of all tanks is h_{deck};
- Although being cylindrical, the effective volume of the cylindrical shaped tanks is equal to the box shape around it since the space around the cylinder can not be used;
- Tanks can be placed over the maximum beam of $0.6 * B_{wl}$;
- Tanks and machinery are placed on the assigned decks which can be found in subsection 5.1.3

5.1.2. Installed power system dimensions

Next, the dimensions of the power systems are calculated. For the minimum power installed on board, the peak values of power consumption are calculated. The peak value is the power required when the vessel is sailing at the maximum design speed with full occupancy. As described in section 3.2, two types of prime movers are considered; the internal combustion engine and the PEM fuel cell.

Internal combustion engine

At current day, there are no marine engine manufactures that produce methanol fueled engine for maritime use. However, pilot projects are known where marine engines are retrofitted into methanol engines by adjusting for example injection, timing and valves. For this reason, dimension and volume assumption of methanol engines are based on diesel engine from the maritime industry.

Next to the volume of the internal combustion engine, also the volume of the generator has to be taken into account. The volume of all other subsystems like piping, ventilators, pumps etc. are not taken into account since it is assumed this will be equal to the volume needed in other configuration considered in this research and thus will not have effect the total design of the vessel.

For this research, multiple combustion engines and generator set in the range from 1,500 to 20,000 kW were analysed in order to calculate the power density in kW per m^3. In Appendix A.5 the 8 engines and corresponding dimensions are displayed. The values of the power density is between the 33 and 63 kW/m^3 with an average value of 41.4 kW/m^3. The volume of the generator is approximately 30% of the total volume.

One important consequence of the use of an ICE on board is the use of a selective catalytic reduction (SCR) system. The SCR system, often referred to as scrubber, is the system on board which reduces the NO_x in the exhaust gasses. This system has to be taken into account when the volume of the prime mover is calculated. The size of the scrubber is depends on the mass flow of the exhaust gasses. This means that the sizing of the scrubber is hard to express in a fixed value. In this research it is assumed that the volume expansion of the scrubber is linear to the increase of power in kW of the engine. When analysing the dimensions of the scrubber, the Wärtsila NO_x-Reducer was used as reference [71]. The average value of 7 different sizes of 3 catalyst layers reactors were used which are displayed in Appendix A.5. At average, the volume of the scrubber is equal to 0.0024 m^3/kW installed.

This results into an assumed value of 38 kW/m^3 for the methanol internal combustion engine including the generator and SCR system. This value will thus be used in the design model. This values is applicable for both the methanol combustion engine and the MGO combustion engine.

PEM fuel cell

The second type of prime mover which is considered in this research is the PEM fuel cell. Information about the dimensions of fuel cells for maritime use is very limited. When considering fuel cell information data from various fuel cell manufacturers was analysed. As can be seen in Appendix A.6, values of fuel cells stacks are in the range between 20 and 460 kW/m^3. The values of the fuel stacks differ widely, this is mainly due to the fact that not every manufacturer takes the cooling and air subsystem into account when specifying the fuel cell dimensions.

When analysing a fuel cell which has both cooling and air subsystem are include like the Ballard FCveloCity HD100, a power density of 115 kW/m^3 was found. When verifying this data, it was concluded that these type of fuel cells were mostly applied in automotive industry and was not applicable for large scale power supply. After discussions with multiple experts within the fuel cell industry, a value of 70 kW/m^3 was confirmed as representative power density.

When ammonia or methanol are used in a fuel cell, both fuels have to be reformed. In order to reform ammonia, an ammonia cracker has to be installed. When reforming methanol, a steam reforming system has to be installed. These system has to be taken into account when the volume of the prime mover are calculated. The volume of the reforming systems are depended on the mass flow required by the fuel cell. For ammonia, the volume of the reformer unit is assumed equal to 0.0041 m^3/kW installed, based on the cracker unit produced by Koyo Thermo Systems Co. [15]. The volume of the methanol reformer unit is assumed equal to 0.0081 m^3/kW. Since the data on methanol reformer units is very limited, assumptions had to be made. The assumption of the methanol reformer unit is based on internet images of methanol cracker units, here it is assumed a 1000 m^3/hour equals the size of eight 20-foot containers.

Fuel	**Power density FC systems**
Hydrogen	70 kW / m^3
Ammonia	54.5 kW / m^3
Methanol	44.6 kW / m^3

Table 5.2: Power density of selected fuel cell systems

The level of uncertainty of the numbers discussed in this subsection and used in the model is high. Although the effect of volume change of the power systems is not as high as the volume change caused by fuel storage, this can lead to inaccurate predictions. Therefor, recommendations about the machinery of alternative fuels are made in section 6.2.

5.1.3. Increase in ship dimensions

The volume of a specific storage system and power system for selected fuels can be calculated by adding up both volumes. In the dimension prediction method it is assumed that the ship is equipped with a MGO power system. The volume the MGO power and storage system has on board of the ship is calculated. The difference between the volume of the MGO systems and the selected alternative fuels is the volume which has to be fitted into the ship. This will automatically lead to an increase in ship dimensions. When estimating the increment of dimension, several assumptions have been made:

- On board of Ship A the lower 2 decks are available for storage and machinery;
- On board of Ship B the lower 3 decks are available for storage and machinery;
- On board of Ship C the lower 4 decks are available for storage and machinery;
- The L/B ratio remains the same unless Panamax beam dimension is reached;
- Only 60% of the beam ($0.6B_{wl}$) can be used for storage and machinery;

The volume difference between the MGO storage and power system and a selected alternative fuel or $\Delta V_{altfuel}$ has to be fitted in the vessel. The space needed can be calculated as follows:

$$\Delta V_{altfuel} = \Delta L * 0.6B * T \tag{5.2}$$

Taken the assumptions made above into consideration, the equation can be rewritten as follows:

$$\Delta V_{altfuel} = \Delta L * 0.6 * (\Delta L + L_{wl}) * \frac{B_{wl}}{L_{wl}} * n * h_{deck} \tag{5.3}$$

Where n is the number of decks which can be used for machinery and storage as determined above. In this equation the ΔL is the unknown variable. This equation can be solved for the required volume resulting in the ΔL and corresponding new L_{wl} and B_{wl}.

The increase in length will automatically lead to an increase of space available for passengers. This automatically means the N_{pax} input condition will be exceeded. Consequently, it also leads to new dimension ratios and an increased power resistance. It is for that reason that an iteration of the design model has to be performed.

5.1.4. Iteration

In the field of ship design, the design process of Evans, is still often used. In 1959 Evans created the design spiral which is illustrated in figure 5.2.

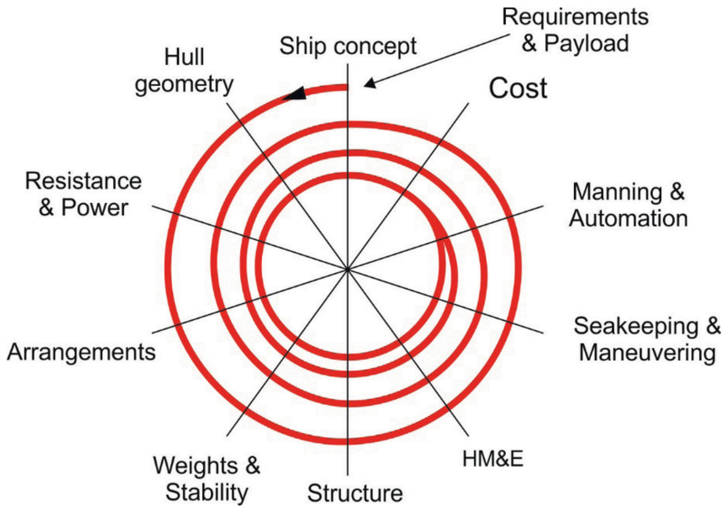


Figure 5.2: The design spiral of Evans

The spiral shaped time line illustrates the iterative characterisation of the design process of a ship. The process start with the input a customer delivers in the form of the mission requirements of the vessel. Consequently, the spiral leads to different phases of design where different types of aspects and subsystems are design. After completing the first round in the spiral, chances are that the ship design is not meeting mission requirements anymore. For example, when the ship length is increased, consequently the installed propulsion power has to be increased.

This is mainly due to the complex nature of ship designs. In the preliminary phases of ship design mostly simple calculations and assumptions are being used. In later stages, more accurate results can lead to adjustments in the first preliminary design. With this information, a new design iteration can be made until the mission requirements are met.

The iteration of the design for a carbon-neutral cruise vessel can be performed per selected fuel for a specific design. The design spiral as described above will not be completely performed since it will be too time consuming. Moreover, the design spiral as displayed in figure 5.2 also deliberates design aspect which are beyond the scope of this research such as seakeeping, stability and automation.

The output of the design model will include the dimension and number of passengers. In most cases, the number of passengers will exceed the number of passengers used as input. The first design iteration can be performed in order to come to the right amount of passengers. Here, the model will test different input for the passengers until the input variable is reached. Since making the design model in Microsoft Excel, the iteration can be performed automatically by making use of the build-in solver function of Excel. The solver is an optimisation tool which function evaluations are based on the recalculating of the model by changing the designated input of a model until the set objective is reached. In this case, the optimisation of the volume available on the ship is the objective of the solver.

The second iteration is based on the new ship resistance and installed power. Since the ship dimensions and volumes has increased, it is evident that the total ship resistance increased consequently. Again, an iteration is performed where the new ship dimensions are used in the Holtrop-Mennen prediction as explained in Chapter 4. Expected is that the increment of installed power will also cause a larger required energy consumption and storage. This again will result in a larger ship dimensions. This so called iteration loop can be performed until all input variables are met.

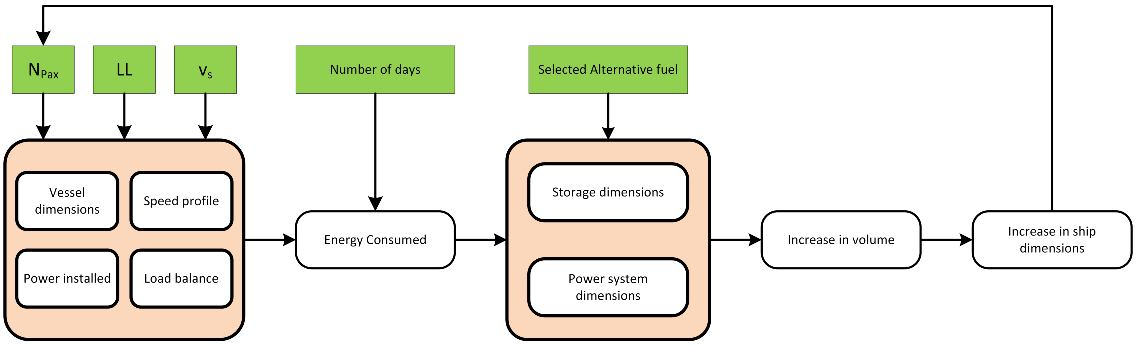


Figure 5.3: Schematic overview of the final design impact tool with iteration included

Since the tool was made in Microsoft Excel, calculation and simulation capacity is limited and the iteration can not be performed completely automatically with the solver. Therefore, iteration has to be performed partly manually. For this reason it was decided to only perform design iteration of the ship designs selected in next subsection. Subsequently, the model as illustrated in figure 5.1 can be adjusted to the following figure where the iteration is included.

5.2. Scenarios

To evaluate the design impact model, different ship types have to be considered. Since the model depends on 4 different input variables, a complete evaluation will be very time consuming and consequently generate too much data to evaluate in the time frame and scope of this research. Therefor, three different vessels will be taken into account. The vessels selected are based on the trends that are found in the parent cruise ship data set. Here it was found that small cruises with less than 750 passenger tend to have a high level of luxury and larger cruise vessel of over 2000 passengers commonly have a low level of luxury. Reasons behind this is the business model behind cruise vessels. When a high level of luxury is offered to the passenger, a higher ticket price with a corresponding higher margin can be charged. When level of luxury is less, the ticket price will decrease consequently since margins are lower when more passengers are on board and risk is lower. This trend was confirmed by several business reports from the Cruise Lines International Association (CLIA).

The Following 3 scenarios were tested in the design tool:

Input			**Ship A**	**Ship B**	**Ship C**
Passengers	N_{pax}		250	1000	2000
Luxury Level	LL		1	2	3
Maximum speed	v_s	[kn]	20	22	24
Specifications					
Gross tonnage	GT		17539	47940	72615
Length over all	L_{oa}	[m]	162.7	217.5	261.9
Length on waterline	L_{wl}	[m]	149.4	199.6	240.4
Beam	B_{wl}	[m]	22.7	29.7	32.3
Draft	T	[m]	5.5	7.2	7.8
Installed power	P_b	[kW]	11370	27072	40499
Minimum endurance	T_{days}	[days]	49	42	37
Energy consumption	E	[MWh/day]	48.1	140.1	241.5
MGO consumption	V_{MGO}	[m^3/trip]	471	1178	1789
Volume of prime mover	$V_{PM,MGO}$	[m^3]	300	712	1066

Table 5.3: Input and specifications of the three selected concept designs

Ship A could be compared to the *Seadream innovation* of Seadream cruises (figure 5.4a) that will be built by Damen Shipyards, ship B could be compared to *Crystal Serenity* of Crystal cruises could be compared to the *Norwegian Spirit* of Norwegian Cruise Lines. Ship C is the only vessel which has a beam that is limited to the panamax dimension of 32.3 meters.

