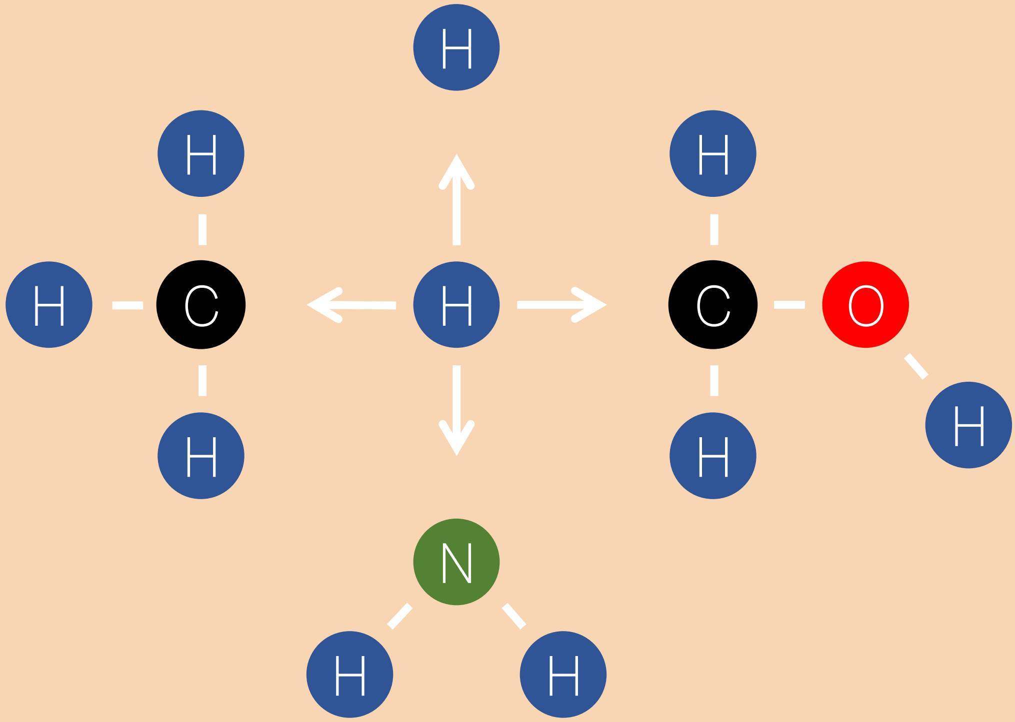
Shipping renewable hydrogen carriers

J. Tijdgat



TU Delft

ANTHONY VEDER

Shipping renewable hydrogen carriers

A study on the impact of shipping renewable hydrogen carriers and using those as a fuel on, the ship design, the different powertrain configurations, and the cost of transported hydrogen

by

J. Tijdgat

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TU Delft

Preface

Over the last seven years, I have been a student at the 3mE faculty. During these years, I have enjoyed the student life in Delft and grew up from a schoolboy to a young adult. The subject of my thesis is a result of my interest in a new world, in which we use renewable sources to fulfil our energy demand. Shipping can play an essential role in this new world, being one of the most efficient and flexible transportation options today. I hope that by reading this thesis, you will all see the importance and the opportunities that shipping has in reaching climate goals and being sustainable. The report is part of my master thesis, which is the final deliverable for the Master of Science degree in Mechanical Engineering at the Delft University of Technology. I specialised within the masters on the track Energy and Process Technology.

For this research, I would like to thank several people. First of all, the chair of my study, Paulien Herder. I think she did great supervising my project, always giving me the feeling that she was interested in my research and supported and motivated me when I needed to. She was fair and transparent and was able to put a lot of comments and ideas into perspective. Dozens of times I had to correct other people that she was not a man but a woman, and I think she is a great role model for a lot of women who aspire a (scientific) career.

Secondly, I want to thank Klaas Visser. The lectures he gave about Diesel Engines B motivated me to dive into shipping propulsion. The ideas and information he gave to me have opened my eyes to see what the possibilities of shipping are in the future.

Thirdly, I want to tank Björn van der Weerdhof, my supervisor at Anthony Veder. He allowed me to do this research at the company, in which I saw a potential research opportunity. He always stimulated me to look at the bigger picture of the work and being critical on my way of writing. Furthermore, I want to thank the people at Anthony Veder, for making these 10 months a great experience.

At last, I would like to thank everyone that has supported me throughout these years, and I hope to talk to you all soon and celebrate this significant milestone.

Jim Tijdgat
Rotterdam, June 2020

Summary

Future climate goals exist in all varieties, from regional to mondial. These goals have one thing in common, and that is to reduce emissions that are harmful to the climate. Renewable energy sources are not spread fairly around the world, and there is intermittency in production. The growing energy demand, and our ambition to be sustainable, asks for a world in which renewable energy is stored and transported to places where there is not the capacity or the space to produce this energy. One of the options to store this energy is by using renewable electricity from the sun or wind to produce hydrogen. One of the possibilities to transport this hydrogen is by ship. The hydrogen can be converted to renewable hydrogen carriers (RHCs), which enable more convenient storage and transportation of hydrogen, but the conversion can cause other challenges. The hydrogen stored in these carriers can be used for multiple applications, such as heat, industrial feedstock, and fuel for mobility.

This research focusses on shipping renewable hydrogen carriers. Shipping is an efficient way of transportation, and particularly useful for transport across oceans and flexible routes. Current research in hydrogen supply chains predominantly focusses on large scale ship transportation. However, shipping is also an effective way of transporting variable streams with smaller volumes and shorter distances. The transport of RHCs, the increasing amount of regulations around emissions, and the fast-improving fuel cell and battery technology, force ship owners to think about how they are going to design their future ships and its powertrain configuration.

The goal of this research is first, to get insight into the way renewable hydrogen carriers are transported by ship. Secondly, what the effects are to the ship propulsion when using the hydrogen carriers as a fuel. Thirdly, how technological developments and future regulations can influence cost of transported hydrogen. Therefore, the main research question of this thesis is: *What is the impact of shipping renewable hydrogen carriers, when using the carriers as fuel, on the ship design, the different power configurations, and the cost of transported hydrogen?*

Various hydrogen carriers are analysed first. Secondly, a model is used to analyse three different cases of transportation. These cases include a small, medium, and large scale ship transport, having different transportation distances and volumes. At last, a more detailed model is used to evaluate different cases and scenarios and indicate the transportation cost of shipping RHCs in terms of €/kgH_2. Based on the results of the cases, the energy carriers DME and the LOHCs MCH and H18-DBT were left out of further research. The production of DME and methanol is similar, but DME is considered less attractive because of its storage conditions. The LOHCs are less attractive, because of their low hydrogen density, low cycle efficiency (replacement needed after a 1000 cycles), and their inability to be used as a fuel directly.

The four most attractive RHCs to be shipped are the synthetically produced: methanol, liquefied natural gas, liquid hydrogen, and liquid ammonia. In the model, short and long term options are evaluated for the same, mild and strict regulations compared to today. The following statements can be made, based on the results of the second model:

- Ammonia is best suited in a scenario with strict regulation compared to today. Ammonia has a non-carbon nature; therefore, it is the most promising option in the long term.
- Methanol is best suited for small scale transportation in the short and long term, in which the same regulations are active. The storage of methanol on board of the ship is relatively simple and it has a relatively high hydrogen density.
- LSNG is best suited for large scale transportation in which the same regulations are active. LSNG has the highest hydrogen density of the discussed RHCs. The advantage of SNG is that during the reconversion to hydrogen, extra hydrogen will be produced because of the added steam, during steam methane reforming (SMR).

- Liquid hydrogen is from a shipping point of view not the most suited for the transport of hydrogen, due to its low volumetric density and complex storage. Shipping liquid hydrogen has the advantage that it reduces extra conversion steps in other parts of the supply chain.

Shipping RHCs and using the carrier as fuel will increase the total cost of transportation compared to using fossil fuels. However, the usage of RHC as fuel will result in a significant reduction of greenhouse gases (GHGs). Looking at the LNG supply chain, using RHCs as fuel, the cost of avoided GHGs in the short term can be 200-300 €/tCO_2 equivalent. In the future, this can drop below €200 €/tCO_2 equivalent, because of lower RHCs prices and improved technology. However this is still a relatively high cost of GHG avoidance.

Shipping RHCs and using the carriers as a fuel is an option which involves higher cost compared to current fossil fuel options. This relatively high share of fuel expenses using RHCs will make efficient powertrains relatively more attractive because it enables higher fuel cost savings. The most attractive engine configurations are a two-stroke internal combustion engine with a mechanical powertrain and a SOFC with a battery in an electric powertrain. The last option is especially promising for the long term, because of the technologic developments and the increasing regulations in shipping. Overall the results indicate that shipping NH_3 and using the carrier as a fuel is the most promising option for the transport of RHCs by ship.

This research and constructed models can be used as a tool to evaluate different transportation options. However, used values are based on various sources and their corresponding assumptions, which can change significantly in the future.

Contents

Nomenclature

Acronyms

AC	Alternative current
CAPEX	Capital expenditure
CH_4	Methane
CO_2	Carbon Dioxide
COP	Conference of the Parties
DC	Direct current
DME	Dimethylether
dwt	Deadweight tonnage
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
GHG	Greenhouse gas
GWP_{100}	Global Warming Potential at a 100 year time horizon
H0-DBT	Dibenzyltoluene (dehydrogenated)
H18-DBT	Octadecahydro Dibenzyltoluene (hydrogenated)
HCCI	Homogeneous Charge Compression Ignition
IMO	International Maritime Organization
IEA	International Energy Agency
kWh	Kilowatt-hour
LH_2	Liquid Hydrogen
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
LPG	Liquefied Petroleum Gas
LSNG	Liquefied Synthetic Natural Gas
MCH	Methylcyclohexane (hydrogenated Toluene)
MeOH	Methanol
MEPC	Marine Environment Protection Committee
NECA	NO_x Emission Control Area

NH_3 Ammonia

nm Nautical miles

ICE Internal combustion engine

PEM Polymer electrolyte membrane

RHC Renewable Hydrogen carrier

SECA Sulphur Emission Control Area

SNG Synthetic Natural Gas

SOFC Solid oxide fuel cell

TOL Toluene (dehydrogenated MCH)

UNFCCC United Nations Framework Convention on Climate Change

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1 Introduction

The earth summit of 1992 in Rio de Janeiro resulted in the United Nations Framework Convention on Climate Change (UNFCCC). This international environmental organisation aims 'to stabilise the amount of greenhouse gases (GHGs) in the atmosphere at a level that would prevent dangerous anthropogenic (human-induced) interference with the climate system' [1].

Two years later, on the 21^{st} of March in 1994, 197 countries ratified with the convention and resulted in the first Conference of Parties (COP), a year later in Berlin. The 21^{st} Conference of Parties in Paris, the COP21, resulted in an agreement that was adopted by 174 countries. In this agreement, a limit on global warming was set to a maximum of 2 degrees Celsius compared to pre-industrial levels. Therefore, the amount of emitted GHGs needs to be reduced. GHGs are a mixture, in which CO_2, has the most significant contribution to the greenhouse effect [2].

The shipping industry is responsible for 2.6% of the global CO_2 emissions [2]. However, during the COP21, in Paris, both the aviation and shipping industry were omitted. If the shipping industry does not reduce its emissions, it is expected that the amount of GHGs emitted by the shipping will increase between 50 - 250% in 2050, with respect to 2012, due to the economic growth that is predicted [3]. To make sure that the shipping industry will also reduce its emissions, the International Maritime Organization (IMO) has set specific standards during the 72^{nd} session of the Marine Environment Protection Committee (MEPC72) to reduce GHG emissions by at least 50% in 2050 with respect to 2008 [4]. One of the most straightforward options to reduce GHGs is to use a fuel which does not produce GHGs when it is produced and burned.

Not only the shipping industry but also other industries have to become more sustainable in the future. To reduce GHG emissions, renewable energy and resources are needed. Renewable electricity, like wind and solar energy, is not always matching the electricity demand and the energy is not always available at the right locations. One of the options to store this energy is by using renewable electricity from the sun or wind to produce hydrogen. One of the possibilities to transport this hydrogen is by ship. The hydrogen can be converted to renewable hydrogen carriers (RHCs), which enable more convenient storage and transportation of hydrogen. The hydrogen stored in these carriers can be used for multiple applications, such as heat, industrial feedstock, and fuel for mobility.

This transportation of energy carriers has two main opportunities for the shipping industry. First, the transportation of RHCs could reduce emissions in different parts of the world. Using RHCs could mean that more countries can meet their climate goals. Secondly, some of the energy carriers have the potential to be used as fuel. This could be an opportunity for the shipping industry because they could use the energy carrier as fuel for the ship. This could reduce harmful emissions produced by the ship and enables ship owners to meet the goals from the IMO, such as Anthony Veder, which will be further discussed in section 1.2.1.

In this report, a study on the transport of renewable hydrogen carriers (RHCs) by ship is presented. This report is a result of a graduation project at the Delft University of Technology in collaboration with Anthony Veder. In this chapter, the problem statement is presented first in section 1.1. Secondly, the stakeholders of this problem will be described in section 1.2. After this, the research gap in section 1.3 followed by the research questions in section 1.4. At last, the research method is presented in section 1.5.

1.1. Problem background

In this section, the problem statement is presented. At this moment, it is unknown what the impact is of shipping renewable hydrogen carriers (RHCs) when using the RHC as fuel on the different powertrain configurations and the total design of transportation. In the paragraphs below this statement will be further explained.

1.1.1. Electricity production

The global renewable electricity production is growing, and prices are declining, especially for solar and wind energy, as can be seen in figure 1.1. This graph shows the average electricity cost of a small and large project. For example, the 2 GW Al Dhafre project can produce electricity for as low as €0.012/kWh [5].

The intermittency of renewable energy can lead to negative electricity prices during low demand and high supply. Negative prices force renewable energy production to shut down because fossil power plants are less flexible. Energy storage can solve this problem because it will enable solar and wind farms to run continuously. In moments of high energy demand and low supply, the energy can be released.

There are different options available for renewable energy storage, which are discussed in the next paragraph.

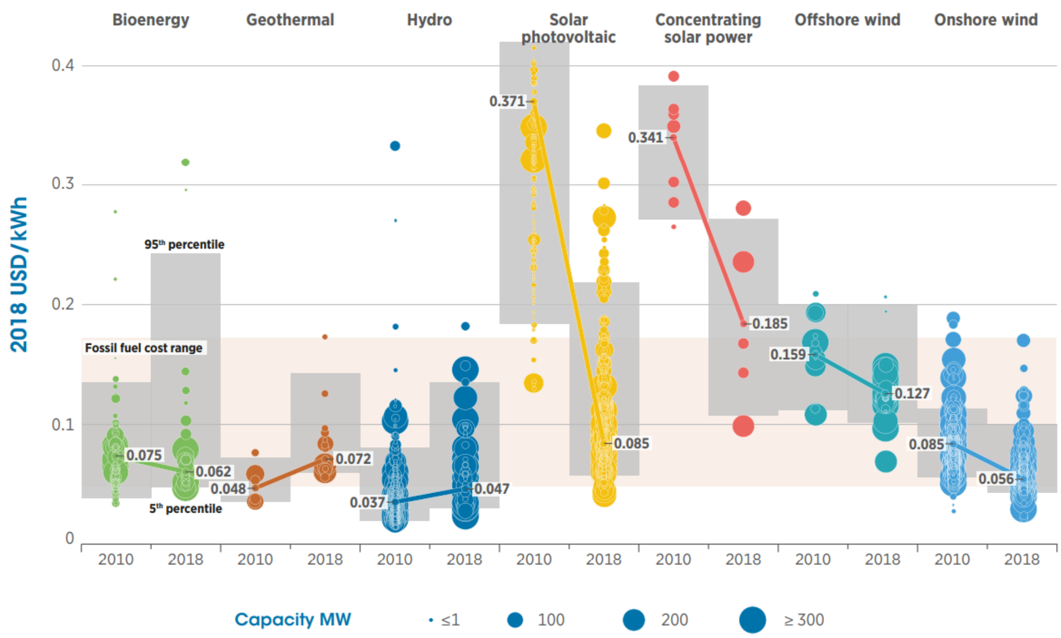

Figure 1.1: Global global weighted-average levelised cost of electricity of utility-scale renewable power generation technologies, 2010–2018 [6]

1.1.2. Energy carriers

There is a wide range of available renewable energy carriers, from batteries until chemical energy storage, shown in figure 1.2. For the storage of large energy quantities, synthetically produced chemicals are most suitable, like hydrogen, methanol or ammonia. These energy carriers all consists of hydrogen atoms, making them essentially renewable hydrogen carriers (RHCs).

Renewable electricity is not always produced at places where those are needed, which creates a demand for transportation. One of the transportation options is to ship the RHCs; this is explained in the next paragraph.

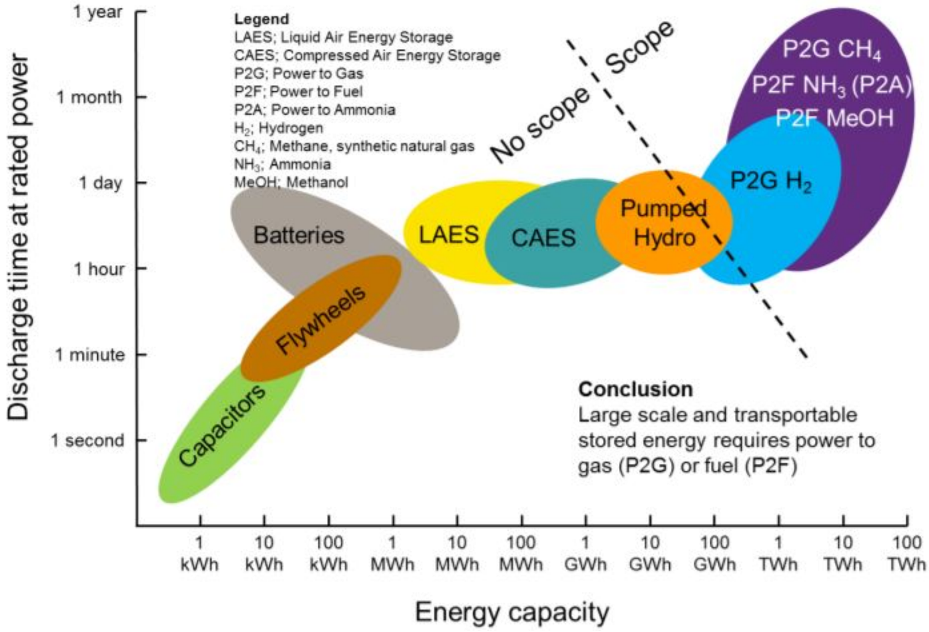

Figure 1.2: Discharge time versus the energy storage capacity of different energy storage techniques [7]

1.1.3. Transport by ship

Transportation by ship, pipeline or train are the most efficient types of transport in terms of energy efficiency as can be seen in figure 1.3. Large quantities of energy are transported in the forms of coal, oil and gas.

Transporting renewable energy over short distances is most efficient when the electricity is transported through high voltage direct current cables or transported as gaseous hydrogen through pipelines. At longer distances, the transportation of renewable hydrogen carriers by ship becomes relatively more efficient. The International Energy Agency (IEA) states that this tipping point lays at 1500 km. At this distance, it becomes more efficient to transport energy carriers by ship and reconverting it to hydrogen, than transporting hydrogen through pipelines or by ship across seas [8]. Other research from Kalavasta implies that transporting RHCs becomes efficient when it is imported from outside Europe to the Netherlands [9]. This would be at distances more than 3000km, which is the distance from North Africa to Rotterdam.

As earlier mentioned, there is intermittency in renewable energy production, meaning that the production of RHCs is not constant. Furthermore, the import of resources by pipeline can make countries dependant on other countries, making these investments also geopolitical. Ships allow this flexibility of import of energy. Inconsistency in product streams and geopolitical strategies are reasons to choose for ship transportation.

The research from the IEA and Kalavasta investigate the whole supply chain of different energy carriers. For the transport of the energy carriers by ship only relatively large scale transport is considered. However, the different types and volumes of energy carrier transport also lead to different ship designs. Transporting 5,000 m^3 or 250,000 m^3 of an energy carrier makes a huge difference in the transport by ship. Therefore ship owners, like Anthony Veder, want to know how these energy carriers can efficiently be transported for different kinds of volumes and distances, this will be further explained in paragraph 1.2.1.

In the next paragraph, the influence of regulations is discussed related to the design of ship transportation.

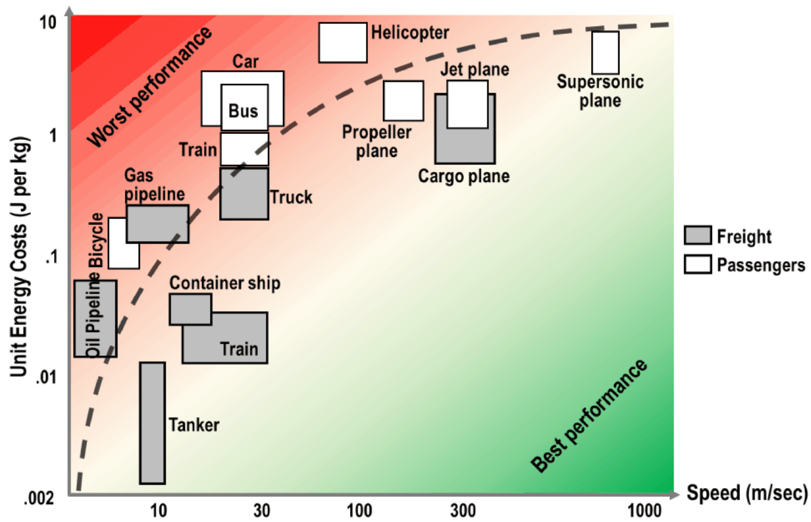

Figure 1.3: Energy efficiency of different forms of transportation [10]

1.1.4. Effects of future regulation

Over the last decades, more regulations have been implemented to reduce the harmful emissions produced by the shipping industry. For example, stricter regulations concerning the emissions of NOx were implemented. Also, a limitation of sulphur content (%S) in ship fuel was introduced. These regulations can are shown in figure 1.4. In 2050, the EU goal is to reduce CO_2 emissions by 40%, and IMO goals is to reduce it with 50% with respect to 2008. If the trend continues, more regulations will be implemented in the coming years, which affects the shipping industry and thus also shipowners.

Most ships are designed for a lifetime of roughly 25 years, and if ships need to comply with new rules sometimes retrofits are needed, this is unwanted to the downtime of a vessel. Therefore scenarios can be used to analyse different ship design.

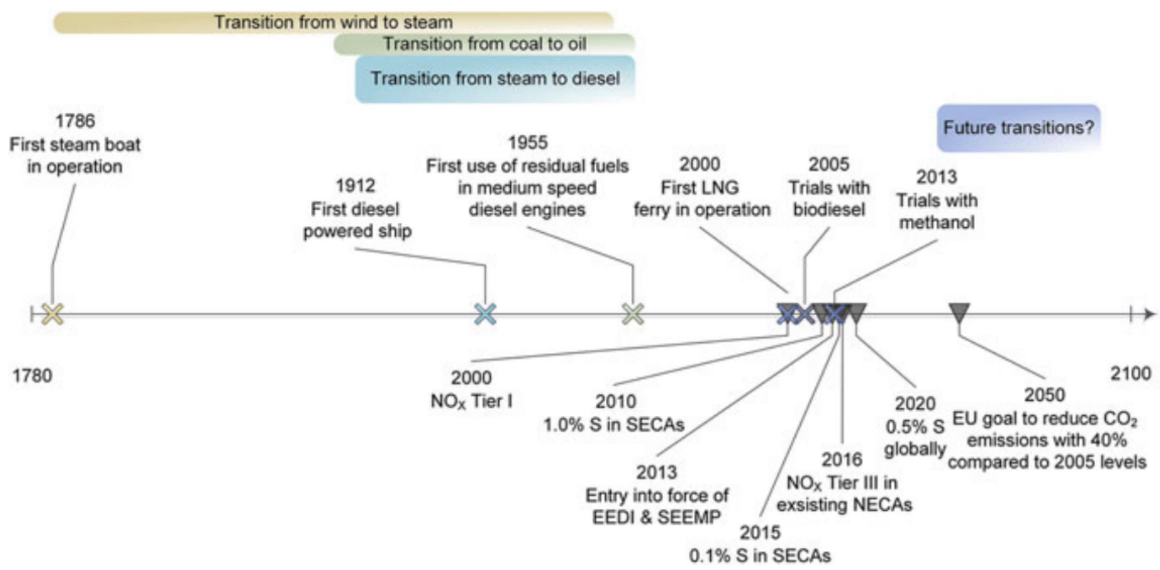

Figure 1.4: Timeline for transition of marine fuels from 1780 to 2100; selected events in history and environmental regulations are depicted [11]

1.1.5. Conclusion

In this section, the problem statement was explained. At this moment, it is unknown what the impact is of shipping renewable hydrogen carriers (RHCs) when using the RHC as fuel on the different powertrain configurations and the total design of transportation.

Renewable energy production will continue to grow, and prices of electricity will decrease. Energy storage is needed because of the intermittency, and the transport is needed because not everywhere in the world is there enough space or resources to produce this renewable energy efficiently. Shipping this energy in the form of RHCs is one of the solutions to supply renewable energy and reaching climate targets.

Since the shipping industry needs to reduce its emissions as well, transporting energy carriers and using those as fuel, could have a positive influence on the sustainability of the sector. This will be further described in the next section about the stakeholders.

1.2. Stakeholders

In this section, the stakeholders will be discussed, which all take part in the supply chain of transporting the RHCs. The supply chain of RHCs is divided into four sections:

- Production facility. Here the electricity is used to produce hydrogen, the main costs for this facility are the investment cost of the electrolysers and the electricity costs.
- Conversion and reconversion plant. At the conversion plant, the hydrogen is converted to a RHC. These include, for example, the conversion to liquid hydrogen, ammonia, and methanol. The reconversion plant is used to convert the RHCs to the desired product, which is hydrogen in this thesis.
- Import and export terminal. At the export terminal, the RHC is loaded onto the ship before it sails to the desired location. At the import terminal, the carrier is discharged from the ship and transferred into the terminal.
- Transport (transmission & distribution). These include the transport between the (re)conversion plant to the terminal using pipelines and the transport by ship.

In figure 1.5, the cost breakdown of the supply chain of green hydrogen is shown for domestic production in Japan and the production in Australia and imported to Japan by ship. The assumed investment cost of a ship transporting 11,000 tons of liquid hydrogen is 412 M$ [8]. However, this does not give a clear breakdown of costs, making it difficult to estimate costs for other ship capacities and designs. Therefore shipowners, like Anthony Veder, want to get more insight into the transport of RHCs.

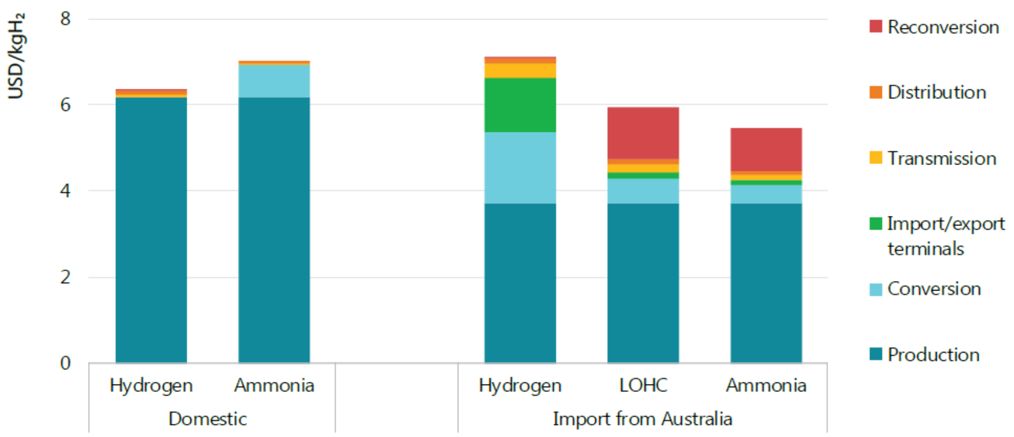

Figure 1.5: Cost of delivering hydrogen or ammonia produced via electrolysis, domestically, or from Australia to an industrial customer in Japan in 2030 [8]

1.2.1. Anthony Veder

One of these shipowners is Anthony Veder, a company in the Netherlands shipping liquefied gases, such as LNG, LPG and NH_3. The company is constantly looking for new niche markets, which is how they became a pioneer in the small scale LNG. The company sees potential in transporting RHCs. However, to step into the market, they need to know what the impact is on the ship design and the total costs when RHCs are transported by ship.

The ship design depends on different factors such as the volume and the covered distance of the transport of RHCs. When transporting these carriers, a logical next step would be to use the carrier not only as cargo but also as fuel to power the ship. This could result in a different strategy to transport RHCs since some are more suited to store energy than to be used as a fuel.

1.2.2. Conclusion

This master thesis will focus on the transport of RHCs by ship. Current supply chain studies of RHCs only give a minor insight into the shipping part of the total supply chain. Therefore more research will be done in comparing different types of ship transport for RHCs.

1.3. Research gap

The following research topics are found about the subject of this thesis:

- The shipping share in the overall costs. In this research, a total supply chain of LNG is investigated, in which there is a focus on ship transportation. This is done for large scale LNG transport (above 150,000 m3). In this transportation, shipping presents 8% of the cost for a 4,208 nm trip, and for a 9,198 nm trip, 17.5% of the cost [12].
- Supply chains of RHCs. Research on RHCs focuses mostly on the whole supply chain. In this way, the cost price for the RHC can be specified. Most of this research focuses on the delivery of hydrogen, and this transportation is designed with several energy carriers such as, but not limited to, LOHCs, ammonia, methanol and liquefied hydrogen [8, 9, 13–15]. However, in this type of research, the shipping part is not evaluated in detail. Next to this, the research is mostly focusing on transporting large volumes, which is a whole different market than transporting smaller volumes.
- The transported energy carrier used as fuel for ships. In this research, the energy carrier, which is the cargo of the vessel, is used a fuel for the ships. This is done for ammonia [16], in which different powertrain configurations are considered. There is also research done in different energy carriers used as fuel [17]. This research is done for different powertrain configurations and is limited to two cases.
- Alternative fuels for ships. Research is done on vessels using alternative fuels for different ships designs, such as cruise ships [18], containerships [19] and ROPAX ferry [20]. The studies focus mostly on the effect of storage and powertrains to the ship design and economics.
- Alternative propulsion. Research is conducted on alternative propulsion of the vessels using SOFC powered by natural gas [21], PEM in combinations with a SOFC powered by hydrogen [22], SOFC in combinations with an ICE powered by natural gas [23] and a SOFC in combination with a homogeneous charge compression ignition (HCCI) powered by natural gas [24]. Powertrain configurations are also present in the research by [16–18].

Evaluating the research that is done in relation to the topic of this thesis, three things can be noticed. First, research is often done on specific transportation cases, in which a fixed ship design transports alternative fuels for a specific operational profile. Secondly, research in which ships are being powered by their cargo, are often limited to specific cases or one alternative fuel is chosen. Thirdly, research is done in total supply chains of energy carriers in which the ship transportation is not explained in detail.

Therefore this research will focus on the transport of different RHCs by ship, to see the consequences of the different carriers. Also, different powertrains configurations will be evaluated, which are powered by various RHCs. Furthermore, transportation cases are flexible in distance and volume. At last, the transportation of RHCs by ship will not be fixed in time. This is done, because, in the future, RHCs will decrease in price, new regulations will be active, and some of the powertrain configurations will decrease in price and increase in lifetime.

1.4. Research questions

In this section, the main research question and the research sub-questions will be discussed. These are based on sections described earlier, and will serve the main research goal. The goal of this research is to get insight into the way RHCs are shipped.

Main question

- *What is the impact of shipping renewable hydrogen carriers, when using the carriers as fuel, on the ship design, the different power configurations, and the cost of transported hydrogen?*

  Renewable hydrogen carriers mean that the hydrogen carrier is climate neutral, meaning that effectively there are no GHGs emitted during the production of the product.

Sub-questions

1. *Which renewable hydrogen carriers are available and suitable for being shipped?*

   The different RHCs need to be analysed to select suitable and available carriers for the specific type of transport. To make a selection of RHCs the production efficiencies will be evaluated from hydrogen to the hydrogen carrier and from hydrogen carrier to hydrogen. Also the properties of the RHCs need to be analysed, to known what the volumetric and gravimetric energy is.

2. *What is the most efficient way of storing renewable hydrogen carriers on ships?*

   Not all energy carriers have the same storage conditions, some are liquid at atmospheric conditions, and some are in the gaseous state. Gaseous products can be liquefied by cooling, which decreases the volume, this process, however, consumes energy. The other options are to leave the product gaseous, compress and cool it or fully compress it.

3. *How can renewable hydrogen carriers be used as fuel in a direct or indirect propulsion system?*

   Not all RHCs are suited to be used as fuel. Therefore first, the requirements have to be set on what defines a good fuel for different propulsion engines. A direct propulsion system is a system in which the RHCs can directly be used as fuel in the power generation system. In an indirect propulsion system, the RHCs first needs to be reformed to a fuel which can be used.

4. *How do voyage distance and the volume of ship transport, influence the cost of transported hydrogen?*

   A ship has to cover the distance between different harbours. However, the length of the voyage influences fuel consumption and fuel storage, affecting the design and costs. The amount of hydrogen that needs to be transported has an impact on the cargo volume of the ship, more hydrogen transported leads to a larger RHC volume and larger ship.

5. *How do technologic developments influence the cost of transported hydrogen?*

   The technology of SOFC, PEMFC and batteries is fast improving. While current lifetimes are relatively low and costs are relatively high, are the technologies fast improving. Meaning that the options might not be economical now, but can be in the future.

6. *What is the influence of future regulations on the design of the ship and cost of transported hydrogen?*

To comply with future regulations, shipowners need to adjust their ships to the required standards. Regulations are getting more strict, in which the local, regional and mondial authorities implement new rules, which means that shipowners continuously have to find new ways to innovate, to comply with the rules. This has a potential effect on the design of the ship.

In the next section, the research method will be described, which will describe the overall structure of the research in which the research questions will be answered.

1.5. Research method

In this section, the method of the research is defined. This approach is used throughout the report and will help to answer the research questions and to achieve the research goal.

In figure 1.6, the methodology of the research is shown. The first step of the research is the system description discussed in chapter 2. This system description will discuss the different elements of RHC supply chain.

In the second step of the research, three cases are used to narrow down the scope, and this is done in chapter 3. In this chapter, a basic model is designed, which will analyse three different cases of transportation. There is one small, one medium, and one large case. In the small case will correspond to the transport of a relatively small amount of hydrogen over a short distance, this idea is also used for medium and large scale case. These cases will give an impression which RHCs are most interesting to look at from a shipping point of view and where tipping points might lay. Based on these case results, in combination with information from literature, a further selection of RHCs can be made.

In the third step of the research, a more detailed model is made. Therefore, the RHCs are analysed on their performance as a fuel for different powertrain configurations. The analysis is based on costs, emissions, lifetime and efficiency. With this new model, three future regulation scenarios for different transportation cases are evaluated. This can be helpful to access when some of the configurations become attractive to implement.

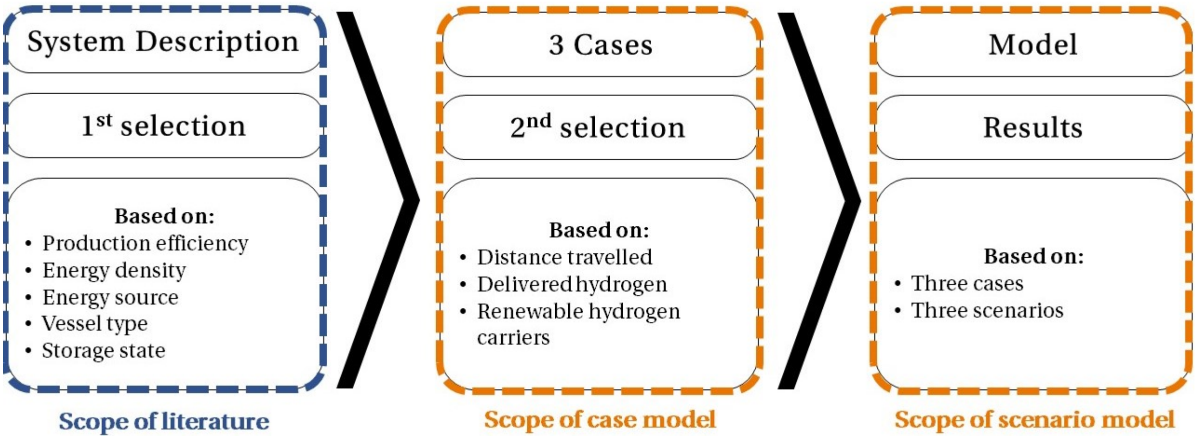

Figure 1.6: Methodology

1.6. Research scope

In this section the scope of the research is defined. Figure 1.7 shows an overview of the research scopes. In the first phase, in chapter 2 there will be a selection on RHCs, hydrogen production, carbon sources, vessel types and storage state.

In the second phase of the research, there will be a focus on the shipping part, which are the two last steps shown in figure 1.7. In this step, a model will be used to get a better understanding of how to efficiently transport RHCs by ship. Any losses in the first three steps shown in figure 1.7 (renewable power → hydrogen production → conversion to carrier) will not affect the design of the actual ship transportation. If this is taken as a starting point, the following parts will determine how the transport is shaped:

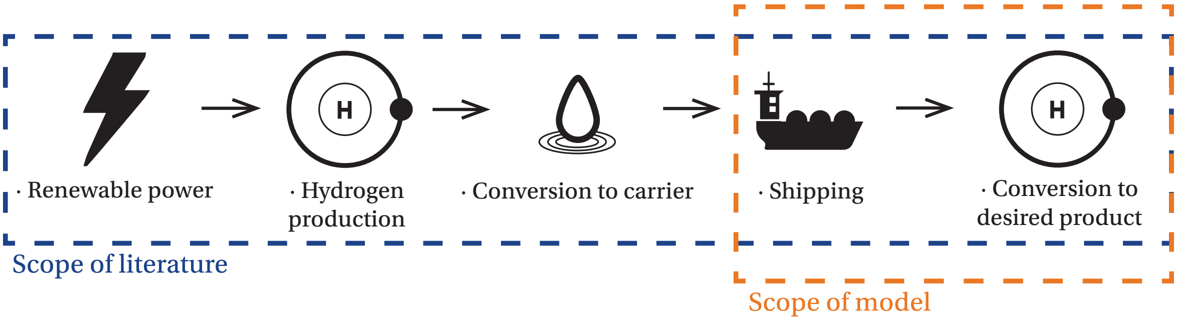

Figure 1.7: Scope of the system description

- *Shipping part:* In this step the RHC will be shipped. The energy that is needed for the ship transport, has to be present at the start of the round trip. This energy can come from two sources. The first option is that the energy comes from the transported RHC. The second option is that an additional fuel tank of synthetic natural gas (LSNG) will be present, this is also a renewable hydrogen carrier. This option of LSNG will be available in the model, because natural gas is at this moment considered as an innovative shipping fuel.
- *Conversion to desired product:* The energy that is needed to convert the energy carrier to the desired product (hydrogen in this thesis) will come from the RHC itself. Depending on the efficiency of the conversion and the hydrogen density of the carrier, more or less of the RHC will be needed. The main idea of importing renewable energy is, is that there is not enough or it is too expensive at the imported location. Therefore the conversion energy should be present at the start of the shipment.

To make a clear comparison between the different transportation options, the mass of delivered hydrogen in tonnes will be fixed. By doing this, different options can be evaluated, which all deliver the same amount of hydrogen. The decision for hydrogen is made, because a hydrogen economy is assumed, in which the molecule will be used for multiple applications from housing to industry. The decision for the physical quantity mass, is made, because hydrogen has different applications. The molecule can be used for heat, in which the amount of energy is important, but the molecule can also be used as a feedstock product in which the chemical properties are more important. By choosing for hydrogen mass, there is no implicit decision for which application it will be used.

2

System Description

This chapter will be used to give an overview of a world in which renewable hydrogen carriers (RHCs) are produced, shipped and converted to hydrogen. First, this chapter will explain how renewable power can be used to produce hydrogen. Secondly, the conversion and reconversion production processes of the RHCs are discussed and where the feedstock that is needed comes from. After the RHCs are discussed, a selection is made based on which of the RHCs are suited to be shipped. Next to this, a selection of vessels and storage types is made, because not all type of vessels will be used to ship RHCs.

