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Conceptual Design of Ammonia-fueled Vessels for Deep-sea Shipping

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Conceptual Design of Ammonia-fueled Vessels for Deep-sea Shipping

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Project in Marine Systems Design

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“Conceptual Design of Ammonia-fueled Vessels for Deep-sea Shipping”

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Background

The pressure and regulatory urgency towards decarbonization of shipping is increasing and the subject is taking center stage. Ammonia pointed out by several studies as a possible option to lower fuel emissions for deep sea shipping. The energy density is low compared to the fossil alternatives, but higher than other low emission alternatives like batteries and compressed or liquified hydrogen. Ammonia is already shipped onboard vessels across the world which presents an opportunity to use the existing infrastructure as a steppingstone to place the first ammonia bunkering terminals. However, several challenges are present, with toxicity posing safety risks to onshore and offshore crew, as well as narrow flammability range compared to conventional fuels. The maturity of the technology for ammonia fuelled power is increasing, with notable increase in interest from governments and the industry. Reaching a commercial level regarding ammonia fuel production and ammonia fuelled power generation for propulsion is still far out, considering both cost and technical maturity.

The future is certain to present regulations regarding reduction of GHG emissions as presented by the IMO. As to what degree or in which form is uncertain which presents a considerable risk for many shipowners. To stay compliant, a vessel must be able to meet these regulations or risk losing contracts to vessels that do. Improving energy efficiency is a step in the right direction, however it is suggested that alternative carbon neutral fuels will be necessary to meet the strategy set by the IMO.

Main goals and focus area

This master thesis extends on a completed project thesis concerning the use of ammonia as primary fuel in deep sea shipping. The main goal is to investigate how using ammonia as fuel in deep sea shipping will affect the design of a vessel and how it affects the competitiveness for selected techno economic KPIs; cost and volume allocation, compared to conventionally fuelled vessels.

A literature review will present a base for the thesis and illuminate important aspects concerning the use of ammonia as fuel in deep sea shipping.

A conceptual design platform where variations of inputs are possible will make the increase the quality of communication of how the use of ammonia affects costs and vessel design. A case study will be made to illustrate the use of the conceptual design platform as well as what could be required in order to make ammonia able to compete on costs compared to conventional vessels.

Main Activities

The candidate should presumably cover the following main tasks:

1. *A literature review concerning ammonia as fuel in deep sea shipping.*
    a. *Describe key characteristics of ammonia as a fuel of special importance to vessel design.*

    b. *Describe fuel cell technology and internal combustion engine technology for ammonia and their design characteristics.*

    c. *Identify safety considerations and relevant regulatory status regarding the use of ammonia as fuel for deep sea shipping.*

2. *Develop a conceptual design platform for ammonia tankers.*

    a. *Use a ship design software to visualize conceptual design of ammonia fuelled vessels with different inputs.*

    b. *Emphasis on the systems affected by using ammonia as fuel.*

    c. *Select a combination of designs to illustrate alternatives for ammonia fuelled vessel designs.*

3. *Perform a case study concerning vessels using ammonia as fuel.*
    a. *Select an operational profile for the case study with relevance to the use of ammonia as fuel.*

    b. *Use a techno-economic approach to determine the technological end economic performance of the designs.*

Modus operandi

From NTNU, Professor Stein Ove Erikstad will be to supervisor, while Øyvind Endresen from DNV will co-supervise. The work will follow guidelines from NTNU.

Professor/Responsible Advisor

Abstract

The pressure and regulatory urgency to reduce greenhouse gas emissions from shipping are increasing and the subject is taking center stage. The path to decarbonization includes alternative fuel technologies using carbon-neutral fuels. A set of potential alternative fuels is identified and among them, ammonia ranks as one of the favorites much due to its favorable volumetric energy density compared to other carbon-neutral fuels. Deep-sea shipping is responsible for the majority of the emissions from shipping. To reduce emissions from this segment, it is essential to find feasible and cost-effective solutions.