(a) Seadream Innovation

(b) Crystal Serenity

(c) Norwegian Spirit

Figure 5.4: Cruise vessels within similar class as test vessels

5.3. Impact analysis of selected alternative fuels

5.3.1. Scenario I: Ship A

The first step is to calculate the volume of the selected fuels when used for Ship A. With this volume, the increase in length can be calculated which consequently results in an increase in GT and number of passengers. When analysing the design impact on ship A the following results can be found:

Ship A							
Fuel	V_{fuel} [m^3/trip]	GT	GT Increase [%]	L_{oa} [m]	L_{oa} increase [%]	N_{pax}	N_{pax} increase [%]
MGO	471	17539	-	162.7	-	250	-
Hydrogen - FC	1256	30465	73.7%	186.0	14.3%	289	15.6%
Ammonia - FC	962	21894	24.8%	170.6	4.8%	262	4.8%
Methanol - FC	775	18345	4.6%	164.2	0.9%	252	0.8%
Methanol - ICE	1086	20519	17.0%	168.1	3.3%	258	3.2%

Table 5.4: Increase in GT, L_{oa} and N_{pax} for selected fuels for Ship A

As expected, the implementation of hydrogen will have the biggest impact on the ship design. Ship length will increase with 14.3% resulting in a passenger increment of 15.6% as well. Noticeable, are the results of the methanol in fuel cell combination. Methanol has the highest volumetric energy content compared to ammonia and hydrogen. The volume of fuel cells is less than the volume of combustion engines resulting in the very small dimension differences between conventional the MGO vessel. Since difference is very small, it is decided that no iteration has to be performed on the MeOH - FC configuration.

The table above is visualised schematically in the following general arrangement:

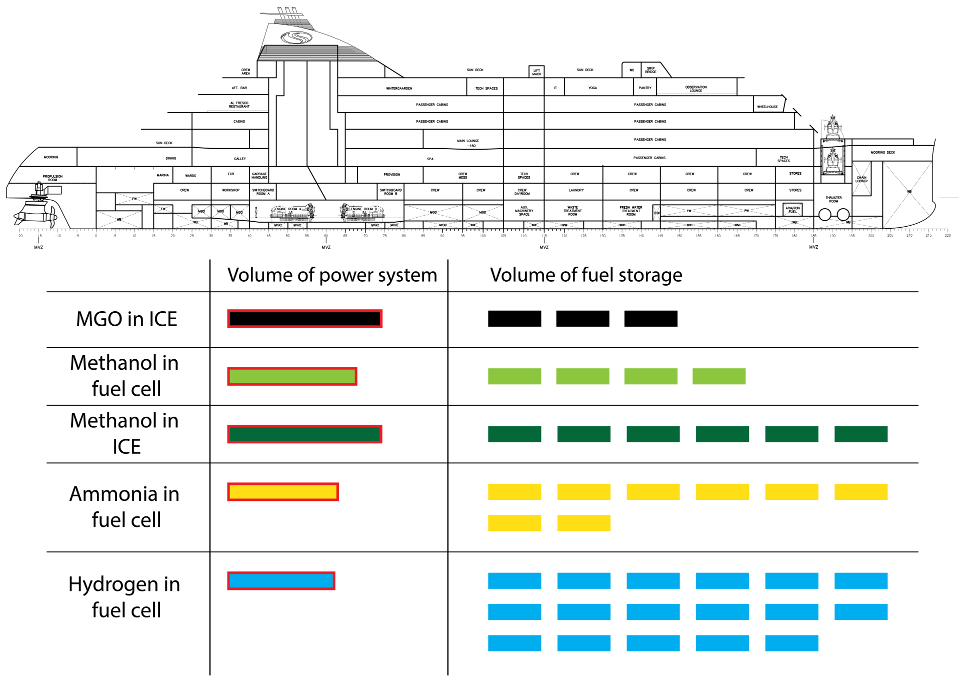


Figure 5.5: Visualization of the volumes of selected fuels and machinery on board of Ship A

Iteration

The first iteration performed is based on the number of passengers. Here, the goal is to find the vessel dimension based on the number of passengers. This is achieved by running the model over a range of passengers until the model output gives the number of passengers required.

Ship A

Fuel	N_{pax}	GT	GT Increase [%]	L_{oa} [m]	L_{oa} increase [%]
Hydrogen - FC	250	27254	55.4%	180.2	10.7%
Ammonia - FC	250	21208	20.9%	169.3	4.1%
Methanol - ICE	250	20006	14.1%	167.2	2.7%

Table 5.5: Increase in GT and L_{oa} after iteration of number of passengers of Ship A

The increase in dimension will consequently lead to an increase in vessel resistance and in required power installed and volume of fuel. Therefor, another design iteration has to be performed. This iteration is based on the new dimensions of the vessel, with the new dimensions, another Holtrop-Mennen prediction leads to the installed power (P_b) required. This leads to the following results shown in table 5.5.

Ship A

Fuel	P_b [kW]	P_b increase [%]	Δ V_{PM} [m^3]	E [MWh/trip]	ΔV_{fuel} [m^3]	ΔV_{Total} [m^3]	ΔL_{oa} [m]	L_{oa} [m]	GT
MGO	11370	-	-	2357	-	-	0.0	162.7	17539
Hydrogen - FC	14972	31.7%	51	3025	1230	1281	16.8	197.0	37143
Ammonia - FC	12707	8.9%	25	2596	171	196	2.6	171.9	23189
Methanol - FC	11604	1.8%	5	2402	19	24	0.3	164.5	19077
Methanol - ICE	12274	7.8%	24	2523	84	108	1.4	168.6	21347

Table 5.6: Increase in GT and L_{oa} after the iteration based on increase in P_b and energy stored for ship A

With both iterations performed, a new analysis of the vessels' dimensions can be made. The following dimensions apply to the carbon-neutral designs:

Ship A

Fuel	GT	GT increase [%]	L_{oa} [m]	B_{wl} [m]	T [m]	P_b [kW]
MGO	17539	-	162.7	22.7	5.5	11370
Hydrogen - FC	37143	111.8%	197.0	25.2	6.1	14972
Ammonia - FC	23189	32.2%	171.9	22.4	5.4	12707
Methanol - FC	19077	8.8%	164.5	21.6	5.2	11604
Methanol - ICE	21347	21.7%	168.6	22.0	5.3	12274

Table 5.7: Dimensions and installed power of Ship A for selected fuels

It is obvious that hydrogen will have the highest impact with an increase in GT of over 100%. Second, ammonia will have an impact of 32.2% on the GT. Methanol in the ICE combination comes after that with an impact of 21.7% in GT. Methanol in the FC combination will have the lowest impact due to the higher efficiency and higher power density of the fuel cells. Here, the GT is increased with 8.8%.

It is evident that in this design, a new series of iteration has to be performed considering the hydrogen, ammonia and methanol-CE designs. However, as stated in section 5.1.4, only one series of iterations is performed due to time limitations.

To visualise the possible designs, simplified general arrangements have been made regarding the 4 carbon-neutral designs which can be found for hydrogen below and in Appendix C.1.

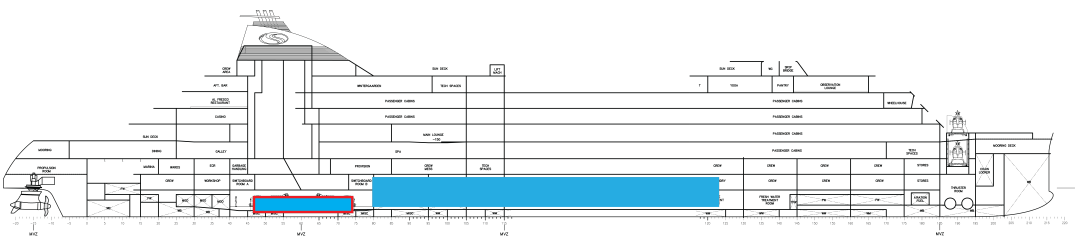


Figure 5.6: Schematic GA for Ship A for the hydrogen test case

5.3.2. Scenario I: Ship B

The first step is to calculate the volume of the selected fuels when used for Ship B. With this volume, the increase in length can be calculated which consequently results in an increase in GT and number of passengers. When analysing the design impact on Ship B the following results can be found:

Ship B

Fuel	V_{fuel} [m^3/trip]	GT	GT Increase [%]	L_{oa} [m]	L_{oa} increase [%]	N_{pax}	N_{pax} increase [%]
MGO	1178	47940	-	217.5	-	1000	-
Hydrogen - FC	2971	65124	35.8%	248.4	14.2%	1105	10.5%
Ammonia - FC	2403	54478	13.6%	229.2	5.4%	1040	4.0%
Methanol - FC	1937	50401	5.1%	221.9	2.0%	1015	1.5%
Methanol - ICE	2712	52439	9.4%	225.6	3.7%	1027	2.7%

Table 5.8: Increase in GT, L_{oa} and N_{pax} for selected fuels for Ship B

As expected, the implementation of hydrogen will have the biggest impact on the ship design. Ship length will increase with 14.3% resulting in a passenger increment of 15.6% as well. Noticeable, are the results of the methanol in fuel cell combination. Methanol has the highest volumetric energy content compared to ammonia and hydrogen. The volume of fuel cells is less than the volume of combustion engines resulting in the very small dimension differences between conventional the MGO vessel. Since difference is very small, it is decided that no iteration has to be performed on the MeOH - FC configuration.

The table above is visualised schematically in the following general arrangement:

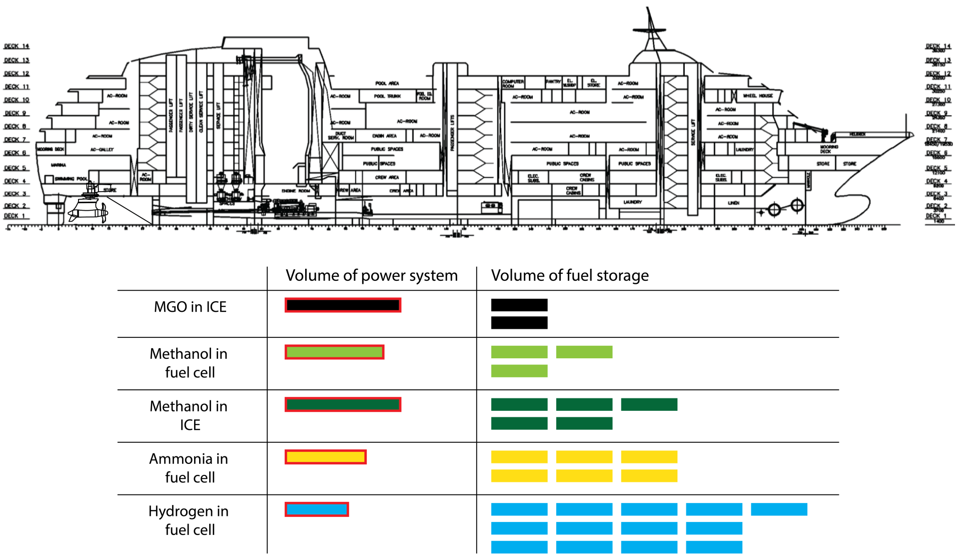


Figure 5.7: Visualization of the volumes of selected fuels and machinery on board of Ship B

Iteration

The first iteration performed is based on the number of passengers. Here, the goal is to find the vessel dimension based on the number of passengers. This is achieved by running the model over a range of passengers until the model output gives the number of passengers required.

Ship B

Fuel	N_{pax}	GT	GT Increase [%]	L_{oa} [m]	L_{oa} increase [%]
Hydrogen - FC	1000	59236	23.6%	237.8	9.4%
Ammonia - FC	1000	52335	9.2%	225.4	3.6%
Methanol - ICE	1000	51068	6.5%	223.1	2.6%

Table 5.9: Increase in GT and L_{oa} after iteration of number of passengers of Ship B

The increase in dimension will consequently lead to an increase in vessel resistance and in required power installed and volume of fuel. Therefor, another design iteration has to be performed. This iteration is based on the new dimensions of the vessel, with the new dimensions, another Holtrop-Mennen prediction leads to the installed power (P_b) required. This leads to the following results shown in table 5.5.