This chapter will answer the first and the second research sub-question, which are discussed in section 1.4:

- *Which energy carriers are available and suitable for being shipped?*
- *What is the most efficient way of storing renewable hydrogen carriers on ships?*

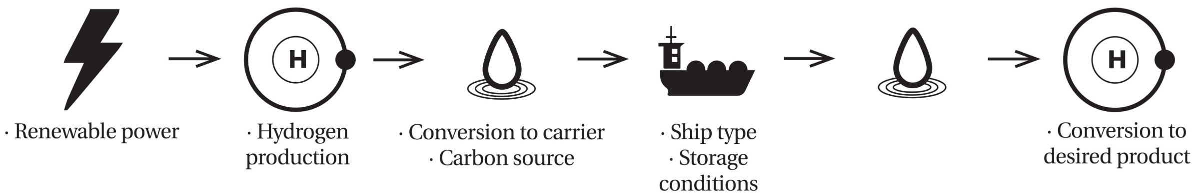

Figure 2.1: Overview of the elements discussed in the system description

The green hydrogen is produced by renewable electricity. Depending on the specific application, the hydrogen can be processed, stored, or transported. To get more insight into the transportation of the RHCs by ship, the following characteristics of RHCs are important:

- Production
  - Electricity to hydrogen
  - Hydrogen to carrier
  - Carrier to hydrogen
  - Feedstock
- Storage conditions of RHCs
- Energy densities
  - Volumetric
  - Gravimetric
- Vessel used for transportation

2.1. Hydrogen production

Conventional hydrogen production is produced from fossil fuels, and this hydrogen can be subdivided into two categories, grey and blue hydrogen. If hydrogen is produced from renewable resources, it will be called green hydrogen. This green hydrogen can be divided into two main categories; hydrogen from green electricity, and hydrogen from biomass. However hydrogen made from biomass will remain out of scope, as earlier mentioned.

Green electricity

The production of green hydrogen is different from the blue and grey hydrogen. The production of green hydrogen makes use of renewable electricity, such as wind or solar power. The electricity goes through an electrolyser which can split the hydrogen and oxygen from the water molecule. This is called electrolysis and is shown in equation 2.1.

$$H_2O \; (+ \; \textit{Electricity}) \longrightarrow H_2 + \frac{1}{2}O_2 \tag{2.1}$$

There are several types of hydrogen electrolysers, these include proton exchange membrane (PEM) electrolysers, alkaline electrolysers (AEC) and solid oxide electrolysers (SOEC). These can also be used in a reversed configuration in which the process of power to fuel can be switch to fuel to power, this will be further explained in chapter 5.2.2, when fuel cells are discussed.

The electrolyser uses electricity to split the water molecule, therefore it is beneficial to have an electrolyser with a high efficiency. Ideally, the efficiency is close to a hundred percent, since this will mean that the used electricity will not be lost. The three most known electrolysers are listed below:

- Alkaline Electrolysis Cells (AEC)
- Proton Exchange Membrane Electrolysis Cells (PEMEC)
- Solid Oxide Electrolysis Cells (SOEC)

The characteristics of these three technologies are summarized in table 2.1. For the production of hydrogen further in this thesis the alkaline electrolysers are used, summarized in table 2.2

	Alkaline Electrolyser		PEM Electrolyser		SOEC Electrolyser	
	Today	Long term	Today	Long term	Today	Long term
Electrolysis efficiency [% HHV]	64	77	60	72	80	85
Operating pressure [bar]	1-30		30-80		1	
Stack lifetime [*1000hr]	60-90	100-150	30-90	100-150	10-30	75-100
Load range [%]	10-110		0-160		20-100	
Plant foodprint [m^2/kW_e]	0.095		0.048		x	
CAPEX [$\$/kW_e$]	500-1400	200-700	1100-1800	200-900	2800-5600	500-1000

Table 2.1: Techno-economic characteristics of different electrolyser technologies based on HHV[8, 25–28]

Parameters	2020	2030	2040	2050	2060	2070
Electrolysis efficiency [% LHV]	68 [29, 30]					
Pressure out [bar]	30 [14]					
Electrolyser cost [€/kW]	757	566	424	317	237	180

Table 2.2: Alkaline electrolysers (AEC) parameters used

2.2. Conversion and Reconversion

The hydrogen that is produced can be used for multiple applications. Hydrogen today is mainly used for oil refining and ammonia production, other hydrogen is hydrogen as a part of synthesis gas, this is mainly used for the steel production and methanol. The value chain of hydrogen is shown in figure 2.3.

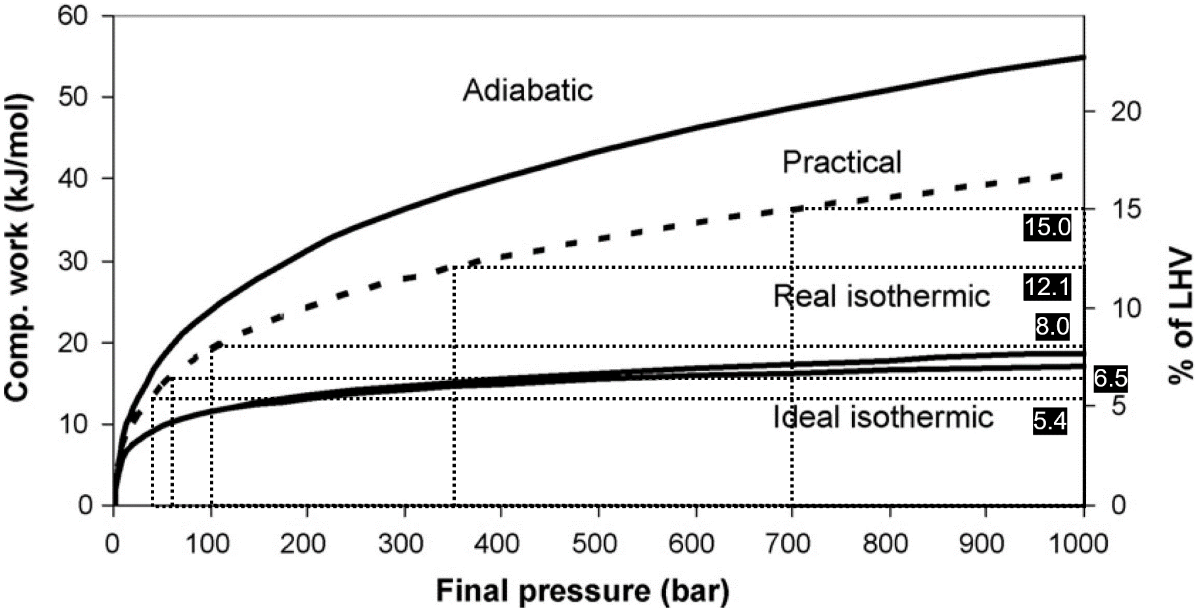

Figure 2.2: The energy needed for the compression of hydrogen[31]

Pressure in [bar]	Pressure out [bar]	Practical efficiency † [GJ/tH_2]	Real compression losses [GJ/tH_2]
0	20	6.5	10.0
20	30	1.3	2.0
30	100	1.8	2.8
100	350	4.8	7.4
350	700	3.6	5.5

†Lays between the values of the adiabatic and isothermal efficiency shown in figure 2.2

Table 2.3: Hydrogen compression energy requirements based on figure 2.2[31]

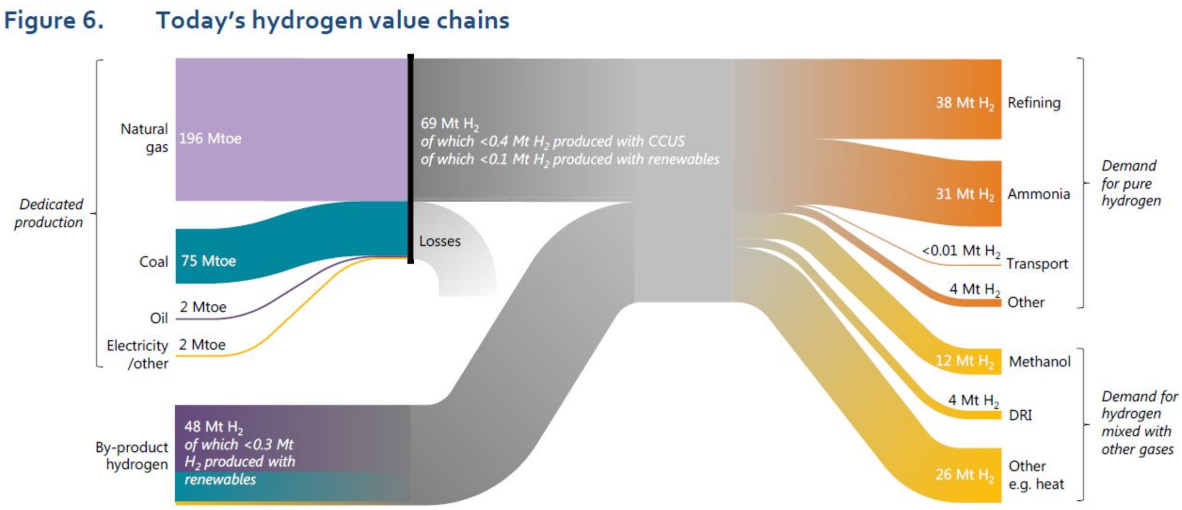

Figure 2.3: Current hydrogen value chain worldwide [8]

2.2.1. Hydrogen (compressed)

The practical compression efficiency of hydrogen is in between the isothermal and the adiabatic efficiency. The practical efficiency is close to the average of the isothermal and adiabatic efficiency as can be seen in figure 2.2, here the energy requirements are shown for the compression of hydrogen. However, in practice greater compression energies are required, because of the losses due to compressor inefficiencies and heating during fast fills [32, 33]. The efficiency of the compressor is assumed to be 65% [34]. Figure 2.2 together with the compression energy will determine the real compression losses shown in table 2.3.

Storing hydrogen at pressures of 350 bar or even at 700 bar, requires significant material strength of the pressurized storage vessel. When increasing the diameter of the storage vessel, the wall thickness also needs to be increased to be able to withstand these forces. The stress formula for a thin walled cylinder is shown in equation 2.2. It can be seen that when increasing the radius (r) for a thin walled cylinder, while maintaining the same pressure (p) and the same material properties σ_θ, the thickness t, needs to increase. Larger tanks have more surface area, which means more force is exerted onto the wall of the storage vessel and a thicker wal is needed. Increasing the thickness creates other problems, because more material is needed thus increases the weight. Due to these limitations compressed hydrogen storage is mainly used in relatively small applications such as the mobility industry.

$$\sigma_\theta = \frac{pr}{t} \tag{2.2}$$

When looking at the natural gas industry, large storage facilities store natural gas as LNG, and the transport of natural gas is also done on ships transporting it in the liquid form. However, research of Anthony Veder shows that for some types of shipment CNG could be more economical, especially for small scale and short distance transport. However, the industry standard of transporting natural gas is in the liquid form and therefore LNG is mainly transported. Hydrogen has an even lower boiling point than natural gas, and thus it can be expected that for large industries such as the shipping industry the transport of hydrogen will not be carried in compressed form but in liquefied form, since there is a physical limitation to compressed storage. This is similar to the developments in the natural gas industry. Other research also mentions that despite the relative complexity of the construction of liquid hydrogen storage vessels, there are indications that liquid hydrogen storage tanks are less costly per weight of hydrogen stored than vessels for pressurized gaseous hydrogen on larger scales [35].

2.2.2. Hydrogen (Liquefied)

To liquefy hydrogen a significant amount of energy is needed. In theory 14.04 GJ is needed to liquefy one ton of hydrogen, which is 11.7% of the total energy stored in hydrogen based on the LHV[36]. However in practice the energy losses are higher and for modern liquefaction plants the losses are around between 21.6 - 24.0 GJ/tonH_2, which means a loss of 18% - 20% based on the LHV [8, 32, 35–43].

In table 2.4 the various parameters are shown for different liquefaction plants. The liquefaction plant will operate at 80 bar, and depending on the outlet pressure of the electrolyser an extra compression step is needed. If the outlet pressure of the electrolyser is 80 bar, than the energy requirement of the liquefaction plant can be reduced to 21.6 GJ/tLH_2 [43]. The energy needed to compress hydrogen from 20 to 80 bar is around 2.6 GJ/tH_2 [43].

Liquefaction plant	IdealHY [43]	Reuß [41]	IEA [44]	Shipping Sunshine [14]
Capacity [tLH_2/day]	50	50	712	7070
Annual operation [hr]	8000	5600	NA	8760
Inlet pressure [bar]	20	30	NA	30
Depreciation period [yrs]	20	20	NA	30
Annual OPEX [%/CAPEX]	4	8	4	3
Losses [%tLH_2]	1.67	1.65	NA	NA
Energy requirement [GJ/tLH_2]	24.3	24.4	22.0	24.3
Electricity price [€/GJ]	13.9 (50€/MWh)	16.7 (60€/MWh)	4.55 (16.3€/MWh)†	3.3 (11.8€/MWh)
Investment cost [M€]	105	105	1261	2755
Liquefaction cost [€/tLH_2]	1,380	1,890	410	120

†Minimum price of electricity assumed in the assumption report by the IEA [44]

Table 2.4: Parameters of different designs of hydrogen liquefaction plants

Liquid hydrogen is often stored in double walled tanks with a vacuum space between the walls, filled with additional insulation material (perlite), this will be explained in more detail in section 5.1.1.

To use hydrogen in, for example a fuel cell, it has to be in the gaseous state. To get the liquid hydrogen in this state it has to move through a vaporizer. This requires 0.6 MWh/tH_2, which is equivalent to 2.16 GJ/tH_2 [41]. Based on the LHV, this is a loss of 1.8% .

2.2.3. Ammonia

Ammonia has been used to produce fertilizer for agriculture for over 100 years. Green ammonia is produced through a reaction between nitrogen and green hydrogen. The production of green hydrogen is explained in section 2.1. Haber and Bosch developed the basic process which is still used today to make (green) ammonia. The reaction, shown in equation 2.3 is carried out at temperatures ranging between 400 and 500 degrees Celsius. The operating pressure is between 100 - 250 bar and to promote the reaction there is an iron oxide based catalyst present [30, 45].

$$N_2 + 3\,H_2 \rightleftharpoons 2\,NH_3\,(+\,\textit{Heat}) \qquad \Delta H = -92\,\text{kJ/mol} \tag{2.3}$$

For the synthesis of 1 ton of ammonia, 0.178 ton of hydrogen is needed. To produce this amount hydrogen, an electrolyser is used, which currently has an efficiency of 68% based on the LHV [29, 30]. To produce 1 ton of hydrogen, 176 GJ is needed. Translating this to the ammonia production, this will mean mean that for 0.178 ton of hydrogen, 31.4 GJ (assuming a 68% efficiency based on the LHV) is needed.

To synthesise ammonia, first nitrogen needs to be separated from the air, this is done by an air separation unit (ASU). Typical ASU techniques include pressure swing absorption (PSA) and cryogenic distillation. Power requirements for the ASU unit are estimated on 0.11 kWh/kgN_2, using 822 kg N_2 for 1 ton of ammonia, requires 0.326 GJ/tNH_3 [46].

Next, the nitrogen and hydrogen are compressed and fed to a Haber-Bosch synthesis reactor. The Haber-Bosch process requires 0.64 kWh/kgNH_3, for 1 ton of ammonia, 640 kWh is needed, which is equivalent to 2.30 GJ/tNH_3 [45].

The whole process of making ammonia through electrolysis consumes around 34 GJ, which is equivalent to an efficiency of 57% based on the LHV, the values of the production are summarized in table 2.5.

Process	Mass needed [ton]	Energy need [GJ]	Efficiency (LHV) [%]
Electrolysis of H_2	0.178	31.4	68
Separation of N_2	0.822	0.33	-
Haber-Bosch Reactor	x	2.30	-
Total	1 ton NH_3	34.03	56

Table 2.5: Energy requirements ammonia synthesis

Ammonia can be stored in multiple ways; in pressurized thermos tanks, in semi-pressurized/semi-refrigerated (SP/SR), and in fully refrigerated tanks. Pressurized thermos tanks and (SP/SR) tanks are designed to keep the refrigerated ammonia as cool as possible with the use of isolation. However the temperature of cargo will always rise, which means that the tanks are also designed to withstand certain amounts of pressure, most of them up to 10 bar. Ships having (SP/SR) tanks can often re-liquefy its cargo, but pressurized thermos tanks cannot. There are also fully refrigerated tanks which hold refrigerated ammonia, but at atmospheric pressure and do not allow, or very limited, pressure to build up inside the tank. When there is some boil off in the tank, the gas is re-liquefied and put back into the tank. LPG carriers were analyzed, to see how ammonia can be stored best, since LPG has similar storage conditions as ammonia, because of the similar boiling points. The storage conditions of different LPG ships are shown in table 2.6

Fuel storage	Pressurized Vessel (Type C) [m^3]	SP/SR Vessel (Type C) [m^3]	Refrigerated Vessel (Type A) [m^3]	Source Source
LPG	0 - 2,400	2,400 - 6,400	6,000 - 100,000	[47]
LPG	0 - 4,000	1,500 - 30,000	30,000 -	[48]
Butene	0 - 5,000	-	-	[47]
Propane	0 - 3,000	-	-	[47]
LPG	500 - 6,000	-	-	[49]
LPG	3,200 (average)	9,200 (average)	63,700 (average)	[50]
NH_3	0 - 400	660 - 4,000	6,600 -	[45]

Table 2.6: The storage capacity of different LPG carriers

Ammonia can be used as a RHC. The theoretical adiabatic efficiency for the process of cracking the ammonia to hydrogen and nitrogen is about 85% [33, 51]. Research suggests efficiency of ammonia crackers of efficiencies between 75-85%, with an average of 79% [8, 9, 33, 51].

2.2.4. Methanol

Methanol can be produced from synthesis gas, which can be produced through steam methane reforming (SMR) and is described in A.1.1. After the syngas is formed it goes into another reactor at high pressure forming methanol, shown by equation 2.5. The reaction is exothermic and the high pressure is needed to shift the reaction to the right, because of the Chatelier principle. Another reaction that takes place is the reaction between CO_2 and hydrogen in which water and methanol are formed, described by equation 2.6 [52]. Water is separated from the methanol. The methanol that is produced using fossil sources, is called grey methanol.

Green hydrogen can also be used for the production of methanol, in which green hydrogen and captured CO_2 are going into a reactor in which a reverse water gas shift reaction (RWGS) takes place, shown in equation 2.4. H_2O and CO are produced in this reactor. After the reactor, the water is separated, and the CO and the CO_2 are mixed with H_2 to form (green) syngas. After this step the production of green methanol doesn't differ from the production of conventional grey methanol.

Green methanol can also be produced directly, in which CO_2 and H_2 go into a reactor at around 250 - 300 degrees Celsius and an operating pressure of 50 - 100 bar with a catalyst of $CuO/ZnO/Al_2O_3$. This reaction is shown in equation 2.6.

$$CO_2 + H_2 (+\ Heat) \rightleftharpoons CO + H_2O \qquad \Delta H = +41.2\,kJ/mol \tag{2.4}$$

$$CO + 2H_2 \rightleftharpoons CH_3OH (+\ Heat) \qquad \Delta H = -90.7\,kJ/mol \tag{2.5}$$

$$CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O (+\ Heat) \qquad \Delta H = -49.5\,kJ/mol \tag{2.6}$$

For a specific methanol production case, an installation with a 1MW electrolyser consumes 4.125 GJ/hr (3.7 GJ/hr consumed by the electrolyser, 0.45 GJ/hr consumed for CO_2 capture, 0.11 GJ/hr produced by methanol reactor, and 0.08 GJ consumed by the compressors)[53]. The flow rate in this system is 97 kg/hour, which produces 97 * 20.1 (LHV of methanol) = 1.9497 GJ/hour.

The methanol reactor produces 0.11 GJ/hr, this is 1.15 GJ/tMeOH. The CO_2 compressor consumes 0.04 GJ/hr, which is equivalent to 0.36 GJ/tMeOH, and the compressor for H_2 and CO_2 consumes 0.48 GJ/tMeOH.

Looking at the electrolyser more closely, the amount of hydrogen that is supplied is 19 kg/hour for the methanol reactor, which is, equivalent to 2.28 GJ (LHV). Using the efficiency of 68%, which was also used for the ammonia process, the amount of energy that is needed is 3.35 GJ (instead of the 3.7GJ/hr).

The carbon capture consumes 124 kWh (0.4464 GJ) and produces 0.140 tCO_2/hr, this is equivalent to 3.188 GJ/tCO_2, translating this to the 1.442 ton of CO_2 that is needed for the process, the carbon capture process for producing methanol is 4.60 GJ/tMeOH needed.

Adding all consumables, 3.77GJ/hr will be consumed during the production of green methanol, equivalent to 38.9 GJ/tMeOH, which is an efficiency of 52% summarised in table 2.7.

Process	Mass needed [ton]	Energy need [GJ]	Efficiency (LHV) [%]
Electrolysis of H_2	0.189	33.4	68
Capture of CO_2	1.442	4.60	-
MeOH reactor	x	-1.15	-
Compression of CO_2 (2 to 30 bar)	x	0.36	-
Compression of $H_2 + CO_2$ (30 to 80 bar)	x	0.48	-
Total	1 ton MeOH	37.7	53

Table 2.7: Energy requirements methanol synthesis

Methanol can be stored in cargo tanks made of carbon steel with coatings or in stainless steel tanks. Prior to the loading the tanks should be in a clean and dry condition [54]. Due to the corrosive nature of methanol, extra attention has to be paid when selecting the tank wall material[18].
MariLine, zinc or epoxy coatings can be used to protect the carbon steel tanks. The type of stainless steel can vary between 300 series stainless steel or duplex 2205 stainless steel [55]. Duplex 2205 stainless steel, can only be constructed at limited suppliers [56], these tanks are used especially for high density chemicals, with densities above 1.86 kg/m^3. 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. [57]. The decision between either of the two tank types is always a trade off, because most chemical tankers are flexible in their cargo transport. However, this research will focus on the transport of a fixed RHC, therefore ships with coated cargo tanks will be used.

Methanol is reformed using steam methanol reforming, or autothermal reforming (ATR). This process consumes 55 GJ/tH_2 [9], meaning that an efficiency of 54%.

2.2.5. DME

Dimethylether (DME) can be produced directly or through an intermediate step. The direct way of synthesising DME is to react hydrogen with carbon monoxide, in which DME and carbon dioxide are formed, shown in equation 2.7. The carbon monoxide is formed during the RWGR, shown in equation 2.4. The assumption is that CO_2 will be captured from air or flue gases. Indirectly, DME can be produced through the dehydration of methanol, shown by equation 2.8 [58, 59], in which also water is produced. The production of methanol is earlier described in section 2.2.4.

$$3\,CO + 3\,H_2 \rightleftharpoons CH_3OCH_3 + CO_2\,(+\,\mathit{Heat}) \qquad \Delta H = -245.0\,kJ/mol \tag{2.7}$$

$$2\,CH_3OH \rightleftharpoons CH_3OCH_3 + H_2O\,(+\,\mathit{Heat}) \qquad \Delta H = -23.4\,kJ/mol \tag{2.8}$$

Data from research states that for the indirect synthesis route of DME the energy penalty during the DME synthesis is 3.25 GJ per tonne of DME produced [60]. The other energy needed comes mainly from the electrolysis and to lower extend from the carbon capture. For electrolysis an energy consumption of 46.7 GJ/tDME will be used and the energy consumption of CO_2 capture will use 6.4 GJ/tDME. The values are summarized in table

2.8.

Process	Mass needed [ton]	Energy need [GJ]	Efficiency (LHV) [%]
Electrolysis of H_2	0.263	46.4	68
Capture of CO_2	2.01	6.40	-
DME reactor	x	3.25	-
Total	1 ton DME	56.1	51

Table 2.8: Energy requirements DME synthesis

The storage of DME is similar to the storage of LPG and ammonia, due to its similar boiling point. This means that for storing relatively small volumes of DME, pressurized thermos tank or SP/SR tank will be used. For larger volumes, refrigerated storage is likely to be more economical.

DME will be reconverted into hydrogen by DME reforming, similar to methanol reforming. Although not a lot of information can be found on DME reforming, it is assumed that the same efficiency applies as for MeOH reforming [9].

2.2.6. Ethanol

Ethanol C_2H_5OH, is best known alcohol since it is the alcohol that is present in alcoholic beverages. Ethanol can be produced either directly from syngas or through a reaction from methanol. The production of syngas is shown in equation 2.4. After the syngas is formed it goes into another reactor in which ethanol is formed, this reaction is shown in equation 2.9. The reaction is exothermic, and occurs below 300 °C. The reaction is promoted by the use of Cobalt and Rhodium as catalysts [18]. However there is only limited information available on this way of synthesising ethanol, therefore it does not seem likely that ethanol will be produced this way.

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

Ethanol can also be produced through a reaction of methanol, this reaction is called homologation and is shown in equation 2.10. The reaction is supported by the use of copper and cobalt as catalyst [18]. As of this moment, most ethanol is produced from fossil feedstock or from biomass, which is explained in A.2. Similar to the ethanol production with the use of syngas, does this reaction also have limited available information. The production of renewable ethanol from biomass is likely to be more economical than the production of ethanol from synthetic green hydrogen. Therefore ethanol will not be further considered.

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

2.2.7. Formic Acid

A direct route for conversion of carbon dioxide is based on hydrogenation of CO_2. The simplest reaction is the conversion of CO_2 to formic acid (CH_2O_2). This direct route has attracted considerable research activities, however, at the moment no commercial process is available where a homogeneous or heterogeneous catalyst can be used to convert CO_2 [61].

$$H_2 + CO_2 \rightleftharpoons CH_2O_2 \tag{2.11}$$

Formic acid can also be formed with a reaction through methanol shown in equations 2.12 2.13. For this reaction methanol will be first needed, which is already a potential energy carrier. Formic acid has a lower volumetric energy density (7.6 GJ/m^3) compared to methanol (15.6 GJ/m^3), and also has a higher density (1.22 t/m^3) compared to methanol (0.79 t/m^3). Therefore it seems unlikely that for the transportation of energy, extra conversion step will be added to make formic acid, since this always will result efficiency losses. Therefore formic acid will not be evaluated further.

$$CH_3OH + CO \rightleftharpoons HCO_2CH_3 \tag{2.12}$$

$$HCO_2CH_3 + H_2O \rightleftharpoons CH_2O_2 + CH_3OH \tag{2.13}$$

2.2.8. Fischer-Tropsch Diesel/Kerosene

Fischer Tropsch diesel/kerosene can be produced through a reaction between hydrogen and a carbon source. Synthetic diesel/kerosene can be produced through the Fischer-Tropsch (F-T) process. In this reaction a mixture of hydrocarbons can be formed within the range of $C_{10}H_{22}$ to $C_{20}H_{42}$. The reaction is shown in equation 2.14. The efficiency of the production of F-T diesel is quite low, with maximum efficiency of 40% [18, 62].

$$(2n+1)\,H_2 + nCO \rightleftharpoons C_nH(2n+2) + nH_2O \tag{2.14}$$

Next to that, diesel and F-T diesel have the problem NO_x and black carbon emissions are emitted when power needs to be generated[63]. The regulations, especially for NO_x emissions are becoming much more strict and black carbon or soot emissions have a significant contribution to the greenhouse effect. Given the fact that F-T diesel also has a low production efficiency it seems unlikely that it will be used as an energy carrier and thus will not be examined further.

2.2.9. Synthetic Natural Gas

Grey methane or conventional methane is the main component in natural gas and is found naturally under the earth surface. Synthetic natural gas (SNG) can also be produced synthetically, this can be done through the Sabatier reaction shown in equation 2.15. In this reaction CO_2 and H_2 react to form water and methane, this reaction is also known as methanation. To form green methane, green hydrogen and captured CO_2 are used for the production. Another way of producing SNG is through the reverse reaction of steam methane reforming, shown by equation 2.16, in which carbon monoxide and hydrogen react to form methane. The carbon monoxide can be received through the RWGS, as shown in equation 2.4.

$$CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O\,(+\,\mathit{Heat}) \qquad \Delta H = -165\,kJ/mol \tag{2.15}$$

$$CO + 3H_2 \rightleftharpoons CH_4 + H_2O\,(+\,\mathit{Heat}) \qquad \Delta H = -206\,kJ/mol \tag{2.16}$$

Next to the losses during the hydrogen production, there are also additional losses including carbon capture, synthesis of SNG and the liquefaction process.The energy requirements of the CO_2 depend on the source. The energy penalty 3.2 [GJ/tCO_2] is assumed to be the same as for DME and MeOH. The efficiency of methanation, which is the actual synthesis part has an efficiency of around 79 % [8, 64–66]. The liquefaction process has an efficiency of around 8%, which is 4.1 GJ per ton of LSNG [67–71]. The values are summarised in table 2.9.

Process	Mass needed [ton]	Energy need [GJ]	Efficiency [%]
Electrolysis of H_2	0.503	88.8	68
Capture of CO_2	2.74	8.74	-
SNG Reactor	x	9.72	-
Liquefaction of SNG	x	4.1	-
Total	1 ton LSNG	111.3	44

Table 2.9: Energy requirements LSNG synthesis

For reconversion, a steam methane reforming plant would be used. A standard SMR plant with a capacity of 100,000 m^3/h, which is operated continuously (capacity factor of 95%), has an overall efficiency of natural gas to hydrogen of 76% [72]. The storage of liquefied synthetic natural gas (LSNG) is described in section 5.1.1.

2.2.10. LOHC

Liquid organic hydrogen carriers (LOHC) are molecules which can bond hydrogen. First there is an exothermic catalytic reaction, in which hydrogen is bonded onto the molecule. In this reaction heat is released of around 50 - 150 °C. When the hydrogen needs to be released, the molecule goes through a catalytic reaction of around 300-350 °C [73]. The hydrogen can afterwards be used for other purposes. Two of the most promising LOHCs are toluene and dibenzyltoluene [74]. The transportation process of these LOHCs is convenient since storage and transportation can be carried out at atmospheric pressures and temperature, while being in the liquid form. Both LOHC chemicals last for 1000 cycles of hydrogenation and dehydrogenation [75].

Dibenzyltoluene

Dibenzyl toluene (H0-DBT) and in hydrogenerated form its perhydro-dibenzyltoluene (H18- DBT) is a LOHC. DBT has many advantages compared to other LOHC systems, due to its high hydrogen storage capacity, thermal stability, high boiling point, low toxicity and low melting point. However the process of hydrogenation and dehydrogenation is more complex, due to the fact that different catalysts are needed in the reactions. If the same catalyst can be used for both reactions and the two reactions can be carried out under the boiling temperature of the LOHC, than both processes can be carried out in the same reactor, making the process a lot simpler [76]. The costs of DBT is assumed to be €3,622/ton [74, 77, 78].

DBT is used in industry as a heat transfer medium but is not produced in large quantities like toluene. With higher production capacities of DBT, the production costs might drop significantly in the future [41]. For the production of DBT mainly toluene is required. Together with chlorine DBT is produced in a catalytic reaction. Next to DBT also hydrochloric acid is produced [74].

The hydrogenation of dibenzyl toluene (H0-DBT) is an exothermic reaction in which heat is released, which can be seen in equation 2.17. The reaction is carried out at high pressures of around 50 bar and a temperature of around 150 °C, the dehydrogenation is carried out at atmospheric pressures and a temperature of around 300 °C [78]. The hydrogen that is obtained from the dehydration of DBT is in theory pure enough for a fuel cell [74], however some experiments indicate that this is not the case yet.

$$C_{21}H_{20} + 9H_2 \rightleftharpoons C_{21}H_{32}\,(+\,\mathit{Heat}) \qquad \Delta H = -72\,\mathrm{kJ/mol} \tag{2.17}$$

The hydrogenation of H0-DBT takes place at 50 bar, therefore the hydrogen needs to be pressurized in the first step. This leads to 3.48 GJ per ton hydrogen [74]. The catalyst (5% platinum and aluminium oxide 95%) of 1kg lasts for 500 ton of LOHC. For H18-DBT, which has 6.2w% of hydrogen, this means that every 31 tons of hydrogen [75] a kilogram of the catalyst is needed. During the process of hydrogenation 1% of the hydrogen is lost and 0.1% of the LOHC [75], equivalent to 1.2 GJ. This leads to 3.48 + 1.2 = 4.68 GJ/tH_2. For the electrolyser the amount of electricity needed for the AEC, is 176 GJ.

The storage of DBT is similar to oil products, since both products can be kept at liquid at atmospheric conditions. The fact that DBT is non toxic, makes it easier to meet the requirements of a storage tank than methanol or toluene.

For the dehydrogenation of H18-DBT to H0-DBT, energy is needed for the pumping and auxiliary equipment, preheating and the actual dehydrogenation itself. In total this process consumes 34.2 GJ per ton H_2 [77, 79], in which 32.4 GJ is used in the hydrogenation itself.

Toluene

Toluene can be used as a LOHC, which is the dehydrogenated version of methyl cyclohexane (MCH) in which hydrogen is stored. Toluene is an aromatic hydrocarbon that is widely used as an industrial feedstock and as a solvent[80]. Toluene occurs naturally at low levels in pine oil and is usually produced by catalytic reforming of naphtha and in smaller amounts from pyrolysis gasoline produced in steam crackers during the manufacturing of ethylene and propylene [81, 82]. Toluene is a widely produced chemical, however a disadvantage of toluene is that it is toxic [8]. Another disadvantage is that hydrogen obtained after dehydration of toluene is not pure enough for PEM fuel cells and extra pressure swing absorption is required, leading to higher costs

[74]. The costs of toluene is assumed to be €630/ton [8, 74].

The hydrogenation of toluene is an exothermic reaction in which heat is released, which can be seen in equation 2.18 [83]. The dehydrogenation is normally conducted at reaction temperatures higher than 350 °C due to its kinetic and thermodynamic limitations [84]. The energy that is needed to release the hydrogen is slightly higher than for dibenzyl toluene. This process is similar to the hydrogenation process of H18-DBT, in which first the hydrogen needs to be compressed to enable the hydrogenation. On average 0.1% of the hydrogen is lost, meaning that this process uses 4.68 GJ per ton hydrogen (based on the LHV).

$$C_7H_8 + 3\,H_2 \rightleftharpoons C_7H_{14}\,(+\,\textit{Heat}) \qquad \Delta H = -205\,\text{kJ/mol} \tag{2.18}$$

The storage of toluene or MCH is similar to methanol, since both chemicals are toxic and have similar densities. Like methanol, MCH/toluene is best kept in stainless steel tanks, however carbon steels tanks with coatings like zinc, epoxy or MariLine can also be used to store MCH, however those have a lower resistance against the chemical, which will lead to higher maintenance cost.

Toluene has a higher standard reaction enthalpy [75] compared to H18-DBT, therefore 36 GJ per ton H_2 is necessary to dehydrogenate the hydrogen from the MCH [74].

2.2.11. Sodium Borohydride

Sodium Borohydride or $NaBH_4$ is a solid powder and can be used as a hydrogen carrier. The product can be stored at atmospheric temperatures and pressures, which is a significant advantage for transportation. There are also some disadvantages, which include high costs and low efficiency of recycling the product.

The current methods of synthesizing NaBH4 are the Schlesingerprocess (also known as the Rohm and Haas process) and the Bayer process, which are shown below in 2.19 and 2.20 [85]. It can be seen that one of the primary reasons for the high cost is the inherently low $NaBH_4$ yield of both reactions (4 mol of Na or NaH are required to produce 1 mol of $NaBH_4$) [86].

$$4\,NaH + B(OCH_3)_3 \longrightarrow NaBH_4 + 3\,NaOCH_3 \tag{2.19}$$

$$Na_2B_4O_7 + 7\,SiO_2 + 16\,Na + 8\,H_2 \longrightarrow 4NaBH_4 + 7\,Na_2SiO_3 \tag{2.20}$$

To use $NaBH_4$ as a a fuel, fresh water needs to be added to the $NaBH_4$. Secondly, to use the $NaBH_4$ as a fuel also an acid or a catalyst precursor is needed, to release the hydrogen. The problem is however that this acid/catalyst precursor is consumed during the usage of the $NaBH_4$. Therefore it needs to be resupplied for every tank of $NaBH_4$, this would add extra costs to the fuel price is already an issue [86].

$$NaBH_4 + 2\,H_2O \longrightarrow NaBO_2 + 4\,H_2\,(+\,\textit{Heat}) \qquad \Delta H = -75\,\text{kJ/mol} \tag{2.21}$$

After the dehydrogenation of $NaBH_4$, the product $NaBO_2$ is formed, this is shown in equation 2.21 [87]. This can be recycled by using Mg or MgH_2. MgO is recycled to Mg either directly or indirectly (via silicon) using carbothermal reduction [86], shown in equation 2.22. The other option of recycling the $NaBO_2$ is to use methane. The methane can be used in the direct carbothermal reduction, using a high temperature plasma of over 1000 °C to provide energy for the reaction. In this process also syngas is produced as a by-product [86], shown in equation 2.23.

$$NaBO_2 + 2\,MgH_2 \longrightarrow NaBH_4 + 2\,MgO \tag{2.22}$$

$$NaBO_2 + 2\,CH_4 \longrightarrow NaBH_4 + 2\,CO + 2\,H_2 \tag{2.23}$$

The production of $NaBH_4$ is quite an intense process, with multiple steps. After the $NaBH_4$ is dehydrogenated into $NaBO_2$, it needs to be reconverted and recycled. This costs energy and additional feedstock. The costs of producing $NaBH_4$ are around 1,802$/ton, which is relatively high given the fact that the product needs to be recycled every time it is used [88]. For the synthesis of 4.7 ton of $NaBH_4$, 181 GJ needed. 4.7 tons of $NaBH_4$ are able to store 1 ton of hydrogen [9]. For the dehydrogenation of $NaBH_4$ only water is needed to release the hydrogen, therefore the energy input for this reaction is negligible. $NaBH_4$ can be stored as dry bulk, but does need a sealed tank, which would prevent any water or moist to enter. However, the technology readiness level of $NaBH_4$ is assumed to be too low, it requires high amounts of energy to produce, and it needs to be recycled every time it is used as an energy carrier. Therefore this $NaBH_4$ will not be further investigated.

2.2.12. Sub conclusion based on production

The RHCs that will not be further evaluated in the research are mentioned below. This is because the RHCs are not considered attractive for the transportation of green hydrogen.

- Biomass based RHCs
- Ethanol
- Fischer-Tropsch Diesel/Kerosene
- Sodium Borohydride

2.2.13. Sub conclusion based on storage state

A number of different RHCs have been discussed. The storage conditions have a significant impact on the vessel, because of the finite space that is available. RHCs which have a low volumetric energy density will have the problem that for an equal ship size less energy or hydrogen can be transported. Having a low gravimetric energy density will mean that the energy carrier is relatively heavy, leading to an extra fuel penalty.

In this research, RHC will be only transported in the liquid form. This means that gaseous forms of transportation are kept out of scope, since it is expected that the volumetric energy density will be optimized and thus liquefied for the transportation of the RHC. To decrease the volume of gaseous RHCs, it will be cooled or compressed until it is liquid. The industry standard for transporting natural gas is to transport it in the cooled liquid form (LNG), it is expected that this will also happen for hydrogen as earlier mentioned in section 2.2.1. For DME and ammonia both compressed and cooled methods for liquefied storage will be considered. Methanol and the LOHCs are already liquid at standard ambient temperature and pressure (SATP).

Therefore the following RHCs are not evaluated:

- Formic Acid
- Gaseous storage
  - Hydrogen
  - Ammonia
  - DME
  - Methane

2.2.14. Economics

The economics of the RHCs are of importance, when the RHCs are used as fuel. The LOHCs will not be used as fuel, but those will need to be replaced after a 1000 cycles. To analyse the cost of the carriers which are used as a fuel, first, the feedstock of the RHCs are summarized in table 2.10. The feedstock requirements are based on production processes described earlier in this chapter. Feedstock prices of hydrogen, carbon dioxide, and electricity are taken into consideration, which are shown in table 2.11. In this table the cost of hydrogen is based on the electricity price and the electrolyser cost [14, 89]. The bold values in table 2.11, are the values from literature the other values are scaled accordingly. The cost of carbon dioxide is based on a point source of CO_2, this is when CO_2 is captured from a source having a high concentration of CO_2. The energy consumption will not be taken into account of capturing CO_2, but is based on a feedstock price.