One of the main activities in this thesis was to develop a conceptual design platform where a user can apply their business case and assumptions for the future and get a better understanding of how using ammonia as fuel will affect their business case. This will provide an important resource for communicating the potential for zero-carbon fuels like ammonia and a tool for an accelerated concept assessment.

This thesis firstly reviews relevant literature regarding the characteristics of ammonia and the current and potential regulations for using ammonia as fuel. Characteristics of the fuel and regulations will affect vessel design and it is, therefore, important to include this knowledge in the conceptual design platform. With emphasis on the toxicity of ammonia as this represents a potential safety challenge. Secondly, the methods used in the thesis are presented. Included are design methods, software tools, data sources and analysis methods. Thirdly, the development of the conceptual design platform is presented and the resulting conceptual design dashboard. Lastly, the conceptual design platform is applied to a case study to compare different designs for a specific business case before discussing and concluding.

The technological maturity of ammonia-fueled propulsion concepts depends on and evolves with some important prime movers. Current promising solutions include combustion engines and fuel cells. Combustion engines have a long history of development, suggesting that the cost and technology development are stagnating. Fuel cells on the other hand show a steeper development curve and already rank high in efficiency of the power system, though with higher investment cost. Internal combustion engines currently appear to be the most cost-effective alternative using ammonia as a fuel for deep-sea shipping based on the cumulative costs as shown in this thesis.

The conceptual design phase is chosen for this thesis as decisions made during this design phase are most significant, while the incurred expenditures are relatively low compared to other design stages. A conceptual design platform for ammonia tankers is developed to adapt the available information to the individual business case. The platform allows the user to input the dimensions for a baseline vessel and a simple operational profile that generates four different designs. The set of developed designs include of a baseline vessel which is heavy fuel oil (HFO) fueled with an internal combustion engine, and then three ammonia-fueled vessels. The first of the ammonia-fueled vessels has an internal combustion engine (ICE), the second has a proton exchange membrane fuel cell (PEMFC) and the third has a solid oxide fuel cell (SOFC) as power generation. The user is also able to input market values for fuel prices and carbon tax rates based on their assumptions regarding the future. The result is a dashboard where the user can compare and visualize different designs using ammonia as fuel based on their business case and future assumption. A selection of required safety measures is also possible to visualize.

The conceptual design platform was successfully tested in a case study where the different designs were compared for one operational profile with three combinations of market values for ammonia price, HFO price and CO_2 tax rate to determine for which scenarios the different ammonia-fueled designs can be able to compete with conventional fueled shipping. The results show that the ammonia-fueled designs generally have higher voyage expenditures than the HFO design which is due to the fuel costs. The results are therefore sensitive to the fuel price assumption of both ammonia and HFO, a low ammonia price and high HFO price contributes to closing the cost gap between the HFO design and the ammonia designs. The market values of HFO and ammonia have historically been varying and predicting their future prices is hence connected with uncertainty.

The results show potential for ammonia-fueled technologies in deep-sea shipping for certain market scenarios where fuel price and/or carbon pricing are important factors. Introducing carbon pricing can be an important incentive to accelerate the decarbonization of shipping and the uptake of carbon-neutral fuels like ammonia. For scenarios introducing carbon pricing, the ammonia-fueled designs were closer to the costs of the HFO fueled vessel for a somewhat ambitious scenario and outperforming the HFO design for an ambitious scenario. The results also show the importance of volume allocation for ammonia-fueled vessels as lost income due to lost volume can be a significant amount.

The case study results also show that there are large differences between the total volumes for the energy converter and fuel tanks between the design alternatives. The SOFC energy converter and fuel tank volumes are almost three times as large as the HFO fueled design due to the increased energy converter system volume. The ammonia-fueled ICE and the PEMFC has about twice the volume as the HFO fueled design which is primarily due to the fuel tank volume. This leads to lost income which is calculated as an expense.