Ship B

Fuel	P_b [kW]	P_b increase [%]	$\Delta\ V_{PM}$ [m^3]	E [MWh/trip]	ΔV_{fuel} [m^3]	ΔV_{Total} [m^3]	ΔL_{oa} [m]	L_{oa} [m]	GT
MGO	27072	-	-	5884	-	-	-	217.5	47940
Hydrogen - FC	30271	11.8%	46	6683	1470	1516	7.6	245.4	64008
Ammonia - FC	28226	3.8%	21	6130	176	197	1.0	226.4	53439
Methanol - FC	27622	2.0%	12	5979	40	53	0.3	222.2	51103
Methanol - ICE	27825	2.7%	20	6055	87	107	0.5	223.6	51920

Table 5.10: Increase in GT and L_{oa} after the iteration based on increase in P_b and energy stored for ship B

With both iterations performed, a new analysis of the vessels' dimensions can be made. The following dimensions apply to the carbon-neutral designs:

Ship B

Fuel	GT	GT increase [%]	Length L_{oa} [m]	Beam B_{wl} [m]	Draft T [m]	P_b [kW]
MGO	47940	-	217.5	29.7	7.2	27072
Hydrogen - FC	64008	33.5%	245.4	30.6	7.4	30271
Ammonia - FC	53439	11.5%	226.4	28.5	6.9	28226
Methanol - FC	51103	6.6%	222.2	28.0	6.8	27622
Methanol - ICE	51920	8.3%	223.6	28.2	6.8	27825

Table 5.11: Dimensions and installed power of Ship B for selected fuels

It is obvious that hydrogen will have the highest impact with an increase in GT of over 100%. Second, ammonia will have an impact of 32.2% on the GT. Methanol in the ICE combination comes after that with an impact of 21.7% in GT. Methanol in the FC combination will have the lowest impact due to the higher efficiency and higher power density of the fuel cells. Here, the GT is increased with 8.8%.

It is evident that in this design, a new series of iteration has to be performed considering the hydrogen, ammonia and methanol-CE designs. However, as stated in section 5.1.4, only one series of iterations is performed due to time limitations.

To visualise the possible designs, simplified general arrangements have been made regarding the 4 carbon-neutral designs which can be found in Appendix C.2.

5.3.3. Scenario I: Ship C

The first step is to calculate the volume of the selected fuels when used for Ship C. With this volume, the increase in length can be calculated which consequently results in an increase in GT and number of passengers. When analysing the design impact on Ship C the following results can be found:

Ship C

Fuel	V_{fuel} [m^3/trip]	GT	GT Increase [%]	L_{oa} [m]	L_{oa} increase [%]	N_{pax}	N_{pax} increase [%]
MGO	1789	72615	-	261.9	-	2000	-
Hydrogen - FC	4364	90986	25.3%	294.9	12.6%	2192	9.6%
Ammonia - FC	3651	79785	9.9%	274.8	4.9%	2075	3.8%
Methanol - FC	2943	74800	3.0%	265.8	1.5%	2022	1.1%
Methanol - ICE	4120	77523	6.8%	270.7	3.4%	2051	2.6%

Table 5.12: Increase in GT, L_{oa} and N_{pax} for selected fuels for ship C

As expected, the implementation of hydrogen will have the biggest impact on the ship design. Ship length will increase with 14.3% resulting in a passenger increment of 15.6% as well. Noticeable, are the results of the methanol in fuel cell combination. Methanol has the highest volumetric energy content compared to ammonia and hydrogen. The volume of fuel cells is less than the volume of combustion engines resulting in the very small dimension differences between conventional the MGO vessel. Since difference is very small, it is decided that no iteration has to be performed on the MeOH - FC configuration.

The table above is visualised schematically in the following general arrangement:

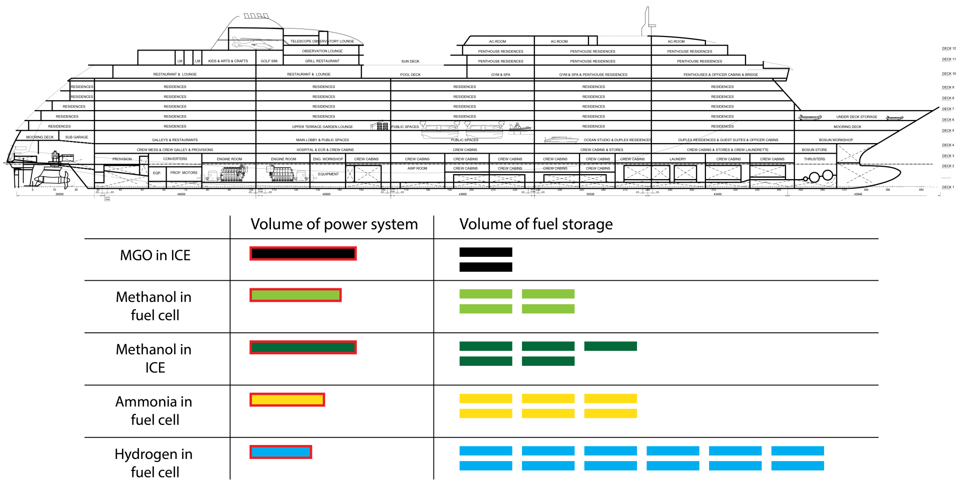


Figure 5.8: Visualization of the volumes of selected fuels and machinery on board of Ship C

Iteration

The first iteration performed is based on the number of passengers. Here, the goal is to find the vessel dimension based on the number of passengers. This is achieved by running the model over a range of passengers until the model output gives the number of passengers required.

Ship C

Fuel	N_{pax}	GT	GT Increase [%]	L_{oa} [m]	L_{oa} increase [%]
Hydrogen - FC	2000	83254	14.7%	281.0	7.3%
Ammonia - FC	2000	76933	5.9%	269.6	3.0%
Methanol - ICE	2000	75648	4.2%	267.3	2.1%

Table 5.13: Increase in GT and L_{oa} after iteration of number of passengers of Ship C

The increase in dimension will consequently lead to an increase in vessel resistance and in required power installed and volume of fuel. Therefor, another design iteration has to be performed. This iteration is based on the new dimensions of the vessel, with the new dimensions, another Holtrop-Mennen prediction leads to the installed power (P_b) required. This leads to the following results shown in table 5.13.

Ship C									
Fuel	P_b [kW]	P_b increase [%]	Δ V_{PM} [m^3]	E [MWh/trip]	ΔV_{fuel} [m^3]	ΔV_{Total} [m^3]	ΔL_{oa} [m]	L_{oa} [m]	GT
MGO	40499	-	-	8937	-	-	-	261.9	72615
Hydrogen - FC	42851	5.8%	34	9447	939	973	3.0	284.0	85469
Ammonia - FC	41208	1.7%	13	9128	137	150	0.6	270.2	77796
Methanol - FC	40675	0.4%	177	8994	24	201	0.7	266.6	75767
Methanol - ICE	40891	1.0%	10	9068	66	77	0.3	267.6	76360

Table 5.14: Increase in GT and L_{oa} after the iteration based on increase in P_b and energy stored for ship C

With both iterations performed, a new analysis of the vessels' dimensions can be made. The following dimensions apply to the carbon-neutral designs:

Ship C						
Fuel	GT	GT increase [%]	Length L_{oa} [m]	Beam B_{wl} [m]	Draft T [m]	P_b [kW]
MGO	72615	-	261.9	32.3	7.8	40499
Hydrogen - FC	85469	17.7%	284.0	32.3	7.8	42851
Ammonia - FC	77796	7.1%	270.2	32.3	7.8	41208
Methanol - FC	75767	4.3%	266.6	32.3	7.8	40675
Methanol - ICE	76360	5.2%	267.6	32.3	7.8	40891

Table 5.15: Dimensions and installed power of Ship C for selected fuels

It is obvious that hydrogen will have the highest impact with an increase in GT of over 100%. Second, ammonia will have an impact of 32.2% on the GT. Methanol in the ICE combination comes after that with an impact of 21.7% in GT. Methanol in the FC combination will have the lowest impact due to the higher efficiency and higher power density of the fuel cells. Here, the GT is increased with 8.8%.

It is evident that in this design, a new series of iteration has to be performed considering the hydrogen, ammonia and methanol-CE designs. However, as stated in section 5.1.4, only one series of iterations is performed due to time limitations.

To visualise the possible designs, simplified general arrangements have been made regarding the 4 carbon-neutral designs which can be found in Appendix
refsec:App$_G A_C$.

5.3.4. CAPEX and OPEX analysis

With the values of the CAPEX and OPEX as stated in section 3.3, an analysis can be made for the 3 test scenarios. Here it should be noted that this part of the research is indicative and characterised by a high level of uncertainty. This is mainly due to the fact that the OPEX values are based on the price of renewable energy, which is fluctuating and varies worldwide. When considering CAPEX values high inaccuracy is expected due to the fact that no fuel cell power system markets are yet established. Prices are all based on assumptions.

The following values are found:

Ship A

Fuel	P_b [kW]	CAPEX [$]	CAPEX increase [factor]	E [MWh / trip]	Fuel costs [$ / trip]	OPEX increase [factor]
MGO	11370	$2,842,500	-	2357	$119,224	-
Hydrogen - FC	14972	$44,915,700	15.8	3025	$605,088	5.1
Ammonia - FC	12707	$38,121,000	13.4	2596	$584,020	4.9
Methanol - FC	11604	$34,811,100	12.2	2402	$540,37	4.5
Methanol - CE	12274	$5,216,280	1.8	2523	$567,587	4.8

Table 5.16: CAPEX and OPEX for selected fuels for Ship A

Ship B

Fuel	P_b [kW]	CAPEX [$]	CAPEX increase [factor]	E [MWh / trip]	Fuel costs [$ / trip]	OPEX increase [factor]
MGO	27072	$6,767,936	-	5884	$297,620	-
Hydrogen - FC	30271	$90,813,600	13.4	6683	$1,336,562	4.5
Ammonia - FC	28226	$84,678,900	12.5	6130	$1,379,141	4.6
Methanol - FC	27622	$82,867,200	12.2	5979	$1,345,243	4.5
Methanol - CE	27825	$11,825,540	1.7	6055	$1,362,374	4.6

Table 5.17: CAPEX and OPEX for selected fuels for Ship B

Ship C

Fuel	P_b [kW]	CAPEX [$]	CAPEX increase [factor]	E [MWh / trip]	Fuel costs [$ / trip]	OPEX increase [factor]
MGO	40499	$10,124,680	-	8937	$452,064	-
Hydrogen - FC	42851	$128,553,300	12.7	9447	$1,889,441	4.2
Ammonia - FC	41208	$123,623,100	12.2	9128	$2,053,845	4.5
Methanol - FC	40675	$122,025,900	12.1	8994	$2,023,634	4.5
Methanol - CE	40891	$17,378,633	1.7	9068	$2,040,219	4.5

Table 5.18: CAPEX and OPEX for selected fuels for Ship C

The values of the CAPEX and OPEX are not considered criteria for the selection of fuels or machinery as determined in 3.3. However, when analysing the data above it is evident that the transition to carbon-neutral cruise vessels will have a significant impact on the CAPEX and OPEX and therefor the business model of cruise operators.

5.4. Conclusion

In this chapter, the primary objective was to investigate the impact of selected alternative fuels on the design and operation of a cruise vessel.

In order to achieve this, a design impact tool was established first. The tool required input regarding the number of passengers (N_{pax}), the level of luxury (LL) and the maximum design speed (v_s) of cruise vessels. Consequently, the tool used the model described in Chapter 4 to calculate the dimensions and installed power of a cruise vessel. Next, the selected fuels and power systems were implemented. Here, the volume required was calculated. After two design iterations where first the number of passengers was required and next the necessary propulsion power was required, 4 different possible designs were found.

In this research, the tool was tested for 3 scenario's: Small cruise vessels with high luxury levels (Ship A), medium-sized cruise vessels with medium luxury levels (Ship B) and large cruise vessels with low luxury levels (Ship C). With information from Chapter 4, the design impact model and data from the test scenario's, the last sub-objective could be answered, which is stated as follows:

ii *Analyse the impact selected carbon-neutral fuels have on the cruise vessels' design and operation*

From this part of the research it was concluded that:

- Hydrogen has the highest impact on the design of a ship when considering the increase in dimension. For smaller cruise vessels this can lead to an increase of GT of over 100%. With large cruise vessels this increase is smaller, as it would result in a 20% increase in GT. This evidently leads to the conclusion that hydrogen is not feasible as an alternative fuel.
- Ammonia has a smaller impact compared to hydrogen with an increase in GT of 30% and 7% for a small and large cruise vessel respectively. The cracker that is installed in order to crack ammonia into hydrogen requires extra volume, however.
- • Methanol has the smallest impact on the design of the vessel compared to hydrogen and ammonia. When used in an ICE the volumetric consumption is higher due to the lower efficiency of the ICE compared to the fuel cell. When used in an ICE on board of a small cruise vessel this leads to an increase of around 22% and 9% when used in a fuel cell. On board of large cruise vessels, the impact of both methanol in an ICE as well as in a fuel cell lies around 5%.
- • When looking at the financial impact selected fuels have on the ship it can be concluded that the use of fuel cells on board will cause a major increase in the CAPEX of the ship, with a value ranging from 12 to 16 times the CAPEX of a conventional diesel engine. The OPEX of selected fuels is also higher, resulting in an increase of around 4.5 times compared to MGO.