RHC [-]	Hydrogen feedstock [tH_2/t]	Carbon dioxide feedstock [tCO_2/t]	Energy requirement [GJ/t]
LH_2	1.00	NA	24.3
NH_3	0.18	NA	2.6
DME	0.26	2.01	3.3
MeOH	0.19	1.44	0.8
LSNG	0.50	2.74	13.8

Table 2.10: Required feedstock for production of the RHCs

	2020	2030	2040	2050	2060	2070
Electricity price [€/GJ]	**10,0**[1]	8.0	6.4	5.2	4.2	**3.3**[2]
Electrolyser cost [€/kW]	**757**[1]	566	424	317	237	**180**[2]
Hydrogen price [€/ton]	**3,180**[1]	2,710	2,309	1,968	1,678	**1,426**[2]
CO_2 price [€/ton]	18,0[3]	18.0	18.0	18.0	18.0	18.0

[1] Estimated based on values [89]
[2] Estimated based on values [14]
[3] Estimated CO_2 price in IEA report, and is based on point source of CO_2 [44]

Table 2.11: Price assumptions for electricity, electrolysers, hydrogen and carbon-dioxide

Next, the cost of production is analysed. The cost of the equipment used for the production is based on large production processes. In reality these costs are not constant, due to the scaling factors and economies of scale. In table 2.12, the production cost are shown. The processes of making NH_3, DME, MeOH, and LSNG are assumed to be constant cost over time. The liquefaction production cost of hydrogen are assumed to decrease [€/ton], due to improved technology. The liquefaction parameters are shown in table 2.4.

	Process steps	RHC[-]	2020	2030	2040	2050	2060	2070
Production cost [€/t]	Liquefaction	LH_2	1,042 [1]	754	510	310[2]	153	40[3]
	ASU + Haber-Bosch process	NH_3 [4]	105	105	105	105	105	105
	Methanol/DME reactor	DME [5]	169	169	169	169	169	169
	Methanol reactor	MeOH [6]	123	123	123	123	123	123
	Methanation + liquefaction	LSNG [7]	284	284	284	284	284	284

[1] Based on IdealHY [43]
[2] Based on IEA assumption annex [44]
[3] Based on shipping solar [14]
[4] Average of values given [89, 90]
[5] Scaled to Methanol reactor, assuming similar components
[6] Average of values given [53, 89]
[7] Average of values given [89, 91]
[8] Can be used for a 1000 cycles of hydrogenation and dehydrogenation

Table 2.12: Production cost of the different RHCs

Using equation 2.24 the cost of the RHC can be calculated and the values are shown in table 2.13. Using the energy density (LHV) of the RHC, the prices based on the energy content [€/GJ] can be calculated as well.

$$
\begin{aligned}
&\text{Cost}_{RHC}\ [€/\text{ton}] \\
&= \\
&H_2\ \text{feedstock}\ [tH_2/tRHC] \cdot H_2\ \text{price}\ [€H_2/t] \\
&+ \\
&CO_2\ \text{feedstock}\ [tCO_2/tRHC] \cdot CO_2\ \text{price}\ [€CO_2/t] \\
&+ \\
&\text{Energy requirement}\ [GJ/tRHC] \cdot \text{Electricity price}\ [€/GJ] \\
&+ \\
&\text{Production cost}\ [€/tRHC]
\end{aligned}
\tag{2.24}
$$

	RHC [-]	2020	2030	2040	2050	2060	2070
Cost price [€/ton]	LH_2	4,465	3,660	2,976	2,403	1,931	1,545
	NH_3	576	505	445	394	350	313
	DME	1,076	946	836	742	662	593
	MeOH	758	668	591	525	469	421
	LSNG	2,072	1,808	1,584	1,395	1,235	1,096
Cost price [€/GJ]	LH_2	37	30	25	20	16	13
	NH_3	30	27	23	21	18	16
	DME	39	33	29	26	23	21
	MeOH	39	33	29	26	23	21
	LSNG	43	37	33	29	25	23

Table 2.13: Assumed cost over time of the various RHCs in terms of tonnage and energy content

Figure 2.4 gives an overview of the cost of the RHCs. All ships can use their own cargo as fuel, except for the ships carrying LOHCs. The operating period of the ship will be important, because over time there are differences in prices, for example the price of liquid hydrogen is assumed to drop significantly.

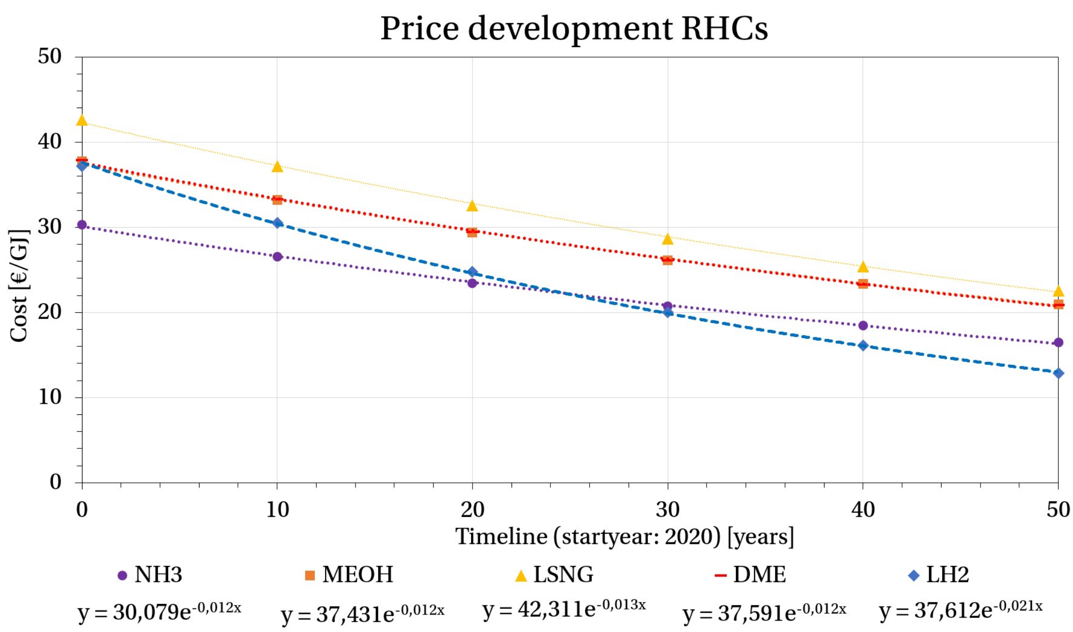

Figure 2.4: Price development of RHCs from the year 2020 to 2070 based on table 2.13

LOHCs

The LOHCs will not be used as fuel, however part of the LOHC will be consumed by the ship. After a 1000 cycles / round trips the LOHCs have to be replaced, equivalent a replacement percentage of 0.1%. In equation 2.25 the cost of using LOHCs are shown.

$$\begin{aligned} \text{Cost of LOHC round trip} \left[\frac{€}{tLOHC.trip}\right] &= \text{Replacement [\%]} \cdot \text{Cost of LOHC [€/ton]} \\ \text{MCH : } 0.630 &\left[\frac{€}{t(Toluene).trip}\right] \\ \text{H}_{18}\text{–DBT : } 3.622 &\left[\frac{€}{t(H0-DBT).trip}\right] \end{aligned} \tag{2.25}$$

2.2.15. Conversion energy

The energy needed for the ship voyage, and the conversion energy from the RHC to hydrogen will be be present at the start of the ship voyage. The energetic conversion ($\eta_{RHC\rightarrow H_2}$) and the mass conversion ($x_{RHC[H_2]}$) are displayed in table 2.14 and used in equation 2.26. To make a fair comparison, the mass of hydrogen that is delivered (M_{RHC}), is fixed in each of the transportation options. The energy that is consumed during the transport and conversion have different origins:

- The energy that is needed to convert the energy carrier to the hydrogen, is assumed to come from the energy carrier itself.
- The ships can either run on their own carried RHC or use LSNG as fuel for propulsion.
  - Ships can use their own cargo as fuel, this will mean that part of the RHC will be used for the operation of the ship. The effect of this is that the ship will have to carry more of the RHC, thus increasing the cargo volume.
  - Ships that run on LSNG as fuel. This means that LSNG provides the energy needed for the operation of the ship. This means that an additional fuel system for LSNG will be needed on the ship. The energy that is needed for the conversion from the RHC to hydrogen will still come form the RHC itself, and not from the LSNG.

$$\begin{gathered} \text{Mass of hydrogen delivered } [\text{tH}_2] \\ = \\ \text{Delivered RHC mass [tRHC]} \ (M_{RHC}) \cdot \text{Conversion Efficiency } [-] \ (\eta_{RHC\rightarrow H_2}) \cdot \text{H}_2 \text{ content } [-] \ (x_{RHC}[\text{H}_2]) \end{gathered} \tag{2.26}$$

RHCs	$\eta_{RHC\rightarrow H_2}$: Conversion efficiency to H_2 [-]	$x_{RHC[H_2]}$: H_2 content [-]
NH_3	0.79	0.18
DME	0.54	0.26†
H18-DBT	0.70	0.062
LH_2	0.98	1.0
LSNG	0.72	0.50†
MeOH	0.54	0.19†
MCH	0.66	0.060

† H_2 content differs from H_2 density in the fuel. During the reforming, water is added which will result in a higher H_2 content after the conversion

Table 2.14: Conversion from energy carrier to hydrogen

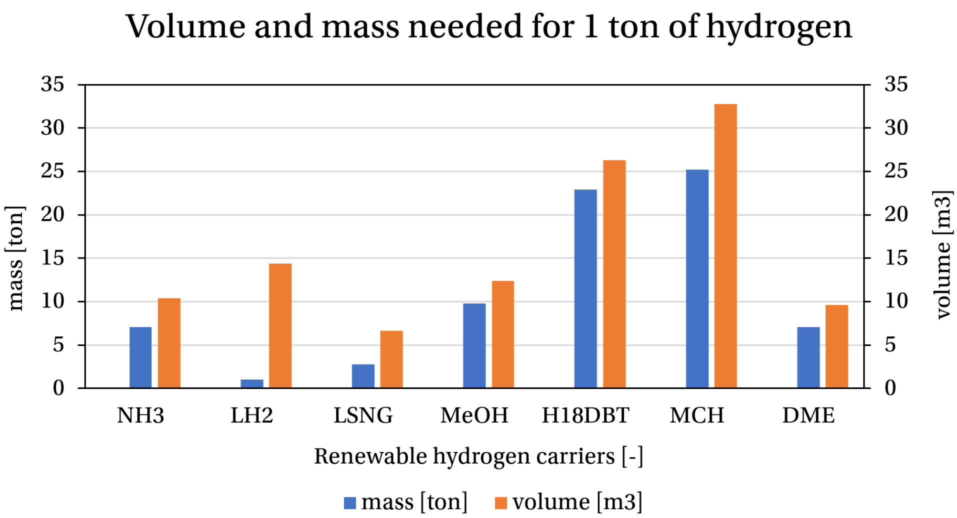

Figure 2.5: Visual presentation of RHC volume and tonnage needed to produce 1 ton of hydrogen based on equation 2.26 and table 2.14

2.3. Conclusion

The first sub research question was answered in this chapter, a selection is made on seven RHCs: LH_2, NH_3, DME, MeOH, LSNG, H18-DBT, and MCH, an overview of the specifcations of the RHCs are shown in table 2.16.

The second sub research question was answered as well, in which only liquid RHCs carriers will be shipped. In the paragraphs below a summary is given on what specific choices were made. Table 2.15 gives an overview of what is included in the research and what is not.

Renewable Hydrogen Carriers

Some of the RHCs will not be considered in this research, these include biofuels, sodium borohydride, formic acid and synthetic diesel. Biofuels will not be considered since there are some serious challenges which include; scaling of production, fuel consistency, availability of biomass and conflict with the food chain [92]. Therefore it is believed that biofuels will be a part of the total solution in decreasing the carbon footprint, but will not be used for large production of RHCs. Formic acid will not be considered since it has a low volumetric energy densities compared to other carbon containing fuels like methanol, DME and LSNG. Due to its low energy density it is expected that this will not be used the transport of energy but more likely to be used as feedstock for industrial processes. Sodium borohydride is not considered in this research mainly due to the difficulty of production and recycling. Like MCH and H18-DBT it stores hydrogen and this hydrogen can be released, however with the LOHC this product can be recycled and can be used for around a 1000 cycles, in contrast to $NaBH_4$ wich needs to be recycled every time it is used. This recycling quite complex and the costs are still too high. Therefore the use of $NaBH_4$ will not be further investigated.

Hydrogen production

In this research the hydrogen that will be considered is produced by renewable electricity like wind and solar energy. Biomass gasification will not be used for the hydrogen production, because of the reasons given in the previous section and in section A.2.

Carbon source

The carbon containing RHCs , Methanol, DME, and LSNG need a carbon source to enable the production of the RHCs. It is assumed that this carbon source will come from carbon capture. However, the research will not further focus on the production of the hydrogen carriers but will focus on the shipment of RHCs and the reconversion to desired products.

Vessel type

The type of vessels that will be used for the transport of RHCs are feeder type vessels. These vessels will move from A to B. During this trip it is assumed that the vessel will not perform special operations, such as dynamic positioning or ship to ship bunkering. This decision is made since the main goal of this thesis is to investigate the transport of RHCs to close the gap between renewable energy demand and supply in the world, by shipping.

	Out of scope	Selection
Renewable Hydrogen Carrier [-]	Biomass based RECs $NaBH_4$ Formic Acid Fischer-Tropsch Diesel Ethanol	LH_2 NH_3 MeOH LSNG DME H18-DBT MCH
Hydrogen production	Blue Hydrogen Nuclear power Biomass gasification	Green electricity Electrolysers
Carbon source	Biomass	Carbon capture (Air/Flue gases)
Vessel type	Bunker	Feeder
Storage state	Dry cargo / Bulk Gas / Compressed	Liquid at SATP Liquefied by cooling Liquefied by pressure

Table 2.15: Overview of the defined scope after the system description

Energy carrier	Vessel used [-]	Pressure [bar]	Temperature [°C]	LHV [GJ/m^3]	LHV [GJ/t]	Density [t/m^3]
Ammonia (compressed)	LPG carriers	9	20	13	19	0.682
Ammonia (refrigerated)	LPG carriers	1	-33	13	19	0.735
DME (compressed)	LPG carriers	5.1	20	18.9	28.4	0.735
DME (refrigerated)	LPG carriers	1	-25	18.9	28.4	0.667
H0-DBT (dehydrogenated)	Crude / product tankers	1	20	- †	- †	1.040
H18-DBT (hydrogenated)	Crude / product tankers	1	20	6.5 †	7.4 †	0.871
Hydrogen (refrigerated)	LH_2 carriers	1	-253	8.5	120	0.0708
LSNG (refrigerated)	LNG carriers	1	-163	22.2	48.6	0.420
Methanol	Chemical tankers	1	20	15.6	20.1	0.792
Toluene (dehydrogenated)	Chemical tankers	1	20	- †	- †	0.870
MCH (hydrogenated)	Chemical tankers	1	20	5.5 †	7.2 †	0.769

† Based on the LHV of hydrogen present in the LOHC, not the LHV of the chemical itself

Table 2.16: Specifications of the different hydrogen carriers [78, 93]

3

Case selection

In this chapter three cases are selected to get more insight in the transportation of renewable energy carriers by ship. In each of the three cases different ship sizes and voyage distances are selected. The analysis of these cases will give a better indication what the impact is of transporting the RHCs by ship. The three cases that are selected are the following:

1. *Small scale:* 708 tons of delivered hydrogen (10,000 m^3 of liquid hydrogen) over 500 nautical miles, representing a typical trip between Norway and Rotterdam.
2. *Mid scale:* 5,664 tons of delivered hydrogen (80,000 m^3 of liquid hydrogen) over 2,000 nautical miles, which resembles a trip between the south of Europe, or the North of Africa to Rotterdam.
3. *Large scale:* 26,267 tons of delivered hydrogen (2 ships of 185,500 m^3 of liquid hydrogen) over 4,000 nautical miles. This trip is based on the planned hydrogen supply chain between Australia and Japan.

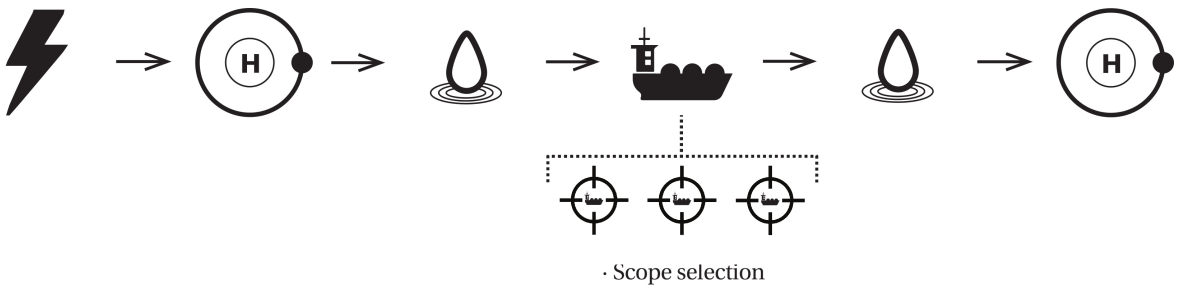

Figure 3.1: Determining the specific scope for the research

First, an overview of the model, which will be used for the cases is discussed. Secondly, the assumptions are discussed, which are used to construct the model. Thirdly, the reference ships that are taken from the database are examined. Furthermore, there will be an economic analysis of the different cases. In the end, the results of the cases will be shown and there will be a further selection:

- Renewable hydrogen carriers that are selected for further research are: LH_2, NH_3, MeOH, LSNG
- The distance of the transportation route will be limited between 500 and 2,000 nautical miles
- The delivered mass of hydrogen will be between 700 and 8,000 tons of hydrogen.

3.1. Case model set-up

In figure 3.2 an overview of the model used for the cases is shown. First, a specific case is selected, this corresponds to a certain voyage distance, transported hydrogen mass, operational profile and a selected RHC. In the second step, the model will determine the reference ship. This reference ship has a specific energy requirement during cruising, cruises at a certain speed, and has certain ship dimensions. In the third step there will be an economic analysis, this will consist out of three parts, the CAPEX, the OPEX , and the fuel cost of the RHCs. This will result in an economic analysis of the ship in terms of lifetime cost [M€] and the cost per delivered ton hydrogen [€/tH_2].

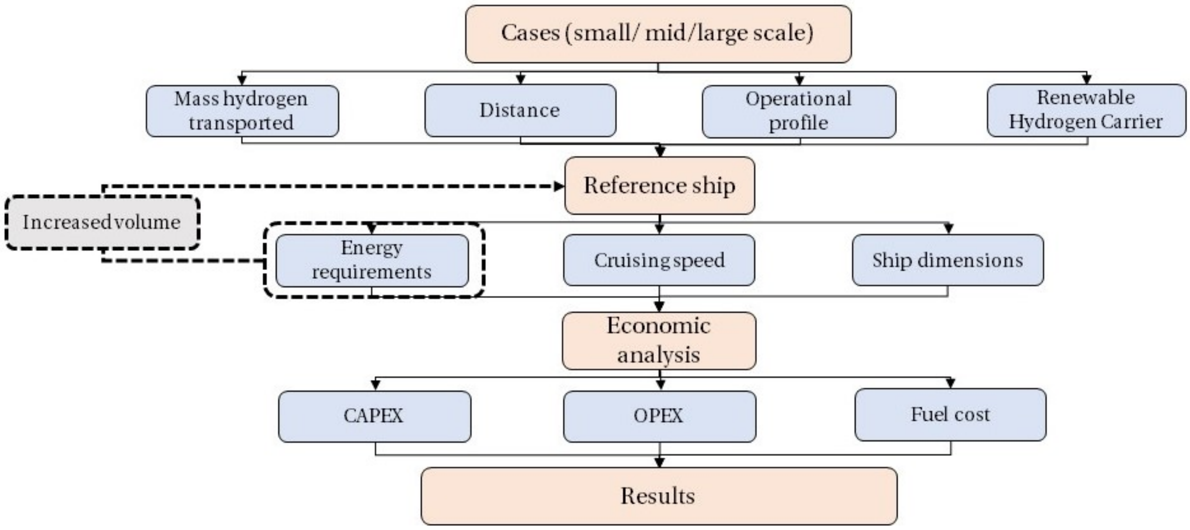

Figure 3.2: Structured overview of the model used for the cases

3.2. Selection of cases

The selection of cases is based on developments in industry. The results of the cases will give a first insight in the price developments in the shipment of RHCs. In table 3.2 an overview is shown of the cases based on the volume and mass transported.

3.2.1. Small scale

Norway is a major energy export country and is considered as a front runner in the production of renewable energy. The country has a potential plans to produce and export renewable powerfuels (such as hydrogen) and is a uncomplicated international trade partner [89].

Next to the renewable energy potential of Norway is the country also planning to make its World Heritage Fjords zero emissions areas, forcing cruise ships to operate without producing any emissions by 2026[94]. This could a start of having even more strict policies in Norway but also in the Baltic and the North Sea.

Hydrogen could be transported to the port of Rotterdam, which has a clear vision of realizing a hydrogen infrastructure, this can be seen in numerous projects like H-Vision, [95], and HyChain [9].

The distance between the two countries is assumed to be 500 nautical miles. Norwegian plans to have an electrolyser of 360 MW [96]. This capacity is in the range of 100-150 tons of hydrogen produced every day. A round trip can be made in a little more 6 days, when a distance of 500 nautical miles is assumed and a cruising speed of 13-15 knots. In this trip 708 ton of hydrogen is assumed to be delivered, equivalent to 10,000 m^3 of liquid hydrogen.

3.2.2. Mid scale

A possible future supply chain is the transport of hydrogen between Portugal and Rotterdam [97, 98]. The distance between Portugal and Rotterdam is around 1300 nautical miles and there are plans to have a 1 GW hydrogen production capacity in Portugal. The 1GW installed electrolyser will produce around 375 tons of hydrogen every day.

For this specific supply chain a LH_2 carrier of 80,000 m^3 was chosen, to make use of existing LNG carriers as reference vessels. This volumes corresponds to 5,664 tons of hydrogen. The trip distance of 2000 nautical miles is chosen to also allow for trips between Morocco, Spain and Algeria. In these countries there is also a high renewable energy potential [99].

3.2.3. Large scale

The large scale case is a case is based on a recent pilot project between Australia and Japan. The two countries started a supply chain in which liquid hydrogen is transported on a vessel, which has two tanks of 1250 m^3. Japan is a country which is dependant on the import of energy in the form of coal, oil and natural gas from countries such as Australia. Australia has a large potential of renewable energy, thus the import of renewable energy carriers from Australia could become a reality in the future.

In 2018, 29 millions tons of LNG was imported from Australia to Japan [100]. Typical large scale LNG carriers have a capacity of 170,000 m^3, using these ships as reference vessels this would be equivalent to shipping 26,242 tons of hydrogen. This quantity of hydrogen would be equivalent to 371,000 m^3 using equation 2.26.

3.3. Reference ships

First, assumptions are set up for the calculation. After this, the required mass of RHC that is needed to be transported needs to be calculated, this is based on the delivered mass of hydrogen. This calculation will results an amount of transported cargo volume, expressed in table 3.2. Based on the database of ships this will results in basic ship dimensions, a cruising speed and energy requirements.

Parameters	Value	Unit
Operating time	25	years
Utilization rate	92	%
Spare hours for each trip	12	hours
Harbour time	24	hours

Table 3.1: Assumptions for the operational profile

3.3.1. Assumptions for the cases

The cases made were based on the following assumptions:

- *Operational profile:* The assumptions for the operational profile are shown in table 3.1. The ship has a lifetime of 25 years during with a utilization rate of 92%, meaning that during 336 days of the 365 the ship will be operational. Every round trip includes the cruising (go and back), 12 spare hours and 24 hours in each harbour. During time in the harbour the ship will be idling, manoeuvring, and loading or discharging.

- *Cargo storage:* The RHCs will be transported on different type of ships, because the RHCs have different boiling points and material properties. Therefore the storage facility is designed differently. Below the assumptions are listed and an overview is shown in table 2.16.

  - All ships use their cargo (the RHC) as fuel. However, the LOHCs do not run on their own cargo, but it is assumed that those run on LSNG.
  - The design of LNG carriers are used for transportation of LSNG and LH_2. When transporting liquid hydrogen (LH_2), extra cost for the tank are added.
  - H18-DBT can be stored in carbon steel tanks due to its non corrosive and non toxic properties. Therefor H18-DBT can be transported using product tankers or crude oil tankers.
  - MeOH and MCH will be transported in cargo tanks with coatings (epoxy, MarineLine or zinc). However, the RHCs can also be transported in more expensive stainless steel tanks, the differences are explained in section 2.2.4.

- *Fuel storage:* No changes were made to the fuel storage of the vessels. Most ships from the database have HFO tanks, however for this analysis no additional fuel tank cost were added.

- *Powertrain:* There were no changes made in the powertrain, meaning that the original engines and powertrains of the vessels are used. Instead of using the energetic value of the conventional fuel, the values from the RHCs were used. Any differences in fuel efficiency were neglected.

- *Fuel consumption:* Only fuel consumption during cruising was taken into account, any fuel consumption related to other operations, such as idling, manoeuvring, loading and discharging was neglected.

- *Fuel efficiency:* There were no changes made in the powertrain, meaning that the original engines and powertrains of the vessels are used. Instead of using the energetic value of the conventional fuel, the values from the RHCs were used. Any differences in fuel efficiency were neglected.

- *Units used:* For liquid chemicals (at SATP), the ships are specified in tonnage, this is done for MeOH, MCH and H18-DBT. DME, NH_3, LH_2 and LNG are gases (at SATP), but stored as liquid, these ships are specified in terms of carried volume.

3.3.2. Cargo needed

To compare the transport of the different RHCs, the same tonnage of delivered hydrogen is used. To deliver this amount of hydrogen different volumes of RHCs are used, and thus also different ship designs. Therefore, the amount RHCs that is needed is calculated. This is done by using equation 2.26, with information from table 2.14. The amount of energy carrier needed is shown in the second column of table 3.2. This leads to certain volumes and tonnages that a ship needs to carry.

Vessel type	Energy carrier	Small scale [m^3]	Mid scale [m^3]	Large scale[m^3]
LPG	Ammonia	7,500	59,000	265,000
	DME	7,000	55,000	248,500
LH_2	Liquid hydrogen	10,000	80,000	371,000
LNG	Synthetic LNG	4,500	36,000	170,000
Oil/Chemical Tankers	Methanol	8,500	67,500	318,000
	MCH (loaded)	22,500	177,000	840,500
	Toluene (unloaded)	19,000	150,000	713,000
	H18-DBT (loaded)	27,000	215,000	1,010,500
	H0-DBT (unloaded)	14,500	114,500	538,500
Vessel type	**Energy carrier**	**Small scale[ton]**	**Mid scale [ton]**	**Large scale[ton]**
LPG	Ammonia	5,100	40,300	180,600
	DME	5,000	40,000	181,100
LH_2	Liquid hydrogen	708	5,664	26,242
LNG	Synthetic LNG	1,900	15,100	71,400
Oil/Chemical Tankers	Methanol	7,000	53,500	252,000
	MCH (loaded)	17,000	136,000	646,500
	Toluene (unloaded)	16,500	130,500	620,000
	H18-DBT (loaded)	16,000	125,000	586,000
	H0-DBT (unloaded)	15,000	119,000	560,000

Table 3.2: Ship sizes in cubic capacity and in tonnage for the same delivered quantity of hydrogen

3.4. Economic Analysis

For the economic analysis the total lifetime cost are divided by the total mass of hydrogen delivered, using equation 3.1. The total lifetime cost are the sum of fuel cost, the OPEX and the CAPEX of the ship. For the ships transporting hydrogen using LOHCs, the cost of MCH or H18-DBT will also be included.

$$\text{Cost per ton hydrogen } [€/\text{ton}] = \frac{\text{CAPEX} + \text{OPEX} + \text{Total}_{\text{fuel,cost}} + \text{Total}_{\text{LOHC,cost}}}{\text{Mass}_{\text{delivered},H_2}} \tag{3.1}$$

For the economic analysis the following assumptions for this trip are made:

- OPEX for LH_2 carriers are based on LNG carriers. For the OPEX cost of MCH, and MeOH, chemical tankers are used. For the shipment of H18-DBT product tankers or crude carriers are used for determining OPEX.
- The costs of RHCs are expected to decrease over time, therefore every year the cost of the RHC decreases. Other costs are assumed to stay constant over lifetime, such as operational, and maintenance cost.
- An exchange rate of 1.11 $/€ is used.

3.4.1. CAPEX

To calculate the CAPEX over lifetime the *PMT* formula in *Excel* is used, shown in equation 3.2, using the the values of table 3.3. The interest rate is set to 8% and monthly payments have to be due over a period of 25 years. The scrap value of the vessel is set at 10% [101].

$$\text{CAPEX}[€] = \text{PMT (rate, nper, pv, fv)} \cdot \text{Operational months} \tag{3.2}$$

Parameters	Meaning	Formula	Value
Rate	Interest rate	8%/12	0.66%
Nper	Total number of payments	Operating period * 12	300 months
PV	Present value	New build cost (+ Cost LH_2 tank)	Variable
FV	Future value (Scrap value)	10% of new build cost	Variable

Table 3.3: Parameters for the PMT formula

The ships are divided into two categories, atmospheric cargo and liquefied gas cargo. As earlier mentioned in section 3.3.1, the atmospheric cargo is expressed in tonnes and the liquefied gas cargo in volume.

Atmospheric cargo

The energy carriers that are transported in atmospheric tanks are MeOH and the LOHCs: H18-DBT and MCH. The new build cost of the atmospheric tankers are shown in figure 3.3. There are different kinds of atmospheric cargo tankers, these are listed below:

- Coated Chemical Tankers, which are carbon steel tanks with a coating such as zinc, MarineLine, or epoxy. The coatings are applied to make the tanks better resistant against chemicals. These will be used to store Methanol and MCH.
- Stainless Steel Chemical Tankers, these are equipped with stainless steel tanks.
- Crude Oil and Product Tankers, are designed for carrying oil products.

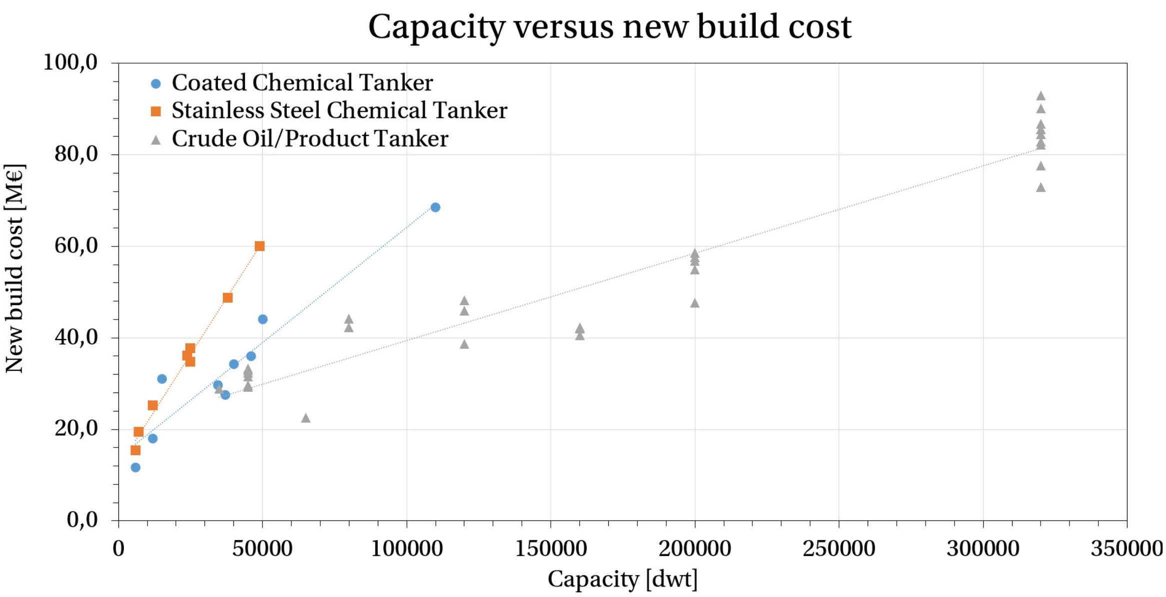

Figure 3.3: New build cost of chemical, crude oil and product tankers

Liquefied gas cargo

The other energy carriers discussed in these cases are DME, NH_3, H_2 and LSNG. These products are gaseous at SATP, but will be transported in the liquid form. To transport these products, ships that are able to handle these kind of products will be discussed. The new build cost of the gaseous product ships are shown in figure 3.4. Two types of ships will be used for carrying these energy carriers:

- LPG carriers
- LNG carriers

Using LPG ship, the energy carriers DME and NH_3 can be stored safely. For the storage of LSNG, LNG ships can be used. For the storage of hydrogen, LNG carriers are used as a ship design, however liquid hydrogen tanks must meet higher requirements than LNG tanks. Therefor the price of the gas plant on LNG ships is adjusted to be compatible with liquid hydrogen. This will give a indication on the price of liquid hydrogen carriers.

Liquid hydrogen storage

In chapter 5.1.1, there will be a more in depth analysis of the construction of a liquid hydrogen tank. For cost of a liquid hydrogen tank, first the cost of the LNG tank needs to be known, based on the size of the tank a price per cubic meter can be calculated. The LH_2 tank is assumed to be 1.56 times as expensive as the LNG tank based on the [€/m^3] [74, 102, 103].

3.4.2. OPEX

In figure 3.6 the operational cost are shown, these include the following items:

- Manning
- Insurance
- Stores, Spares, Lubricating Oils
- Maintenance and Repair
- Management and Administration

$$\text{OPEX}\,[€] = \text{Operational cost}\ [€/\text{day}] \cdot \text{Total lifetime}\ [\text{days}] \tag{3.3}$$

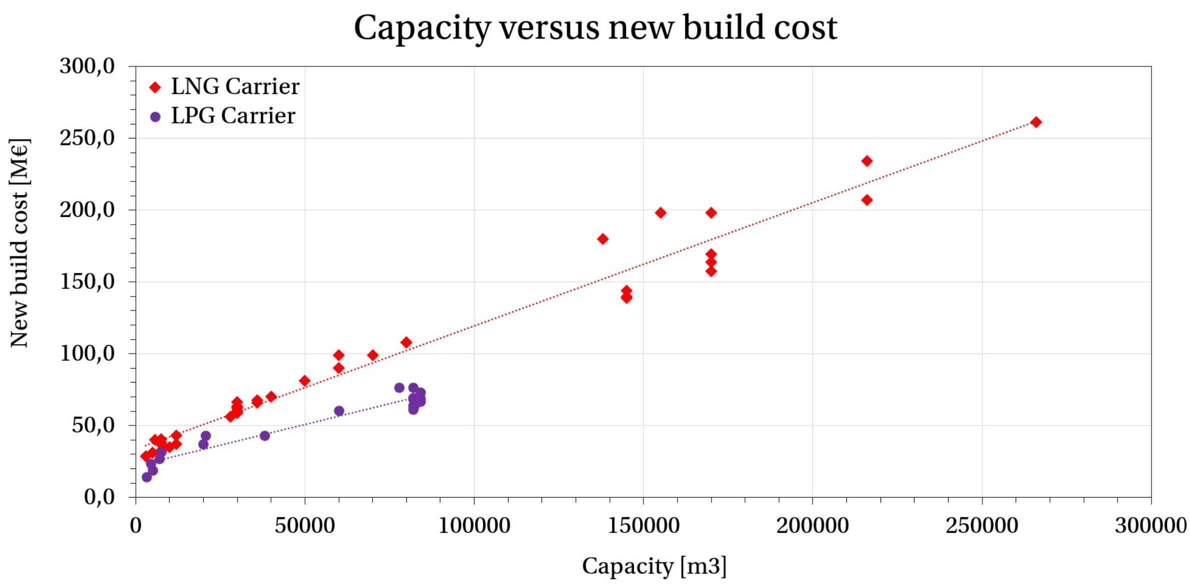

Figure 3.4: New build cost of LNG and LPG carriers

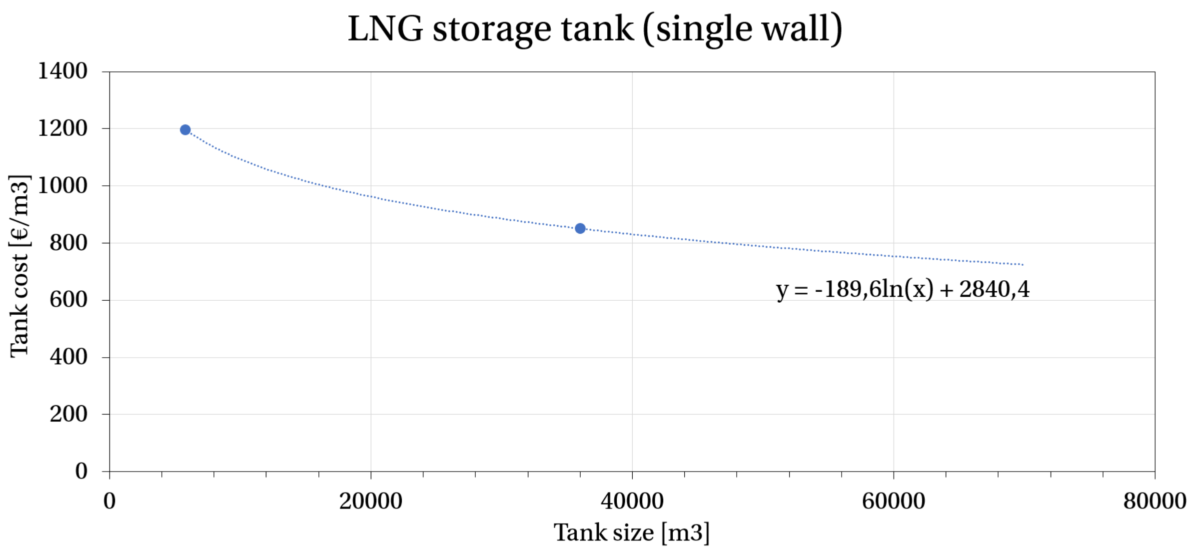

Figure 3.5: Cost per volume unit of a type C single wall LNG storage tank, above approximately 2000 m^3

The values for the OPEX are based on values from Anthony Veder and from Drewry, and are corrected for the inflation for the year 2020 [101, 104]. In figure 3.6 the operational cost of the different vessels are shown. The OPEX of chemical and oil tankers are based on the cargo weight [dwt] and the OPEX of the other vessels is based on the cargo volume [m^3]. The OPEX will be categorized in ship types, this was earlier described in table 2.16. This means that the OPEX of the methanol and MCH carriers are based on the OPEX of chemical tankers. The OPEX of DME and the NH_3 ships will be based on LPG carriers. The OPEX of ships carrying LNG or LH_2 will be based on LNG carriers. Finally the OPEX of H18-DBT carriers will be based on crude oil / product tankers.

3.4.3. Cost of RHCs

The use of the RHCs as fuel, will be based on the fuel consumption of the original vessel. For example if the ship has a fuel consumption during cruising of 50 GJ/hr, this fuel consumption will also be used for the RHC. However, the RHC will have a different volume, which influences the design of the ship. The specific energy densities are shown in table 2.16 and the cost of the RHCs are explained in section 2.2.14.