The conceptual design platform is a useful tool to communicate the challenges and potential for ammonia as fuel. It would be desirable to expand the platform to include other ship segments as well as other fuel technologies and efficiency-increasing technologies. Including emissions like NO_x, SO_x and PM will further improve the platform as the users will have more information to assist their decision-making process. The resulting conceptual design platform would then give a more holistic impression of the design alternatives for a user business case or study and a more profound ground for solid decisions.

Sammendrag

Nødvendigheten for å redusere klimagassutslipp og behovet for nye reguleringer for karbon nøytral skipsfart øker, og temaet er stadig i fokus. Veien til dekarbonisering inkluderer alternative drivstoffteknologier som bruker karbonnøytralt drivstoff. Et sett med potensielle alternative drivstoff er identifisert, og blant dem er ammoniakk rangert blant favorittene mye på grunn av sin gunstige volumetriske energitetthet sammenlignet med andre karbonnøytrale drivstoff. Langdistanseskipsfart er ansvarlig for størstedelen av utslippene fra skipsfart. For å redusere utslipp fra dette skipsegmentet er det viktig å finne gjennomførbare og kostnadseffektive løsninger.

En av hovedaktivitetene i denne oppgaven var å utvikle en konseptuell designplattform der en bruker kan anvende sin business case og antagelser for fremtiden og få en bedre forståelse av hvordan bruk av ammoniakk som drivstoff vil påvirke deres business case. Dette vil være en viktig ressurs for å kommunisere potensialet for karbonfrie drivstoff som ammoniakk og et verktøy for en akselerert konseptvurdering.

Denne masteroppgaven gjennomgår først relevant litteratur om egenskapene til ammoniakk og gjeldende og potensielle regler for bruk av ammoniakk som drivstoff. Egenskaper ved drivstoffet og regelverk vil påvirke fartøyets design, og det er derfor viktig å inkludere denne kunnskapen i den konseptuelle designplattformen. Spesielt toksisiteten til ammoniakk gir en sikkerhetsutfordring. Deretter presenteres metodene som brukes i oppgaven. Inkludert her er designmetoder, programvareverktøy, datakilder og analysemetoder. Så presenteres utviklingen av den konseptuelle designplattformen og det resulterende dashbordet for konseptuell design. Til slutt blir den konseptuelle designplattformen brukt for en casestudie for å sammenligne forskjellige design for en bestemt business case før resultatene blir diskutert og konkludert.

Den teknologiske modenheten til ammoniakkdrevne fremdriftskonsepter avhenger av og utvikler seg ved hjelp av noen viktige drivkrefter. Nåværende lovende løsninger inkluderer forbrenningsmotorer og brenselceller. Forbrenningsmotorer har en lang historie med utvikling, noe som tyder på at kostnadene og teknologiutviklingen stagnerer. Brenselceller viser derimot en brattere utviklingskurve og har allerede høy virkningsgrad, men med høyere investeringskostnader. Forbrenningsmotorer ser for tiden ut til å være det mest kostnadseffektive alternativet som bruker ammoniakk som drivstoff for langdistanseskipsfart basert på kumulative kostnader i henhold til resultatene i denne oppgaven.

Den konseptuelle designfasen er valgt å fokusere på ettersom beslutningene som tas i løpet av denne designfasen er av stor betydning, mens de påløpte utgiftene er relativt lave sammenlignet med andre designfaser. En konseptuell designplattform for ammoniakk-tankskip er utviklet for å tilpasse tilgjengelig informasjon til den enkelte businesscase. Plattformen lar brukeren legge inn dimensjonene for et basefartøy og en enkel driftsprofil som genererer fire forskjellige design. Settet med utviklede design består av et basefartøy som er tungolje (HFO)-drevet med forbrenningsmo-

tor, og deretter tre ammoniakkdrevne fartøy. Den første av de ammoniakkdrevene har en forbrenningsmotor (ICE), den andre har en protonutvekslingsmembranbrenselcelle (PEMFC) og den tredje har en solid oksidbrenselcelle (SOFC). Brukeren kan også legge inn forskjellige markedsverdier basert på deres antakelser om fremtiden. Resultatet er et dashbord der brukeren kan sammenligne og visualisere forskjellige design med ammoniakk som drivstoff basert på deres business case og fremtidige antakelser om drivstoffpriser og karbonprising. Et utvalg av nødvendige sikkerhetstiltak er også mulig å visualisere.