6 Conclusions and recommendations

6.1. Conclusions

The objective of this thesis was stated as follows:

Evaluate possible alternative power sources and carriers that can power carbon-neutral cruise vessels

From the findings in this thesis the following can be concluded:

- Within the wide range of alternative carbon-neutral fuels, hydrogen, DME, methanol, ethanol, methane, FT Diesel and ammonia produced with renewable electric energy have the potential to be applied on board of cruise vessels;
- Based on production properties, liquid hydrogen, liquid ammonia and methanol are selected as the most feasible alternative fuels for use on board a cruise vessel;
- On-board storage of liquid hydrogen and ammonia will be challenging. When stored in dedicated storage tanks, liquid hydrogen and ammonia will take respectively 10 and 4 times as much space as conventional MGO for the same amount of energy. Methanol is not limited by storage requirements and requires 2.2 times as much volume as MGO due to the volumetric energy content;
- All selected fuels can be used in both a combustion engine and fuel cell. Ammonia needs to be cracked before being used in a fuel cell or ICE. Methanol can be used directly in an ICE but has to be reformed for use in a fuel cell;
- Efficiency of hydrogen and ammonia in an ICE is low and is still a technology which has yet to be proven. Methanol shows most favourable characteristics when used in an ICE;
- Hydrogen will have the most impact on ship design due to the volume increase on board of smaller ships (<500 pax) as GT can increase with 100% when hydrogen is used. On larger cruise vessels (>2000 pax) this is around 20%. This makes hydrogen unfeasible for use on board a cruise ship;
- • Ammonia has the second most impact on ship design. The GT increase lies around 30% on board of smaller ships and 7% on board of larger ships. Although impact on GT is smaller, the uncertainty of the usage on board is higher. The TRL is low compared to that of hydrogen and methanol due to uncertainties regarding, for example, the cracking of ammonia on board of ships. Ammonia is considered unfeasible on board of small cruise vessels, and further research has to prove the use of ammonia on larger cruise vessels;
- Methanol has the least impact on board of a cruise vessel. On smaller cruise vessels methanol in a fuel cell will have the lowest impact with an increase in GT of only 9%. Methanol in ICE results in an increase of 22%. When considering large cruise vessels the impact for both methanol in a fuel cell and ICE is around 5%. Based on the production, implementation requirements and design impact of the selected fuels, methanol in a fuel cell shows to be the most feasible alternative carbon-neutral fuel. When TRL is considered, methanol in a combustion engine has more favourable characteristics causing it to be the most feasible carbon-neutral fuel for implementation on board a cruise ship in the short-term.

6.2. Recommendations

It is inevitable that current maritime fuels and associated energy conversions will have to change in the short term to reduce CO_2 emissions from ships and to help combat climate change. The maritime industry will have to prepare for this. The type of research that has been done in this thesis is thus of great importance in identifying possible alternative fuel solutions. Despite the large number of uncertainties and the many assumptions that must be made in this type of research, it will not be the outcome of specific analyses but the research as a whole that can help lead to a solution. New technologies have always been an summation of individual efforts by students, academics, knowledge institutes and industry. Having said this, the main recommendation of this thesis will therefore be to continue carrying out research in the field of alternative fuels for different types of ships, in different design spaces, with different fuels and for different configurations.

Based on the outcomes of this research, the last sub-objective as described in section 1.2 can be answered:

iv *Provide an outline for future developments and research of alternative carbon-neutral fuels in the cruise ship industry.*

The following recommendations can be made:

- In this research selected fuels have been researched within a fixed design space, being cruise vessels. Several assumptions regarding fuel production, fuel storage and efficiency of machinery have let to the selection of fuels. It is recommended to conduct a sensitivity study regarding the assumptions made within this design space. Here, the goal would be to perform the design iteration again for a most optimal and least optimal set of parameters regarding the selected fuels.
- It is recommended to conduct research where the design space is expanded. Cruise vessels have a very high load balance making this type of vessels less suitable for the implementation of alternative fuels. This research could also be a partial solution for the power demand on board of a cruise vessel where for example, only passenger services energy is being generated in a carbon-neutral way.
- A study has to be performed regarding the global availability and production of alternative fuels. In this point in time it is highly uncertain what alternative fuel has the most potential being a feasible maritime fuel. One reason is the fact that this is highly depended on the geographical location where the fuel is available. The goal of this study should be to create a better insight in local fuel production and how the fuel is transported to the location where it is used.
- When further research does support the conclusions of this research, being that methanol is a feasible alternative fuel for carbon-neutral cruise vessels. Further research has to be conducted where the level of detail of design aspects of cruise vessels has to be taken into account. In this kind of research the goal would be to perform more design iterations resulting in reliable dimension predictions.

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A

Appendix A: General Appendix

A.1. Alternative fuels

	Category	Name	Selected	Reason when not selected	Literature
Electrofuel	Hydrogen	Hydrogen	Yes		[8] [36]
Electrofuel	Hydride	Ammonia	Yes		[67] [40]
Electrofuel	Syntethic hydrocarbon	FT Diesel	Yes		[22] [41] [2] [53] [43] [56] [36]
Electrofuel / Biofuel	Alcohol	Methanol	Yes		[12] [70] [14] [13] [43] [36] [13]
Electrofuel / Biofuel	Alcohol	Ethanol	Yes		[38] [7] [62] [14] [23] [20] [36]
Electrofuel / Biofuel	Ether	DME	Yes		[11] [73] [58] [63] [37] [57]
Electrofuel / Biofuel	Alkane	Methane	Yes		[34]
Electrofuel	Hydrides	Sodium borohydride	No	TRL	[55]
	Hydride	Borium hydride	No	TRL	[55]
Crude	-	Metal powder	No	TRL	[9]
Crude	-	Alluminium powder	No	TRL	[59]
Mechanical	-	Flying wheel	No	Energy Density	[30] [27]
Mechanical	-	Compressed air	No	Energy Density	[30] [27]
Thermal energy	-	Cryogens	No	Energy Density	[32] [29] [49]
Electro chemical	-	Battery	No	Energy Density	[19]
Thermal energy	-	Molton salts	No	Energy Density	[74]