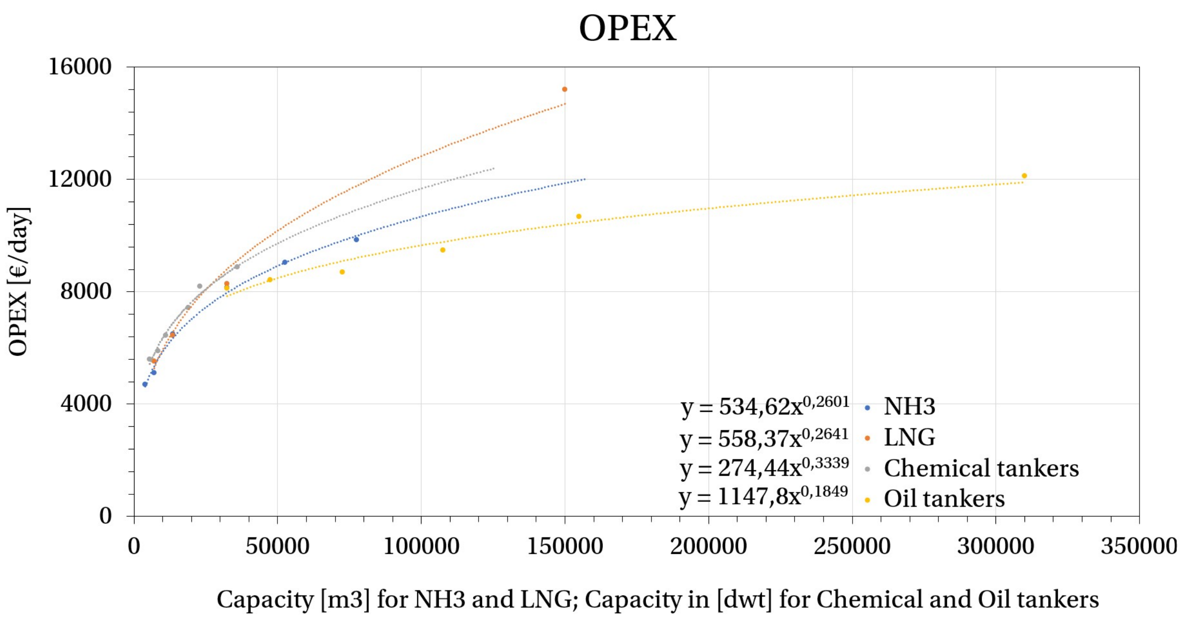

Figure 3.6: OPEX for the different vessels [101, 104]

$$\text{Total}_{\text{fuel,cost}}\ [€] = \text{Cruising fuel consumption [GJ/hr]} \cdot \text{Total hours cruising [hrs]} \cdot \text{RHC cost [€/GJ]} \tag{3.4}$$

3.4.4. Cost of LOHCs

The LOHC have to be replaced after a 1000 cycles, therefore short trips will be relatively more expensive to carry using the LOHCs, because than more trips during the lifetime of the ship will be made. Using equation 3.5, the cost of the LOHCs can be calculated. In section 2.2.14, the cost of the MCH/Toluene and H0-DBT/H18-DBT is explained, costing respectively: 0.63 $[\frac{€}{tonToluene.trip}]$ and 3.622 $[\frac{€}{tonH0-DBT.trip}]$.

$$\text{Total}_{\text{LOHC,cost}}\ [€] = \text{Cost}_{\text{round,trip}} \left[\frac{€}{ton.trip}\right] \cdot \text{Mass}_{\text{LOHC,used}}\,[\text{ton}] \cdot \text{Total}_{\text{trips}} \tag{3.5}$$

3.5. Results

In this section the results of the three different cases are presented. The results will give an insight in cost per delivered ton hydrogen operating in a short term period (2020-2045) and a ship operating in the long term period (2045-2070). The different time periods are chosen to see the effects of the development of the RHC cost. In section 3.5.4, the results will be analysed.

3.5.1. Small scale (Norway - Rotterdam)

In table 3.4 the results of the small case scenario is shown. A visual presentation of the results are shown in figure 3.7 and figure 3.8.

	Unit	NH_3	DME	H18-DBT	LH_2	LSNG	MEOH	MCH
Fuel	[-]	NH_3	DME	LSNG	LH_2	LSNG	MEOH	LSNG
Ships required	[-]	1	1	1	1	1	1	1
Speed	[kn]	14.9	14.9	14.8	14.7	14.5	14.8	14.8
Total hydrogen transported	[Mton]	1.11	1.11	1.11	1.11	1.11	1.11	1.11
Ship capacity	[-]	7,379 m^3	6,765 m^3	16,071 ton	10,356 m^3	4,852 m^3	6,963 ton	17,707 ton
Fuel storage per ship	[-]	126.3 m^3	82.2 m^3	48.6 ton	429.0 m^3	161.7 m^3	104.3 ton	49.6 ton
Fuel consumption per ship	[GJ/hr]	24.5	23.1	35.0	35.0	20.0	25.0	35.7
Total fuel cost 2020-2045	[M€]	68	84	136	111	78	87	139
Total fuel cost 2045-2070	[M€]	50	63	98	66	57	64	100
OPEX per ship	[€/day]	5,040	5,040	8,038	6,396	5,405	5,895	7,414
New build cost per ship [1]	[M€]	26.3	26.0	23.4	47.3	36.1	17.3	22.7
LOHC cost	[M€]	NA	NA	88	NA	NA	NA	17

[1] Undiscounted cost

Table 3.4: Results of small scale transport

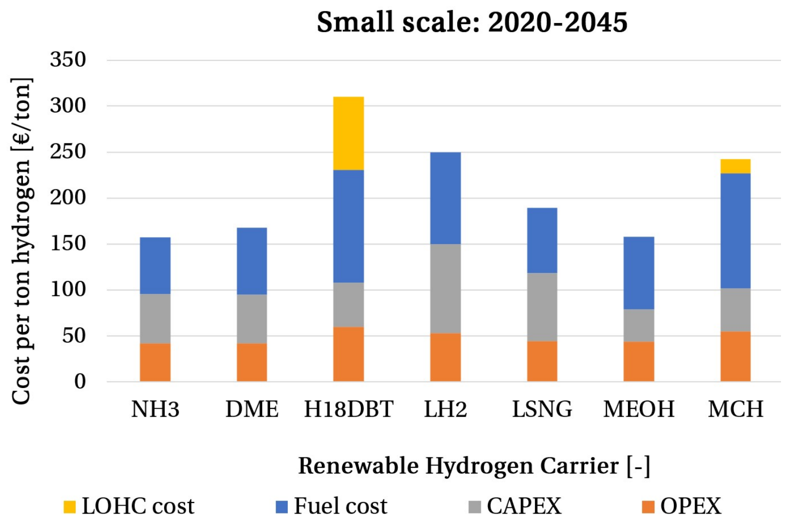

Figure 3.7: Cost per ton hydrogen delivered for the small scale case based on RHC prices in the short term

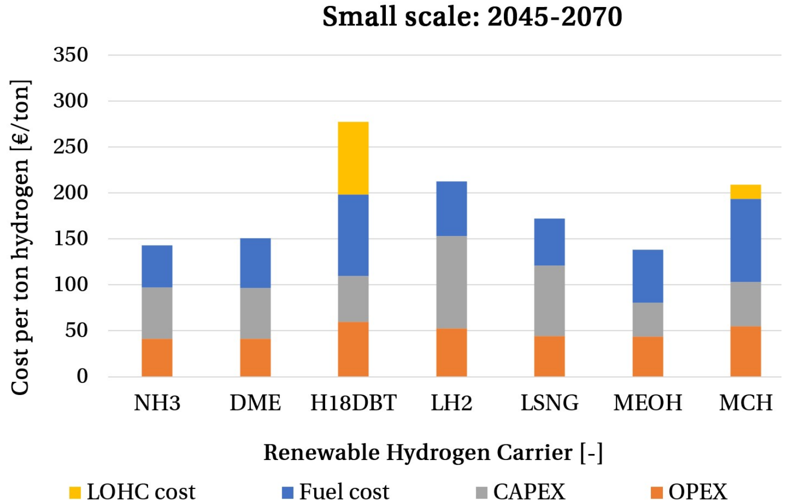

Figure 3.8: Cost per ton hydrogen delivered for the small scale case based on RHC prices in the long term

3.5.2. Mid scale (Portugal - Rotterdam)

In table 3.4 the results of the small case scenario is shown. A visual presentation of the results are shown in figure 3.9 and figure 3.10.

	Unit	NH_3	DME	H18-DBT	LH_2	LSNG	MEOH	MCH
Fuel	[-]	NH_3	DME	LSNG	LH_2	LSNG	MEOH	LSNG
Ships required	[-]	1	1	1	1	1	1	2[1]
Speed	[kn]	16.9	16.9	15.1	17.0	15.6	14.9	15
Total hydrogen transported	[Mton]	3.9	3.9	3.9	3.9	3.9	3.9	3.9
Ship capacity	[-]	61,129 m^3	56,007 m^3	145,178 ton	83,335 m^3	41,571 m^3	63,686 ton	80,345 ton
Fuel storage per ship	[-]	1,151 m^3	744 m^3	599 ton	2,215 m^3	804 m^3	1,120 ton	489 ton
Fuel consumption per ship	[GJ/hr]	63	59	110	104	70	84	89
Total fuel cost 2020-2045	[M€]	68	80	167	97	105	115	272
Total fuel cost 2045-2070	[M€]	50	59	121	57	76	85	197
OPEX per ship	[€/day]	9,396	9,185	10,335	12,065	9,564	10,367	11,024
New build cost per ship [2]	[M€]	57	54	48	140	70	46	54
LOHC cost	[M€]	NA	NA	312	NA	NA	NA	60

[1] Based on largest chemical tanker, having a capacity of 81,000 dwt
[2] Undiscounted cost

Table 3.5: Results of mid scale transport

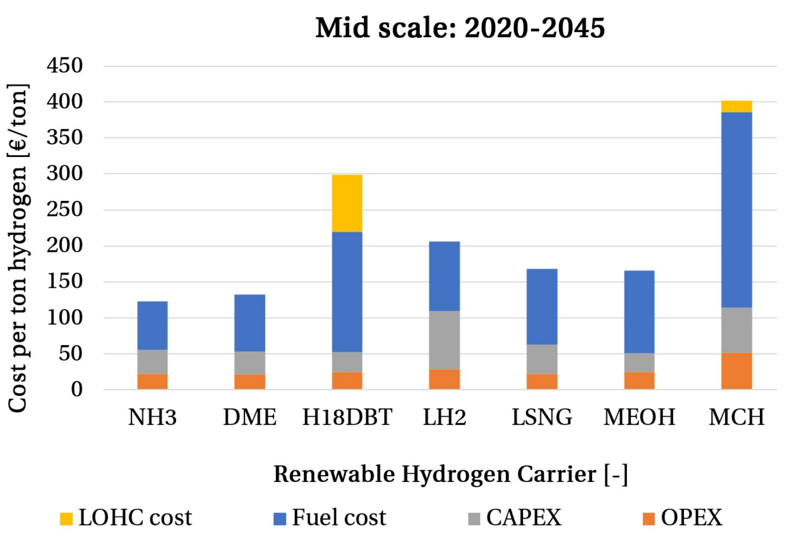

Figure 3.9: Cost per ton hydrogen delivered for the mid scale case based on RHC prices in the short term

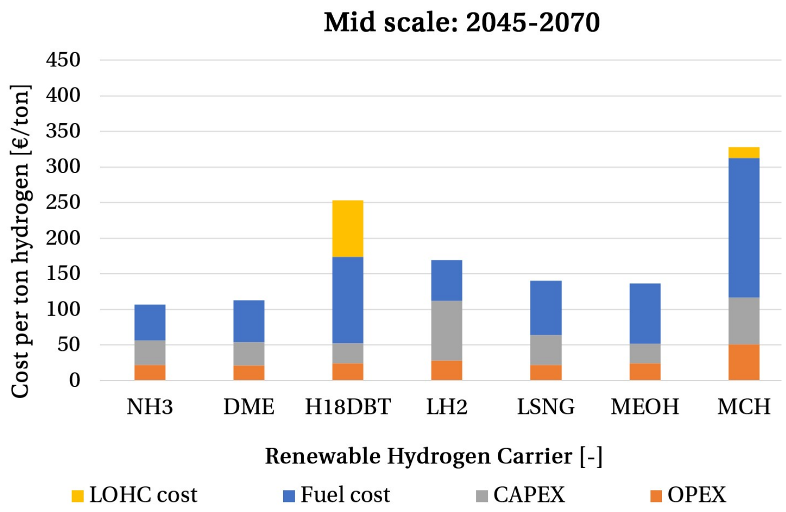

Figure 3.10: Cost per ton hydrogen delivered for the mid scale case based on RHC prices in the long term

3.5.3. Large scale (Australia - Japan)

In table 3.4 the results of the small case scenario is shown. A visual presentation of the results are shown in figure 3.11 and figure 3.12.

	Unit	NH_3	DME	H18-DBT	LH_2	LSNG	MEOH	MCH
Fuel	[-]	NH_3	DME	LSNG	LH_2	LSNG	MEOH	LSNG
Ships required	[-]	3 [1]	3 [1]	2 [2]	2 [3]	1	4 [4]	10 [4]
Speed	[kn]	16.9	16.9	15.7	19.0	19.0	15	15
Total hydrogen transported	[Mton]	11	11	11	11	11	11	11
Ship capacity	[-]	106,769 m^3	93,372 m^3	365,824 ton	199,753 m^3	181,566 m^3	81,740 ton	83,762 ton
Fuel storage per ship	[-]	3,549 m^3	2,265 m^3	1,890 ton	9,994 m^3	3,538 m^3	2,378 ton	991 ton
Fuel consumption per ship	[GJ/hr]	97	90	180	202	187	90	90
Total fuel cost 2020-2045	[M€]	121	141	210	187	106	188	528
Total fuel cost 2045-2070	[M€]	90	104	152	111	77	139	382
OPEX per ship	[€/day]	10,863	10,606	12,261	16,154	15,647	11,074	11,145
New build cost per ship [5]	[M€]	84	78	90	273	198	55	56
LOHC cost	[M€]	NA	NA	895	NA	NA	NA	172

[1] Based on largest LPG tanker, having a capacity of 101,000 m^3
[2] Based on largest crude oil tanker, having a capacity of 441,500 dwt
[3] Based on LNG carrier, having a capacity of 266,000 m^3
[4] Based on largest chemical tanker, having a capacity of 81,000 dwt
[5] Undiscounted cost

Table 3.6: Results of large scale transport

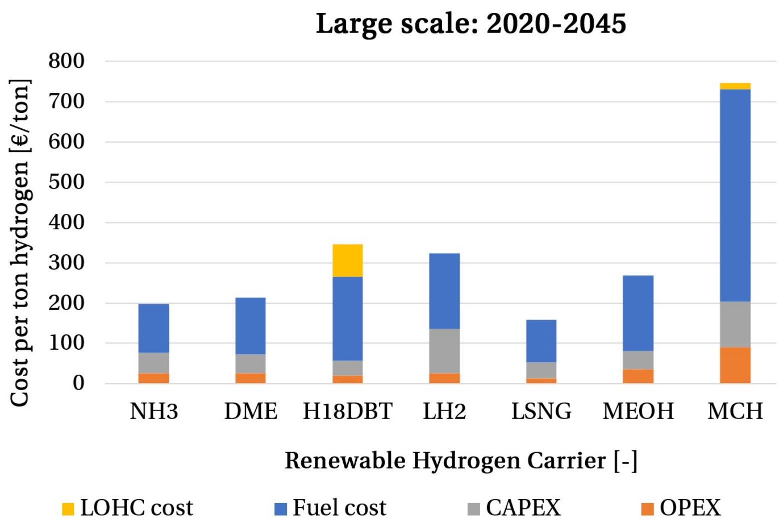

Figure 3.11: Cost per ton hydrogen delivered for the large scale case based on RHC prices in the short term

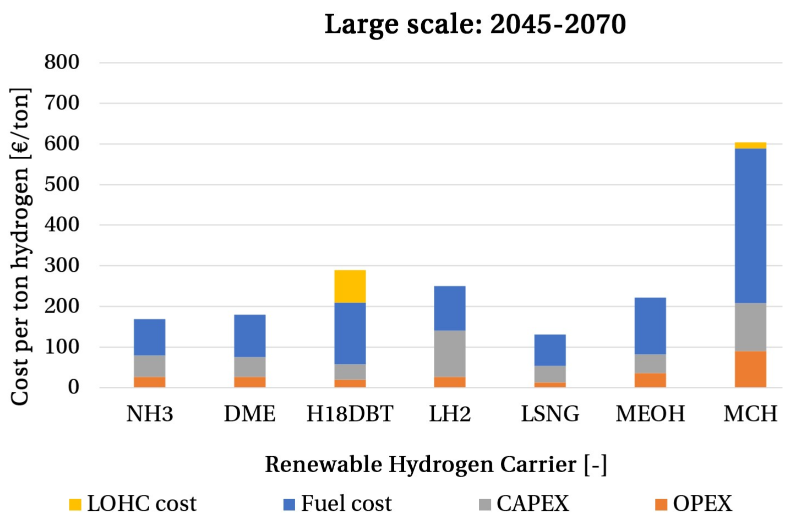

Figure 3.12: Cost per ton hydrogen delivered for the large scale case based on RHC prices in the long term

3.5.4. Summary of results

Based on the results of the small, mid and large scale transport, several conclusions can be drawn:

- Transportation of RHCs:
  - Most attractive options to transport RHCs from the cases are MeOH, NH_3, DME and LSNG.
  - Transporting H18-DBT and MCH by ship are overall the least efficient options to deliver hydrogen from a shipping point of view. This is due to its low energy density, and the high cost of the carrier itself which is assumed to be replaced after every 1000 cycles. For transporting MCH, chemical tankers are used, these ships have a limited capacity as of today.
  - The transportation of LH_2 is third to worst option to deliver hydrogen. LH_2 is inefficient based on the high investment cost of the vessel, and the current high price of the RHC. In the long term it is expected that liquid hydrogen will be available at a more competitive cost, as can be seen in figure 2.4. Another advantage for LH_2 is that, the supply chain doesn't need to change the molecule, while this is neccesary for all the other RHCs. This could make a supply chain with LH_2 still attractive, although there is a high shipping cost involved.

- For the non carbon options, ammonia is more efficient to ship hydrogen than liquid hydrogen in all cases. NH_3 is the more favorable option, due to the higher hydrogen density, and lower complexity of engineering.
- The developments in the production of renewable DME are rare, and therefore it is difficult to make statements about this RHC, and how it will perform in the future. The production is similar to methanol, but methanol can be stored atmospherically. Analysing the results, DME cost are in all cases slightly higher than NH_3. Furthermore, NH_3 is a non carbon carrier, this makes it a more promising RHC compared to DME. MeOH is similarly produced, and performs better in the small scale cases, therefore it is worth investigating MeOH.
- The shipment of LSNG is interesting because this product has the largest volumetric hydrogen density. When large quantities of hydrogen need to be shipped, choosing for LSNG could mean that only one ship is needed, while the alternative ship methods require 2 or 3 vessels.

- Based on the transport volumes:
  - In the small scale transport CAPEX is has more influence on the cost of hydrogen delivery compared to large scale transport.
  - In the large case, only 1 ship transporting LSNG is needed while the other options do need more ships to deliver the same amount of hydrogen. The infrastructure for shipping already exists, and ships up to 266,000 m^3 are available.
- Based on the transport distance:
  - Mid and large scale transport have a larger share of fuel cost, in the delivered price of hydrogen. Meaning that the longer the distance travelled, the higher the share fuel cost will be. Therefore it could be beneficial to make a relatively high investment cost to improve fuel economy.
- Based on the OPEX:
  - OPEX have a relatively large effect on small scale transport, however when transport volume increases the share of OPEX becomes much lower.

3.6. Conclusion

In this chapter three different cases were discussed, one small scale, one medium scale and one large scale. Based on the results in this chapter, the research will further focus on the parameters shown in table 3.7
Based on the findings above, the research focuses on four RHCs: methanol, liquid ammonia, liquid hydrogen and liquefied synthetic natural gas. DME has a higher cost of delivering hydrogen in all cases than ammonia. Furthermore has methanol the lowest cost of delivering hydrogen in the small case transportation, therefore DME will not be further evaluated. The LOHCs, MCH and H18-DBT, have low hydrogen densities, have a high gravimetric density and need to be replaced after a 1000 cycles. This makes the ship transportation of LOHCs not efficient.

The distance will be limited between 500 and 2000 nautical miles, based on literature these are the typical distances, when ship transport becomes more efficient than pipeline transportation. Above 2000 nautical miles the total cost of the ship transport becomes more dependant on fuel cost, and less dependant on how to efficiently design the ship.

The amount of hydrogen delivered will be between 700 and 8,000 ton. This is done to make a comparison between single vessels only. Transporting more than 8,000 tons of hydrogen, will mean that some RHCs need more than 1 vessel to transport the required hydrogen. This is because there are physical limitations to the existing ships. However, this limitation might change once there is a market for larger volumes, this makes a prediction much more complex. For example, largest LPG carriers (which can transport NH_3) have a capacity of 101,000 m^3, this is based on the LPG and ammonia market. If LPG carriers transport RHCs in the future, this maximum volume capacity could change due to an increased demand, and larger LPG carrier are constructed. To limit these variables, a maximum of 8,000 tons of delivered hydrogen is chosen.

	Out of scope	Selection for cases	Final selection
Energy carrier [-]	Biomass based RECs $NaBH_4$ Formic Acid Fischer-Tropsch Diesel Ethanol	LH_2 NH_3 MeOH LSNG DME H18-DBT MCH	LH_2 NH_3 MeOH LSNG
Distance [nautical miles]	<500 and >4,000	500 - 4,000	500 - 2,000
Delivered hydrogen [tonnes]	<700 and >26,300	700 - 26,300	700 - 8,000

Table 3.7: Overview of the final scope for this research

4
Model

In this chapter the model of the research will be described. In figure 4.1 an overview of the model is shown. The model is an updated version, of the one that was used for the cases, shown in figure 3.2. This model will be different on the following aspects:

- The sizes of the cases, which were used in chapter 3 are adjusted in terms of transported volume and distance.
- Fuel storage cost are added for ships that will not use the carried cargo as fuel.
- Different operations (than cruising) will also be considered in the fuel consumption.
- Various powertrain configurations will be used to calculate the cost of transportation.
- The volume needed of various powertrain configurations will be included in the size of the reference vessel. This is was already done with extra fuel volume.
- Scenarios will be used to give a better view of a future world and how this influences the ships which transport RHCs.

The model will calculate the cost of transported hydrogen per ship for a specific case within a certain scenario. The cases have specific transport distances and volumes (small scale, mid scale, and large scale). The scenario is based on future worlds, in which different rules and regulations are active.

Scenario conditions

Based on which scenario is chosen, scenario conditions will be put in the model. The conditions will be used to make a selection later in the model, as can be seen in figure 4.1. These conditions can be a CO_2 price, or zero emission harbouring explained in appendix C.

Cases

The scope of the new model is shown in table 3.7. In this table the boundaries are set for the mass hydrogen transported, the voyage distance and the selection of RHCs. The following cases will be discussed in terms of mass hydrogen transported and the distance travelled :

- *Small scale:* 708 tons of delivered hydrogen (10,000 m^3 of liquid hydrogen) over 500 nautical miles.
- *Mid scale:* 2,000 tons of delivered hydrogen (30,000 m^3 of liquid hydrogen) over 1,000 nautical miles.
- *Large scale:* 8,000 tons of delivered hydrogen (115,000 m^3 of liquid hydrogen) over 2,000 nautical miles.

The operational profile of the vessel is shown in table 3.1, based on the reference ship the ship will be further specified.

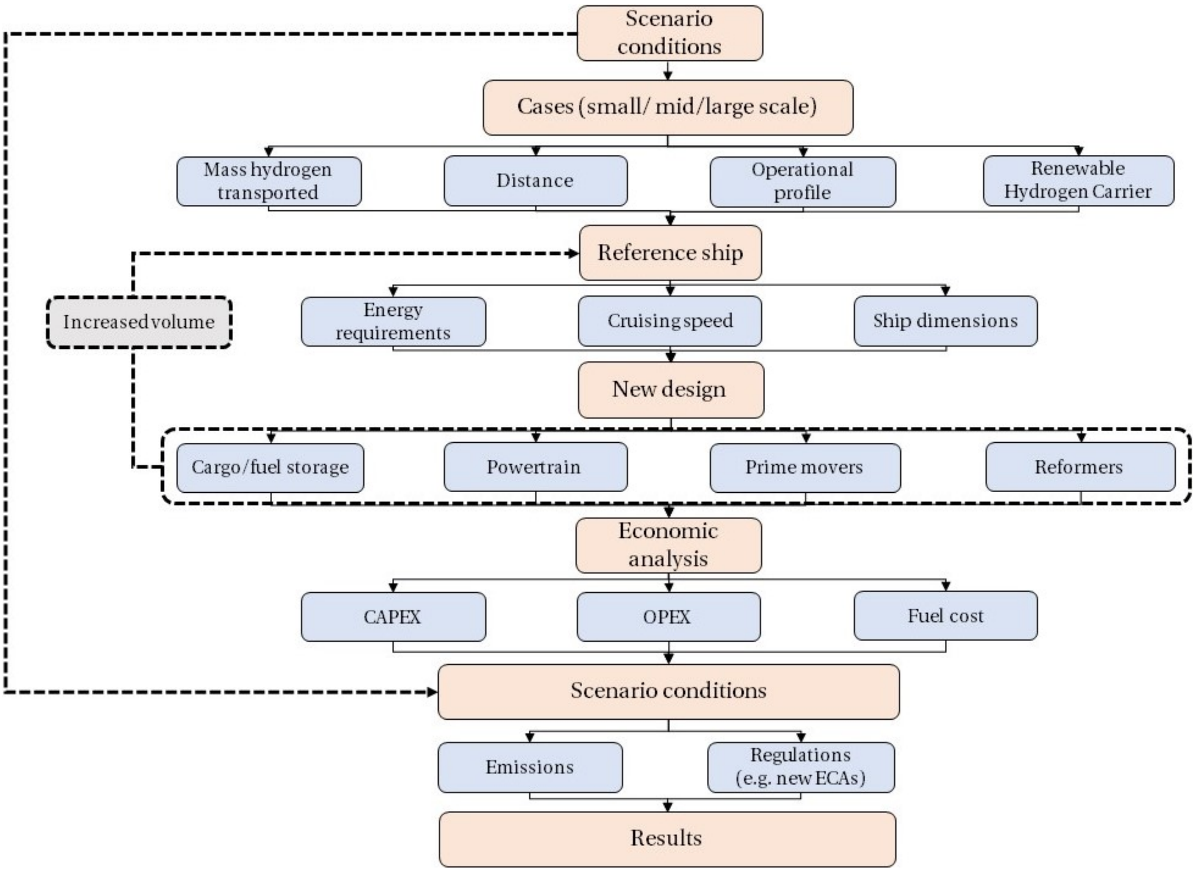

Figure 4.1: Structured overview of the model which is used to evaluate the different ways of transporting RHCs by ship

Reference Ship

RHC	Case	Cargo volume volume	Speed [kn]	ICE (2 or 4 stroke) [-]	Propulsion power insatlled [kW]
NH_3	Small scale	7,359 m^3	14.9	4	4,023
	Mid scale	22,077 m^3	16.7	2	8,352
	Large scale	84,628 m^3	16.7	2	12,762
LH_2	Small scale	10,000 m^3	15.6	4	5,727
	Mid scale	30,000 m^3	15.9	4	8,042
	Large scale	115,000 m^3	18.1	2	15,100
LSNG	Small scale	4,691 m^3	13.6	4	3,836
	Mid scale	14,073 m^3	15.8	4	7,717
	Large scale	53,945 m^3	16.7	4	11,128
MeOH	Small scale	6,934 dwt	13.4	4	3,815
	Mid scale	20,802 dwt	14.2	2	6,486
	Large scale	79,741 dwt	14.9	2	11,862

Table 4.1: Reference ships used for the different cases

The reference ships that are chosen for the model are based are taken from the ship database, which is the same database used for the cases, described in chapter 3.3. However, the reference ships in the new model will be further modified, for example to evaluate the different powertrains. The basic ships that are used for the model, are shown in table 4.1. These dimensions will be further modified in the new design described in the next section, for example, extra volume will be added to the ship for fuel, this will change the dimensions, this can be seen in figure 4.1.

New design

In chapter 5, the reference ship can be changed on the following aspects:

- *Cargo / fuel storage*: In case of a liquid hydrogen vessel, there will be a different design for cargo tank. The original LNG tank cannot be used for storing hydrogen, therefore a new liquid hydrogen storage tank needs to be designed.
- *Fuel storage*: When the ship doesn't run on its own cargo, it will run on LSNG. Natural gas is at this moment seen as a transition fuel in the shipping industry, therefore this option is put in the model. Using natural gas as a fuel this requires another fuel tank.
- *Prime movers*: Various prime movers will be evaluated for the new design, these include: combustion engines, fuel cells and batteries.
- *Powertrain*: Various powertrains are used for the new designs. There are two main types, mechanical powertrains and electrical powertrains. Within these two main types there are various combinations possible with different prime movers and batteries.
- *Additional systems*: Other systems will be installed, based on the requirements of the vessels and corresponding requirements. This include a cracker for the ammonia systems, a selective catalytic reduction system for the powertrains which have high NO_x emissions, and additional fuel systems which are needed because the conventional ship runs on fuel oils or diesel.

To determine how much power is used during the operations of the vessel, equation 4.1 is used. The share of power used during the different operations are shown in table 4.2. This share of power will be used to determine the fuel consumption during the other operations.

$$\text{Power share}\,[\%] = \frac{\text{Power used during specific operation}\,[\text{kW}]}{\text{Propulsion power installed}\,[\text{kW}]} \tag{4.1}$$

Operation	Average power share [%]	Power share [%] Small scale [105]	Mid scale [105]	Small scale [17]	Large scale [17]
Manoeuvring	**14**	13	12	16	15
Idling	**5**	6	2	7	NA
Discharging	**24**	31	15	31	21
Loading	**12**	16	9	11	13

Table 4.2: Share of power used during different operations relative to the total installed propulsion power

Based on the propulsion power installed shown in table 4.1, the power to the propeller (P_D) of the ship can be calculated, using equations: 4.2, 4.3, and 4.4. To engine break power is assumed to be the same as the propulsion power installed. The propulsion engines are assumed to run at the nominal continuous rating (NCR), which is 85% of the maximum continuous rating (MCR). The propulsion efficiency (η_e) is based on the rotational speed of the internal combustion engines, for this the book the "Design of Propulsion and Electric Power Generation Systems" is used [106]. A distinction is made between two and four stroke combustion engines, which have different rotational speeds. This difference in rotational speed results in other engine efficiencies (η_e), this will be further described in chapter 5.2. The difference in engines used also has an influence on the transmission efficiency (η_{TRM}), which is determined based on the assumption that two stroke engines will have a direct shaft and four stroke engines will have an additional gearbox.

By doing this analysis about the power configuration of the original vessel, the power to propeller (P_D) of the original vessel can be estimated using equation 4.4. After this analysis, the new powertrain design can be made having the same power to propeller (P_D), thus keeping the original propeller power intact. The different powertrains will have different engine efficiencies (η_e) (fuel cells and combustion engines), other transmissions efficiencies (η_{TRM}) (direct shaft/gearbox/electric motor), and other LHV of the fuels used (hydrogen, methanol, ammonia and synthetic methane). The powertrains are further explained in section 5.3.

$$P_B \approx P_{propulsion,installed} \tag{4.2}$$

$$P_{propulsion,delivered} = P_B \cdot \frac{NCR}{MCR} \cdot \eta_e \tag{4.3}$$

$$P_D = P_B \cdot \eta_{TRM} \tag{4.4}$$

The new designs are evaluated based on their volume. The volume of the ship will be based on the following items:

- Cargo volume for delivering the hydrogen
- Fuel volume needed to make the round trip
- Volume needed for new powertrain

The increase in volume will result in an iteration in the model, as can be seen in figure 4.1. This will mean that a reference ship with an increased volume will be chosen. As a result the ship dimensions and required propulsion energy will change according to the increased volume.

Economic Analysis

The economic analysis will be similar to the analysis made in chapter 3.4. However, in this new analysis, more items will be taken into consideration, such as new powertrains and different prime movers. This will be discussed in chapter 6.

Results

The scenario conditions explained earlier in this chapter, can have an affect on certain ship designs. This can be a based future regulations or an emission tax, in which extra cost will be added or a type of ship will not be selected. After this step, the model will show the results in which the cost of the transport will be expressed in a price of transported hydrogen (€/tH_2).

Conclusion

In this chapter the outline for the new model was described. The previous model which was used for the cases was modified in this chapter, to get a better insight in the transport of RHCs by ship in the future. This is done by evaluating various new ship designs which are powered by RHCs.

In the next chapter the new designs of the ships will be explained, and how this will be implemented in the model.

5

New design

In this chapter new designs for the ship transporting the RHCs will be discussed. The new design will be specified on the following items:

- Cargo & fuel storage is explained in section 5.1. In this section the cargo storage of liquid hydrogen tanks is explained, as well as the fuel storage of LSNG.
- Prime movers are explained in section 5.2, in this chapter the efficiencies (η_e)of the different devices are analysed.
- Powertrain configurations will be described in section 5.3, these powertrains will be used to determine the transmission efficiency (η_{TRM}) during different operations
- Additional Systems will be explained in section 5.4, here the selective catalytic reduction system (SCR) and the ammonia cracker will be described.

In this chapter the sub research question will be answered: *How can renewable hydrogen carriers efficiently be used as fuel in a direct or indirect propulsion system?*

5.1. Cargo & Fuel storage

In this section the cargo and fuel storage of the ship will be described, which will affect the design of the ship. Therefore the following type of storage will be discussed:

- LSNG fuel tank, for the use of LSNG as fuel, when the RHC on the ship is not used as fuel.
- LH_2 storage tank, for storing the liquid hydrogen at -253 °C.

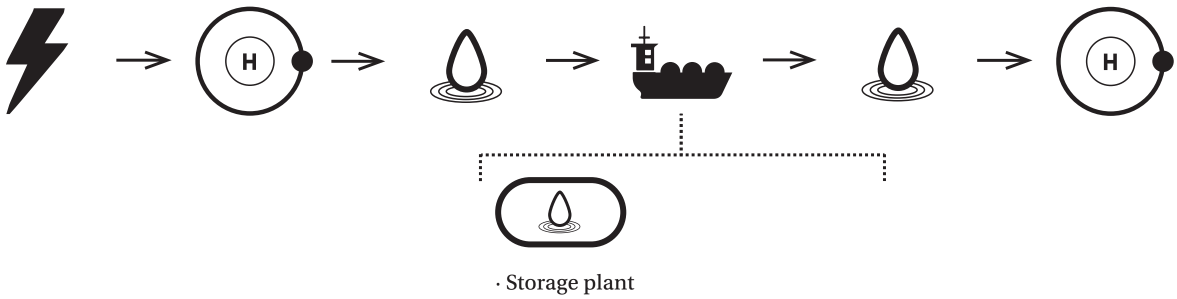

Figure 5.1: Cargo and fuel storage in the overall scope the research

5.1.1. Cargo storage

The vessels that are used for transporting the RHCs are already equipped with the required cargo tank, except for the liquid hydrogen vessel. Therefore, the storage of the liquid hydrogen vessel is discussed, this will be done by first analysing LNG storage tanks, because the LNG is stored at low temperatures of -163°C.

LNG storage

The three most conventional options of storing LNG are the following:

- *Type C single wall*: These type of tanks are used for relatively large storage sizes, typically above 1000 m^3. When the volumes of these tanks increase, the ratio between the surface area and the volume decreases, meaning that the boil off gas (BOG) percentage decreases. The pressure inside the tank can build up, this is typically between the 3 and 4 bar gauge. The material of the insulation is made of Polyurethane (PUR) or Polyisocyanurate (PIR), with a thickness of 0.3 to 0.4 meters, and have a typical insulation value (k-value) of around 0.06 [W/m^2K]. The tanks can be made from nickel steel, with a percentage of around 9% nickel, or the tanks can be made from stainless steel. The prices of the tanks are dependant on the steel and nickel prices. A ballpark price of LNG storage tanks is around 1000 €/m^3, this value decreases for larger tanks and increases for smaller tanks. In figure 3.5 the values for the cost of the tanks used in this thesis are shown.

- *Type C double wall*: This type of tank is used for relatively small storage volumes, typically below 1000 m^3 of LNG. Therefore, these tanks are mostly used as fueltanks. The higher insulation value of the tanks make sure that limited amount of BOG is produced. This is considered as positive, since this makes extra systems which control BOG unnecessary. The temperature of the LNG is rising less fast than in the single wall tanks and the tanks can also build up some pressure. The tank is better insulated, because of the two walls and the vacuum space between the two walls. The relative cost of the tank are higher [€/m^3] than the single wall tanks, because the tanks have a more complex design. The tanks have tank walls and the vacuum space in between filled with perlite. The insulation value (k-value) for these type of tanks is around 0.007 [W/m^2K].

- *Membrane tank:* The use of membrane tanks will not be considered, due to limited shipyards that are able to construct these tanks.

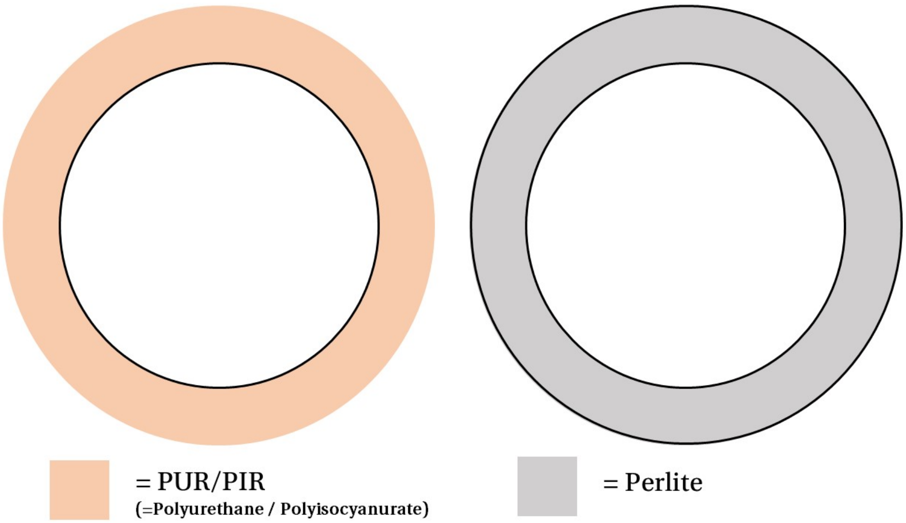

Figure 5.2: The storage types of LSNG considered in this thesis, on the left the single wall storage tank and on the right the double wall storage tank

Liquid hydrogen storage

The conventional way of storing liquid hydrogen is in vacuum double wall tanks (type C). Single wall tanks are not likely to be used, because more boil off gas will be produced. This is mainly due to the larger difference between storage temperatures (-163 °C vs. -253 °C). The liquid hydrogen double wall tanks are similar to the

LNG double wall storage tanks. The main difference is the material that is used which is in contact with the liquid hydrogen, such as the inner tank. The type of stainless steel that is used for LNG storage vessels cannot be used for liquid hydrogen tanks. The hydrogen molecules are much smaller than methane molecules, which can result in leakages. The material also needs to meet higher standards, because of the lower temperatures. Storing the liquid hydrogen can result in losses in ductility and fractures in the steel caused by this low temperature. 316L Stainless steel, or SUS304L stainless steel can be used as a material for the hydrogen containment system [107, 108].

The tanks will most likely be equipped with an Glass Fiber Reinforced Polymer (GFRP) support structure for less cold bridges between the outer tank and the vessel structure [109].

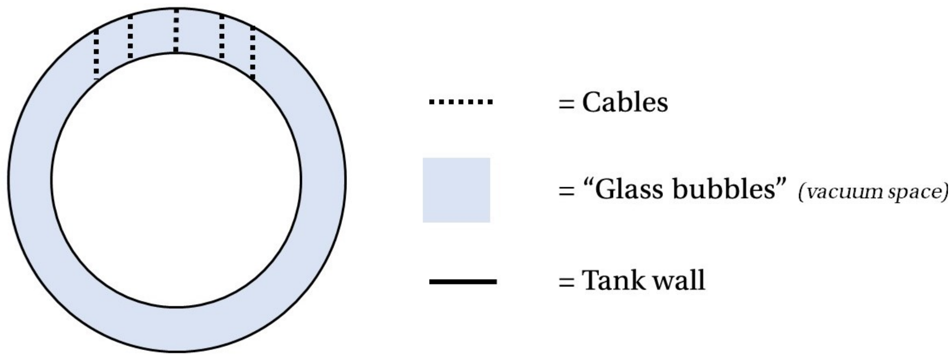

Figure 5.3: Storage tank design from NASA for liquefied hydrogen (LH_2)

The storage of liquid hydrogen at larger scale is more complicated. For LNG storage the switch can be made to single wall tanks, this is because the relative BOG is decreasing. For example, in LNG vessels the BOG that is produced is can directly be used as fuel for the engine, meaning that no extra cooling or liquefaction is needed. When storing liquid hydrogen in single wall tanks, much more BOG will be produced. This amount of BOG, will be too high to use for cruising only. Meaning that still re-liquefaction or re-cooling is needed. Ideally, liquid hydrogen is stored in vacuum tanks at larger volumes as well. The problem is that at larger volumes (around 1000 - 2000 m^3, depending on the diameter of the tank) the perlite between the two walls cannot hold the mass of the inner tank and its hydrogen anymore. Therefore stronger construction have to be made. However, stronger connections between the two walls will also cause cold bridges, which should be prevented.

The largest liquid hydrogen tank is from NASA, storing around 3800 m^3 of liquid hydrogen [102]. This is a spherical storage with the inner tank "hanging" inside the outer tank, as shown in figure 5.3. A similar material as perlite is used, called glass bubble insulation [102]. This tank is used for land based storage, and thus has a stable foundation. However on the ship the storage tank is never stable, and therefore it is unlikely that this type of storage used by NASA can also be used for storage on ships.

Based on these founding it seems unlikely that a type C single wall tanks will be used for storing hydrogen, producing high amounts of BOG. This means that large liquefaction plants are necessary, requiring a lot of energy. The option of using a double wall tanks to reduce BOG seems the better option, however technical solutions need to be found to construct larger volume tanks.

5.1.2. Conclusion

In this section the storage of L(S)NG and LH_2 were discussed. For LSNG storage (cargo & fuel) below 1,000 m^3, double wall vacuum type C tanks will be used. For storage of LNG above 1,000 m^3, typically single wall type C tanks will be used. For LH_2 storage, double wall vacuum tanks are used for the storing the hydrogen. When storing LH_2 volumes larger than 1,000 m^3, the tanks will become very long, keeping the diameter as small as possible. However, going to larger scale volumes, the technology for the larger storage tanks is not available yet, and solutions need to be found. The cost assumption for the liquid hydrogen tank is decribed in section 3.4.1. If BOG are too high, large liquefaction plants need to be build on the vessel, increasing cost and energy consumption significantly.

5.2. Prime movers

In this section the prime movers of the ship will be described, and the prime mover efficiency (η_e) will be analysed. The following prime movers are evaluated:

- Internal combustion engines
- Fuel cells

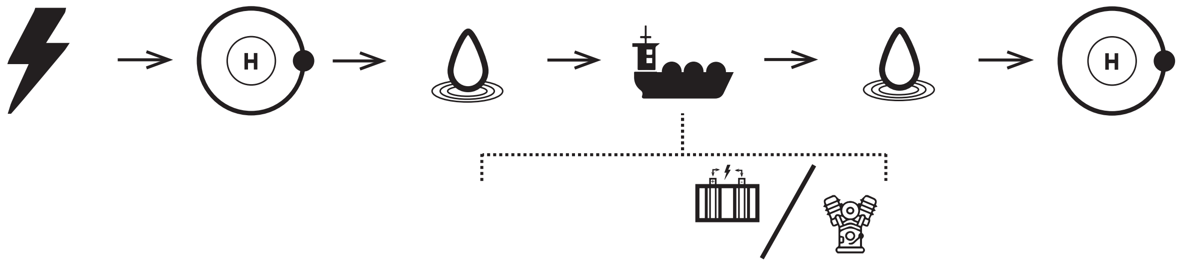

Figure 5.4: Prime movers which can be used to power the ship transporting RHCs

5.2.1. Combustion engine

The combustion engine is the most conventional type of prime mover on ships. The combustion engines can be separated into two groups; two stroke engines, and four stroke engines. These combustion engines use different ways of ignition, in which most conventional ways of ignition are spark and compression ignition methods.

The two stroke engines are mostly used in a direct shaft configuration, in which the engine drives a shaft, which is connected directly to the propeller. The slow rotational speed of the engine enables direct configuration. By powering the shaft directly from the engine, gears are not always necessary, and thus the amount of mechanical losses can be kept to a minimum. Two stroke engines have a relatively low power density, and in general those are mainly used for high power outputs.

Four stroke engines are in general more used for smaller power outputs and are used to produce electric output for auxiliary engines or for electric propelled vessels. The rotational speed of four stroke engines is higher than two stroke engines. Therefore ships which are powered by four stroke engines, need an additional gearbox. This gearbox is needed to control the rotational speed of the propeller.

In general combustion engines will generate mechanical power, which can be used to rotate the propeller of the ship. Combustion engines can also be coupled to a (shaft) generator, in which electricity can be generated. This electricity can be used for different purposes, such as powering electric motors, pumps or electricity for the accommodation of the ship. The lifetime of ICE is set on 25 years, the same as the lifetime of the ship. The power densities of the two and four stroke engines are shown in table 5.2.

Rotational speed and efficiency

Using figure 5.5, the rotational speed of the engine can be determined. Therefore the following two specifications need to be known:

- If the propulsion engine of the ship is a two or a four stroke engine. This is determined using the database of vessels, the results are shown in table 4.1. The different reference vessels and sizes are categorized, which will have a two or a four stroke engine bases on the data available of the ships.

- The propulsion power installed of the engine [kW], this value is taken from the database of ships, and is shown in table 4.1.

The rotational speed can be used in figure 5.6, to determine the engine efficiency (η_e). In equations 4.2, 4.3, 4.4, the calculation is described which is used to determine the power to propeller (P_D) of the reference vessel. The transmission efficiency (η_{TRM}) will be discussed in chapter 5.3.

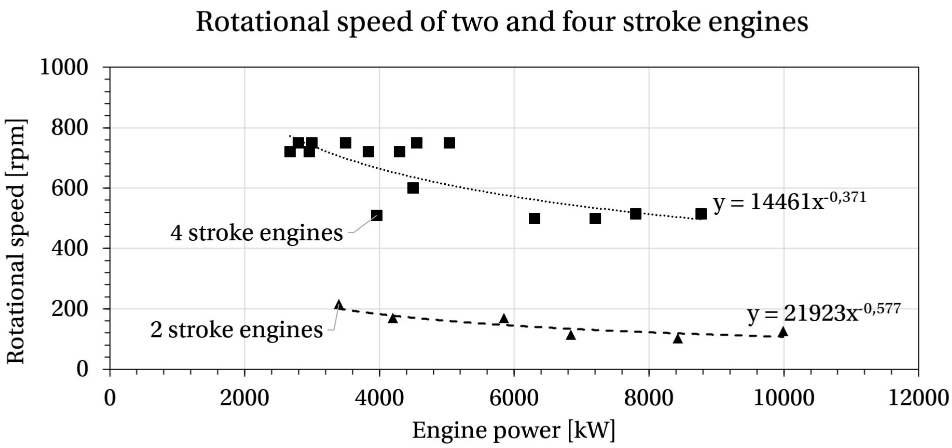

Figure 5.5: The rotational speed of combustion engines against the engine power based on database of Anthony Veder

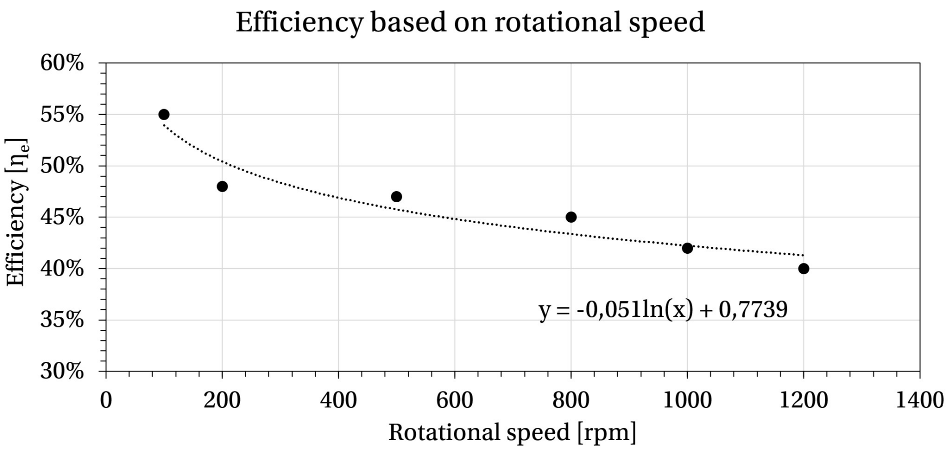

Figure 5.6: The effect of the rotational speed on the efficiency of the engine[106]

5.2.2. Fuel Cell

Fuel cells can produce electric power through a chemical reaction, therefore those are a subcategory of electrochemical cells. The best known electrochemical cells are batteries. Fuel cells differ from batteries since fuel cells need a continues flow of oxygen to be able to keep the reaction going. Fuel cells are in essence reversed electrolysers as can be seen from figure 5.7 and figure 5.8.

A fuel cell consist of an anode, a cathode and a electrolyte. The fuel, flows into the fuel cell at the anode and the fuel is split into protons and electrons. The negatively charged electrons flow away from the anode and are forced to move through an electric circuit towards the cathode. The electrolyte membrane is positioned between the anode and the cathode and only protons (hydrogen ions) can move through the electrolyte. The electrons moving through the electric circuit and thus supplying power.

Protons can either flow from the cathode to the anode or the other way around, depending on the specific type of fuel cell. The Proton Exchange Membrane Fuel Cell (PEMFC) and the Solid Oxide Fuel Cell (SOFC) will be described below, since those type of fuel cells are most applicable and promising for the maritime industry

[110]. The power densities of the SOFCs and the PEMFC are shown in table 5.2.

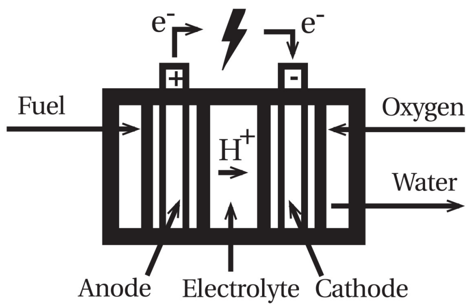

Figure 5.7: The working principle of a PEMFC

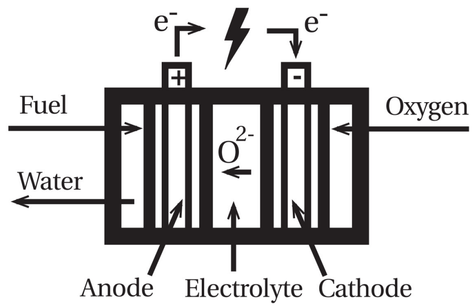

Figure 5.8: The working principle of a SOFC

The fuel cells exist of a system and a stack. The system has an assumed operating time of 25 years. The operating time of the stack is less and thus needs to be replaced. The cost of the stack in relation to the whole system is around 40% [21, 29].

PEMFC

PEMFC is a fuel cell in which hydrogen flows into the cell at the anode and the protons from the hydrogen move towards the cathode at which the it forms water with the electrons and the oxygen from the air. The fuel cell only operates on very pure hydrogen, in which a contamination can harm the fuel cell. An impurity in the fuel or air can cause degradation of the fuel cell and could lead to lower efficiencies and even failure.

The lifetime of a PEMFC is at this moment is around 5 to 6 years [6, 19] if operational at 8,760 hours a year. The lifetime of PEMFC is expected to increase in the coming years to 7 to 11 years in 2050 [6, 25, 111, 112]. This will be used for the economic analysis in chapter 6. An efficiency of 60% is used for PEMFCs [17, 19].

For the usage of NH_3 in PEMFC, a cracker is needed which can split the hydrogen from the nitrogen atom, after which it can be used in the fuel cell. This is explained in chapter 5.4.1.

SOFC

SOFC is a fuel cell in which hydrogen flows into the cell at the anode, which is the same for PEMFC. However in the SOFC the oxygen ions from the cathode move towards the anode through the electrolyte, to form water at the anode side. The electrolyte in this fuel cell is made from ceramic material.

The lifetime of a SOFC is at this moment around 5 years [19, 21, 113], when assuming that the SOFC is constantly working, meaning operational 8,760 hours a year. This lifetime is expected to increase during the coming years. In 2050 a lifetime of a stack of a SOFC could be operational for 10 to 14 years [21, 25, 113]. This will be used for the economic analysis in chapter 6.

The SOFC can be used for different fuels, however the efficiencies for LSNG and hydrogen are expected to be higher than for methanol and ammonia. Based on literature the efficiency for SOFC for LSNG and hydrogen is assumed to be 65%, while ammonia and methanol will operate with an efficiency of 60% [8, 16, 17, 111, 114, 115].

In table 5.1 the specifications of the fuel cells considered are shown.

	Fuel cell options			
	PEMFC		SOFC	
RHC	Fuel use	Efficiency (η_e) [%]	Fuel use	Efficiency (η_e) [%]
NH_3	Indirect (cracking H_2)	60	Direct	60
LH_2	Direct	60	Direct	65
LSNG	No	-	Direct	65
MeOH	No	-	Direct	60

Table 5.1: The efficiencies of renewable hydrogen carriers when used for fuel cells[16, 114–118]

5.2.3. Turbines

The use of turbines will not be used in this thesis. Steam turbines have been used in the past, but due to lower power densities and lower efficiencies compared to the combustion engine, ships are not equipped with this type of power propulsion. Gas turbine however do have higher power densities compared to the steam turbine, however these efficiencies are still lower than conventional combustion engines. Therefor only naval vessels still use this type of power generation, since those need high power densities to sail at high speeds [16].

5.2.4. Batteries

Batteries will not be used as prime movers, because those have a too low energy density for sea going vessels. However, the batteries can be used for support of other prime movers. This can be helpful for operations such as peak shaving. An efficiency of 93% for batteries is used [21]. The lifetime of today's batteries is around 9 years, but is expected to increase to around 13 years in 2050 [19, 21, 111]. The power densities of the batteries are shown in table 5.2.

Power generator	Power density [kW/m^3]
ICE (2 stroke)	33
ICE (4 stroke)	51
PEMFC	96
SOFC	7
Battery	91

Table 5.2: Power densities of the power generators[16, 18–21]

5.2.5. Combination

A combination of prime movers can also be used for improved performances, these will be described in chapter 5.3

5.2.6. Conclusion

The power generation onboard of the vessels will be done by either fuel cells or combustion engines and possibly in combination with a battery. Batteries will only be used to accompany fuel cells or combustion engines. Combustion engines and fuel cells will be investigated in any combination and also alone.

Prime movers	Additional Supply	Out of scope
ICE	Battery	Steam/Gas turbine
SOFC		
PEM		

Table 5.3: Overview of the defined scope for this research

5.3. Powertrain

In this section the different power configurations will be described. A ship can be powered by electrical and mechanical energy, or a combination of both. The analysis of the systems will determine the efficiency of the powertrain. As earlier seen in section 5.2, the different power generation options can either produce mechanical energy or electrical energy.

Therefore in this section, different powertrains will be analysed determine the efficiencies of the powertrains during various operations. The following configurations will be examined:

- Powertrain
  - Mechanical powertrain
    - ◇ Internal combustion engine (2 stroke)
    - ◇ Internal combustion engine (4 stroke)
  - Electric powertrain
    - ◇ Internal combustion engine (ICE) (4 stroke)
    - ◇ Internal combustion engine (ICE) (4 stroke) + Battery
    - ◇ Fuel cell (SOFC/PEM) + Battery
    - ◇ Fuel cell (SOFC/PEM) + Internal combustion engine (ICE) (4 stroke)
    - ◇ Fuel cell (SOFC/PEM) + Internal combustion engine (ICE) (4 stroke) + Battery

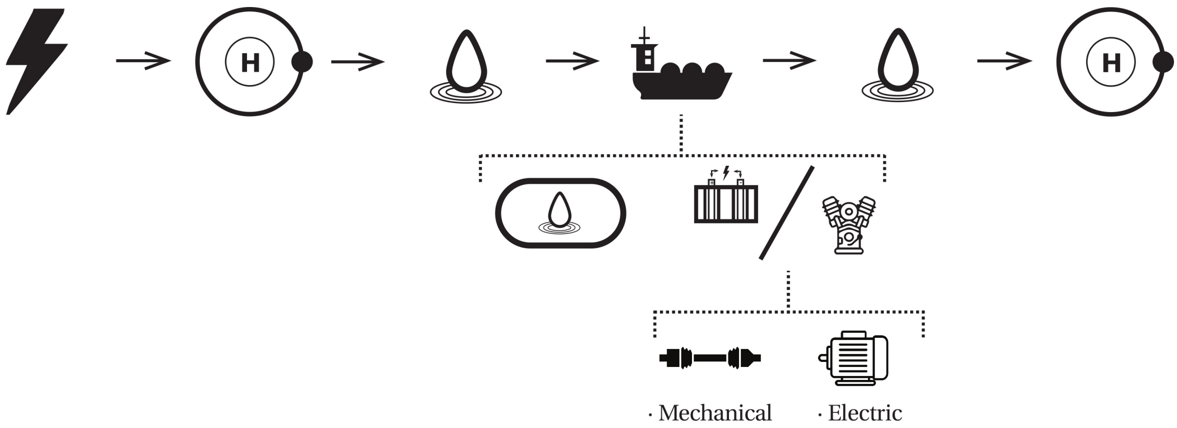

Figure 5.9: Overview of ship powertrain options

5.3.1. Transmission efficiency

The transmission efficiency (η_{TRM}), can be determined by evaluating the components between the prime mover and the propeller. The power to the propeller (P_D) for the new ship design is assumed to be the same as for reference ships. This transmission efficiency is used for two things:

1. Determining the power to propeller (P_D) of the reference ships
2. Determining the efficiency of the different powertrain configurations during various operations, such as during cruising ($\eta_{propulsion}$) and during electric loads (η_{other}).

The transmission efficiency differs for the various operations. For example, in an electric powered ship, the power travels a different path when it is going from the engine to the propeller than when the power travels from the engine to the pumps. This different path leads to another transmission efficiency. The different components of the powertrains are shown in table 5.4.

Electric powered ships will use electric power for propulsion as well as for the other electric loads, however mechanically powered ships are not always able to do this. In mechanically powered ships, additional auxiliary engines are used for electric loads. These auxiliary engines are used for example during the times when the ship is idling and needs electric power. Therefore these type of ships will have different engines with different efficiencies.

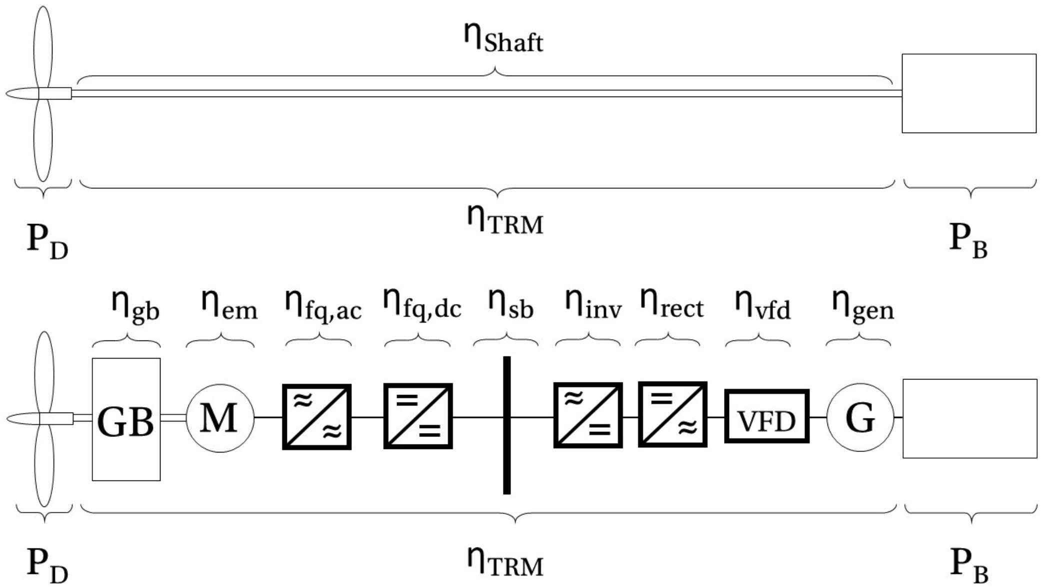

Figure 5.10: Different powertrain configurations can affect the efficiency of the transmission from the prime mover to the propeller

Component	Symbol	Efficiency [-]	Source
Propeller shaft	η_{shaft}	0.963	[18]
Gearbox	η_{gb}	0.988	[16, 106]
Electric motor	η_{em}	0.970	[16, 18, 19]
Frequency converter (AC/AC)	$\eta_{fq,ac}$	0.980	[16, 19]
Frequency converter (DC/DC)	$\eta_{fq,dc}$	0.990	[16, 18, 19]
Switchboard (AC)	$\eta_{sb,ac}$	0.978	[16, 18, 19, 119]
Switchboard (DC)	$\eta_{sb,dc}$	0.980	[19]
Rectifier (AC/DC)	η_{rect}	0.980	[19]
Inverter (DC/AC)	η_{inv}	0.980	[16, 120]
Generator	η_{gen}	0.995	[119]
Variable Frequency Drive (VFD)	η_{vfd}	0.97	[19]

Table 5.4: Transmission efficiency of the different powertrain components

5.3.2. Mechanical Powertrain

A ship can be mechanically propelled, this means that mechanical energy is used to rotate the propeller. An internal combustion engine (ICE) can directly rotate the shaft or indirectly with a gearbox in between the engine and the propeller. The combustion engines are described in section 5.2.1.

Power needed during cruising for other the "other loads" (e.g. hotel load, heat and ventilation air conditioning (HVAC), pumps, heaters and cooling systems) will be powered by the shaft generator, which is connected to the shaft of the main engine. This shaft generator produces electricity with alternative current which is sent to the switchboard. The switchboard distributes power to the other loads. During the time when the vessel is not cruising, the shaft generator doesn't produce electricity, because the main engine is shut down. The power needed for the other loads will come from the auxiliary engines, which are connected to generators which will produce electricity electricity with alternative current which is sent to the switchboard.

The auxiliary engines that will be used in four and two stroke configurations, are four stroke engines with an assumed rotational speed of 1250 rpm, this is based on data available from the reference ships. Using figure 5.6, the efficiency of the auxiliary (η_e) engine will be 41%.

For mechanical powertrains, the assumption is made that the power used for the operations other than cruising, will come from the auxiliary engines, shown in table 5.5.

Operations	Engine	Efficiency (η_e)
Cruising	Main engine	Depending on figures 5.5, 5.6
Idling, Manoeuvring, Loading, Discharging	Auxiliary engines	41%

Table 5.5: Engines used for the mechanical powertrains during the different operations

Two stroke

Two stroke engines have a relatively low engine speed, which enables direct shaft propulsion. As shown in table 5.5, the operations other than cruising will be powered by the auxiliary engines. The transmission efficiency of two stroke engines during cruising is shown in equation 5.1.

$$\begin{aligned}\eta_{TRM_{2S,ME,cruising}} &= \eta_{shaft} \\ \eta_{TRM_{2S,ME,cruising}} &= 0.963\end{aligned} \tag{5.1}$$

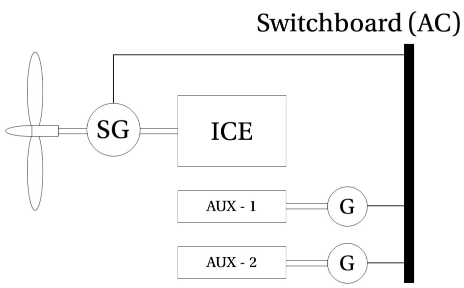

Figure 5.11: Two stroke engine configuration with two auxiliary engines

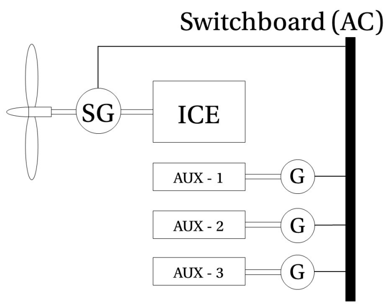

Figure 5.12: Two stroke engine configuration with three auxiliary engines

Figure 5.5 shows that two stroke engines will have a rotational speed of around 70 - 200 rpm. This means that the engine efficiency (η_e) of the two stroke engines is between 45-55% depending on size and rotational speed. The power to propeller (P_D) of two stroke engine configurations is shown in equation 5.2.

$$\begin{aligned}P_D &= P_B \cdot (NCR/MCR) \cdot \eta_{TRM_{2S,cruising}} \cdot \eta_e \\ P_D &= P_B \cdot 0.85 \cdot 0.963 \cdot (0.50 - 0.56) \\ P_D &= P_B \cdot 0.819 \cdot (0.50 - 0.56)\end{aligned} \tag{5.2}$$

For the other operations the main engine or the auxiliary engines can be used, however in this thesis the assumption is made that this power will come from the auxiliary engines. Using equation 5.3, the transmission efficiency of the other loads is determined.

$$\begin{aligned}\eta_{TRM_{aux,ac,other}} &= \eta_{gen} \cdot \eta_{sb} \\ \eta_{TRM_{aux,ac,other}} &= 0.973\end{aligned} \tag{5.3}$$

Four stroke

Four stroke combustion engines have higher engines speeds, which is why often a gearbox is coupled to the engine shaft. The typical four stroke engine powertrain configuration is shown in figure 5.13. The transmission efficiency of the powertrain configuration during cruising is shown in equation 5.4, and the power to propeller (P_D) of the four stroke configuration in shown in equation 5.5.

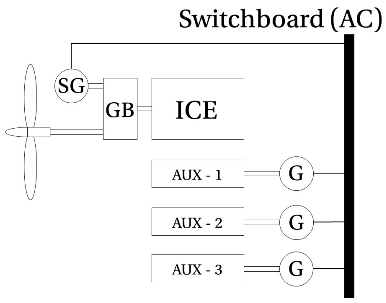

Figure 5.13: Four stroke engine powertrain configuration

$$\begin{aligned} \eta_{TRM_{4S,ME,cruising}} &= \eta_{shaft} \cdot \eta_{gb} \\ \eta_{TRM_{4S,ME,cruising}} &= 0.951 \end{aligned} \tag{5.4}$$

$$\begin{aligned} P_D &= P_B \cdot (NCR/MCR) \cdot \eta_{TRM_{4S,cruising}} \cdot \eta_e \\ P_D &= P_B \cdot 0.85 \cdot 0.951 \cdot (0.42 - 0.46) \\ P_D &= P_B \cdot 0.81 \cdot (0.42 - 0.46) \end{aligned} \tag{5.5}$$

5.3.3. Electric powertrain

In an electric powertrain configuration the propeller of the ship is rotated by electrical energy. In the electrical powertrains there will be no distinction between the auxiliary engines and the main propulsion engine, because all energy is produced as electricity. The fuel is converted to electrical energy and is sent to the switchboard. This can be an alternative current (AC) or a direct current (DC) switchboard. In the model the average efficiency of the two systems (AC and DC) will be used.

Internal combustion engines can also be used in an electrical system, but also other components can be added to the switchboard, such as fuel cells and batteries. This makes an electrical powertrain more flexible.

ICE with or without battery

Combustion engines can be used in an electrical powertrain configuration, the mechanical energy of the combustion engine is used to power a generator, producing electricity in alternative current (AC). This electricity can be send directly to the switchboard. However when the alternative current needs to be converted to direct current, an rectifier can be used.

For an alternative current switchboard often an additional frequency converter is used, to make because the electric motor for the engine has another electric frequency that the other loads which are connected to the switchboard as well.

Direct Current

The electric powertrain configuration powered by an ICE using a direct current switchboard is shown in figure 5.14, and with a battery paired is shown in figure 5.15.

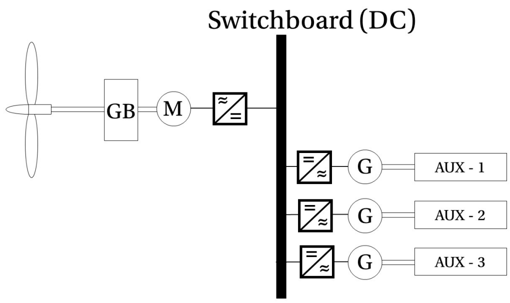

Figure 5.14: An electric powertrain configuration powered by an ICE with a direct current switchboard

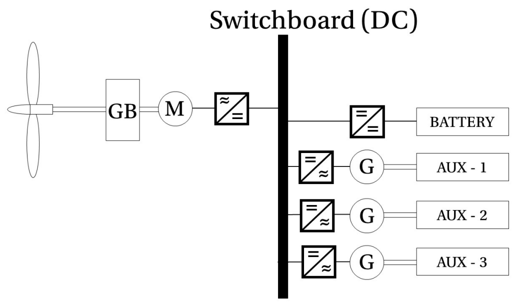

Figure 5.15: An electric powertrain configuration powered by an ICE and a battery with a direct current switchboard

The transmission efficiency of the powertrain during cruising, using the combustion engines only, is shown in equation 5.6. The transmission efficiency of the other loads are shown in equation 5.7.

$$\begin{aligned} \eta_{TRM_{aux,dc,cruising}} &= \eta_{gen} \cdot \eta_{rect} \cdot \eta_{sb} \cdot \eta_{inv} \cdot \eta_{em} \cdot \eta_{gb} \cdot \eta_{shaft} \\ \eta_{TRM_{aux,dc,cruising}} &= 0.862 \end{aligned} \tag{5.6}$$

$$\begin{aligned} \eta_{TRM_{aux,dc,other}} &= \eta_{gen} \cdot \eta_{rect} \cdot \eta_{sb} \\ \eta_{TRM_{aux,dc,other}} &= 0.954 \end{aligned} \tag{5.7}$$

The transmission efficiency during cruising of the powertrain using the battery only is shown in equation 5.8. During the other loads the transmission efficiency is shown in equation 5.9.

$$\begin{aligned} \eta_{TRM_{batt,dc,cruising}} &= \eta_{fq} \cdot \eta_{sb} \cdot \eta_{inv} \cdot \eta_{em} \cdot \eta_{gb} \cdot \eta_{shaft} \\ \eta_{TRM_{batt,dc,cruising}} &= 0.875 \end{aligned} \tag{5.8}$$

$$\begin{aligned} \eta_{TRM_{batt,dc,other}} &= \eta_{fq} \cdot \eta_{sb} \\ \eta_{TRM_{batt,dc,other}} &= 0.968 \end{aligned} \tag{5.9}$$

Alternative Current

The electric powertrain configuration powered by an ICE using an alternative current switchboard is shown in figure 5.16, and with a battery paired is shown in figure 5.17.

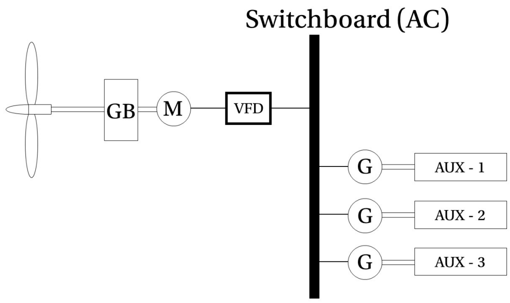

Figure 5.16: An electric powertrain configuration powered by an ICE with an alternative current switchboard

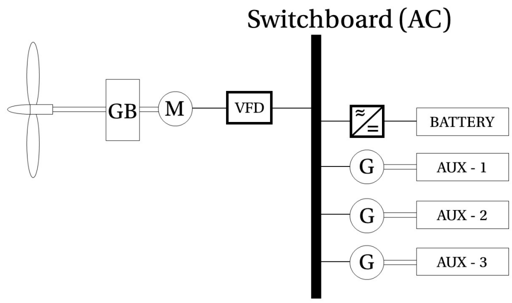

Figure 5.17: An electric powertrain configuration powered by an ICE and a battery with an alternative current switchboard

The transmission efficiency of the powertrain with the alternative current switchboard during cruising, using the combustion engines only, is shown in equation 5.10. The transmission efficiency of the other loads are shown in equation 5.11.

$$\begin{aligned} \eta_{TRM_{aux,ac,cruising}} &= \eta_{gen} \cdot \eta_{sb} \cdot \eta_{vfd} \cdot \eta_{em} \cdot \eta_{gb} \cdot \eta_{shaft} \\ \eta_{TRM_{aux,ac,cruising}} &= 0.889 \end{aligned} \tag{5.10}$$

$$\begin{aligned} \eta_{TRM_{aux,ac,cruising}} &= \eta_{gen} \cdot \eta_{sb} \\ \eta_{TRM_{aux,ac,other}} &= 0.973 \end{aligned} \tag{5.11}$$

The transmission efficiency during cruising of the powertrain using the battery only is shown in equation 5.12. During the other loads the transmission efficiency is shown in equation 5.13.

$$\begin{aligned}\eta_{TRM_{batt,ac,cruising}} &= \eta_{inv} \cdot \eta_{sb} \cdot \eta_{vfd} \cdot \eta_{em} \cdot \eta_{gb} \cdot \eta_{shaft} \\ \eta_{TRM_{batt,ac,cruising}} &= 0.875\end{aligned} \tag{5.12}$$

$$\begin{aligned}\eta_{TRM_{batt,ac,cruising}} &= \eta_{inv} \cdot \eta_{sb} \\ \eta_{TRM_{batt,ac,other}} &= 0.958\end{aligned} \tag{5.13}$$

5.3.4. Fuel cells in powertrain

Combining a fuel cell, an internal combustion engine and a battery results in a system which is very flexible and redundant. However this can make the electrical system more complex and thus more expensive. The combination of the fuel cell, ICE, and the battery with an alternative current switchboard is shown in figure 5.18, the combination using an direct current switchboard is shown in figure 5.17.

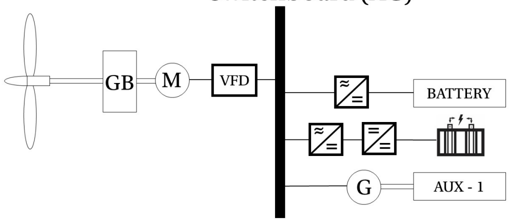

Figure 5.18: An electric powertrain configuration powered by an ICE,a battery and a fuel cell with an alternative current switchboard

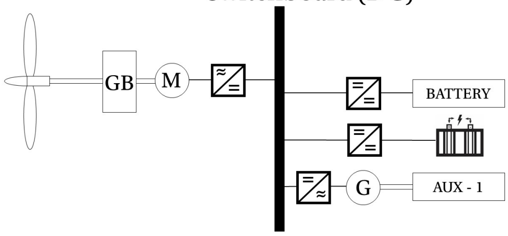

Figure 5.19: An electric powertrain configuration powered by an ICE,a battery and a fuel cell with direct current switchboard

Direct Current

The transmission efficiency of the powertrain with the direct current switchboard during cruising, using the fuel cells only, is shown in equation 5.14. The transmission efficiency of the other loads are shown in equation 5.15.

$$\begin{aligned}\eta_{TRM_{FC,dc,cruising}} &= \eta_{fq} \cdot \eta_{sb} \cdot \eta_{inv} \cdot \eta_{em} \cdot \eta_{gb} \cdot \eta_{shaft} \\ \eta_{TRM_{FC,dc,cruising}} &= 0.893\end{aligned} \tag{5.14}$$

$$\begin{aligned}\eta_{TRM_{FC,dc,other}} &= \eta_{fq} \cdot \eta_{sb} \\ \eta_{TRM_{FC,dc,other}} &= 0.968\end{aligned} \tag{5.15}$$

Alternative Current

The transmission efficiency of the powertrain with an alternative current switchboard during cruising, using the fuel cells only, is shown in equation 5.16. The transmission efficiency of the other loads are shown in equation 5.17.

$$\begin{aligned}\eta_{TRM_{FC,ac,cruising}} &= \eta_{fq} \cdot \eta_{inv} \cdot \eta_{sb} \cdot \eta_{vfd} \cdot \eta_{em} \cdot \eta_{gb} \cdot \eta_{shaft} \\ \eta_{TRM_{FC,ac,cruising}} &= 0.849\end{aligned} \tag{5.16}$$

$$\begin{aligned}\eta_{TRM_{FC,ac,other}} &= \eta_{fq} \cdot \eta_{inv} \cdot \eta_{sb} \\ \eta_{TRM_{FC,ac,other}} &= 0.949\end{aligned} \tag{5.17}$$

Other combinations

The following combinations can be possible as well:

- ICE + Fuel Cell.
- Fuel Cell + Battery

The transmission efficiencies of the single components can be calculated using the information in the previous sections.

5.3.5. Determining efficiencies and power densities with multiple prime movers

In section 5.2.5 is described that power on board of the ships can be generated by multiple systems. However when determining the efficiency of the powertrain, the distribution of power between the different systems (FC, ICE, and battery) need to be known. An assumption is made that the distribution of power will be 50% - 50% when a fuel cell and an ICE will be used. The different prime movers can also be used in combination with a battery, the distribution of this power is taken from literature [19]. The distribution of power for the different powertrain is shown in table 5.6.

Research shows that an improved electrical efficiency can be reached for an ICE in combination with a fuel cell of 5 to 10% [23, 24]. Combining a SOFC with an ICE, the efficiency of the system can be improved to 59% in a system with natural gas [24]. The distribution is that 16% of the power comes from the ICE (HCCI engine) and 84% from the SOFC.

To determine the efficiency of the prime movers combinations, assumptions are needed. Taking the average efficiency between the prime movers, for example, for a system powered by LSNG with an ICE and a SOFC, a theoretical efficiency of 54% (the average of an η_e of 44% (ICE) and η_e of 65% (SOFC)) would be the result. This is below the 59% efficiency reached in other research [24] and is still within the 10% efficiency increase which can be reached suggested in the research [23]. Therefore, when determining the efficiency of the prime mover combinations, the power distribution in combination with the efficiency of the prime movers will be used. The calculation of the overall efficiency of the prime mover combination is shown in equation 5.18.

$$\begin{gathered} \eta_{e,overall} : \text{Overall efficiency of prime movers} \\ \eta_{e,overall} = \eta_{e,ICE} \cdot X_{ICE} + \eta_{e,FC} \cdot X_{FC} + \eta_{e,Battery} \cdot X_{Battery} \end{gathered} \tag{5.18}$$

The same principle is used to determine the transmission efficiencies. The average transmission efficiency is taken between the AC and DC transmission efficiencies. The calculation is shown in equation 5.19.

$$\begin{gathered} \eta_{TRM} : \text{Average transmission efficiency of powertrain configuration} \\ \eta_{TRM,overall} \\ = \\ \frac{\eta_{TRM,ICE,AC} \cdot X_{ICE} + \eta_{TRM,FC,AC} \cdot X_{FC} + \eta_{TRM,Battery,AC} \cdot X_{Battery}}{2} \\ + \\ \frac{\eta_{TRM,ICE,DC} \cdot X_{ICE} + \eta_{TRM,FC,DC} \cdot X_{FC} + \eta_{TRM,Battery,DC} \cdot X_{Battery}}{2} \end{gathered} \tag{5.19}$$

The power densities of the different power generators are shown in table 5.2 and using the power distribution, the density of the powertrain configuration will be determined as well. The power densities are shown in table 5.6.

Powertrain configuration	X_{ICE} [% kW]	$X_{Fuelcell}$ [% kW]	$X_{Battery}$ [% kW]	Power density [kW/m^3]
ICE (2 stroke)	100	-	-	33
ICE (4 stroke)	100	-	-	51
ICE (4 stroke electric)	100	-	-	36
ICE + Battery	98.3	-	1.7	36
PEM + Battery	-	96.9	3.1	95
SOFC + Battery	-	91.1	8.9	7.2
ICE + PEM	50	50	-	66
ICE + SOFC	50	50	-	21
PEM + ICE + Battery	49.2	49.2	1.7	53
SOFC + ICE + Battery	49.2	49.2	1.7	11

Table 5.6: The power distribution and the power density of the different powertrains[16, 18, 19, 21]

Based on the power distribution in table 5.6, in combination with equation 5.18 and equation 5.19, table 5.7 can be made. In this table the overall efficiency ($\eta_{e,overall}$) of the powertrains are shown, which is the efficiency from the fuel to mechanical or electrical energy, depending on the specific powertrain. In the next two columns the transmission efficiencies are shown, these show the efficiency from the prime mover to the specific operation. ($\eta_{TRM,overall,propulsion}$) is the transmission efficiency when the ship is cruising and ($\eta_{TRM,overall,other}$) is the transmission efficiency for the other operations. The efficiency of the powertrain configurations when cruising ($\eta_{propulsion}$) and during other operations (η_{other}) can be calculated using equation 5.20. This is shown in the last two columns in table 5.7.

$$\eta_{e,overall} \cdot \eta_{TRM,overall,propulsion} = \eta_{propulsion}$$
$$\eta_{e,overall} \cdot \eta_{TRM,overall,other} = \eta_{other} \quad (5.20)$$

	Fuel	Efficiencies				
Mechanical propulsion		Prime mover(s) $\eta_{e,overall}$ [-]	Transmission propulsion $\eta_{TRM,overall,propulsion}$ [-]	Transmission other $\eta_{TRM,overall,other}$ [-]	Overall propulsion $\eta_{propulsion}$ [-]	Overall other η_{other} [-]
ICE (2S)	All	0.50-0.56†	0.96	0.87 (ME)	0.49-0.54†	-
ICE (2S)	All	0.41† †	-	0.97 (aux)	-	0.40 (aux)
ICE (4S)	All	0.42-0.46†	0.95	0.86 (ME)	0.40-0.44†	-
ICE (4S)	All	0.41† †	-	0.97 (aux)	-	0.40 (aux)
Electric propulsion						
ICE (4S)	All	0.44 † † †	0.88	0.96	0.38	0.42
ICE (4S) + Battery	All	0.45 † † †	0.88	0.96	0.39	0.43
PEM + Battery	H_2	0.59	0.87	0.96	0.51	0.56
PEM + Battery	NH_3	0.47	0.87	0.96	0.41	0.45
SOFC + Battery	H_2	0.66	0.87	0.96	0.58	0.64
SOFC + Battery	MeOH	0.62	0.87	0.96	0.54	0.59
SOFC + Battery	NH_3	0.62	0.87	0.96	0.54	0.59
SOFC + Battery	LSNG	0.66	0.87	0.96	0.58	0.64
ICE (4S) + SOFC	H_2	0.54	0.87	0.96	0.47	0.52
ICE (4S) + SOFC	MeOH	0.52	0.87	0.96	0.45	0.50
ICE (4S) + SOFC	NH_3	0.52	0.87	0.96	0.45	0.50
ICE (4S) + SOFC	LSNG	0.54	0.87	0.96	0.47	0.52
ICE (4S) + PEM	H_2	0.50	0.87	0.96	0.44	0.48
ICE (4S) + PEM	NH_3	0.45	0.87	0.96	0.39	0.43
ICE (4S) + PEM + Battery	H_2	0.52	0.87	0.96	0.46	0.50
ICE (4S) + PEM + Battery	NH_3	0.47	0.87	0.96	0.41	0.45
ICE (4S) + SOFC + Battery	H_2	0.56	0.87	0.96	0.49	0.54
ICE (4S) + SOFC + Battery	MeOH	0.54	0.87	0.96	0.47	0.52
ICE (4S) + SOFC + Battery	NH_3	0.54	0.87	0.96	0.47	0.52
ICE (4S) + SOFC + Battery	LSNG	0.56	0.87	0.96	0.49	0.54

† Depending on the installed power(kW) and rotational speed (rpm)

† † For auxiliary engines a rotational speed of 1250 rpm is chosen, which corresponds to this efficiency using figure 5.6

† † † A rotational speed of 720 rpm is used for ICE used in an electrical powertrain

Table 5.7: The efficiencies of the different powertrains considered

The ($\eta_{propulsion}$) can be used to determine the power to propeller of the new powertrain configurations using equation 5.21. The (η_{other}) will be used to determine the fuel consumption during the other operations.

$$P_D = P_B \cdot (NCR/MCR) \cdot \eta_{propulsion} \tag{5.21}$$

5.3.6. Emissions

The powertrain configurations do not have the same efficiency and especially with combustion engines there are problems related to incomplete combustion. The emissions from the vessels will only be considered during the combustion, so from tank to wake, this is because it is assumed that the production of the renewable fuels is sustainable. So any upstream emissions will not be discussed. The following emissions during the combustion, will be discussed:

- CO_2
- CH_4
- NO_x

In table 5.6, the power distribution is shown for the different powertrain designs, this distribution will also be used in the analysis of how much emissions are produced by the powertrains. This is shown in table 5.8.