Table A.1: Alternative carbon-neutral fuels as analysed in this research

A.2. Possible porpulsion system lay out of selected fuels

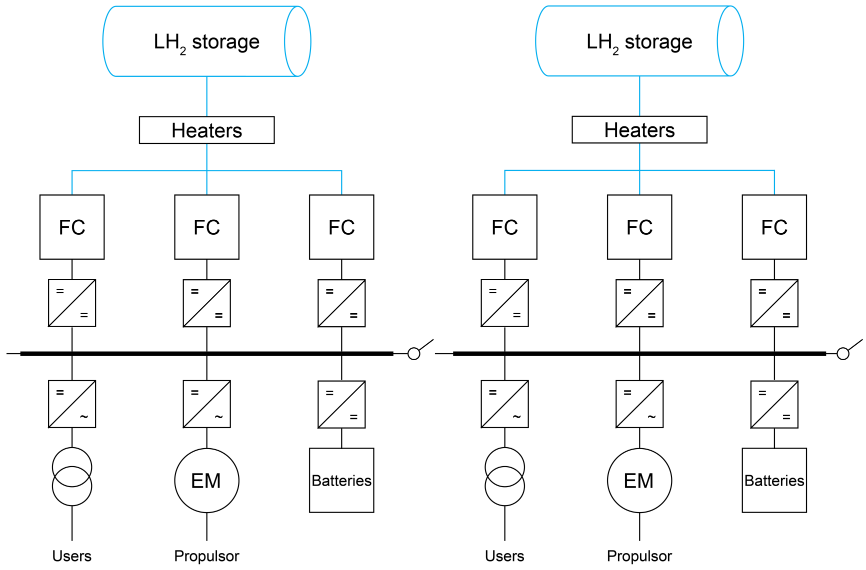

Figure A.1: Potential lay-out of liquid hydrogen power system

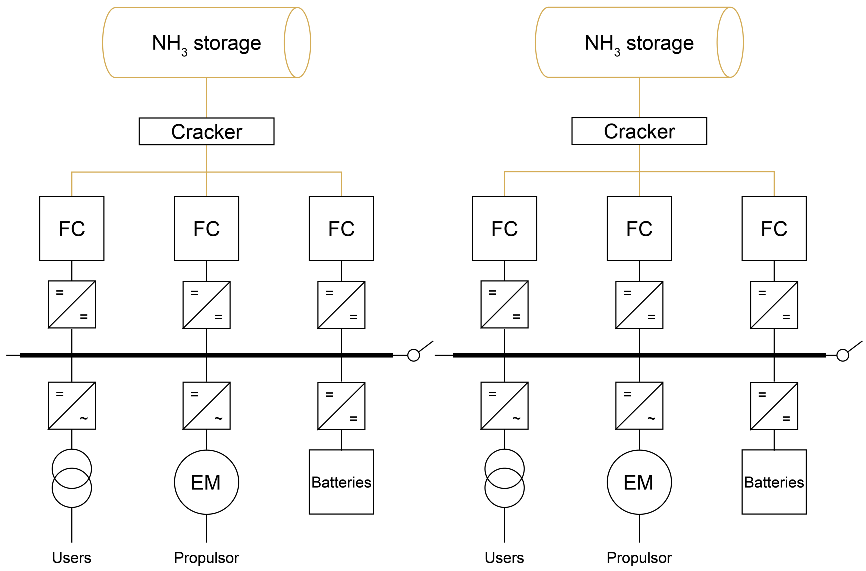

Figure A.2: Potential lay-out of liquid ammonia power system

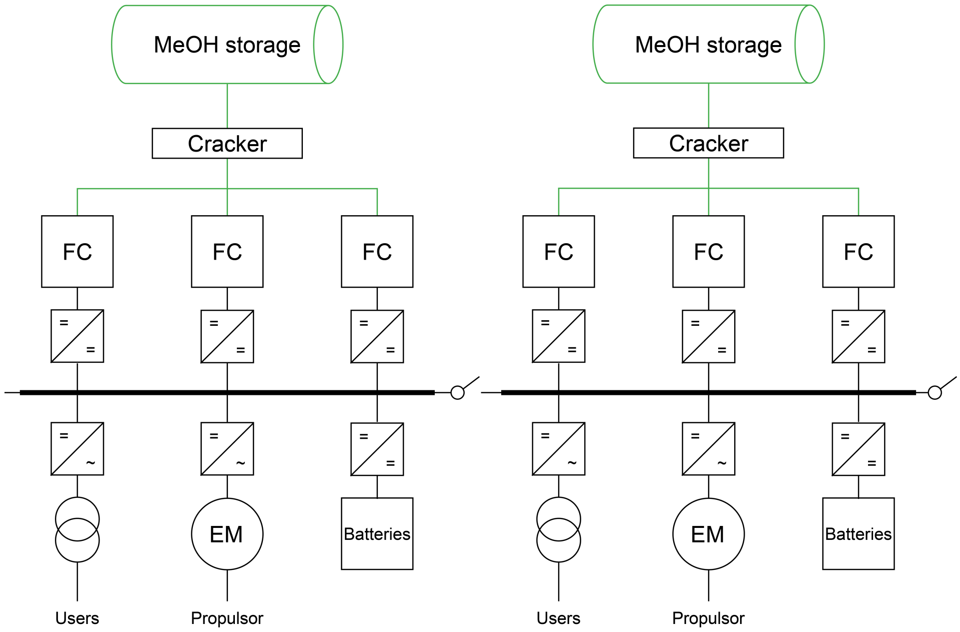

Figure A.3: Potential lay-out of methanol fuel cell power system

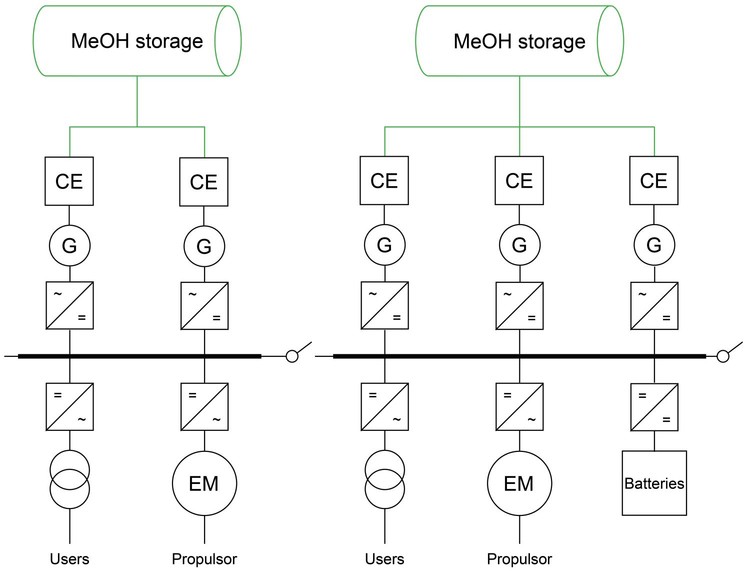

Figure A.4: Potential lay-out of methanol ICE power system

A.3. Method of Townsin

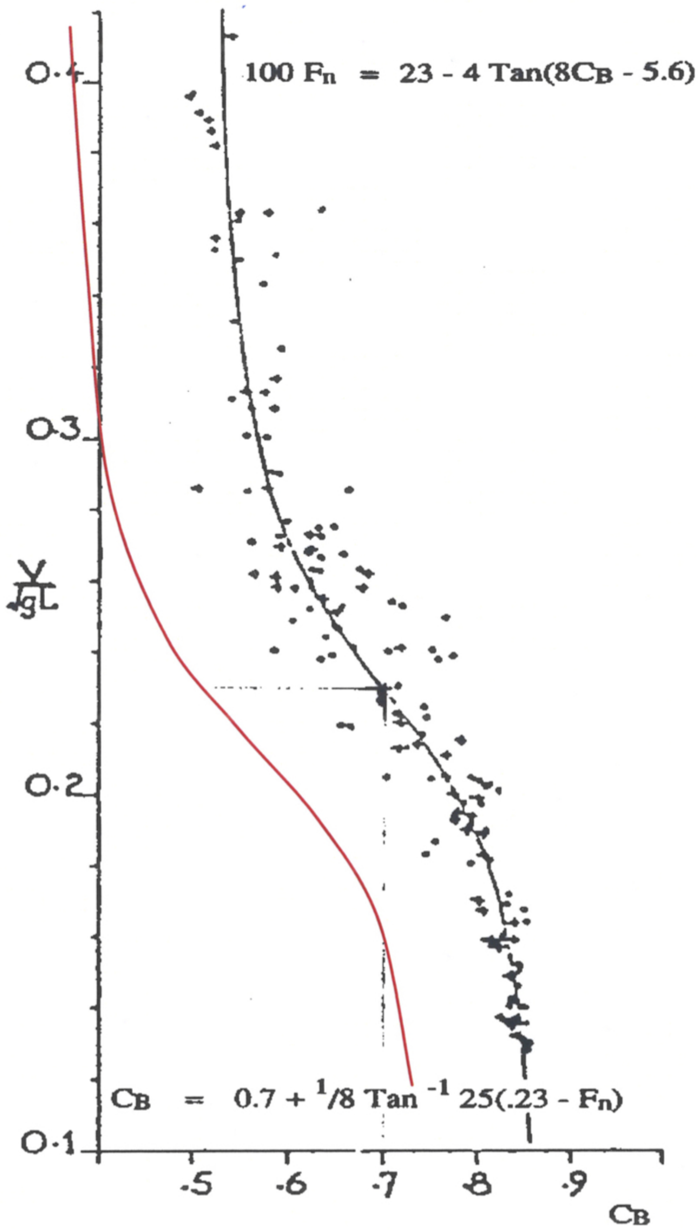

Figure A.5: The correlation found by Townsin

A.4. Resistance and power prediction method of Holtop and Mennen

The resistance and power prediction used in this research is based on the Holtrop-Mennen prediction [25]. This method relies on the following equation that determines total resistance:

$$R_{Total} = R_F * (1+k) + R_{App} + R_W + R_B + R_{Tr} + RA$$

The total resistance is subdivided into the following restitance components:

$R_F = 0.5 * \rho_{sw} * S * v_s^2 * C_F$
$R_{App} = 0.5 * \rho_{sw} * A_{app} * v_s^2 * (1+k_2)$
$R_W = c_1 * c_2 * c_5 * \nabla * \rho_{sw} * \exp m_1 * Fn^d + m_2 * \cos\lambda * Fn^{-2}$
$R_B = 0.11 * \exp -3 * P_B^{-2} * Fn_i^3 * A_{bt}^{1.5} * \rho_{sw} * g/(1+Fn_i^2)$
$R_{Tr} = 0.5 * \rho sw * v_s^2 * A_m * c_6$
$R_A = 0.5 * \rho_{sw} * S * v_s^2 * C_A$

The area of the vessel, described as S is calculated as follows:

$S = L(2T+B)\sqrt{C_M}(0.453 + 0.4425C_B - 0.2862C_M - 0.003467B/T + 0.3696C_{WP}) + 2.38A_{BT}/C_B$

The area of the appendages on board of the vessel has been assumed based on the area of 2 Azimuth thruster pods (100 m^2 each) and 2 stabiliser fins (20 m^2 each):

$A_{app} = 240$

Other area surface can be calculated as follows:

$A_{bt} = A_m * C_{ABT}$
$A_m = B * T * C_M$

Form factors used are calculated as follows:

$(1+k_1) = c_{13} * (0.93 + c_{12}(\frac{B}{L_R})^{0.92497} * (0.95 - C_p)^{-0.521448} * (1 - C_p + 0.225lcb)^{0.6906})$
$(1+k_2) = 2$

The constants used in the equations are described as follows:

$c_1 = 2223105 * c_7^{3.78613}(T/B)^{1.07961}(90 - i_E)^{-1.37565}$
$c_2 = e^{-1.89*\sqrt{c_3}}$
$c_3 = 0.56A_{BT}^{1.5}/(BT(0.31\sqrt{A_{BT}} + T_F - h_B))$
$c_4 = \frac{T}{L_{wl}}$
$c_5 = 1 - 0.8 * A_M * \frac{1}{B*T*C_M}$
$c_6 = 0.2 * (1 - 0.2 * Fn_t)$
$c_7 = \frac{B}{L}$
$c_{12} = 48.20(T/L - 0.02)^{2.078} + 0.479948$
$c_{13} = 1 + 0.003 * C_{stern}$
$c_{15} = -1.69385 + (L/\tau^{1/3} - 8.0)/2.36$
$C_A = (5.68 - 0.6\log Re) * 10^{-3}$
$C_{ABT} = 0.075$
$C_B = 0.7 + 0.125\tan^{-1}\frac{23-100*Fn}{4}$
$C_F = \frac{.075}{log[10][2]Rn-2}$
$C_M = 0.8 + 0.21 * C_B$
$C_P = \frac{}{L_{WL}*A_M}$

$C_{WP} = \frac{2}{3} * C_B + \frac{1}{3}$
$C_{Stern} = +10$
$\lambda = 1.446 * C_P - 0.03 * L_{WL}/B$

For the froude number, Fn_i, which is the Froude number based on the immersion where the coefficient, Fn_t, which is the Froude number based on the transom immersion, and P_B which is a measure for the emergence of the bow, the following calculations are used:
$Fn = \frac{v_s}{\sqrt{g*L_{wl}}}$
$Fn_i = \frac{v_s}{g*(T-h_b-0.25*\sqrt{A_{BT}})+0.15*v_s^2}$ $Fn_t = \frac{v_s}{\sqrt{\frac{2*g*A_t}{B+B*C_{WP}}}}$
$Rn = \frac{L_{wl}*v_s}{\mu}$
$P_B = 0.56 * \sqrt{A_{BT}}/(T_F - 1.5 * h_B$

In this research, the following constants are used:
$\rho = 1010$
$\mu = 0.00108$
$g = 9.81$

Lastly, the effective power required, P_E, can be calculated with the total resistance and maximum design speed:

$P_E = R_{Total} * v_s$

A.5. Power density of internal combustion engines and scrubbers

Combustion engine volumes

Manufacturer	**MAK**	
Model	**VM 46 DF**	
L	16.9	m
B	6.5	m
H	4.0	m
Volume	443	m3
Rated power	14807	kW
Power densit	**33**	**kW / m3**

Manufacturer	**Caterpillar**	
Model	**C280-8**	
L	8.0	m
B	2.0	m
H	3.9	m
Volume	62.1	m3
Rated power	2420	kW
Power densit	**39.0**	**kW / m3**

Manufacturer	**MAN**	
Model	**18V60**	
L	18.6	m
B	4.7	m
H	6.5	m
Volume	570	m3
Rated power	18900	kW
Power densit	**33**	**kW / m3**

Manufacturer	**Wartsila**	
Model	**A32 W9L32**	
L	10.5	m
B	2.9	m
H	3.9	m
Volume	119	m3
Rated power	5010	kW
Power densit	**42**	**kW / m3**

Manufacturer	**MAN**	
Model	**L32/40**	
L	18.6	m
B	4.7	m
H	6.5	m
Volume	570	m3
Rated power	18900	kW
Power densit	**33**	**kW / m3**

Manufacturer	**Wartsila**	
Model	**16V32**	
L	11.5	m
B	3.4	m
H	4.4	m
Volume	171	m3
Rated power	8600	kW
Power densit	**50**	**kW / m3**

Manufacturer	**Wartsila**	
Model	**9L20DF**	
L	6.5	m
B	2.3	m
H	2.8	m
Volume	43	m3
Rated power	1600	kW
Power densit	**38**	**kW / m3**

Manufacturer	**Caterpillar**	
Model	**C280-16**	
L	9.3	m
B	2.0	m
H	4.2	m
Volume	77	m3
Rated power	4840	kW
Power densit	**63**	**kW / m3**

Minimum power density	**38**	**kW / m3**
Maximum power density	**63**	**kW / m3**
Average power density	**41.4**	**kW / m3**

Scrubber volumes

Wartsila Engine Type	6L20	8L20	6L32	8L32	9L32	8L46F	12V46F
L [m]	3.2	3.2	3.5	3.5	4.0	4.2	4.4
B [m]	1.2	1.2	1.6	1.6	1.8	2.3	2.6
H [m]	1.0	1.2	1.5	1.6	1.8	2.1	2.6
Volume [m^3]	3.7	4.2	8.5	9.4	13.0	20.3	29.7
Engine power [kW]	1200	1600	3480	4640	5220	9600	14400
Volume scrubber [m^3 / kW]	**0.0030**	**0.0026**	**0.0024**	**0.0020**	**0.0025**	**0.0021**	**0.0021**

Average volume	**0.0024 [m^3 / kW]**

A.6. Power density of fuels cells

Manufacturer	Type	kW / m3
Nedstack	2 KW	165
	5 KW	254
	8 KW	292
	9.5 KW	309
Ballard	30kW FCveloCity®-MD	185
	HD60	121
	HD85	171
	HD100	190
	FCveloCity-HD6	114
	FCveloCity-HD6	227
	FCveloCity-XD100	128
	FCveloCity-XD200	101
Hydrogenics	Celerity	204
	HyPM-HD 180	167
	HyPM-HD 90	157
	HyPM-HD 30	407
	R120	70
	R30	24
PowerCell	MS 100	333
US hybrid	Fce 150 (130 continous)	227
	Fce 80	159
UTC Power	pure motion 120	66
Horizon Fuel Cell Technologies	VL-30 Fuel Cell	460
HES Energy Systems	Aerostak 1000	219
SerEnergy A/S	30k rack	19
Siemens	FCM 34	102
	FCM 120	257
	FCM BG 80	172
	FCM NG 135	289

Table A.2: Power density of PEM fuel cells as found on the corresponding company website

B

Appendix B: Parent cruise ship database

B.1. Specifics of parent cruise ship database

Vessel name	IMO number	Operator	Year launched	Gross Tonnage (GT)	Length over all [m]	Breadth waterline [m]	Draft [m]	Decks	Passengers	Crew
AidaAura	9221566	Aida	2003	42289	202.8	28.1	6.2	12	1300	418
Amsterdam	9188037	HAL	2000	62735	237.0	32.3	8.1	15	1380	647
Aurora	9169524	P&O	2000	76152	270.0	32.3	7.9	13	1950	850
Azamara Journey	9200940	Azmara	2000	30277	181.0	25.5	5.8	11	694	372
Carnival Miracle	9237357	Carnival	2003	85942	294.0	32.3	8.0	14	2124	930
Crystal Serenity	9243667	Crystal	2003	68870	250.0	32.3	8.0	13	980	665
Grandeur of the Seas	9102978	RCI	1996	73817	279.0	32.3	7.8	14	2446	760
Le Lyrial	9704130	Ponant	2015	10700	142.0	18.0	4.8	8	264	139
Marina	9438066	Oceania	2010	66084	238.4	32.3	7.3	16	1250	780
Nieuw Amsterdam	9378450	HAL	2009	86700	285.3	32.3	7.9	15	2106	929
Noordam	9230115	HAL	2006	82318	285.3	32.3	7.9	15	1916	800
Norwegian Spirit	9141065	NCL	1998	75400	267.9	32.3	7.9	13	1996	965
Oceana	9169550	P&O	2000	77499	261.3	32.3	8.1	15	2272	889
Pride of America	9209221	NCL	2005	80439	280.6	32.3	8.0	14	2186	927
Seabourn Encore	9731171	Seabourn	2016	41865	210.5	28.0	6.5	12	635	380
Seabourn Odyssey	9417086	Seabourn	2009	23346	197.0	26.0	6.4	11	450	330
Seadream	-	Seadream	2021	15000	155.1	21.4	5.2	10	220	182
Seven Seas Explorer	9703150	RSS	2015	54000	224.0	31.1	7.1	14	750	552
Seven Seas Mariner	9210139	RSS	2001	48075	216.1	28.3	6.4	12	700	445
Seven Seas Navigator	9064126	RSS	1999	28550	170.7	24.8	7.3	12	490	340
Seven Seas Voyager	9247144	RSS	2001	42363	206.5	28.8	7.1	12	706	447
Silver Muse	9784350	Silversea	2017	40700	212.8	27.0	6.6	11	596	411
Silver Spirit	9437866	Silversea	2009	39519	196.0	26.0	6.2	12	540	376
Silver Whisper	9192179	Silversea	2000	28258	190.0	24.9	6.0	10	382	295
Veendam	9102992	HAL	1996	57092	218.0	31.0	7.5	13	1350	568
Viking Sky	9650420	Viking	2016	47842	228.2	28.2	6.5	13	930	550