CO_2

Carbon dioxide is a product that is formed during the combustion of carbon containing fuels, which are the RHCs: LSNG, and MeOH. These RHCs are produced using carbon dioxide as a feedstock product, this assumption is made and explained in chapter 2. Therefore, the carbon dioxide balance will be neutral, because the CO_2 is captured and converted into LSNG and MeOH.

The emissions of carbon dioxide can however be a problem when local or regional authorities implement a zero emission policy, in which no emissions of any kind can be emitted. For these kind of scenarios it is important to know the emissions of carbon dioxide. The emission of CO_2 will be based on the amount of fuel that is used during the operations. This means that a certain tonnage of CO_2 will be emitted per ton fuel, this is known as the emission factor EF [$kgCO_2/GJ_{fuel}$], this is shown in table 5.8.

CH_4

Methane is also a greenhouse gas, which can be released during incomplete combustion of LSNG. In this thesis, the long term effects (100 year equivalent) are taken into account, this is also known as the Global Warming Potential at a 100 year time Horizon (GWP_{100}). This gives an indication of how other emissions perform as a greenhouse gas compared to CO_2. A GWP_{100} of 28 for methane is used, this value differs between different research between 25 and 36 [21, 121–123]. A factor of 28 is used in the latest version (version 5) of the assessment report of the international panel on climate change (IPCC), therefore this value will be used.

Methane slip is a result of an incomplete combustion in a combustion engine, but the amount of slip depends on the specific engine. Therefore the two stroke and four stroke engines will be discussed on methane slip.

CH_4 - two stroke

The 2 stroke engines can be separated in two categories:

- *Slow speed diesel dual fuel engines:* These are high pressure engines, such as the ME-GI engine from MAN. Methane slip occurs less in these engines, however the engines have higher NO_x emissions, therefore, SCRs are needed to be compatible with TIER III regulation. The engines are mostly used in container ships, car carriers, general cargo carriers, and bulk carrier [121]. Therefore, these engines will not be considered in this research.

- *Slow speed otto dual fuel engines:* The most modern type of these engines are the Wärtsilä X-DF engines. These engines are mostly used for for container ships, oil and chemical tankers [121]. These engines will be used to determine the methane slip from two stroke engines.

The X-DF engines from Wärtsilä have a methane slip of 1.8% during the combustion [122]. LSNG has a LHV of 48.6 MJ/kg. For 1 kg of LSNG, 18 grams of methane slips through the engine, which is equivalent to 0.37 gCH_4/MJ, equivalent to 1.33 gCH_4/kWh. This is a lower amount than other values of 2.1gCH_4/kWh and 2.5gCH_4/kWh mentioned in other reports [121, 122], which use also older engines types for the analysis. This thesis focusses on the design of new ships also having modern technology and modern engines. Therefore, 18kgCH_4/tLSNG or 0.37kgCH_4/GJ of methane slip will be used for two stroke engines.

CH_4 - four stroke

The four stroke otto cycle medium speed engines are generally used for smaller power outputs, than the two stroke engines. These engines do have a higher methane slip. This slip varies quite a lot between the different reports: 5.5 gCH_4/kWh [121] , 3.8 gCH_4/kWh [122] and 4.1 gCH_4/kWh[21]. Wärtsilä state that the methane slip is 3.6 gCH_4/kWh at higher loads and at lower loads of around 30% MCR this can go as high as 4.5 gCH_4/kwh [124].

The amount of methane slip can vary a lot for different loads and different engine settings. There will be a NO_x / CH_4 trade-off, meaning that less NO_x produced by the engine will lead to more methane slip and and vice versa. The value of 4.1 gCH_4/kWh was used, this is the value given by Wärtsilä with an additional 15% of uncertainty, which they mention (3.6 * 1.15) [124] and also corresponds to the value stated in research [21]. The value is equivalent to 1.1kgCH_4/GJ.

NO_x

NO_x emissions can occur during the combustion in combustion engines, often the result of too high temperatures in the combustion chamber, in which nitrogen and oxygen undergo a reaction forming NO_x. NO_x emissions are not a problem with the use of fuel cells.

- *LH_2*: ABC engines are working on hydrogen combustion engines, in which they report NO_x emissions of 0.2 g/kWh, which is 1/10 of the requirements for TIER III regulation [125]. This 1/10 is also assumed for two stroke hydrogen combustion engines.

- *MeOH*: For the MAN methanol ME-LGIM engine an SCR or EGR will not be needed to comply with TIER III regulation [126], therefor TIER III emissions are assumed for the two stroke engines. For the four stroke engines 0.4 kgNO_x/GJ is used, based on literature [127].

- *NH_3*: For NH_3 combustion engines a SCR is likely to be needed to reduce NO_x emissions [128], after the fuel treatment of the SCR, it will comply with TIER III regulations, which are shown in table 5.8.

- *LSNG*: The NO_x emissions from the LSNG engines are relatively low compared to conventional diesel engines. The gas engines that were selected in this thesis do tend to have low NO_x emissions, but higher methane slip. The values shown in table 5.8 are taken from literature [122].

Fuel used	Powertrain	CO_2 [kg/GJ fuel]	CH_4 [kg/GJ fuel]	NO_x [kg/GJ fuel]	GHG (CO_2-eq) [kg/GJ fuel]
LH_2	ICE (2 stroke) mechanic	0	0	0.09 [125]	0
LH_2	ICE (4 stroke) mechanic	0	0	0.06 [125]	0
LH_2	ICE (4 stroke) electric	0	0	0.06 [125]	0
LH_2	ICE + FC + battery (electric)	0	0	0.03 [125]	0
LH_2	FC + battery	0	0	0	0
MeOH	ICE (2 stroke) mechanic	69.1	0	0.9 [126, 129]	69.1
MeOH	ICE (4 stroke) mechanic	69.1	0	0.4[127]	69.1
MeOH	ICE (4 stroke) electric	69.1	0	0.4[127]	69.1
MeOH	ICE + FC + battery (electric)	69.1	0	0.2[127]	69.1
MeOH	FC + battery	69.1	0	0	69.1
NH_3	ICE (2 stroke) mechanic + SCR	0	0	0.9 (with SCR) [128]	0
NH_3	ICE (4 stroke) mechanic + SCR	0	0	0.6 (with SCR) [128]	0
NH_3	ICE (4 stroke) electric + SCR	0	0	0.6 (with SCR) [128]	0
NH_3	ICE + FC + battery (electric) + SCR	0	0	0.6 (with SCR) [128]	0
NH_3	FC + battery	0	0	0	0
LSNG	ICE (2 stroke) mechanic	56.7	0.4	0.34 [122]	67.9
LSNG	ICE (4 stroke) mechanic	56.7	1.1	0.76 [122]	87.5
LSNG	ICE (4 stroke) electric	56.7	1.0	0.76 [122]	84.7
LSNG	ICE + FC + battery (electric)	56.7	0.5	0.38 [122]	70.7
LSNG	FC + battery	56.7	0	0	56.7

Table 5.8: Emissions from the different powertrain configurations

5.4. Additional systems

5.4.1. Reformers

Some of the energy carriers cannot be used directly as a fuel in either the combustion engines or fuel cells. The reforming of methanol and LSNG on the ship is not considered. As of this moment these installations are voluminous and costly and other alternatives are believed to be better suited.

Reformer NH_3 to H_2

One of the crackers which could be used to reform ammonia into hydrogen is the one that is in development from CSIRO [130]. This reformer is an example of something that could be used for PEMFC, shown in figure 5.20. The company Koyo Thermo Systems Co is also developing a ammonia cracker. For the reformer that produces a pure stream of hydrogen for PEMFCs, an efficiency of 79% is assumed for the reformer , which is also used for converting ammonia to hydrogen in table 2.14.

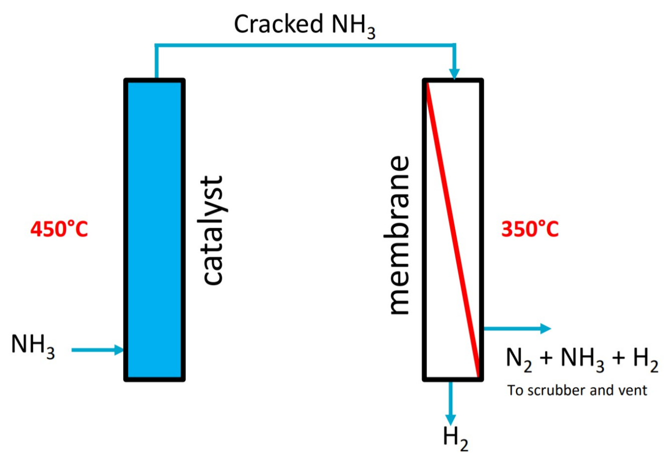

Figure 5.20: Ammonia reformer developed by CSIRO[130]

Also more basic reformers can be used, these can be used to add a small amount of hydrogen to the combustion chamber in an ammonia engine. The efficiency of such system is not taken into account because it is assumed that the heat from the engine can be used for the cracking process [19].

5.4.2. Selective Catalytic Reduction (SCR) system

A selective catalytic reduction system (SCR) is an exhaust treatment technology, the principle of this system shown in figure 5.21. The system will be used on a vessel which is (partly) powered by ammonia. The technology is considered nowadays to be one of the most effective ways to reduce NO_x emissions, reducing the emissions to 90 - 95% [131]. In the reactor the ammonia reacts with the NO_x to form nitrogen and water, two harmless compounds. It is likely that the SCR will be running on pure ammonia, since it is more effective and the the storage of ammonia is already available.

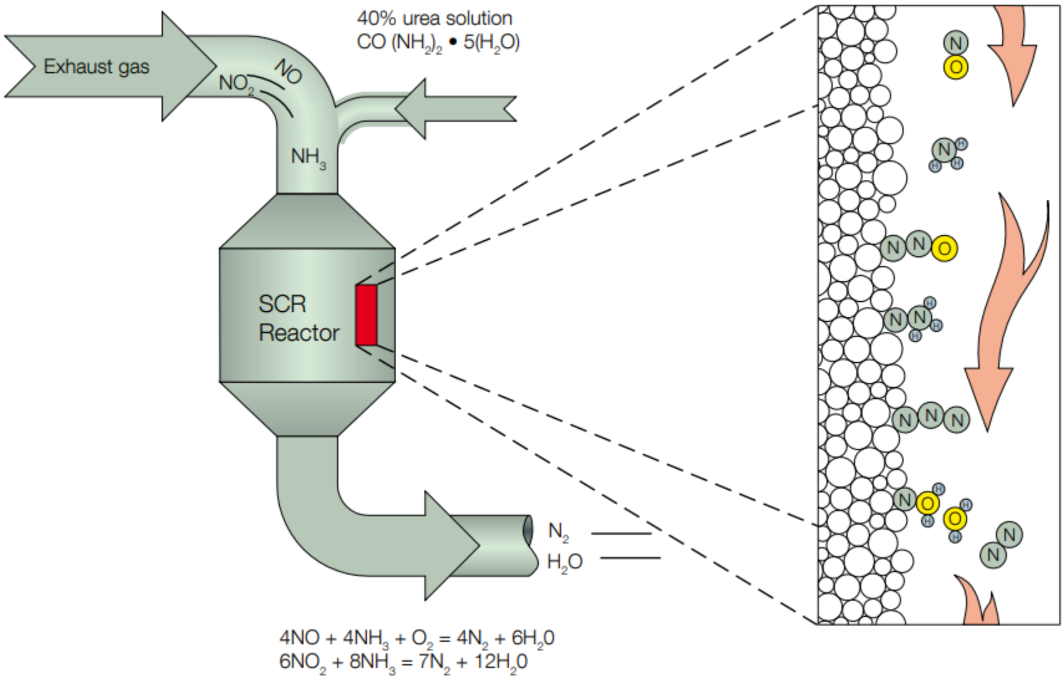

Figure 5.21: Working principle of an selective catalytic reduction (SCR) reactor[132]

5.5. Conclusion

In this chapter alternative designs of the ships transporting RHCs were evaluated, this was done to give an answer to the sub research question: *How can renewable hydrogen carriers be used as fuel in a direct or indirect propulsion system?*

To answer this question first the cargo and fuel storage of RHCs on the ship were evaluated. Secondly, the different prime movers which can be used in the powertrains were discussed. Thirdly, the various powertrain configurations were discussed. In which the efficiency of the powertrains were determined during the different ship operations. Furthermore, the emissions produced by the powertrain configurations were discussed. At last, additional systems were discussed which are needed in some of the powertrain configurations.

In the next chapter there will be an economic analysis on the new designs that were discussed in this chapter.

6

Economic Analysis

In this chapter the economic analysis of the model will be described. This will be done based on equation 6.1, in which OPEX, CAPEX, fuel cost, and emission cost will be considered in this analysis. In this economic analysis the cost per ton hydrogen will be calculated, as similarly done in the case analysis in chapter 3.4, however several adjustments are made, which are described in this chapter.

$$\text{Cost per ton hydrogen [€/ton]} = \frac{\text{CAPEX} + \text{OPEX} + \text{Total}_{\text{fuel,cost}} + \text{Total}_{\text{emission,cost}}}{\text{Mass}_{\text{delivered},\text{H}_2}} \tag{6.1}$$

6.1. CAPEX

The CAPEX calculations will be done done the same as in section 3.4.1. However the Present Value (PV), is different in this analysis and will be described by equation 6.2. Based on the original vessel, a two or a four stroke engine is used, this is shown in table 4.1. Based on the considered designs in the model, the old powertrain cost will be subtracted from the original vessel cost. After this additional cost will be added, basic on the specific design. In table 6.1 and 6.2 the economic parameters are shown which are used to determine the new present value.

$$\text{Present Value} = \text{New build cost (original vessel)} - \text{Original powertrain} + \text{New powertrain} \tag{6.2}$$

Mechanical components	Powertrain application	Price [€/kW]	Source
2 stroke ICE	ICE 2 stroke (mechanical powertrain)	400	[16]
4 stroke ICE	ICE 4 stroke (mechanical powertrain)	454	[16–21, 133]
Electrical components	Powertrain application	Price [€/kW]	Source
4 stroke ICE + generator	ICE electric	464	[16–21, 133]
Electric motor	All electric powertrains	154	[16, 17, 19]
Electrical system	ICE electric + optional Battery	320	[133, 134]
Electrical system	FC + optional Battery + optional ICE	587	[16, 19, 124]
Other components	Powertrain application	Price [€/kW]	Source
SCR	for NH_3 fueled ICEs	42	[17, 19]
Cracker	NH_3 to H_2 for ICE	45	[19]
Cracker	NH_3 to H_2 for PEMFC	575	[16, 17, 19]
Fuel handling system	MeOH,NH_3	57	[17, 135]
Fuel handling system	LNG,LH_2	178	[17]

Table 6.1: Economic analysis of the powertrain components with assumed lifetime of 25 years

	Period	System cost [€/kW]	# of replacements [-]	Total stack cost [€/kW]	Lifetime cost [€/kW]
PEM	2020-2045	1062	3	586	1649
	2025-2050	659	3	562	1220
	2030-2055	506	3	562	1067
	2035-2060	506	3	562	1067
	2040-2065	506	2	374	880
	2045-2070	506	2	374	880
SOFC	2020-2045	2,521	3	1,319	3,840
	2025-2050	1,890	2	772	2,661
	2030-2055	1,495	2	656	2,150
	2035-2060	1,275	2	591	1,866
	2040-2065	1,125	2	552	1,677
	2045-2070	1,063	2	538	1,601
Battery	2020-2045	-	2	-	952
	2025-2050	-	2	-	803
	2030-2055	-	2	-	653
	2035-2060	-	2	-	571
	2040-2065	-	1	-	363
	2045-2070	-	1	-	326

Table 6.2: Economic analysis of fuel cells and batteries[17, 19, 21, 25, 26, 29, 111–113]

6.2. OPEX

The OPEX will calculated in the same way as calculated in chapter 3.4.2, in which the calculations for the OPEX for the cases were made.

6.3. Fuel cost

The fuel cost will be calculated in the same way as calculated in chapter 2.2.14, in which the calculations for the fuel cost for the cases were made. However in this analysis also the other operations are considered.

$$\begin{aligned} &\text{Total}_{\text{fuel,cost}}\ [€] = \\ &\text{Cruising fuel consumption [GJ/hr]} \cdot \text{Total hours cruising [hrs]} \cdot \text{RHC cost [€/GJ]} \\ &+ \\ &\text{Fuel consumption idling [GJ/hr]} \cdot \text{Total hours idling [hrs]} \cdot \text{RHC cost [€/GJ]} \\ &+ \\ &\text{Fuel consumption loading [GJ/hr]} \cdot \text{Total hours loading [hrs]} \cdot \text{RHC cost [€/GJ]} \\ &+ \\ &\text{Fuel consumption discharging [GJ/hr]} \cdot \text{Total hours discharging [hrs]} \cdot \text{RHC cost [€/GJ]} \\ &+ \\ &\text{Fuel consumption manoeuvring [GJ/hr]} \cdot \text{Total hours manoeuvring [hrs]} \cdot \text{RHC cost [€/GJ]} \end{aligned} \tag{6.3}$$

6.4. Cost of GHG emissions

The total cost of GHG emissions will be described by equation 6.4. In which methane emissions will be translated to a CO_2 equivalent measure, which is explained in section 5.3.6.

$$\text{Total}_{\text{emission,cost}}\ [€] = CO_2 \text{ equivalent emissions } [tCO_2{-}eq] \cdot CO_2 \text{ equivalent tax [€/ton]} \tag{6.4}$$

7 Results

In this chapter the results of the research will be discussed. These will consists out of the following sections:

- An evaluation of the three cases in combination with three scenarios, which will be used to get more insight in the transportation of RHCs by ship.
- Transportation of LSNG compared to fossil LNG, to see how the usage of the RHC as fuel performs compared to the fossil based version.
- Fixing or increasing the cargo volume of the ship when additional storage space for fuel and powertrains is needed.
- An analysis of the OPEX of the vessel, which can vary between the different powertrain configurations.

Using the results of these sections will help answering the following research sub questions:

- *What is the influence of future regulations on the design of the ship and cost of transported hydrogen?*
- *How do voyage distance and the volume of ship transport, influence the cost of transported hydrogen?*
- *How do technologic developments influence the cost of transported hydrogen?*

7.1. Scenarios

To account for future regulations, three cases are evaluated for three scenarios, an unchanged scenario, a scenario which is following the trend, and a scenario which implements rigorous regulations. The cases are used to investigate, what the impact is, of the trip distance and the volume of the transport, on the cost of transported hydrogen. The scenarios are used to see the impact of future regulations on the design of the ship and to the cost of transported hydrogen for the different cases explained in chapter 3. The results are shown in appendix E, and a summary of the best options is shown in table 7.1.

- CO_2 equivalent tax: The introduction of emission taxes in shipping can have a significant impact on the fuel cost of ships. CO_2 and CH_4 emissions are considered for the CO_2 equivalent tax. Important to notice is, when using carbon neutral fuels such as LSNG or synthetic MeOH, it will be up to authorities to determine whether ship owners will have pay for the emissions. In this analysis, the emissions will need to be paid for. In the long term, the goal is to reduce absolute emissions from ships to zero, and stimulate zero emission fuels. This can be seen from the ambition of local harbours, explained in appendix C. A CO_2 equivalent price or GHG price can be a measure to enable this. Therefore, a CO_2 equivalent tax will be €0/tCO_2-eq in the "Unchanged" scenario, €50/tCO_2-eq in the "Following trend" scenario and €200/tCO_2-eq in the "Rigorous" scenario, based on appendix C.
- Zero emissions policies: The introduction of zero emission policies in the harbour can have effects on the design of ships. At first, this will be limited to shore power for inland vessels and cruise ships, but in the future it is expected that also other vessels, such as tankers can make use of shore power and

can be stimulated or forced to do so [136]. This will make developments for electric powered ships more attractive and can lead to zero emissions ships in the long term. In the "Unchanged" scenario no regulations are considered, the "Following trend" scenario will have a policy in which only electric ships are allowed to enter the harbour in the long term, and in the "Rigorous" scenario only zero emission vessels are allowed on the international waters in the long term, based on appendix C.

7.1.1. Scenario A "Unchanged"

In this scenario, the regulations will be active as they are now, in which no new regulations will be implemented. This means that there will not be a price on GHG emissions, and no regulations for zero emission harbouring. The best options for delivery of hydrogen by ship are mentioned below.

- Small scale short and long term: The most efficient option is to transport ammonia as cargo in a mechanical powertrain configuration with a two stroke ICE powered by ammonia. However, two stroke engines for small scale ammonia vessels are not likely to be installed, as can be seen in the reference ships made for the model in chapter 4. Therefore, transporting methanol as cargo in an electric powertrain with a SOFC and a battery powered by LSNG is most likely to be the best option to deliver hydrogen by ship. The CAPEX of methanol tankers is quite low, due to the relatively simple storage, and the efficiency of LSNG in a SOFC powertrain configuration is high.
- Mid scale short term: Transporting methanol as cargo in a mechanical powertrain configuration with a two stroke ICE powered by methanol. This is the best option, due to the low CAPEX of the methanol tankers, and the relatively high efficiency of two stroke engines.
- Mid scale long term: Best option is transporting methanol as cargo in an electric powertrain configuration with a SOFC and a battery powered by LSNG. Again, the methanol tankers have a low new build price. The technological developments in SOFCs and the high efficiency of LSNG in such systems, will cause this option to be best in the long term.
- Large scale in short and long term: Transporting NH_3 as cargo in a powertrain configuration with a two stroke ICE powered by NH_3. This is considered the best option, because of the relatively high efficiency of the powertrain and NH_3 has a low energy cost [€/GJ]

7.1.2. Scenario B "Following trend"

In scenario B, the regulations follow the trend over the last years. The price for GHG emissions will be €50/tCO_2-eq, and in the long term only electric ships will be allowed in the harbour. The best options for this scenario are summarized below:

- Small scale short term and long term: Transporting ammonia as cargo in an electric powertrain with a SOFC and a battery powered by ammonia has the lowest cost in delivering hydrogen by ship. For the small cases, the two stroke engines are not considered, as explained earlier (otherwise that would be the most competitive option). Using ammonia as RHC and fuel, is the better option compared to the previous scenario A, because of the introduced GHG taxation in this scenario.
- Mid and large scale short term: Transporting ammonia as cargo in a mechanical powertrain with a two stroke engine powered by ammonia, has the lowest cost in delivering hydrogen by ship. For the mid and large scale options, in contrast to the small scale option, the two stroke engine configuration is considered, that is why those the two stroke engine configuration is considered the best option.
- Mid scale long term: Best option is transporting MeOH as the RHC in an electric powertrain configuration with a SOFC and a battery powered by LSNG. The mechanical powertrain with the two stroke engine powered by ammonia is not allowed in the harbour in this scenario. Therefore, the option of transporting MeOH and using LSNG as fuel is the best option is this case, because of the low CAPEX of the methanol tanker and the high efficiency of the LSNG in the SOFC powertrain.
- Large scale long term: Best option is using LSNG in an electric powertrain configuration with a SOFC and a battery powered by LSNG. This is because the LSNG has a high hydrogen density, and although the CAPEX of the vessel is relatively high, it becomes competitive at larger volumes as can be seen also in the chapter 3. The consequence of this high hydrogen density is that the fuel consumption does not increase as steep compared to the other ships transporting RHCs. Furthermore, the efficiency of the LSNG in the SOFC is high.

7.1.3. Scenario C "Rigorous"

In scenario C, the most severe regulations will be active. The target is to have zero emissions vessels only in the long term, this process is stimulated by the fact that a GHG price of €200/tCO_2-eq will be active. In this scenario, ships need to be zero emissions vessels in the long term. The results are stated below:

- Small scale short term: Transporting ammonia as cargo in an electric powertrain with a SOFC and a battery powered by ammonia has the lowest cost in delivering hydrogen by ship. As earlier mentioned, the two stroke engine configuration is not considered in the short term, making the SOFC powertrain the better option of the delivery of hydrogen, like in scenario B.

- Mid and large scale short term: Transporting ammonia as cargo in a mechanical powertrain with a two stroke engine powered by ammonia has the lowest cost in delivering hydrogen by ship. This was also the result of scenario B, but the further stimulated by the increased GHG taxation.

- All options long term: Transporting ammonia as cargo in an electric powertrain with a SOFC and a battery powered by ammonia is considered the best option for the delivery of hydrogen. The regulations for zero emission vessels and the GHG taxation make this option the most attractive in the long term.

Scenario	Scale	Best option short term	Best option long term
"Unchanged"	small	MeOH - (Fuel: LSNG) - (SOFC+battery)	MeOH (Fuel: LSNG) - (SOFC+battery)
0 €/CO_2-eq	mid	MeOH (Fuel: MeOH) - ICE (2 stroke)	MeOH (Fuel: LSNG) - (SOFC+battery)
Long term: No regulations	large	NH_3 (Fuel:NH_3) - ICE (2 stroke)	NH_3 (Fuel: NH_3) - ICE (2 stroke)
"Following Trend"	small	NH_3 (Fuel:NH_3) - (SOFC + Battery)	NH_3 (Fuel: NH_3) - (SOFC + Battery)
50 €/CO_2-eq	mid	NH_3 (Fuel:NH_3) - ICE (2 stroke)	MeOH (Fuel: LSNG) - (SOFC+battery)
Long term: Electric harbouring policy	large	NH_3 (Fuel:NH_3) - ICE (2 stroke)	LSNG (Fuel: LSNG) - (SOFC + Battery)
"Rigorous"	small	NH_3 (Fuel:NH_3) - (SOFC + Battery)	NH_3 (Fuel: NH_3) - (SOFC + Battery)
200 €/CO_2-eq	mid	NH_3 (Fuel:NH_3) - ICE (2 stroke)	NH_3 (Fuel: NH_3) - (SOFC + Battery)
Long term: Zero emission policy	large	NH_3 (Fuel:NH_3) - ICE (2 stroke)	NH_3 (Fuel: NH_3) - (SOFC + Battery)

Table 7.1: Overview of the best options for the the transport of hydrogen by ship

7.2. Transportation of LSNG compared to fossil LNG

The model can be used to compare the usage of LSNG as fuel compared to fossil LNG. Therefore, two LNG "feeder" vessels are investigated. A 10,000 m^3 and a 30,000 m^3 vessel. LNG transport is often expressed in MMBtu (Million British thermal unit), which is an energy unit, and can be converted to GJ using equation 7.1.

$$1\,\text{MMBtu}\,(\text{Million British thermal unit}) = 1.055\,\text{GJ} \tag{7.1}$$

First, the small scale LNG transport will be analysed, in which a LNG "feeder" vessel of 10,000 m^3 transports LNG over a distance 1000 nautical miles (2000 nm for a round trip). The expected rate of this transported LNG is $2/MMBtu, which is $1.9/GJ using equation 7.1. Using an exchange rate of $1.11/€, this value is equivalent to a price of 1.7€/GJ. The price of fossil LNG is assumed to be 400 €/ton. The cost of the LSNG transport using fossil LNG as fuel calculated from the model is 1 €/GJ, which is relatively low compared to the expected 1.7 €/GJ. This can be explained by the fact that some costs are left out of the economic analysis such as the costs of port calls. Also, the low value of 1 €/GJ can be explained by the large amount of yearly trips that the model calculates, which are 39 trips. In reality, this amount of trips will be lower, which increases the price of transport cost in terms of [€/GJ]. The fuel price of the LSNG is taken from figure 2.4 and cost on average over the lifetime of the vessel 1780 €/ton. The usage of the own cargo as fuel (LSNG) can increase the cost of transporting LSNG from 1.0 €/GJ to 1.7 - 2.3 €/GJ, this would be a significant increase to the transportation price. The results are illustrated in figure 7.1.

Comparing the specifications to an existing vessel, it can be seen that the prime mover power is on the lower side. Coral Favia has a power of 7,000 kW, compared to the value of around 6,000kW shown in table 7.2. The size of the vessel does correspond correctly, 137 meter is also the LOA of the Coral Favia.

Carrier	Fuel	Propulsion Configuration	Powertrain	Total cost (Fuel cost) [M€]	Transported cost [€/GJ]	LOA [m]	Prime mover power [kW]	price of CO_2-eq avoidance [€/ton]
LSNG	LSNG	ICE (2 stroke)	Mechanic (direct)	320 (178)	1.7	137	5,046	245
LSNG	LSNG	ICE (4 stroke)	Mechanic (gears)	383 (240)	2.0	137	5,917	518
LSNG	LSNG	ICE (4s)	Electric	448 (296)	2.3	138	6,641	745
LSNG	LSNG	ICE (4s) + Battery	Electric	437 (285)	2.3	138	6,514	696
LSNG	LSNG	ICE (4s) + SOFC + Battery	Electric	351 (180)	1.8	137	5,140	316
LSNG	LSNG	ICE (4s) + SOFC	Electric	369 (196)	1.9	137	5,375	357
LSNG	LSNG	SOFC + Battery	Electric	317 (135)	1.7	140	4,476	225
LSNG	**LNG**	**ICE (4 stroke)**	**Mechanic (gears)**	**196 (53)**	**1.0**	**137**	**5,917**	**-**

Table 7.2: Results of a typical 10,000 m^3 LNG carrier transporting LSNG

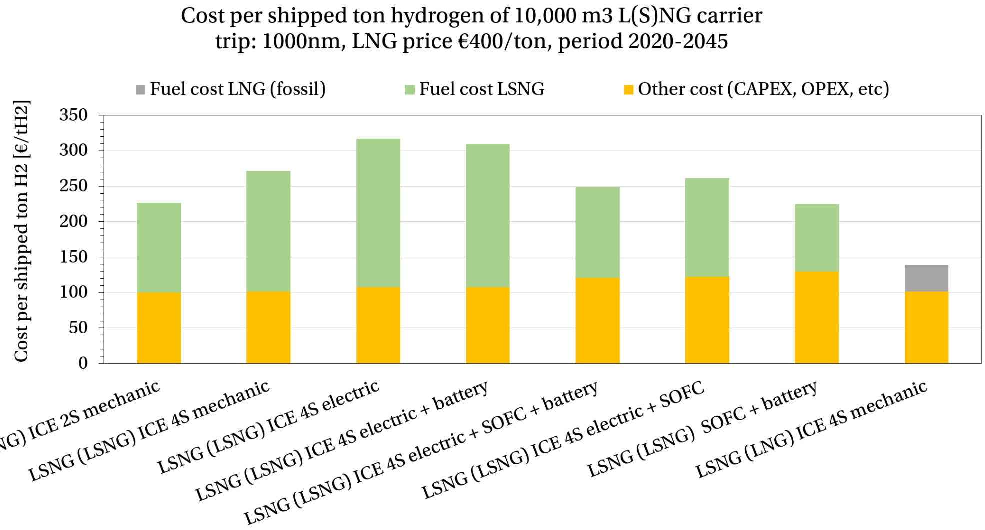

Figure 7.1: Cost of transported hydrogen per ship in a typical LNG 10,000 m^3 carrier operating between 2020 and 2045

The mid scale LNG carriers are in the range of 30,000 m^3. The expected price of transportation is around $1/MMBtu = $0.95/GJ = 0.85 €/GJ. For this mid scale transport a distance of 2000 nautical miles is used (4000 nm for a round trip). The value calculated by the model comes down to 0.8 €/GJ, which is comparable to the expected rate of 0.85 €/GJ. The usage of LSNG as fuel can increase these cost to 1.3 - 1.9 €/GJ, this would be again a significant increase to the transportation price.

Comparing the mid scale transportation with other vessels of Anthony Veder, it can be seen that the prime mover power is on the high side. Coral Encanto has a prime mover of 8,800 kW, compared to the value of around 9,390kW shown in table 7.3. The LOA of the vessel does corresponds with the length of this vessel.

Carrier	Fuel	Propulsion Configuration	Powertrain	Total cost (Fuel cost) [M€]	Transported cost [€/GJ]	LOA [m]	Prime mover power [kW]	price of CO_2-eq avoidance [€/ton]
LSNG	LSNG	ICE (2 stroke)	Mechanic (direct)	515 (302)	1.3	180	7,956	238
LSNG	LSNG	ICE (4 stroke)	Mechanic (gears)	631 (415)	1.6	181	9,390	518
LSNG	LSNG	ICE (4s)	Electric	762 (533)	1.9	181	10,713	801
LSNG	LSNG	ICE (4s) + Battery	Electric	743 (514)	1.9	181	10,512	748
LSNG	LSNG	ICE (4s) + SOFC + Battery	Electric	584 (325)	1.5	180	8,315	329
LSNG	LSNG	ICE (4s) + SOFC	Electric	515 (354)	1.6	181	8,690	371
LSNG	SNG	SOFC + Battery	Electric	306 (238)	1.3	181	7,131	216
SNG	**LNG**	**ICE (4 stroke)**	**Mechanic (gears)**	**12.3 (91)**	**0.8**	**181**	**9,390**	**-**

Table 7.3: Results of a typical 30,000 m^3 LNG carrier transporting LSNG

7.2.1. GHG avoidance

From the data generated by the model, the price for GHG avoidance can be calculated. The GHGs are expressed in the amount of tonnes of CO_2 equivalents that can be avoided. The CO_2 equivalent tonnes are calculated using the global warming potential of GWP_{100}. Using this, methane emissions can also be ex-

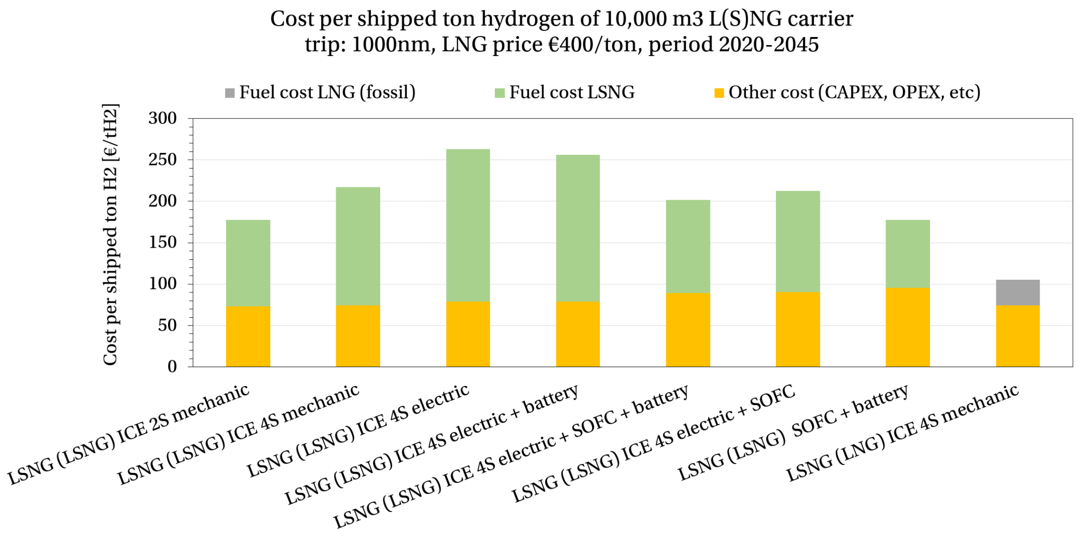

Figure 7.2: Cost of transported hydrogen per ship in a typical LNG 30,000 m^3 carrier operating between 2020 and 2045

pressed and related to carbon dioxide emissions. This is explained in 5.3.6.

When using the RHCs as fuel, GHG emissions can be prevented. The price of an avoided ton CO_2-equivalent gives an idea how much is needed to be paid to prevent GHG emissions. This can be used to determine which fuel and powertrain configuration is most economical to reduce the GHG emissions.

Tables 7.2 and 7.3 show that the 2 stroke ICE configuration and the SOFC + battery configuration reduce GHG emissions for the most economical price, between €210/tCO_2-eq and €250tCO_2-eq for the time period between 2020-2045. The current ETS prices of 20 - 30 €/tCO_2 are not high enough to make the use of LSNG a competitive option against the fossil alternative, LNG.

Figure 7.3, shows the LSNG carrier operating from 2045 to 2070. In this case the lifetime and cost of the SOFC technology have improved, and the cost of the RHC has decreased. In this period the cost of GHG avoidance is €172/tCO_2-eq. Which is still on the high side compared to the ETS prices of today.

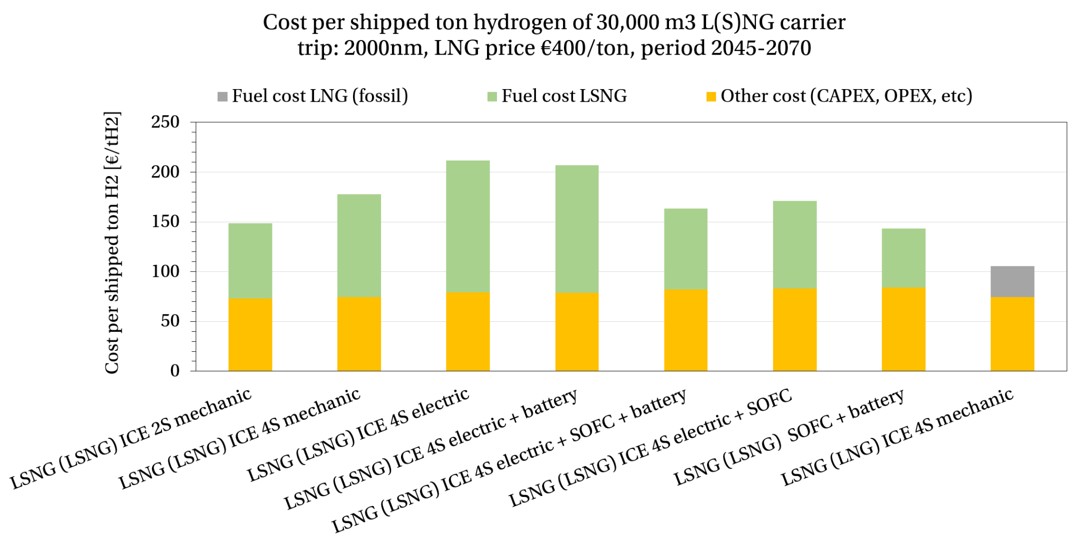

Figure 7.3: Cost of transported hydrogen per ship in a typical LNG 30,000 m^3 carrier operating between 2045 and 2070

7.3. Fixed or changing cargo volume

The model which is used in this research makes use of an iteration, to determine the new cargo volume of the vessel. This increase in volume is caused by the volume of fuel that is needed for a specific voyage, and the volume of the optionally new powertrain configuration. The iteration in the model is used to be able to compare the different ship designs based on the same amount of transported hydrogen.

Another way of comparing the performance of RHCs and using the carrier as fuel, is to fix the ship dimensions. By doing so, the volume of the fuel and the new powertrain are subtracted from the original cargo volume. This will result in a reduced amount of hydrogen that the ship can transport. This subtracted amount of volume will not be the same for every ship design. Meaning that there won't be an equal comparison, because the amount of transported hydrogen will not be the same for every ship design. The reason for this is that not all the fuels have the same energy density, and not all the powertrain configurations have the same power density. To see the difference between the two options (fixing or increasing the cargo volume of the ship) the following case has been analysed:

- A transported amount of 700 ton of hydrogen. The design of the ship will be based on this amount of hydrogen. Meaning that extra cargo space needed for the powertrain or te fuel will be subtracted from this amount, when fixing the cargo volume of the ship.
- Trip distance of 2000 nautical miles. This is the longest voyage distance in the model, and this will have the relatively largest effect on the amount of fuel that is needed for the voyage.

Figure 7.4 shows the average volume distribution of the different powertrains when increasing the cargo volume. For the LH_2 configuration with a 4 stroke engine and an electric powertrain configuration the largest increase of volume is needed, which is 1,770 m^3 (1,755 m^3 for fuel and 15 m^3 for the powertrain). Figure 7.5 shows the average volume distribution of the different powertrains when fixing the cargo volume of the ship. For the LH_2 configuration with a 4 stroke engine and an electric powertrain configuration, 1,588 m^3 will be subtracted from the original cargo volume (1575 m^3 for fuel and 13 m^3 for the powertrain).

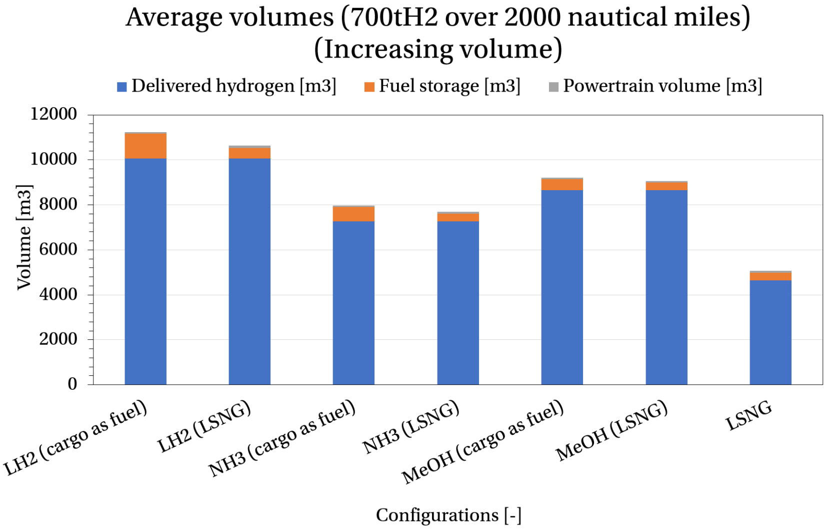

Figure 7.4: Average volume distribution of the different powertrain configurations for a trip over 2000 nautical miles with a design based on the transport of 700 ton hydrogen

The electric powertrain configuration with a 4 stroke engine powered by LH_2 and transporting LH_2, will have the largest influence on the added volume of the ship design. The results of the two different ways of approaching the model (adjusting or fixing the ship volume) are shown in figure 7.6, 7.7, 7.8, 7.9. When fixing the dimensions of the ship the cost of transported hydrogen become higher, but the total lifetime costs of the ship are lower. This result is expected, because the ship design is not increased in size, so the investment cost are lower. Furthermore, fixing the ship dimensions will reduce the amount of transported hydrogen, which results in the fact that less hydrogen can be transported per trip. For a small scale vessel, this reduced volume of shipped RHC significantly increases the cost of transported hydrogen.

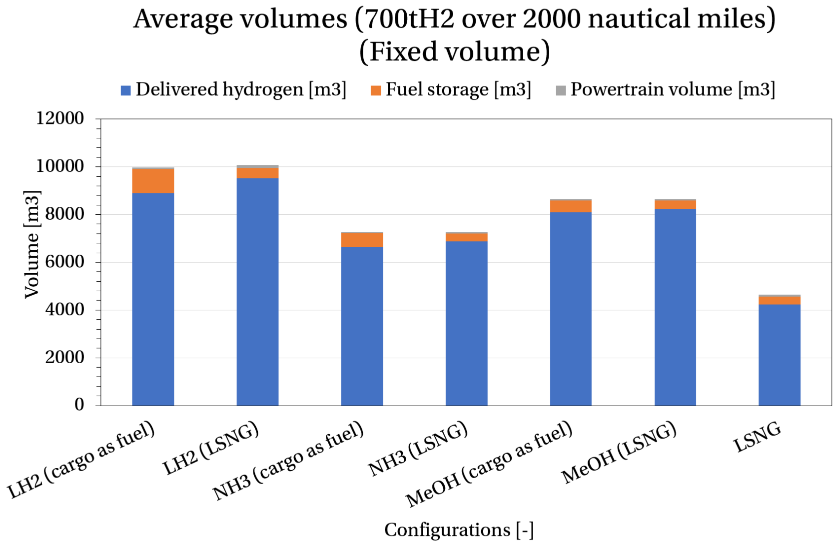

Figure 7.5: Average volume distribution of the different powertrain configurations for a trip over 2000 nautical miles with a design based on the transport of 700 ton hydrogen. This is for a fixed cargo volume

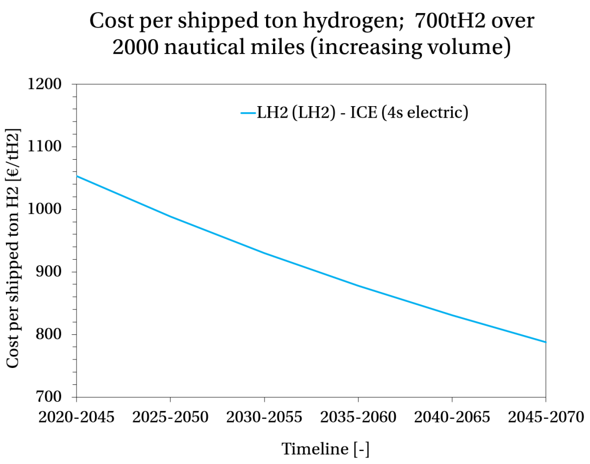

Figure 7.6: Cost per shipped ton hydrogen, when increasing ship size

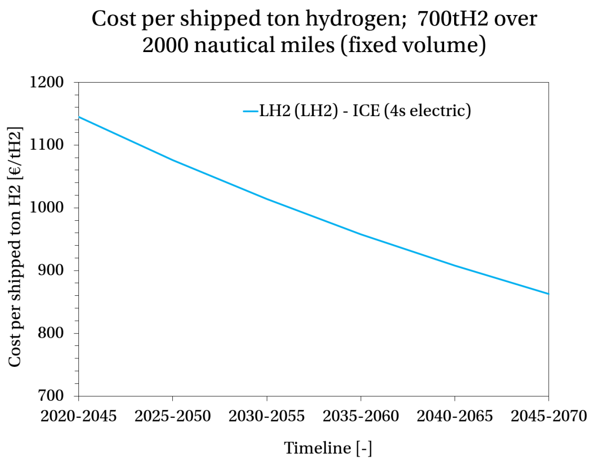

Figure 7.7: Cost per shipped ton hydrogen, when fixing the size of the ship

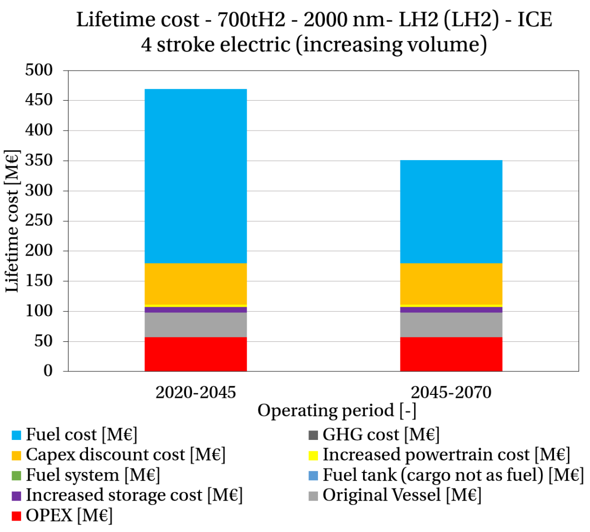

Figure 7.8: Total cost over lifetime, when increasing ship size

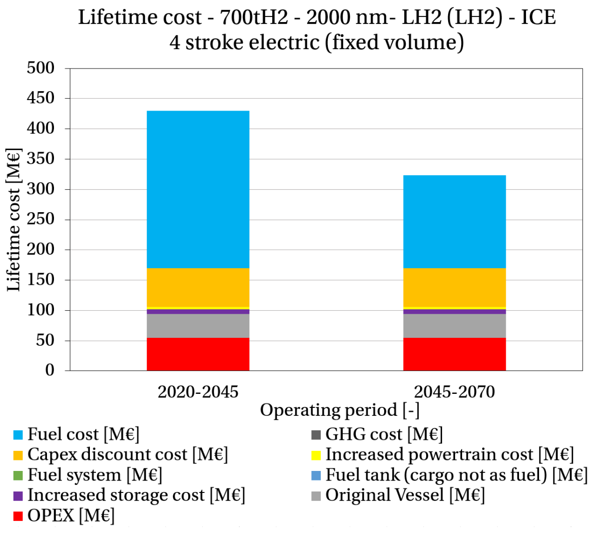

Figure 7.9: Total cost over lifetime, when fixing ship size

7.4. OPEX sensitivity

In this research the OPEX in the model are assumed to be constant for the specific transported RHC. However, fuel cells and batteries could change the OPEX. Powertrains with internal combustion engines are more complex and will need more maintenance actions during the lifetime of the vessel than fuel cell powertrains [137].

OPEX have a relatively large effect on the lifetime cost of small scale vessels. Therefore, the small scale cases will be analysed. For this specific analysis the methanol carriers are chosen, this is done, because the 2 stroke mechanical powertrain is considered more efficient than the SOFC + battery electric powertrain configuration as can be seen in figure 7.10.

The OPEX of the small scale methanol carrier is 52.5 M€ over lifetime. The OPEX in the model are the same for all small scale methanol carriers. Literature suggest the following about the OPEX related to ICEs and FCs:

- A SOFC powertrain consists of around 1000 parts, while the internal combustion engine powertrains can consist of over 4000 parts. Reducing the amount of parts from 4000 to 1000, is a drastic decrease of 75% of parts [137].

  - Analysing OPEX of chemical tankers, there are two categories within the OPEX that will change when switching from powertrain configuration [104], these are

    - ◇ Maintenance & Repair & Drydocking: this makes up 12.8% of OPEX. Maintenance and Repair cost could decrease due to fewer parts. Drydocking however will still be needed.
    - ◇ Stores & Spares & Lubricating oils: this is 21.5% of total OPEX. This will change to a lower extend, because stores, spares and lubricating oils will still be needed.

- Other research suggests that OPEX of a SOFC powertrain is 75% of the OPEX related to a mechanical powertrain with an ICE [17]

Based on these findings three OPEX scenarios are made:

1. No change in OPEX

2. Small change in OPEX: 75% reduction of the Maintance & Repair & Drydocking cost (6.7M€), which is a reduction of 5.0M€. New OPEX for SOFC powertrain is 47.5 M€.

3. Large change in OPEX, using the average of two sources, which results in an OPEX reduction of 13.3 M€, bringing OPEX to 39.2 M€. This is based on:

   - 25% reduction of total OPEX which is 39.4 M€[17].

   - 75% reduction of Maintance & Repair & Drydocking cost and a 75% reduction of Stores & Spares & Lubricating oils cost, based on the 75% reduction of parts. Reducing the costs by 75%, is a reduction of 13.5M€, which will result in an OPEX of 39.0 M€.

Lifetime cost (no OPEX change)

No change in OPEX will mean that the powertrain configuration with the two stroke combustion engine is the most efficient in the short and long term, as can be seen in figure 7.10.

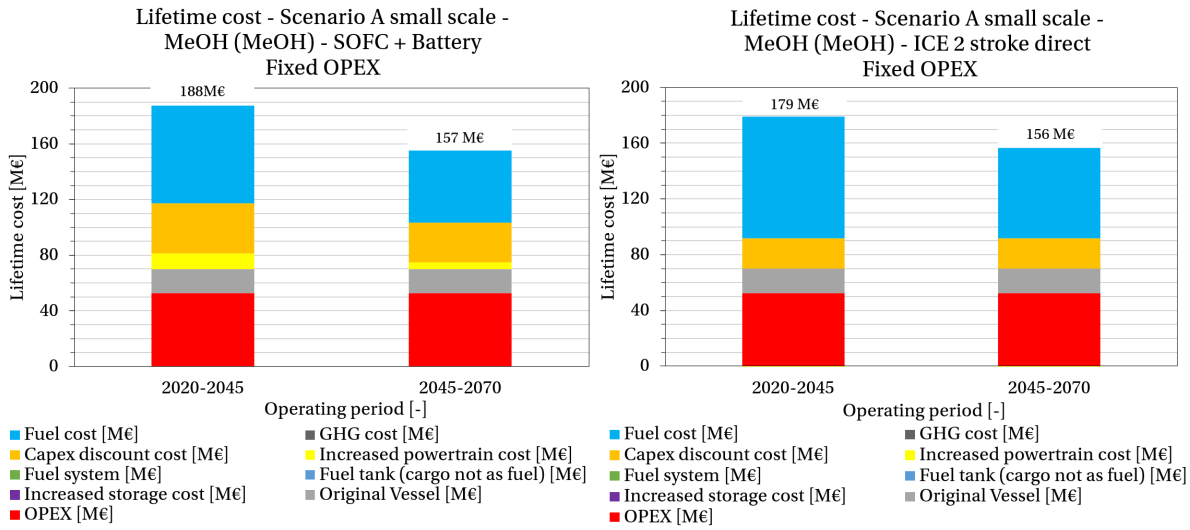

Figure 7.10: Total cost over lifetime, of two different powertrain configurations (left: SOFC + Battery, right: ICE 2 stroke) on a methanol carrier with a fixed OPEX

Lifetime cost (small OPEX change)

A small change in OPEX for the SOFC with battery powertrain configuration will result that in the long term this will be the more efficient option. Compared to the mechanical powertrain configuration with the two stroke engine, which can be seen in figure 7.11.

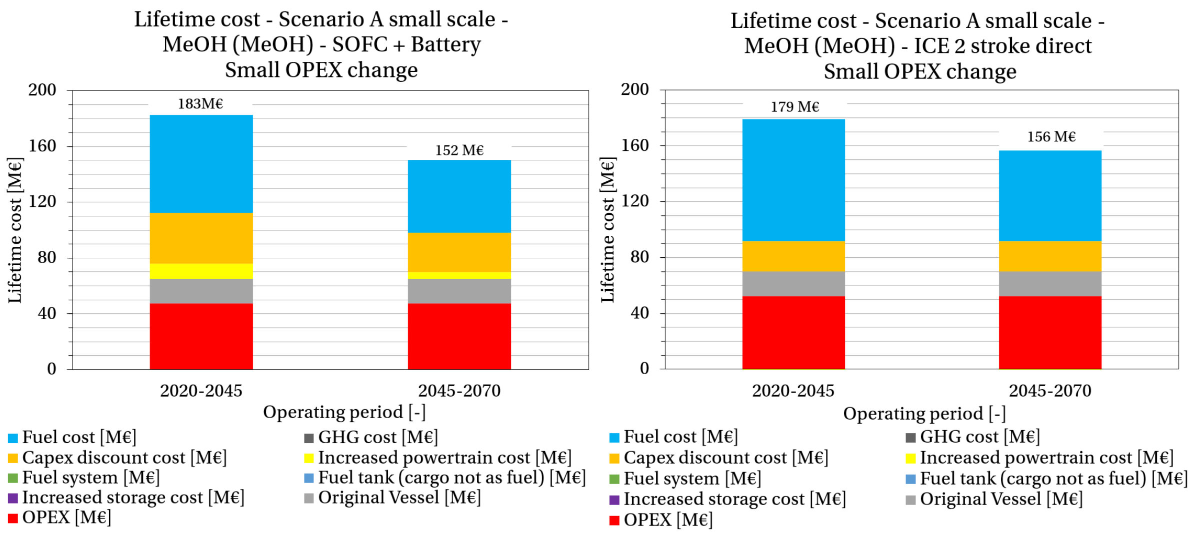

Figure 7.11: Total cost over lifetime, of two different powertrain configurations (left: SOFC + Battery, right: ICE 2 stroke) on a methanol carrier with a small reduction of OPEX for the SOFC + Battery powertrain

Lifetime cost (large OPEX change)

In figure 7.12, the lifetime cost of a methanol carriers using its own cargo as fuel are shown. On the left the lifetime cost are shown for a powertrain with an SOFC with a battery and on the left an two stroke ICE configuration. A large decrease in OPEX for the SOFC option will result that this option will be the more competitive option in the short and long term compared to the ICE powertrain option.

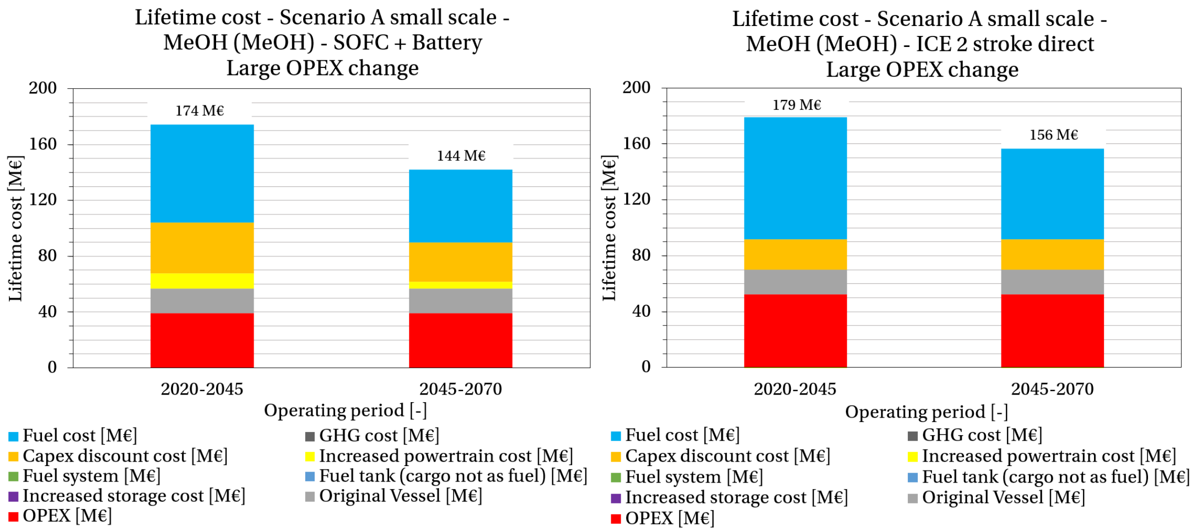

Figure 7.12: Total cost over lifetime, of two different powertrain configurations (left: SOFC + Battery, right: ICE 2 stroke) on a methanol carrier with a large reduction of OPEX for the SOFC + Battery powertrain

7.5. Conclusion

In this chapter the main objective was to get more insight in different factors which can influence the cost of transported hydrogen. To achieve this, first three scenarios were used to analyse the three cases. Secondly, the transportation of LSNG was analysed, to see the difference between using the RHC as fuel and using fossil LNG as fuel. In this comparison also the cost were calculated of the avoided GHGs. Thirdly, a closer look was taken at the effects of changing the volume of the ship or fixing it. At last, the OPEX of different powertrains were examined, to see how those can influence the cost of transported hydrogen.

First, the three scenarios are used to get insight in how the future regulations can affect the cost of transported hydrogen. The strict regulations with GHG taxation make ammonia the best option to deliver hydrogen when used as a fuel. In the same to mild regulations compared to today, the options are more divided. Methanol is due to its simple storage most suited for small scale transportation, in which CAPEX has a relatively high share in the total cost. LSNG as RHC is the best option in the large scale transportation cases in the "following trend" scenario, because of its high hydrogen density. This high density will result in relatively small vessels having a low fuel consumption compared to similar RHC transport options. At this moment, the most efficient powertrain option for most of the RHC transportation cases, is the two stroke mechanical engine. However, technological developments and the increasing regulations in shipping will make especially SOFCs in combination with a battery a promising option for the long term. This is because of the rising lifetime and the decreasing cost of the technology, and the fact that harbours could require electric or zero emission harbouring in the future.
Secondly, the usage of LSNG as fuel is compared to fossil LNG. The results show that the cost of using the RHC as a fuel is relatively high, and the cost of energy transportation (€/GJ) increases with more than 60%. The usage of the LSNG as fuel will reduce GHG emissions, but at a relatively high price of more than 150 €/tCO_2-equivalent.

Thirdly, increasing the transport volume of RHC ships will decrease the cost of transported hydrogen [€/tH_2], however it will increase the lifetime cost. Increasing the voyage distance, will also increase the ship dimensions, because more volume is needed to make the round trip. This extra volume will result in an increased price per ton hydrogen.

At last, the OPEX can vary between the different powertrain configurations, however this is not implemented in the model. This difference in OPEX between the various powertrain configurations can make a significant impact, as can be seen in section 7.4. This shows, for example, that it is worth investigating the OPEX of SOFC in combination with batteries, because it can result in a significant reduction of OPEX which can lead a more efficient transportation option for the RHC.

8 Conclusions

In this chapter, the conclusions of the report are explained and discussed. These are based on the results of the previous chapters. The conclusion will give an answer to the main and sub research questions. After the conclusions, a discussion of the results is presented, followed by the recommendations for future work.

8.1. Conclusion

The main research question of this thesis is: *What is the impact of shipping renewable hydrogen carriers, when using the carriers as fuel, on the ship design, the different power configurations, and the cost of transported hydrogen?* First, the sub research questions are answered to answer the main research question.

1. Which renewable hydrogen carriers are available and suitable for being shipped?

   MCH, H18-DBT, DME, NH_3, LH_2, LSNG, MeOH are considered suitable renewable hydrogen carriers to be shipped. This analysis is based on the storage specifications and the production efficiencies, which is explained in detail in chapter 2. Based on the results of the cases, in chapter 3, the most promising RHCs for shipping are NH_3, LH_2, LSNG and MeOH.

2. What is the most efficient way of storing renewable hydrogen carriers on ships?

   Although storing RHCs in the gaseous (compressed) state can in some cases be more efficient, it is expected that RHCs will be shipped in the liquid form, because of industry standards. This means that LSNG and LH_2 will be liquefied by refrigeration. NH_3 is liquefied by either refrigeration or compression, and methanol is liquid at atmospheric conditions.

3. How can renewable hydrogen carriers be used as fuel in a direct or indirect propulsion system?

   - LSNG and MeOH can be used directly in SOFCs and ICEs. The RHCs, LSNG and MeOH are not considered as a fuel to used in PEMFC directly or indirectly.
   - NH_3 can be used directly in SOFCs and can be combusted in an ICE indirectly. A small amount of NH_3 needs to be cracked to produce hydrogen, after which the remaining NH_3 can be combusted in the ICE. Similar is true for PEMFC, however, to use NH_3 in a PEMFC, all NH_3 needs to be cracked into hydrogen. Depending on which cracker is used, another purifier for the cracked hydrogen is needed.
   - H_2 can be used directly in SOFCs, PEMFCs and ICEs.
   - Batteries will be charged using SOFCs, PEMFCs or ICEs, depending on which power configuration is used.

4. How do voyage distance and the volume of ship transport, influence the cost of transported hydrogen?

Increasing the transport volume of RHC ships will decrease the cost of transported hydrogen [€/tH_2], however it will increase the lifetime cost. Increasing the voyage distance, will also increase the ship dimensions, because more volume is needed to make the round trip. This extra volume will result in an increased price per ton hydrogen. The increase in cost will be most significant for the transport of small volumes covering long distances.

The share of fuel costs in the total transportation cost, when using RHCs as fuel, will be higher than the current fossil fuel share in the total cost. This relatively high share of fuel expenses using RHCs will make efficient powertrains relatively more attractive because it enables higher fuel cost savings. The most attractive engine configurations are a two-stroke internal combustion engine with a mechanical powertrain and a SOFC with a battery in an electric powertrain. The mechanical powertrain option is considered best for mid to large scale transportation when electric harbouring is not needed. For mild to strict regulations, the electrical powertrain option with the SOFC in combination with a battery will be more attractive.

5. How do technologic developments influence the cost of transported hydrogen?

   PEMFCs, SOFCs, and batteries will increase in lifetime in the coming years, while the investment cost of the technologies will decrease. This development will reduce the number of replacements needed during the lifetime of the vessel, and the replacement costs itself are also lower. Although more research is needed, there are indications that the usage of fuel cells in the powertrain will lead to lower maintenance and repair (M & R) costs in OPEX, making the technology more promising.

6. What is the influence of future regulations on the design of the ship and cost of transported hydrogen?

   The scenarios discussed in chapter 7.1 give a presentation on the effects of the regulation on future shipping. In the model, short and long term options are evaluated for the same, mild and strict regulations compared to today. The following statements can be made, based on the results of the second model and its scenarios:

   - Ammonia is best suited to be used in a scenario with strict regulation compared to today. Ammonia has a non-carbon nature; therefore, it the most promising option in the long term.
   - Methanol is best suited for small scale transportation in the short and long term, in which the same regulations are active. The storage of methanol on board of the ship is relatively simple and it has a relatively high hydrogen density.
   - LSNG is best suited for large scale transportation in which there are mild regulations compared to today. LSNG has the highest hydrogen density of the discussed RHCs. The advantage of LSNG is that during the reconversion to hydrogen, extra hydrogen will be produced because of the added steam, during steam methane reforming (SMR).
   - Liquid hydrogen is from a shipping point of view not the most suited for the transport of hydrogen, due to its low volumetric density and complex storage. Shipping liquid hydrogen does have the advantage that it reduces extra conversion steps in other parts of the supply chain.

   Shipping RHCs and using the carrier as fuel will increase the total cost of transportation compared to using fossil fuels. However, the usage of RHC as fuel will result in a significant reduction of greenhouse gases (GHGs). Looking at the LNG supply chain, using RHCs as fuel, the cost of avoided GHGs in the short term can be 200-300 €/tCO_2 equivalent. In the future, this can drop below €200 €/tCO_2 equivalent, because of lower RHCs prices and improved technology. However this is still a relatively high cost of GHG avoidance.

To finalize, shipping RHCs and using the carriers as a fuel is an option which involves higher cost compared to current fossil fuel options. This relatively high share of fuel expenses using RHCs will make efficient powertrains relatively more attractive because it enables higher fuel cost savings. The most attractive engine configurations are a two-stroke internal combustion engine with a mechanical powertrain and a SOFC with a battery in an electric powertrain. The last option is especially promising for the long term, because of the technologic developments and increasing regulations in shipping. Overall the results indicate that shipping NH_3 and using the carrier as a fuel is the most promising option for the transport of RHCs by ship.

8.2. Discussion

In this section, the results of the research are discussed. This thesis is used to get insight in the future transportation of RHCs. The values of this thesis will give an indication, which is based on other literature, making their assumptions as well. Using this model, always up to date values should be used to give a clear representation.

Based on the scope of this thesis:

- This research is focussing on the ship transportation of RHCs and the energy needed for the reconversion of the RHC to hydrogen. However, the model does not focus on other parts of the supply chain. When setting up a specific RHC supply chain the different parts within the supply chain should be considered and not only the shipping part.
- The prices of the RHCs are based on assumptions for the electricity price, electrolyser cost, hydrogen prices, CO_2 prices and production cost prices. Setting up a supply chain of RHCs, specific parameters should be chosen to define the RHC price.
- The shipment of hydrogen using LOHCs has a relatively high cost. The main drawback of using MCH is the low hydrogen density and the fact that it needs to be shipped in chemical tankers. H18-DBT has a higher hydrogen density and can be stored in convectional oil and product tankers. However, the price of H18-DBT is still relatively high. Technological developments were not considered for the LOHCs, the current lifetime of a 1000 cycles can be improved and the price of both the LOHCs could decrease in the future, increasing the competitiveness of the LOHC.
- The RHCs need to be produced from the specific feedstock. When producing green hydrogen, large amounts of fresh water are needed. For the production of LSNG and methanol, CO_2 is needed, in which there is a significant cost difference in CO_2 taken from the air or from flue gases. Setting up a RHC supply chain, feedstock availability should be into taken account, because the production location can have a significant impact on this.
- The research focusses on single vessel transportation to investigate the impact on the design of the ships. For large supply chains in which more vessels are needed, more factors will play a role. This is briefly explained in chapter 3, in which a large supply chain will only need one LSNG vessel. However, for the same amount of transported hydrogen with another RHC, more than one vessel is needed, which results in a significant increase in cost of transportation. At this moment, the largest LPG and chemical tankers have smaller cargo volumes than LNG or crude oil tankers. This is based on fossil energy transportation, but these ship volumes can change when a market develops for the RHCs.

Based on the results of the model and the scenarios:

- The results of the model can be used to get an impression of how hydrogen efficiently can be shipped using various hydrogen carriers.
- Once a decision is made for a particular supply chain, for example, a liquid hydrogen supply chain. Then the model can be used to get an insight into the costs of ship transportation and what different powertrain options can impact the ship transportation.
- The transportation options are based on a fixed duration of time in the harbour, discharging, loading, manoeuvring and idling. The main share of the fuel cost are determined by the time spent cruising. For example, in the small case transportation, the amount of time spend during cruising was the lowest for all cases, in which 40% of the time spent was cruising. During this time the ship consumes around 90% of total fuel consumption. However, for the different transportation sizes these length of such operations can vary, and can thus influence the results of cost of transported hydrogen.
- The results of the scenarios are based on future regulations in which a GHG tax, and electric/zero emission harbouring can be active. However, the future scenarios are unknown, and more research should be done to investigate what the most likely timeline is for the future regulations. The scenarios used are based on literature and interviews, however these are only based on expectations and not on facts, therefore a these developments should be closely watched to see the effects on the transport of RHCs.

Based on the ship design:

- The storage of liquid hydrogen above 2,000 m^3 is yet to be designed for ship applications. In chapter 5.1.1, this is briefly explained, and technical issues need to be solved. Therefore, the cost of liquid hydrogen carriers is difficult to estimate, and thus the price of the LH_2 storage in this research is based on other literature. However, in future research liquid hydrogen storage can be further analysed. The costs can be estimated based on the higher requirements of the storage medium, such as the material and the insulation value. Using these kind of parameters a more in depth assessment can be made for determining the cost of liquid hydrogen storage on board of ships.

- The electric powertrain efficiencies are based on the average efficiency of the specific AC and DC powertrain configurations. However, designing a ship for a particular supply chain a specific decision should be made between the two systems, because one system can be more efficient for other loads, while the other system can be more efficient during cruising.

- The OPEX in the model is based on two things: the volume or mass of the RHC and the type of RHC. However, the different powertrain configurations will also have a significant effect on the OPEX. The number of parts in fuel cells and batteries are significantly lower than in combustion engines. In chapter 7.4, this is discussed briefly, but this should be further investigated.

- The emissions of CO_2, NO_x, CH_4 are based on values from the literature. Fuel cells and batteries have the advantage that these do not emit NO_x or CH_4, while these emissions can be a problem for ICEs. Technologic developments are considered in the form of cost reduction and lifetime improvement of fuel cells and batteries, but not for ICEs. Combustion engines are more developed than fuel cells and batteries, but there will also be improvements for ICEs. The improved technology can result in higher combustion efficiencies and less emissions in the form of CO_2, NO_x and CH_4 depending on the type of fuel used.

8.3. Future work

In this section, the recommendations for future work are presented related to shipping RHCs.

- The three scenarios in this thesis are, an "unchanged", a "following trend" and a "rigorous" scenario, with all specific regulations. A more detailed view of the impact of regulations can be achieved by using a Monte Carlo Simulation. In this type of simulation, all the possible regulations options are simulated. While in this thesis, the most obvious regulations are used for specific scenarios.

- Transport efficiency: In a future model, the transportation efficiency could be calculated. This can be done to see which of the transportation options is the most efficient, based on the amount of energy that is used during the shipping.

- Delivered commodity: The model in this thesis is based on a hydrogen demand; however, this hydrogen could be used for heat, electricity, feedstock or other industrial applications. Adjusting the model to a deliverable commodity could have other results. For example, if ammonia is the desired commodity, then it could be beneficial to produce ammonia at the production site before shipping it.

- Feedstock sources and prices: Varying the sources of feedstock helps to get a better understanding where the sensitives are within the model. At this point the CO_2 source is assumed to come from a point source, however when this is not available CO_2 could be captured from the air. Air capture involves higher energy cost and investment cost, and would change prices of MeOH and LSNG. Another example is the production of MeOH, which has lowest energy requirements for the synthesis (assuming CO_2 is already captured). Increasing energy prices, could mean that MeOH is a more competitive option compared to the other RHC. Sensitivities like these two, could be analysed to get a better understanding of the transport of RHC and using the carrier as fuel.

- Fuel usage: The fuel options for the ship transport are the RHC itself, as well as LSNG. This decision was made, because using LNG as fuel is considered an innovative option today. However, the usage of LH_2, NH_3, or MeOH can also be considered as fuel.

- Other emission taxation: In this research the emissions of CO_2 and CH_4 are used for GHG taxation. Other emissions can also be considered for future research, such as NO_x, black carbon, SO_x, and also other emissions such as noise.
- The model which is developed can be coupled to supply chain study of one the investigated RHCs: LSNG, MeOH, LH_2, or NH_3. This would give a better insight and a more accurate value in the shipping part of the total supply chain of the specific RHC. This could be done, for example for the supply chain study between Australia and Japan. In this supply chain, there are plans to upscale from small scale hydrogen transport to large scale, using a model like this could help optimizing the ship transport in this supply chain.
- Quality of the product: The delivered hydrogen from the various RHCs can have differences in purity, which affect the value of the hydrogen. Liquid hydrogen has very high purity, while hydrogen from LSNG produced by SMR will have a lower purity level, this could be taken into account in an improved model.
- GHG avoidance: If the main goal of transporting RHCs and using the carriers as fuel, is to reduce GHG emissions, other methods should be evaluated as well. These include fuel saving methods, such as speed reduction or air lubrication systems, or even carbon capture systems on board of the vessel.
- OPEX of different powertrain configurations: The number of parts in fuel cells and batteries are significantly less than in combustion engines. In chapter 7.4, this is discussed briefly. However, this should be further investigated to get a better understanding of OPEX and more specifically, (M&R) cost for different powertrain configurations.

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A

Energy carriers

A.1. Fossil based energy carriers

A.1.1. Grey Hydrogen

$$CH_4 + H_2O\,(+\,\textit{Heat}) \rightleftharpoons CO + 3\,H_2 \qquad \Delta H = 206\,\text{kJ/mol} \tag{A.1}$$

$$CO + H_2O \rightleftharpoons CO_2 + H_2\,(+\,\textit{Heat}) \qquad \Delta H = -41\,\text{kJ/mol} \tag{A.2}$$

Grey hydrogen, is produced by using fossil resources like coal and methane as can be seen in figure 2.3. Most conventional techniques of producing hydrogen include coal gasification and steam methane reforming (SMR). Other techniques like auto thermal reforming (ATR) and partial oxidation (POX) are less common, due to lower efficiencies. During SMR, methane and steam react in an endothermic reaction at high temperatures, in which synthesis gas (syngas) is formed shown by equation A.1. Once the syngas is formed the hydrogen is separated from the carbon monoxide, and in the next stage, additional hydrogen can be obtained through the water gas shift reaction (WGSR). Equation A.2 shows this reaction in which water is added to the carbon monoxide in a mildly exothermic reaction, after which hydrogen is separated from the CO_2 [138].

A.1.2. Blue Hydrogen

The production of blue hydrogen is similar to the production of grey hydrogen, in which fossil sources are used to produce the hydrogen. However, during the production of blue hydrogen, the CO_2 from the production is captured and stored or utilized, this capturing takes place during the WGSR, shown in equation A.2. However, in SMR, there is next to syngas production (equation A.1) also some additional CO_2 produced in the reforming step, therefore SMR is not the most suitable technology for blue hydrogen, because it is difficult to capture the CO_2 in the flue gases due to a high concentration of nitrogen[139]. ATR is better suited for producing blue hydrogen, because the operating pressure is higher compared to SMR, leading to a higher carbon conversion [140]. For both reforming technologies, blue hydrogen can be produced depending on which measures are taken. The hydrogen production through ATR is more suited for carbon capture and therefore the cost of CO_2 avoidance is the lower than SMR, which can be seen in table A.1.

	CO_2 capture [%]	Leveled cost H_2 [€/m^3]	CO_2 avoidance cost [€/kgCO_2]
SMR (without capture flue glass)	50 - 70	0.135 - 0.146	0.037 - 0.060
SMR (with capture from flue gas or H_2 as fuel)	85 - 90	0.154 - 0.165	0.049 - 0.070
ATR (NTNU)	> 90	0.143	0.048
ATR (Air Liquide)	88	-	-

Table A.1: Overview of different steam methane reforming techniques with techno-economic specifications [139–142]

A.1.3. Grey ammonia

Conventional grey ammonia is produced from grey hydrogen, which is mostly produced from gas, however oil and coal can also be used for this production, as earlier mentioned in section A.1.1. The grey hydrogen reacts with nitrogen to form ammonia described by equation 2.3. The nitrogen is taken from the air, and can be separated from the air by using multiple techniques such as pressure swing absorption (PSA) or cryogenic distillation. The production emissions of ammonia with the use of gas are much lower than for oil and coal. In table A.2 the average production emissions of ammonia can be seen. These emissions can be further reduced and state-of-the-art techniques for the production of grey ammonia will only emit 1.6 tons of CO_2 per ton NH_3 [143, 144].

A.1.4. Blue Ammonia

Blue ammonia has a similar production process to grey ammonia, with the important difference that (part of) the CO_2 is captured and stored, which is happening during the production of the hydrogen. The amount of CO_2 that is captured is only 65% of the total CO_2 emissions, this is based on current emissions of blue ammonia which are used in the industry [145].

	Gas [%]	Oil [%]	Coal [%]	GJ/t NH_3	t CO_2 eq/ t NH_3
Western Europe	100	x	x	35.0	2.34
North America	100	x	x	37.9	2.55
Russia and Central Europe	98.9	1.1	x	40.7	3.31
China and India	26.5	18.7	54.7	47.6	5.21
Rest of the world	100	x	x	36.4	2.45
World average	70.7	8.2	21	41.5	3.45

Table A.2: Fossil fuels used for the ammonia production worldwide and the greenhouse gas emissions [146, 147]

A.2. Biomass based energy carriers

Biomass can be divided into three categories; first generation, second generation, and third generation. These different type of generations give an indication how the biomass is produced. First generation biomass include food for humans and animals such as wheat, sugar, corn and potato which are used a lot for the production of bioethanol. Oil seed rape is also first generation biomass, which is mainly used for the production of biodiesel. Second generation include non food based products such as wood and organic waste. Third generation biomass is special engineered material such as algae [148].

Biomass is considered as green energy or carbon neutral, because by photosynthesis the CO_2 from the air is converted into biomass, meaning that all the carbon that is stored in crops, originates from CO_2 from the atmosphere. As can be seen in figure A.1, this biomass can be used for a number of products, such as biohydrogen, biomethane and biosyngas. All these products can be used to produce green hydrogen. The main problem with first generation biomass is that it uses potential food for humans and animals and thus creates a competition. Second and third generation biomass does not compete with humans, but it does needs land space to enable production. This means that large amounts of land are needed to produce enough biomass for our future energy demand. For example, to meet future shipping energy demands, 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 [149]. This indication for biomass is just for the shipping industry alone, and with an increasing population and increasing energy demand, it seems unrealistic that biomass will provide our sustainable future energy demand. Therefor, biomass will not be further evaluated in this research, however this does not mean that biomass won't be a part of our future energy demand. It is believed that this will be on a relatively small scale compared to the synthetically produced energy carriers.