Vessel name	Operator	Gross Tonnage (GT)	Passengers	Installed power [kW]	Propulsion power [kW]	Design speed [kn]	Area of staterooms [m2]
AidaAura	Aida	42289	1300	27550	18800	20.0	10526
Amsterdam	HAL	62735	1380	55216	31000	23.9	16793
Aurora	P&O	76152	1950	58800	40000	24.0	23940
Azamara Journey	Azmara	30277	694	32100	13500	21.0	7519
Carnival Miracle	Carnival	85942	2124	62370	35200	24.0	21534
Crystal Serenity	Crystal	68870	980	52198	27000	23.0	14602
Grandeur of the Seas	RCI	73817	2446	50400	34000	23.5	16245
Le Lyrial	Ponant	10700	264	7280	4600	16.0	3446
Marina	Oceania	66084	1250	42000	24000	20.0	22234
Nieuw Amsterdam	HAL	86700	2106	64000	35200	23.9	24893
Noordam	HAL	82318	1916	67340	35200	24.0	23427
Norwegian Spirit	NCL	75400	1996	58800	40000	25.5	17374
Oceana	P&O	77499	2272	46080	28000	22.4	17078
Pride of America	NCL	80439	2186	50400	25000	22.2	22202
Seabourn Encore	Seabourn	41865	635	23040	12000	18.6	10589
Seabourn Odyssey	Seabourn	23346	450	15000	15000	21.0	8101
Seadream	Seadream	15000	220	8600	5600	17.0	4201
Seven Seas Explorer	RSS	54000	750	32000	18000	21.0	17817
Seven Seas Mariner	RSS	48075	700	34800	17000	20.0	12113
Seven Seas Navigator	RSS	28550	490	23200	15536	20.0	8719
Seven Seas Voyager	RSS	42363	706	23040	17000	20.0	12822
Silver Muse	Silversea	40700	596	26100	17000	21.0	15583
Silver Spirit	Silversea	39519	540	26100	17000	21.0	10956
Silver Whisper	Silversea	28258	382	22720	15700	21.0	8377
Veendam	HAL	57092	1350	34560	24000	20.9	15851
Viking Sky	Viking	47842	930	23520	14500	20.0	13723

B.2. B/T ratio of parent cruise ship database

Vessel name	**Breadth waterline [m]**	**Draft [m]**	**B/T ratio**
AidaAura	28.1	6.2	4.5
Amsterdam	32.3	8.1	4.0
Aurora	32.3	7.9	4.1
Azamara Journey	25.5	5.8	4.4
Carnival Miracle	32.3	8.0	4.0
Crystal Serenity	32.3	8.0	4.0
Grandeur of the Seas	32.3	7.8	4.1
Le Lyrial	18.0	4.8	3.8
Marina	32.3	7.3	4.4
Nieuw Amsterdam	32.3	7.9	4.1
Noordam	32.3	7.9	4.1
Norwegian Spirit	32.3	7.9	4.1
Oceana	32.3	8.1	4.0
Pride of America	32.3	8.0	4.0
Seabourn Encore	28.0	6.5	4.3
Seabourn Odyssey	26.0	6.4	4.1
Seadream	21.4	5.2	4.2
Seven Seas Explorer	31.1	7.1	4.4
Seven Seas Mariner	28.3	6.4	4.4
Seven Seas Navigator	24.8	7.3	3.4
Seven Seas Voyager	28.8	7.1	4.1
Silver Muse	27.0	6.6	4.1
Silver Spirit	26.0	6.2	4.2
Silver Whisper	24.9	6.0	4.2
Veendam	31.0	7.5	4.1
Viking Sky	28.2	6.5	4.4

Average	**4.13**
Average deviation	**0.15**
Average deviation in %	**3.7%**

Table B.1: The B/T ratio of selected cruise vessels in parent cruise ship database

B.3. Data plots and correlations of parent cruise ship database

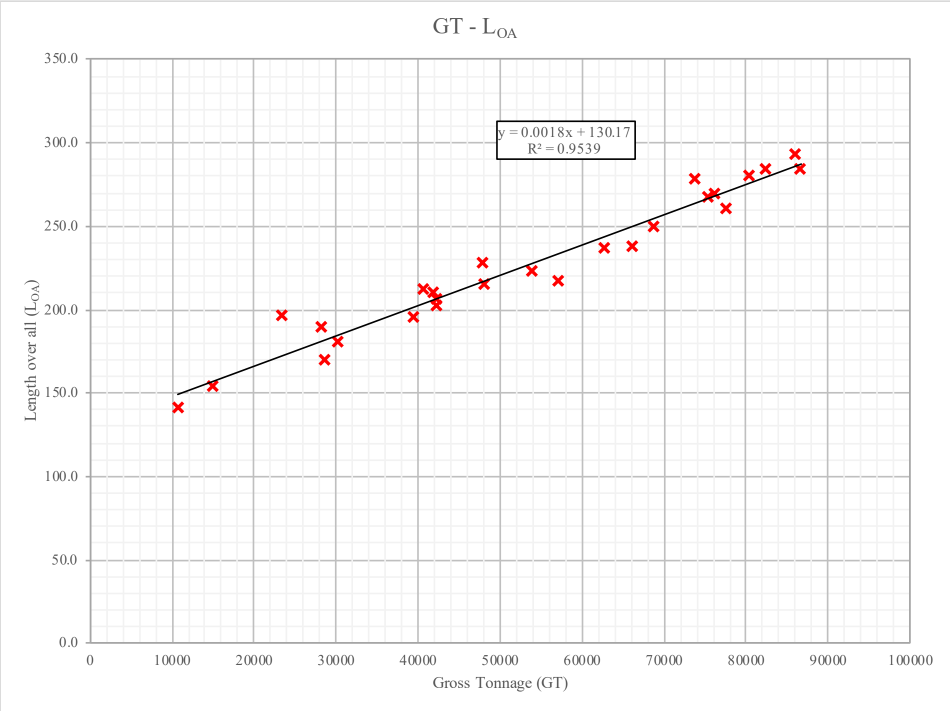

Figure B.1: Correlation between GT and L_{oa}

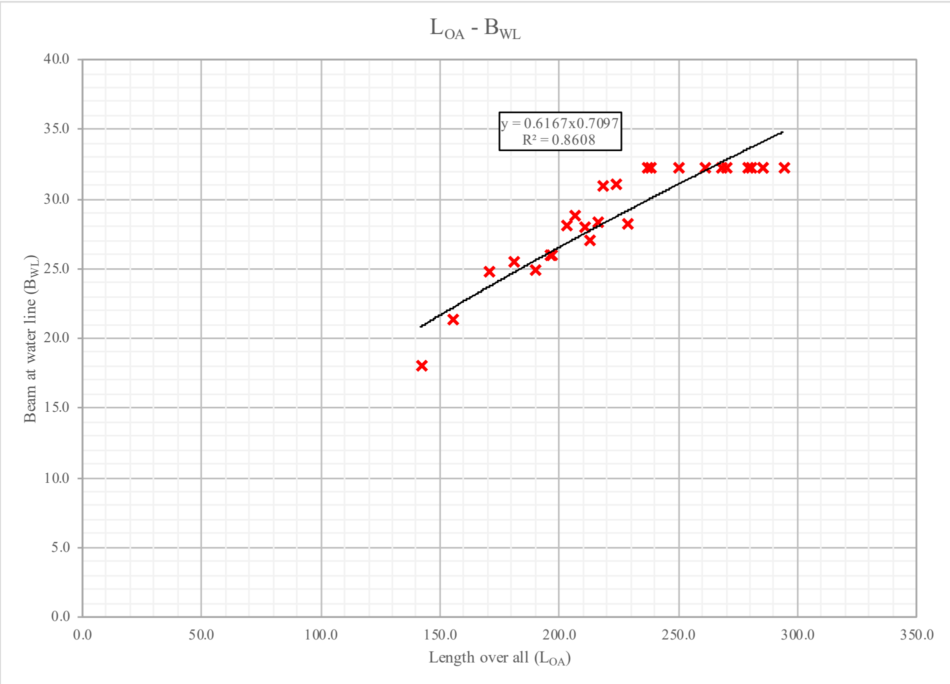

Figure B.2: Correlation between L_ooa and B_wl

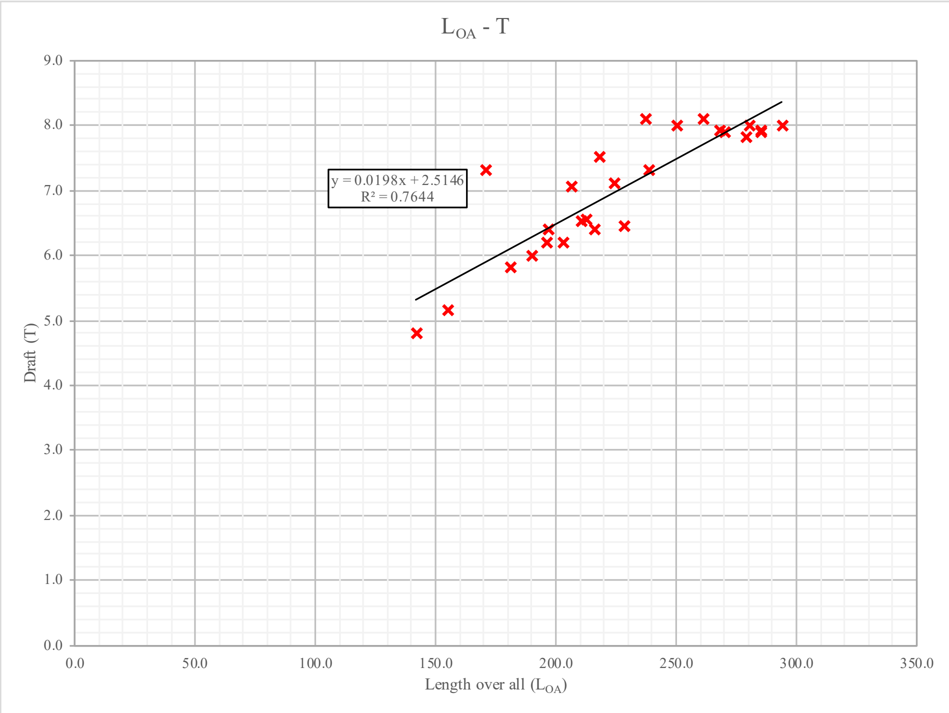

Figure B.3: Correlation between L_ooa and T

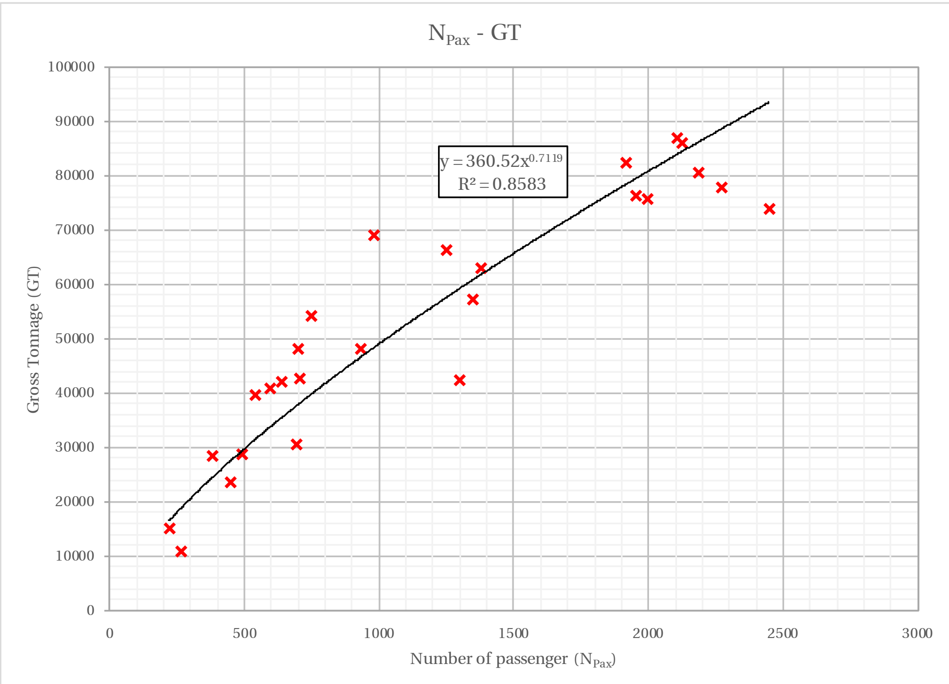

Figure B.4: Correlation between N_{pax} and GT

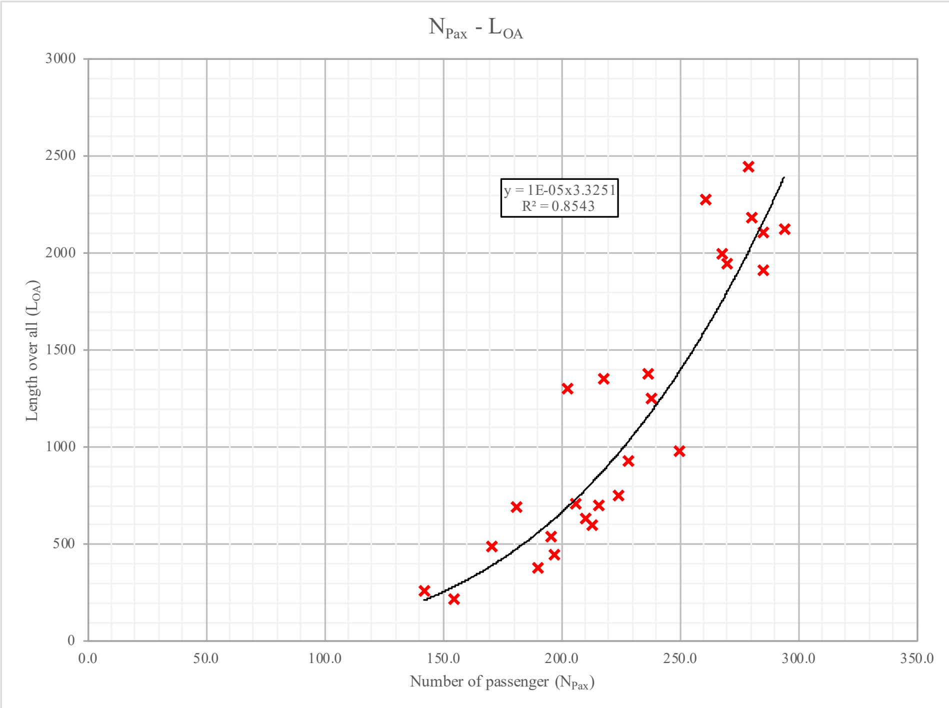

Figure B.5: Correlation between N_{pax} and L_{oa}

B.4. Installed power vs pax

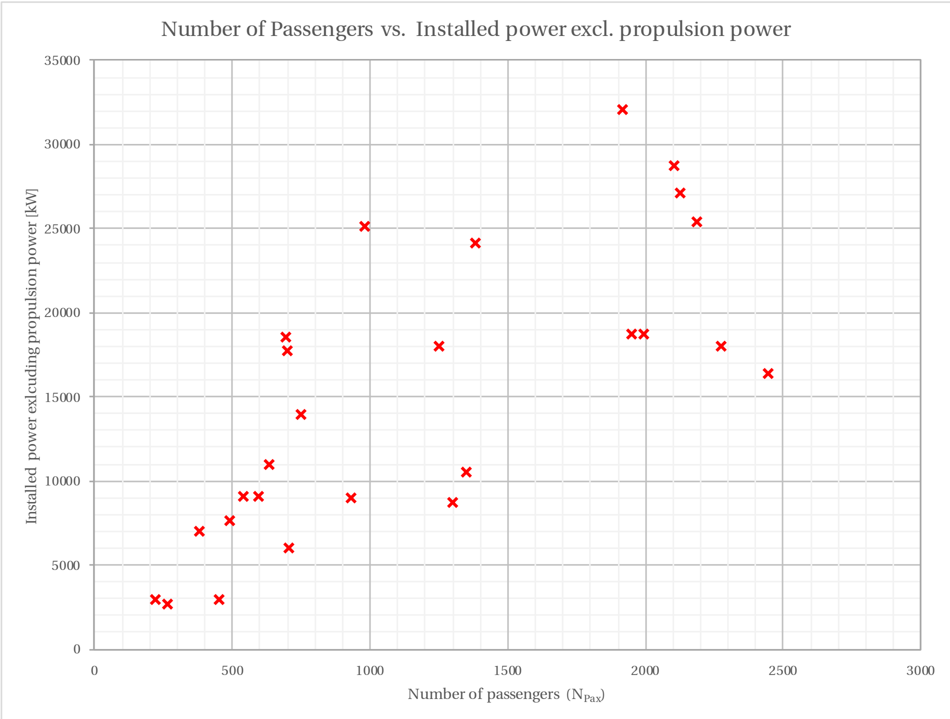

Figure B.6: The number of passengers against the installed power minus the propulsion power

B.5. AIS data of selected vessels from parent cruise ship database

Vessel Name	AidaAura			
Total hours logged	10399.0			
Total Days	434			
Design speed	20 [kn]			
Speed	**Average Speed [kn]**	**Speed %**	**Time [h]**	**%**
0% - 20%	0.61	3%	3193.25	31%
20% - 40%	6.58	33%	778.95	7%
40% - 60%	10.43	52%	2686.30	26%
60% - 90%	15.11	76%	3466.60	33%
90% - 100%	18.72	94%	201.03	2%

Vessel Name	Amsterdam			
Total hours logged	11119.6			
Total Days	464			
Design speed	23.9 [kn]			
Speed	**Average Speed [kn]**	**Speed %**	**Time [h]**	**%**
0% - 20%	1.54	6%	3628.28	33%
20% - 40%	7.37	31%	1540.66	14%
40% - 60%	12.26	51%	3860.15	35%
60% - 90%	18.35	77%	1884.18	17%
90% - 100%	22.05	92%	205.40	2%

Vessel Name	Crystal Serenity			
Total hours logged	10437.8			
Total Days	435			
Design speed	23 [kn]			
Speed	**Average Speed [kn]**	**Speed %**	**Time [h]**	**%**
0% - 20%	0.05	0%	7155.18	69%
20% - 40%	7.54	33%	601.42	6%
40% - 60%	11.63	51%	1531.74	15%
60% - 90%	16.79	73%	1139.74	11%
90% - 100%	21.85	95%	9.70	0%

Vessel Name	Le Lyrial			
Total hours logged	10497			
Total Days	438			
Design speed	16 [kn]			
Speed	**Average Speed [kn]**	**Speed %**	**Time [h]**	**%**
0% - 20%	0.21	1%	7860.21	75%
20% - 40%	5.01	31%	1196.04	11%
40% - 60%	8.06	50%	934.81	9%
60% - 90%	11.85	74%	439.36	4%
90% - 100%	15.22	95%	56.61	1%

Vessel Name	Marina			
Total hours logged	10430			
Total Days	435			
Design speed	20 [kn]			
Speed	**Average Speed [kn]**	**Speed %**	**Time [h]**	**%**
0% - 20%	1.35	7%	6117.62	59%
20% - 40%	5.97	30%	1014.74	10%
40% - 60%	10.58	53%	837.37	8%
60% - 90%	14.84	74%	1852.09	18%
90% - 100%	18.94	95%	555.01	5%

Vessel Name	Nieuw Amsterdam			
Total hours logged	11279			
Total Days	470			
Design speed	23.9 [kn]			
Speed	**Average Speed [kn]**	**Speed %**	**Time [h]**	**%**
0% - 20%	2.42	10%	6943.00	62%
20% - 40%	7.96	33%	1088.10	10%
40% - 60%	12.05	50%	1477.47	13%
60% - 90%	17.64	74%	1759.46	16%
90% - 100%	21.89	92%	9.03	0%

Vessel Name	Noordam			
Total hours logged	11495			
Total Days	479			
Design speed	24 [kn]			
Speed	**Average Speed [kn]**	**Speed %**	**Time [h]**	**%**
0% - 20%	2.66	11%	6520.89	57%
20% - 40%	8.16	34%	1036.23	9%
40% - 60%	12.13	51%	2137.85	19%
60% - 90%	17.21	72%	1796.05	16%
90% - 100%	22.03	92%	2.99	0%

Vessel Name	Norwegian Spirit			
Total hours logged	10991			
Total Days	458			
Design speed	25.5 [kn]			
Speed	**Average Speed [kn]**	**Speed %**	**Time [h]**	**%**
0% - 20%	1.41	6%	5061.30	46%
20% - 40%	7.95	31%	1889.57	17%
40% - 60%	12.87	50%	2651.78	24%
60% - 90%	18.38	72%	1388.35	13%
90% - 100%	-	-	0.00	0%

Vessel Name	Seabourn Encore			
Total hours logged	11024			
Total Days	460			
Design speed	18.6 [kn]			
Speed	**Average Speed [kn]**	**Speed %**	**Time [h]**	**%**
0% - 20%	1.51	8%	4150.25	38%
20% - 40%	5.74	31%	4141.72	38%
40% - 60%	9.59	52%	1245.15	11%
60% - 90%	13.60	73%	1454.55	13%
90% - 100%	17.02	92%	32.26	0%

Vessel Name	Seven Seas Mariner			
Total hours logged	10976			
Total Days	458			
Design speed	20 [kn]			
Speed	**Average Speed [kn]**	**Speed %**	**Time [h]**	**%**
0% - 20%	2.99	15%	5640.96	51%
20% - 40%	6.20	31%	2236.39	20%
40% - 60%	10.36	52%	1919.42	17%
60% - 90%	14.81	74%	1019.46	9%
90% - 100%	18.64	93%	141.94	1%

Vessel Name	Seven Seas Voyager			
Total hours logged	10909			
Total Days	455			
Design speed	20 [kn]			
Speed	**Average Speed [kn]**	**Speed %**	**Time [h]**	**%**
0% - 20%	1.78	9%	5444.01	50%
20% - 40%	6.51	33%	1788.06	16%
40% - 60%	10.11	51%	1313.52	12%
60% - 90%	14.68	73%	2334.05	21%
90% - 100%	18.24	91%	29.17	0%

Vessel Name	Silver Spirit			
Total hours logged	10952			
Total Days	457			
Design speed	21 [kn]			
Speed	**Average Speed [kn]**	**Speed %**	**Time [h]**	**%**
0% - 20%	1.27	6%	5381.46	49%
20% - 40%	6.62	32%	1621.21	15%
40% - 60%	10.64	51%	1908.46	17%
60% - 90%	14.96	71%	2013.13	18%
90% - 100%	19.66	94%	27.30	0%

Vessel Name	Viking Sky			
Total hours	10319			
Total Days	430			
Design speed	20 [kn]			
Speed	**Average Speed [kn]**	**Speed %**	**Time [h]**	**%**
0% - 20%	0.78	4%	5809.13	56%
20% - 40%	6.34	32%	1049.05	10%
40% - 60%	10.26	51%	1193.70	12%
60% - 90%	14.97	75%	2157.28	21%
90% - 100%	18.49	92%	107.48	1%

Vessel Name	Seven Seas Explorer			
Total hours logged	10535			
Total Days	439			
Design speed	21 [kn]			
Speed	**Average Speed**	**Speed %**	**Time [h]**	**%**
0% - 20%	0.88	4%	4082.11	39%
20% - 40%	6.64	32%	2237.18	21%
40% - 60%	10.67	51%	2088.43	20%
60% - 90%	15.77	75%	2019.74	19%
90% - 100%	19.48	93%	60.98	1%

Vessel Name	Seven Seas Navigator			
Total hours logged	10725			
Total Days	447			
Design speed	20 [kn]			
Speed	**Average Speed**	**Speed %**	**Time [h]**	**%**
0% - 20%	0.71	4%	2970.92	28%
20% - 40%	6.36	32%	1622.76	15%
40% - 60%	10.23	51%	4082.66	38%
60% - 90%	15.03	75%	1985.03	19%
90% - 100%	18.33	92%	64.09	1%