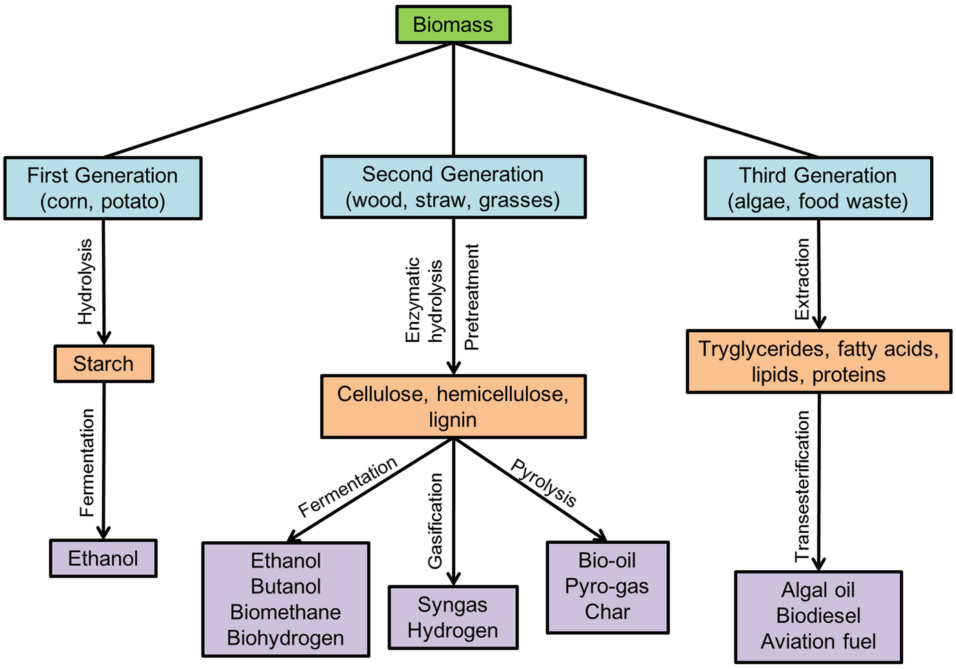

Figure A.1: Different generations of biomass production[150]

B

Current Fuels

The main fuels which are used in the shipping industry are the residual type of fuels, called marine fuel oil (MFO), or heavy fuel oil (HFO). Since the fuel types are residuals, the price per ton of the fuels is mostly cheaper than the price of crude oil. The low sulphur heavy fuels oil (LSHFO) and the ultra low sulphur fuel oil (ULSFO), which contain lower sulphur concentrations also belong to the group of residual fuels. The lower sulphur fuels are more expensive than HFO and MFO, since they need to be processed to get to the lower sulfur percentages. The distillate fuels include marine gas oil (MGO) and marine diesel oil (MDO), these are the 'cleaner' fuels, containing fewer contaminants like sulphur. The properties of the fuels can be found in table B.2. In 2015 the percentage of residual fuel usage was 72%, distillates came second with 26%. In third place with 2% of the total mass of all fuel used was LNG. In total 298 million tonnes of fuel were used in 2015 in the shipping industry. 88 percent of this fuel was consumed by international shipping, 8 percent by domestic shipping and 4 percent by the fishing industry [2].

	% of total	total consumption [Mton]
Residual fuels	72	215
Distillate fuels	26	77
LNG	2	6
Total	100	298

Table B.1: Fuel consumption by the global shipping fleet in 2015 [2]

Fuel type	Fuel category	Sulfur concentration [%m/m]	Viscocity [cSt] at 50 °C for residual fuels at 40 °C for distillate fuels
HFO / MFO	Residual	1,0 - 3,5	10-700
MDO	Distillate	0,1 - 1,5	2-11
MGO	Distillate	0,1 - 1,0	2-4
LSHFO	Not standardized	0,1 - 0,5	not found
ULSFO	Not standardized	<0,1	9-67

Table B.2: Properties of marine fuel [151]

C

Regulations

CO_2 reduction

The Energy Efficiency Design Index (EEDI) is a ship design parameter, which relates the CO_2 emissions of ships to the amount of transported goods over distance, for the specific vessels. New built ships need to comply with the EEDI, which is becoming more strict over time. With this tool, the IMO will be able to make ships more energy efficient in the future, the regulations are shown in figure C.1. It is one of three ambitions from the IMO MEPC Subcommittee the others being: the carbon intensity of international shipping to decline and the GHG emissions from international shipping to peak and decline[4]. CO_2 emissions are related to four aspects on the ship.

- The carbon dioxide directly attributable to the ship's propulsion machinery.
- The carbon dioxide arising from the auxiliary and hotel power loads of the ship.
- The reduction of carbon dioxide due to energy efficiency technologies. For example, heat recovery systems.
- The reduction of carbon dioxide due to the incorporation of innovative energy efficiency technologies in the design. Typically, these might include the introduction of sails or novel hydrodynamic devices.

$$EEDI = \frac{Engine\ power\ *\ Specific\ fuel\ consumption\ *\ Carbon\ factor}{Dead\ weight\ tonnage\ *\ Speed} \tag{C.1}$$

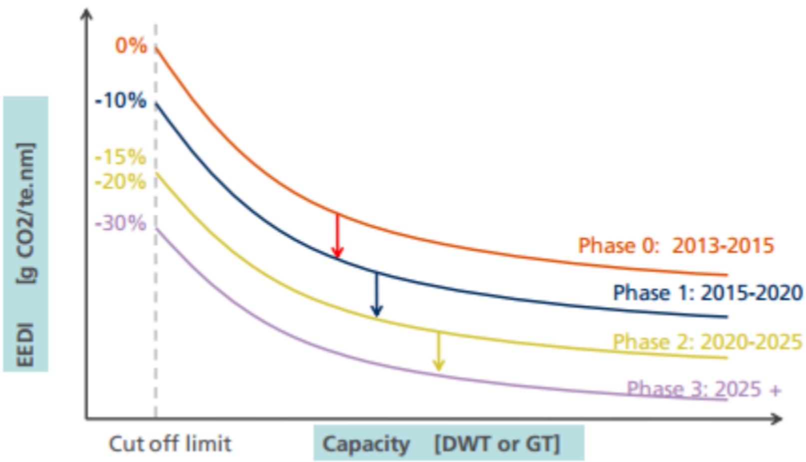

Figure C.1: The energy efficiency design index of the IMO[152]

A carbon tax, or a CO_2 equivalent tax could be a measure to force ship owners to reduce their GHG emissions. A CO_2 tax can be introduced, like the Europese Emissions Trading System (ETS). The ETS prices are expected to increase in the following years. In figure C.2, different CO_2 pricing scenarios are shown to reach the 2 degrees Celsius goal.

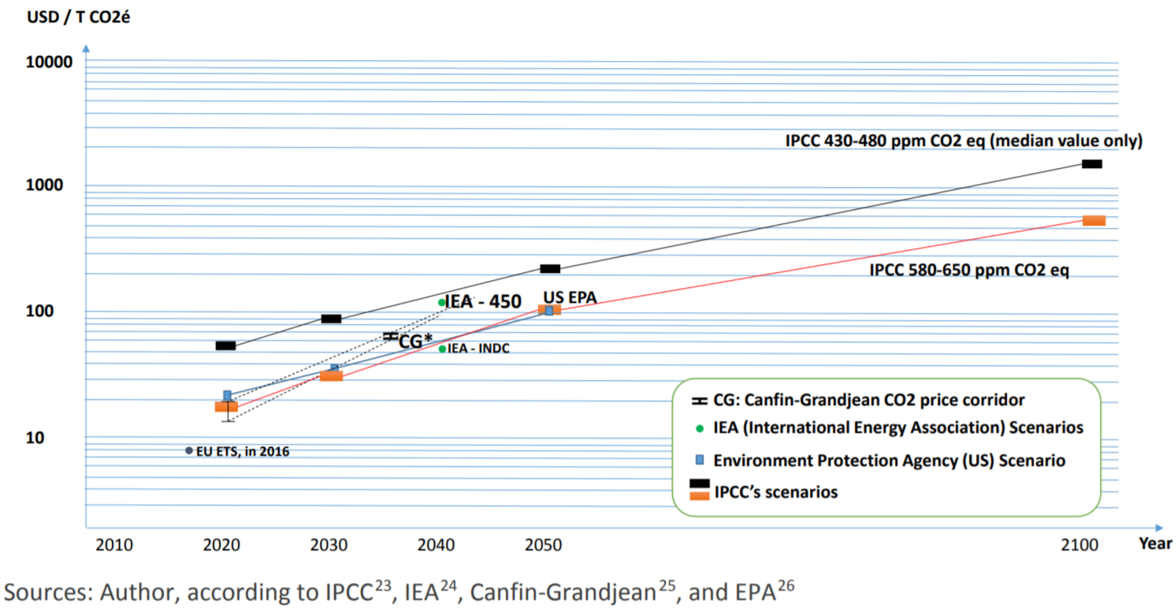

Figure C.2: Various CO_2 pricing scenarios to meet the 2 degrees Celsius goals in the Paris agreements[153]

NO_x & SO_x

In the international waters there are so-called emission control areas (ECAs). Those area's were initiated to control the emissions of SO_x, NO_x, Ozone-depleting substances (ODs) and Volatile Organic Compounds (VOCs). Existing areas include the North Sea, the Baltic Sea, North American and Caribbean coast. In those areas there is a maximum mass percentage of sulphur in the fuel of 0.1%, a control area for sulphur is also known as a SECA. Outside these SECAs the maximum amount, as of 2019, is 3.5%. However in 2020 there will be a global sulphur cap of 0.5%, China's coastal waters will have this cap already in 2019 [154]. From 2020 the areas of the Yangtze River and the Xijiang River will also be part of the SECAs. From 2022 the domestic area of Hainan Island will also be an SECA [155]. When higher percentages of sulphur is present in the fuel, the ships are obliged to make use of scrubbers which can remove sulphur from the exhaust gases.

NO_x control is currently divided into three Tiers as can be seen in table C.2. The most strict NO_x regulation, TIER III, is currently only applicable to the coastal areas of North America, but in 2021 these regulation will also be introduced for newly designed ships sailing in the ECAs in Europe. A control area for the maximum amount of emitted NO_x is also known as a NECA.

To reach those goals, shipowners will need to decide how they are going to comply with those rules. There are several options: shipowners can run on desulfurized fuels, distillate fuels, install a scrubber onboard or retrofit the vessel to run on other fuels, or invest in a totally new ship. There is not one best option available since the benefits highly depend on the kind of vessel, where it's sailing, and with what speeds etc. Therefore shipowners need to investigate what option is best. For instance, it is not allowed to have a scrubber onboard in the coastal area's of California (only for temporary research exemption), while in other ECAs this is allowed [154].

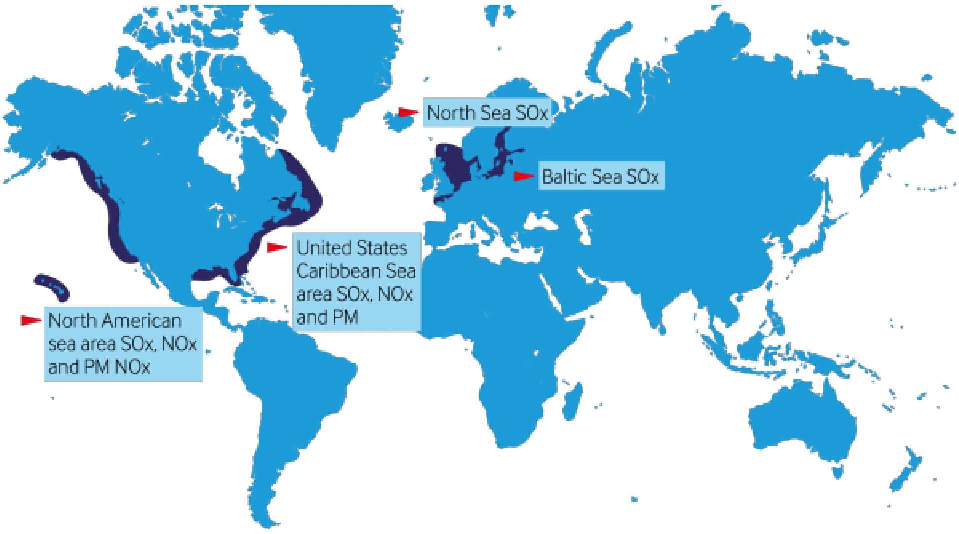

Figure C.3: The current ECAs in the world [156]

<table>
<tr><th rowspan="2">Date</th><th colspan="2">Sulfur Limit in Fuel [%m/m]</th></tr>
<tr><th>SO_x ECA</th><th>Global</th></tr>
<tr><td>2010</td><td>1.5</td><td rowspan="2">4.5</td></tr>
<tr><td>2010 (July)</td><td rowspan="2">1.0</td></tr>
<tr><td>2012</td><td rowspan="2">3.5</td></tr>
<tr><td>2015</td><td rowspan="2">0.1</td></tr>
<tr><td>2020</td><td>0.5</td></tr>
</table>

Table C.1: MARPOL Annex VI sulfur fuel limits [157]

The NO_x emission regulation applies to ships which have higher outputs than 130kW.

Tier	Year of construction (on or after)	NO_x Limit, g/kWh		
		n[rpm] <130	130 ≤ n[rpm] < 2000	n[rpm] ≥ 2000
Tier I	2000	17.0	$45 \cdot n^{-0.2}$	9.8
Tier II (outside ECAs)	2011	14.4	$44 \cdot n^{-0.23}$	7.7
Tier III (inside ECAs)	2016	3.4	$9 \cdot n^{-0.2}$	1.96

Table C.2: MARPOL Annex VI NOx Emission limits [157]

Methane regulations

Due to growing demand for LNG in the shipping industry, the amount of methane in the atmosphere could rise due to leakages during the production and slip during the combustion. If not handled correctly the high methane slip can cancel out the benefits of using LNG, which are that less CO_2, NO_x, SO_x and black carbon are produced. Methane slip can occur at numerous moments in the chain. To see where methane slip has most effect an distinction is made between the upstream, midstream and downstream emissions. Upstream and midstream are due to LNG leakages during the liquefaction, delivery and storage, as downstream emissions are caused by methane slip during incomplete combustion [158]. Currently there are no regulations for the emissions of methane.

Black Carbon

Black carbon (BC) is a part of overal particulate matter (PM) emissions. However, where PM reflects light and reduces the global warming effect, black carbon increases the greenhouse effect and absorbs light. Most accurate definition is from the report 'Bounding the role of black carbon in the climate system' by Bond et al.

[159], also recognized by the IMO:

1. It strongly absorbs visible light with a mass absorption cross section of at least 5 $\frac{m^2}{g}$ at a wave length of 550 nm.
2. It is refractory; that is, it retains its basic form at very high temperatures, with a vaporization temperature near 4000 K.
3. It is insoluble in water, in organic solvents including methanol and acetone, and in other components of atmospheric aerosol.
4. It exists as an aggregate of small carbon spherules

Black carbon has a significant impact on the greenhouse effect. These small black particles absorb sunlight, therefore trapping heat. The relatively short-term impact is due to the fact that these particles can be broken down by nature, and can be precipitated on the world's oceans and lands. However, due to growing transport across arctic oceans, black carbon also precipitates on ice. This has a dramatic effect since these particles fall down on the ice and form a layer of black carbon on the ice. Normally the ice reflects most of the sunlight and heat, but with this layer of black carbon particles the heat is absorbed making the ice melt faster. Less ice means that it becomes more attractive for ships to make a trip through arctic waters since distances are much shorter.

Zero emissions

Entering the port without producing any emissions may be one of the requirements of future entering vessels. Norway has announced that in 2026 the vessels entering the fjords cannot produce any harmful emissions, making the fjords the first zero emission zones at sea [160]. The port of Los Angeles want to achieve a zero emissions cargo handling system in 2030 [161]. The port of Rotterdam want to become a zero-emission port by 2050 [162]

Silent/Electric harbor

There are currently no regulations considering the amount of noise a ship can emit, other than the fact that no nuisance can be experienced in the harbor [163]. DNV GL annouced a new class notation called "QUIET", this is for airborne external noise from ships. Port authorities may use the information provided by the class notation in their planning work to ensure compliance with relevant noise regulations, and ship owners have the possibility to demonstrate a low noise emission level to lower their port fees or get access to the most attractive berthing locations in port [164].

D
Powertrain configuration

The powertrain configuration options are stated below, and are based on table 5.6, table6.1 , and table 6.2. In the first table D.1, the specific power distribution is shown, to determine the power share of specific systems. Table D.2, is a result of the previous table and shows the specific costs of the powertrain configurations at certain moments in time .

Powertrain Configuration						Power distribution [%kW]								Additional Systems	
Fuel	Prime mover	Extra	Battery	Mechanic / Direct	Gears/Direct	ICE (2 stroke)	ICE (4 stroke)	E. Generator	PEM system	SOFC system	PEM stack	SOFC stack	Battery	Cracker	SCR
LSNG	ICE	NO	NO	MECHANIC	DIRECT	100%	0%	0%	0%	0%	0%	0%	0%	NO	NO
LSNG	ICE	NO	NO	MECHANIC	GEARS	0%	100%	0%	0%	0%	0%	0%	0%	NO	NO
LSNG	ICE	NO	NO	ELECTRIC	NA	0%	0%	100%	0%	0%	0%	0%	0%	NO	NO
LSNG	ICE	NO	YES	ELECTRIC	NA	0%	0%	98%	0%	0%	0%	0%	2%	NO	NO
LSNG	ICE	SOFC	YES	ELECTRIC	NA	0%	0%	49%	0%	49%	0%	49%	2%	NO	NO
LSNG	ICE	SOFC	NO	ELECTRIC	NA	0%	0%	50%	0%	50%	0%	50%	0%	NO	NO
LSNG	SOFC	NO	YES	ELECTRIC	NA	0%	0%	0%	0%	91%	0%	91%	9%	NO	NO
LH_2	ICE	NO	NO	MECHANIC	DIRECT	100%	0%	0%	0%	0%	0%	0%	0%	NO	YES
LH_2	ICE	NO	NO	MECHANIC	GEARS	0%	100%	0%	0%	0%	0%	0%	0%	NO	YES
LH_2	ICE	NO	NO	ELECTRIC	NA	0%	0%	100%	0%	0%	0%	0%	0%	NO	YES
LH_2	ICE	NO	YES	ELECTRIC	NA	0%	0%	98%	0%	0%	0%	0%	2%	NO	YES
LH_2	ICE	PEM	YES	ELECTRIC	NA	0%	0%	49%	49%	0%	49%	0%	2%	NO	YES
LH_2	ICE	PEM	NO	ELECTRIC	NA	0%	0%	50%	50%	0%	50%	0%	0%	NO	YES
LH_2	ICE	SOFC	YES	ELECTRIC	NA	0%	0%	49%	0%	49%	0%	49%	2%	NO	YES
LH_2	ICE	SOFC	NO	ELECTRIC	NA	0%	0%	50%	0%	50%	0%	50%	0%	NO	YES
LH_2	SOFC	NO	YES	ELECTRIC	NA	0%	0%	0%	0%	91%	0%	91%	9%	NO	NO
LH_2	PEM	NO	YES	ELECTRIC	NA	0%	0%	0%	97%	0%	97%	0%	3%	NO	NO
NH_3	ICE	NO	NO	MECHANIC	DIRECT	100%	0%	0%	0%	0%	0%	0%	0%	ICE	YES
NH_3	ICE	NO	NO	MECHANIC	GEARS	0%	100%	0%	0%	0%	0%	0%	0%	ICE	YES
NH_3	ICE	NO	NO	ELECTRIC	NA	0%	0%	100%	0%	0%	0%	0%	0%	ICE	YES
NH_3	ICE	NO	YES	ELECTRIC	NA	0%	0%	98%	0%	0%	0%	0%	2%	ICE	YES
NH_3	ICE	PEM	YES	ELECTRIC	NA	0%	0%	49%	49%	0%	49%	0%	2%	PEM	YES
NH_3	ICE	PEM	NO	ELECTRIC	NA	0%	0%	50%	50%	0%	50%	0%	0%	PEM	YES
NH_3	ICE	SOFC	YES	ELECTRIC	NA	0%	0%	49%	0%	49%	0%	49%	2%	NO	YES
NH_3	ICE	SOFC	NO	ELECTRIC	NA	0%	0%	50%	0%	50%	0%	50%	0%	NO	YES
NH_3	SOFC	NO	YES	ELECTRIC	NA	0%	0%	0%	0%	91%	0%	91%	9%	NO	NO
NH_3	PEM	NO	YES	ELECTRIC	NA	0%	0%	0%	97%	0%	97%	0%	3%	PEM	NO
MEOH	ICE	NO	NO	MECHANIC	DIRECT	100%	0%	0%	0%	0%	0%	0%	0%	NO	YES
MEOH	ICE	NO	NO	MECHANIC	GEARS	0%	100%	0%	0%	0%	0%	0%	0%	NO	YES
MEOH	ICE	NO	NO	ELECTRIC	NA	0%	0%	100%	0%	0%	0%	0%	0%	NO	YES
MEOH	ICE	NO	YES	ELECTRIC	NA	0%	0%	98%	0%	0%	0%	0%	2%	NO	YES
MEOH	ICE	SOFC	YES	ELECTRIC	NA	0%	0%	49%	0%	49%	0%	49%	2%	NO	YES
MEOH	ICE	SOFC	NO	ELECTRIC	NA	0%	0%	50%	0%	50%	0%	50%	0%	NO	YES
MEOH	SOFC	NO	YES	ELECTRIC	NA	0%	0%	0%	0%	91%	0%	91%	9%	NO	NO

Table D.1: Powertrain configuration options with power distribution between the ICEs, FCs and batteries

Powertrain Configuration						Investment cost [€/kW]					
Fuel	Prime mover	Extra	Battery	Mechanic / Direct	Gears/Direct	2020	2025	2030	2035	2040	2045
LSNG	ICE	NO	NO	MECHANIC	DIRECT	400	400	400	400	400	400
LSNG	ICE	NO	NO	MECHANIC	GEARS	464	464	464	464	464	464
LSNG	ICE	NO	NO	ELECTRIC	NA	937	937	937	937	937	937
LSNG	ICE	NO	YES	ELECTRIC	NA	953	951	948	947	943	943
LSNG	ICE	SOFC	YES	ELECTRIC	NA	2873	2290	2037	1896	1799	1761
LSNG	ICE	SOFC	NO	ELECTRIC	NA	2893	2303	2048	1906	1811	1773
LSNG	SOFC	NO	YES	ELECTRIC	NA	4324	3236	2758	2492	2301	2229
LH_2	ICE	NO	NO	MECHANIC	DIRECT	442	442	442	442	442	442
LH_2	ICE	NO	NO	MECHANIC	GEARS	506	506	506	506	506	506
LH_2	ICE	NO	NO	ELECTRIC	NA	979	979	979	979	979	979
LH_2	ICE	NO	YES	ELECTRIC	NA	995	993	990	989	985	985
LH_2	ICE	PEM	YES	ELECTRIC	NA	1837	1624	1547	1545	1450	1449
LH_2	ICE	PEM	NO	ELECTRIC	NA	1839	1625	1548	1548	1455	1455
LH_2	ICE	SOFC	YES	ELECTRIC	NA	2915	2332	2079	1938	1841	1804
LH_2	ICE	SOFC	NO	ELECTRIC	NA	2935	2345	2090	1948	1853	1815
LH_2	SOFC	NO	YES	ELECTRIC	NA	4324	3236	2758	2492	2301	2229
LH_2	PEM	NO	YES	ELECTRIC	NA	2368	1949	1795	1793	1605	1604
NH_3	ICE	NO	NO	MECHANIC	DIRECT	487	487	487	487	487	487
NH_3	ICE	NO	NO	MECHANIC	GEARS	550	550	550	550	550	550
NH_3	ICE	NO	NO	ELECTRIC	NA	1024	1024	1024	1024	1024	1024
NH_3	ICE	NO	YES	ELECTRIC	NA	1040	1040	1040	1040	1040	1040
NH_3	ICE	PEM	YES	ELECTRIC	NA	2412	2199	2122	2120	2025	2024
NH_3	ICE	PEM	NO	ELECTRIC	NA	2414	2200	2123	2123	2030	2030
NH_3	ICE	SOFC	YES	ELECTRIC	NA	2915	2332	2079	1938	1841	1804
NH_3	ICE	SOFC	NO	ELECTRIC	NA	2935	2345	2090	1948	1853	1815
NH_3	SOFC	NO	YES	ELECTRIC	NA	4324	3236	2758	2492	2301	2229
NH_3	PEM	NO	YES	ELECTRIC	NA	2943	2524	2371	2368	2180	2179
MEOH	ICE	NO	NO	MECHANIC	DIRECT	442	442	442	442	442	442
MEOH	ICE	NO	NO	MECHANIC	GEARS	506	506	506	506	506	506
MEOH	ICE	NO	NO	ELECTRIC	NA	979	979	979	979	979	979
MEOH	ICE	NO	YES	ELECTRIC	NA	995	993	990	989	985	985
MEOH	ICE	SOFC	YES	ELECTRIC	NA	2915	2332	2079	1938	1841	1804
MEOH	ICE	SOFC	NO	ELECTRIC	NA	2935	2345	2090	1948	1853	1815
MEOH	SOFC	NO	YES	ELECTRIC	NA	4324	3236	2758	2492	2301	2229

Table D.2: Powertrain configuration options and the associated investment cost at specific moments

E

Scenarios & Cases

The different transportation options are shown in table E.1, with the associated RHC and the used fuel. These different options are analysed based on the three cases (small, mid and large scale transport) and the three scenarios ("unchanged" scenario A, "following trend" scenario B, and the "rigorous" scenario C). The plots show the top three performing RHCs in each of the time frames. The values in the legend are interpreted the following: the first value is the RHC that is transported, between the brackets is the fuel used and the next value is the specific powertrain.

Option	Carrier	Cargo as fuel	Fuel	Main propulsion	Additional Propulsion	Battery	Electric / Mechanic
1	LH2	YES	LH2	ICE	NO	NO	MECHANIC
2	LH2	YES	LH2	ICE	NO	NO	MECHANIC
3	LH2	YES	LH2	ICE	NO	NO	ELECTRIC
4	LH2	YES	LH2	ICE	NO	YES	ELECTRIC
5	LH2	YES	LH2	ICE	PEM	YES	ELECTRIC
6	LH2	YES	LH2	ICE	PEM	NO	ELECTRIC
7	LH2	YES	LH2	ICE	SOFC	YES	ELECTRIC
8	LH2	YES	LH2	ICE	SOFC	NO	ELECTRIC
9	LH2	YES	LH2	SOFC	NO	YES	ELECTRIC
10	LH2	YES	LH2	PEM	NO	YES	ELECTRIC
11	LH2	NO	LSNG	ICE	NO	NO	MECHANIC
12	LH2	NO	LSNG	ICE	NO	NO	MECHANIC
13	LH2	NO	LSNG	ICE	NO	NO	ELECTRIC
14	LH2	NO	LSNG	ICE	NO	YES	ELECTRIC
15	LH2	NO	LSNG	ICE	SOFC	YES	ELECTRIC
16	LH2	NO	LSNG	ICE	SOFC	NO	ELECTRIC
17	LH2	NO	LSNG	SOFC	NO	YES	ELECTRIC
18	NH3	YES	NH3	ICE	NO	NO	MECHANIC
19	NH3	YES	NH3	ICE	NO	NO	MECHANIC
20	NH3	YES	NH3	ICE	NO	NO	ELECTRIC
21	NH3	YES	NH3	ICE	NO	YES	ELECTRIC
22	NH3	YES	NH3	ICE	PEM	YES	ELECTRIC
23	NH3	YES	NH3	ICE	PEM	NO	ELECTRIC
24	NH3	YES	NH3	ICE	SOFC	YES	ELECTRIC
25	NH3	YES	NH3	ICE	SOFC	NO	ELECTRIC
26	NH3	YES	NH3	SOFC	NO	YES	ELECTRIC
27	NH3	YES	NH3	PEM	NO	YES	ELECTRIC
28	NH3	NO	LSNG	ICE	NO	NO	MECHANIC
29	NH3	NO	LSNG	ICE	NO	NO	MECHANIC
30	NH3	NO	LSNG	ICE	NO	NO	ELECTRIC
31	NH3	NO	LSNG	ICE	NO	YES	ELECTRIC
32	NH3	NO	LSNG	ICE	SOFC	YES	ELECTRIC
33	NH3	NO	LSNG	ICE	SOFC	NO	ELECTRIC
34	NH3	NO	LSNG	SOFC	NO	YES	ELECTRIC
35	MEOH	YES	MEOH	ICE	NO	NO	MECHANIC
36	MEOH	YES	MEOH	ICE	NO	NO	MECHANIC
37	MEOH	YES	MEOH	ICE	NO	NO	ELECTRIC
38	MEOH	YES	MEOH	ICE	NO	YES	ELECTRIC
39	MEOH	YES	MEOH	ICE	SOFC	YES	ELECTRIC
40	MEOH	YES	MEOH	ICE	SOFC	NO	ELECTRIC
41	MEOH	YES	MEOH	SOFC	NO	YES	ELECTRIC
42	MEOH	NO	LSNG	ICE	NO	NO	MECHANIC
43	MEOH	NO	LSNG	ICE	NO	NO	MECHANIC
44	MEOH	NO	LSNG	ICE	NO	NO	ELECTRIC
45	MEOH	NO	LSNG	ICE	NO	YES	ELECTRIC
46	MEOH	NO	LSNG	ICE	SOFC	YES	ELECTRIC
47	MEOH	NO	LSNG	ICE	SOFC	NO	ELECTRIC
48	MEOH	NO	LSNG	SOFC	NO	YES	ELECTRIC
49	LSNG	YES	LSNG	ICE	NO	NO	MECHANIC
50	LSNG	YES	LSNG	ICE	NO	NO	MECHANIC
51	LSNG	YES	LSNG	ICE	NO	NO	ELECTRIC
52	LSNG	YES	LSNG	ICE	NO	YES	ELECTRIC
53	LSNG	YES	LSNG	ICE	SOFC	YES	ELECTRIC
54	LSNG	YES	LSNG	ICE	SOFC	NO	ELECTRIC
55	LSNG	YES	LSNG	SOFC	NO	YES	ELECTRIC

Table E.1: Evaluated options of the transportation of RHCs

Scenario A small scale

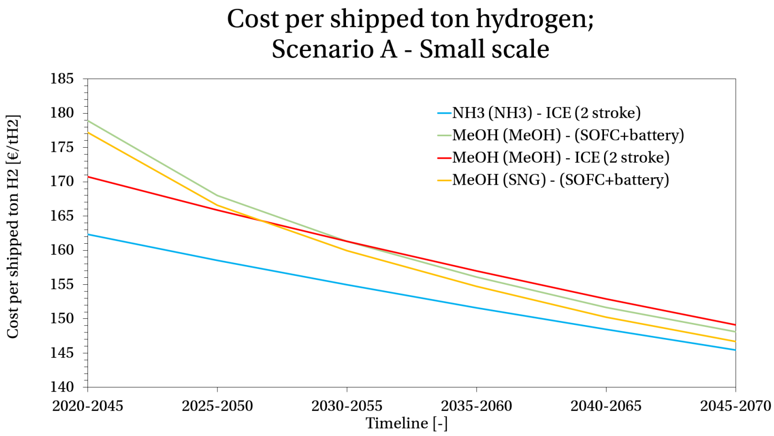

Figure E.1

Scenario A mid scale

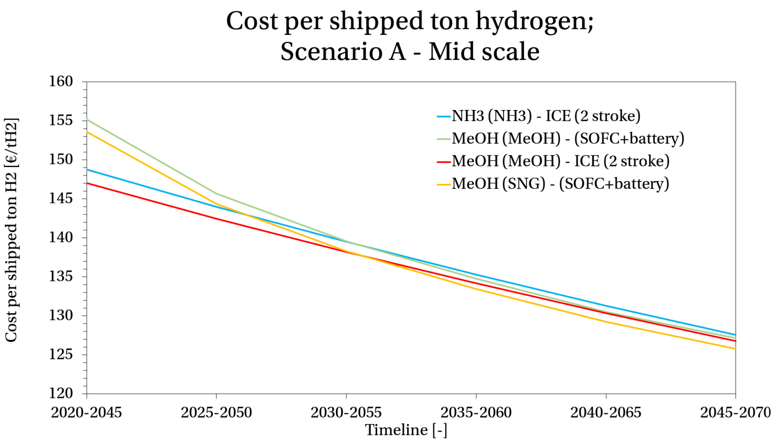

Figure E.2

Scenario A large scale

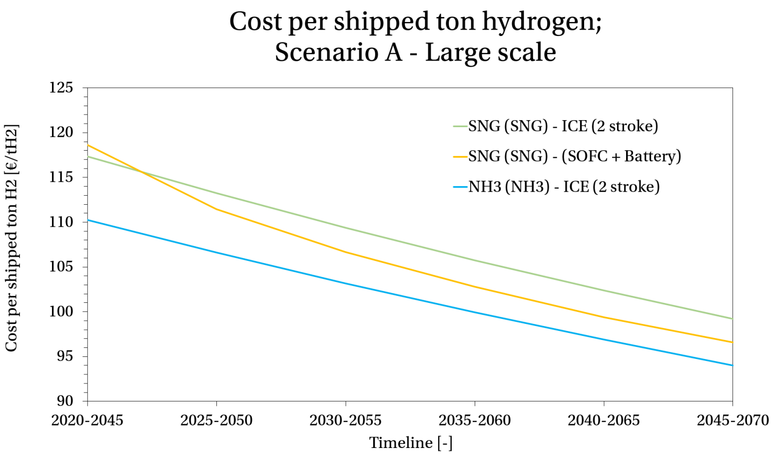

Figure E.3

Scenario B small scale

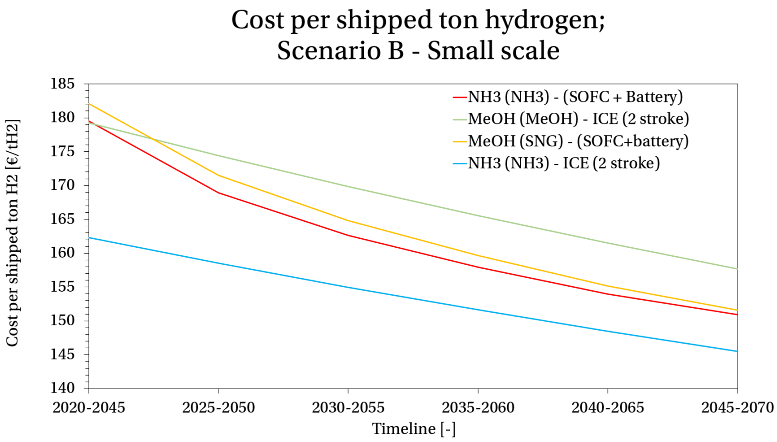

Figure E.4

Scenario B mid scale

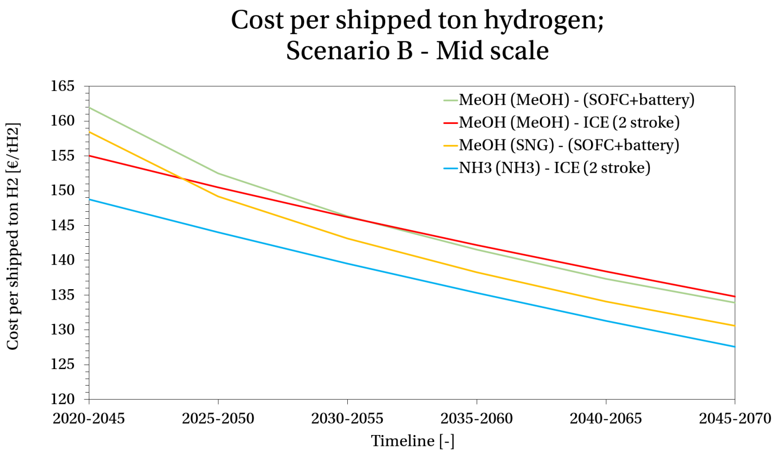

Figure E.5

Scenario B large scale

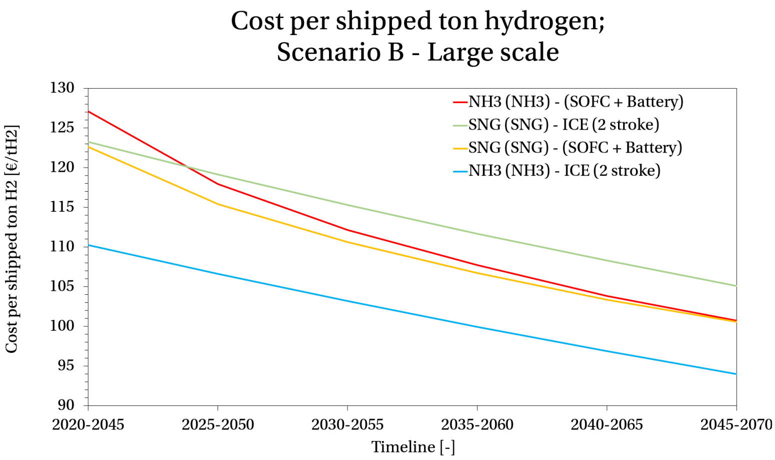

Figure E.6

Scenario C small scale

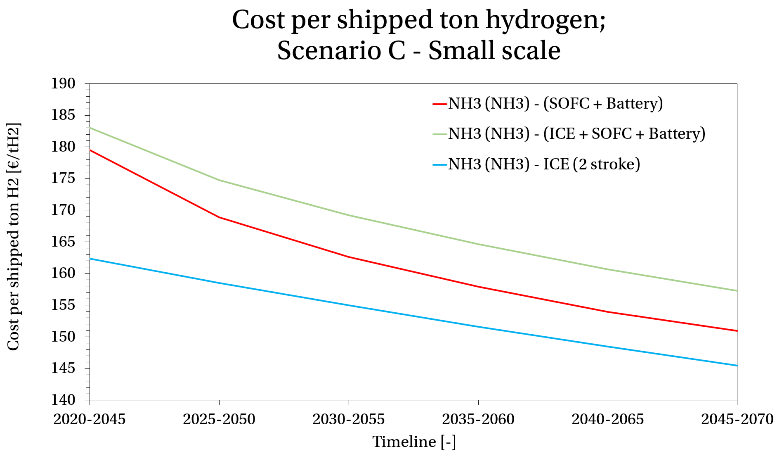

Figure E.7

Scenario C mid scale

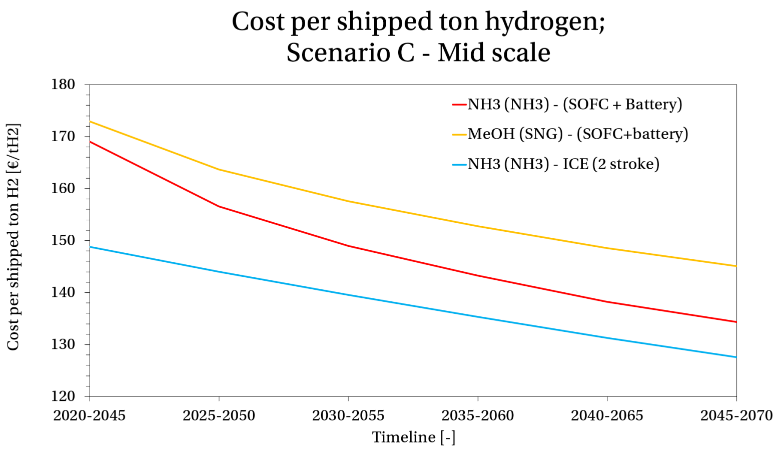

Figure E.8

Scenario C large scale

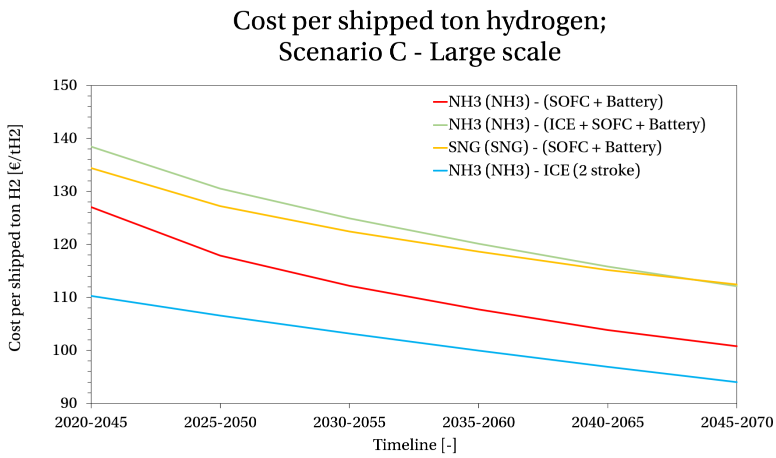

Figure E.9