Vessel Name	Silver Muse			
Total hours logged	11167			
Total Days	466			
Design speed	21 [kn]			
Speed	**Average Speed**	**Speed %**	**Time [h]**	**%**
0% - 20%	2.08	10%	5348.94	48%
20% - 40%	6.83	33%	3348.83	30%
40% - 60%	10.77	51%	1439.90	13%
60% - 90%	14.62	70%	922.74	8%
90% - 100%	-	-	0.00	0%

Vessel Name	Silver Whisper			
Total hours	10847			
Total Days	452			
Design speed	21 [kn]			
Speed	**Average Speed**	**Speed %**	**Time [h]**	**%**
0% - 20%	1.14	5%	4797.98	44%
20% - 40%	6.53	31%	1157.32	11%
40% - 60%	10.94	52%	2930.31	27%
60% - 90%	14.43	69%	1960.62	18%
90% - 100%	20.04	95%	0.98	0%

C

Appendix C: General arrangements of test scenario's

C.1. General arrangement Ship A

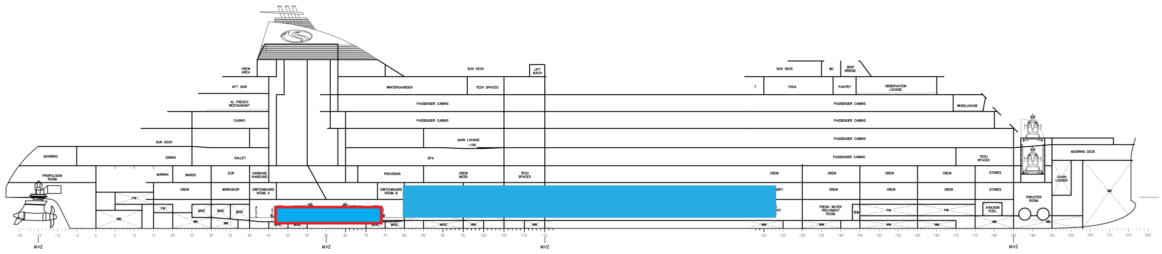

Figure C.1: Schematic GA for Ship A for the hydrogen test case

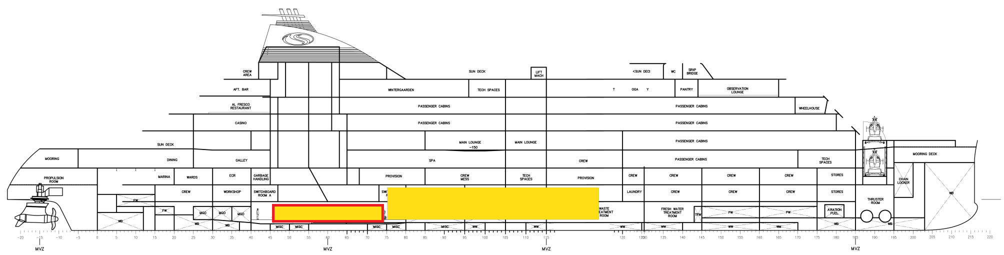

Figure C.2: Schematic GA for Ship A for the ammonia test case

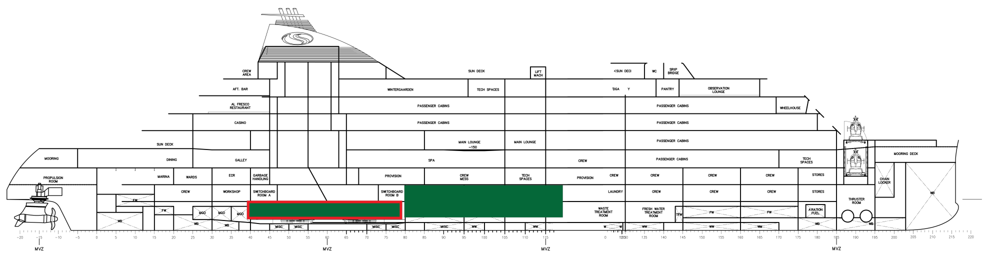

Figure C.3: Schematic GA for Ship A for the methanol ICE test case

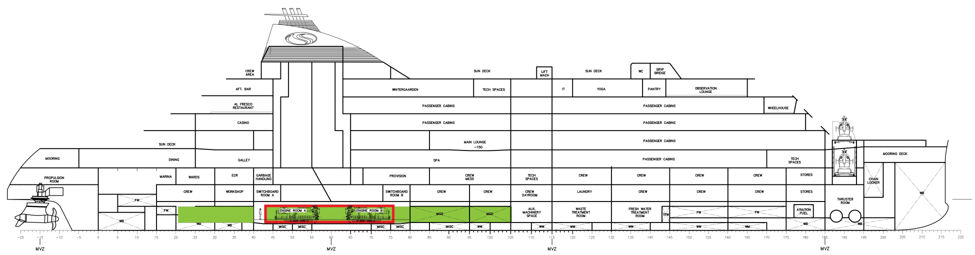

Figure C.4: Schematic GA for Ship A for the methanol FC test case

C.2. General arrangement Ship B

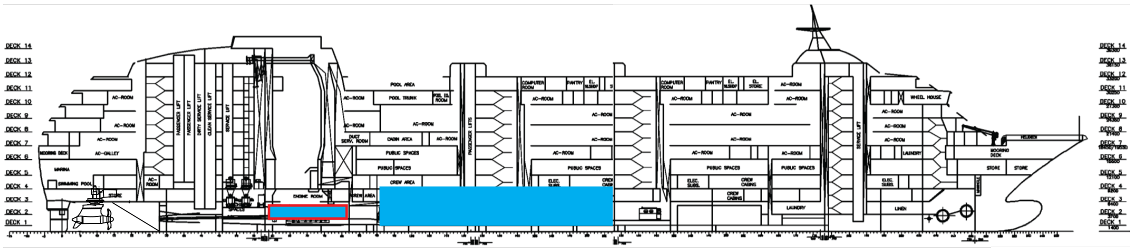

Figure C.5: Schematic GA for Ship B for the hydrogen test case

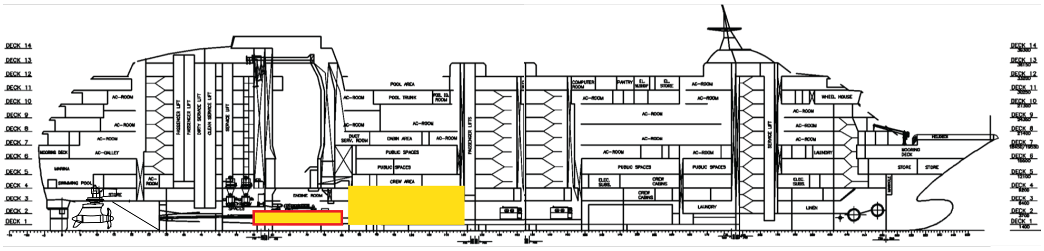

Figure C.6: Schematic GA for Ship B for the ammonia test case

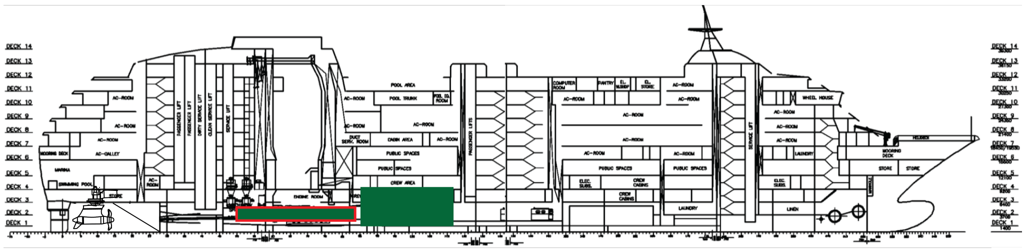

Figure C.7: Schematic GA for Ship B for the methanol ICE test case

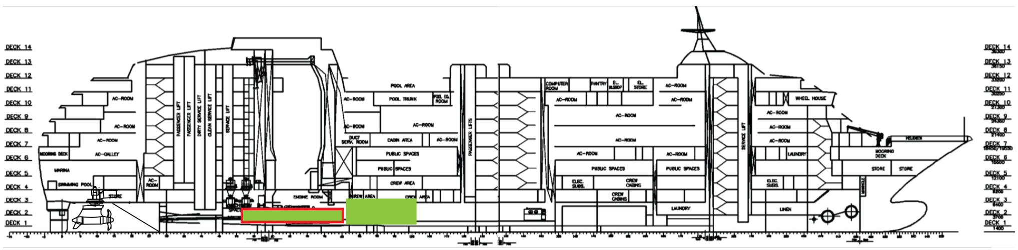

Figure C.8: Schematic GA for Ship B for the methanol FC test case

C.3. General arrangement Ship C

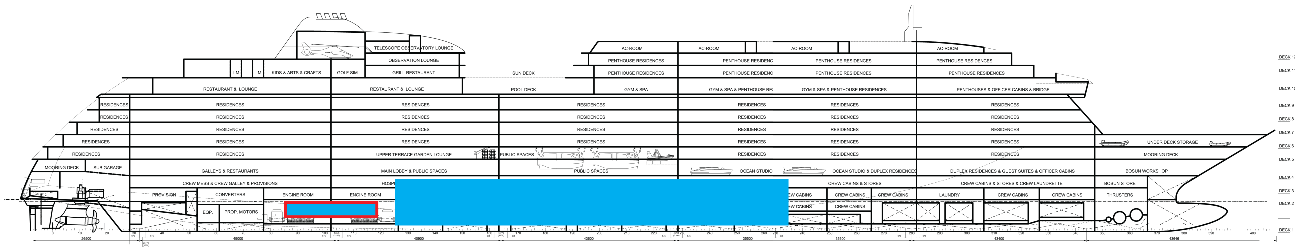

Figure C.9: Schematic GA for Ship A for the hydrogen test case

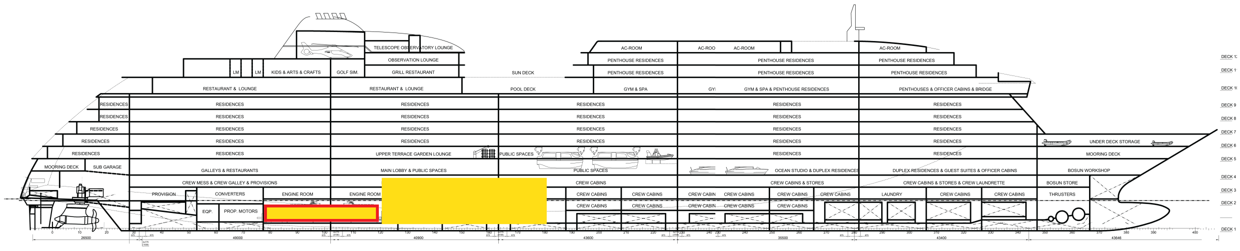

Figure C.10: Schematic GA for Ship A for the ammonia test case

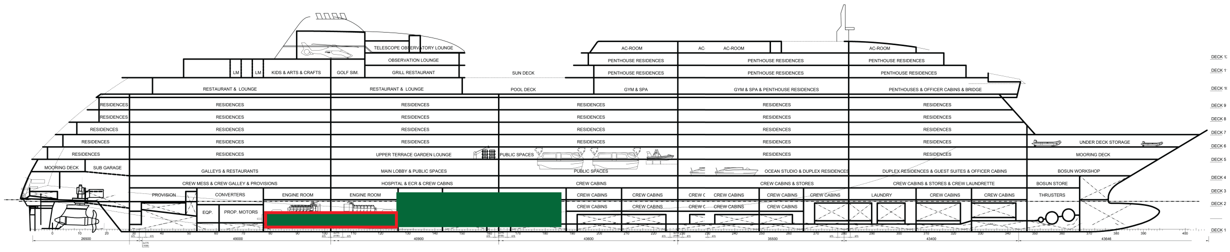

Figure C.11: Schematic GA for Ship A for the methanol ICE test case

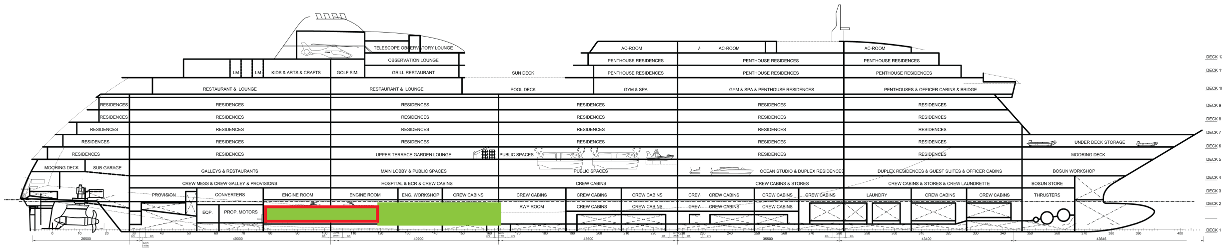

Figure C.12: Schematic GA for Ship A for the methanol FC test case