Den konseptuelle designplattformen ble testet med suksess i en casestudie der de forskjellige designene ble sammenlignet for en operasjonsprofil med tre kombinasjoner av markedsverdier for ammoniakkpris, HFO-pris og CO_2-skattesats for å bestemme hvilke scenarier de forskjellige ammoniakkdrevne designene kunne konkurrere med konvensjonell skipsfart. Resultatene viser at ammoniakkdrevne design generelt har høyere reiseutgifter enn HFO-design som skyldes drivstoffkostnadene. Resultatene er derfor følsomme for antagelsen om drivstoffpris for både ammoniakk og HFO, en lav ammoniakkpris og høy HFO-pris bidrar til å lukke kostnadsgapet mellom HFO-designet og ammoniakkdesignet. Markedsverdiene for HFO og ammoniakk har historisk vært varierende, og forutsi deres fremtidige priser henger dermed sammen med usikkerhet.

Denne oppgaven viser et potensial for ammoniakkdrevet teknologi i havfart for visse markedsscenarier der drivstoffpris og/eller karbonprising er viktige faktorer. Å innføre karbonprising kan være et viktig insentiv for å akselerere dekarbonisering av skipsfarten og opptaket av karbonnøytralt drivstoff som ammoniakk. For scenarier som introduserte karbonprising, var de ammoniakkdrevne designene nærmere kostnadene for det HFO-drevne fartøyet for et noe ambisiøst scenario og bedre enn HFO-designet for et ambisiøst scenario. Resultatene viser også viktigheten av volumallokering for ammoniakkdrevne skip, da tapte inntekter på grunn av tapte volum kan være et betydelig beløp.

Casestudieresultatene viser også at det er store forskjeller mellom de totale volumene for energiomformeren og drivstofftankene mellom designalternativene. SOFC-brenselcellen og drivstofftankvolumene er nesten tre ganger så store som HFO-drevet design, mye på grunn av det økte volumet til energiomformersystemet. Forbrenningsmotoren med ammoniakk, og PEMFC har omtrent dobbelt så mye volum som HFO-drevet design, som hovedsakelig skyldes drivstofftankvolumet. Dette fører til tapt inntekt som blir beregnet som en kostnad.

Den konseptuelle designplattformen er et nyttig verktøy for å kommunisere utfordringene og potensialet for ammoniakk som drivstoff. Det ville være ønskelig å utvide plattformen til å omfatte andre skipssegmenter samt andre drivstoffteknologier og effektivitetsøkende teknologier. Å inkludere utslipp som NO_x, SO_x og PM vil ytterligere forbedre plattformen ettersom brukerne vil ha mer informasjon for å hjelpe beslutningsprosessen. Den resulterende konseptuelle designplattformen vil da gi et mer helhetlig inntrykk av designalternativene for en business case eller studie og mer grunnlag for robuste beslutninger.

Preface

This thesis presents the work of a Master of Science degree with specialisation in Marine Systems Design at the Department of Marine Technology at the Norwegian University of Science and Technology (NTNU) written from January to June 2021. The master thesis is part of the 10th semester curriculum where the student shall write a paper within their specialization field with one or more supervisors.

The motivation for the subject of this thesis is the decarbonization of shipping and to find feasible and cost effective solutions using zero-carbon fuels and technologies.

Parts of the work is based on a pre-project from the fall of 2020. This mainly concern a review of literature regarding the use of ammonia as fuel for shipping.

This master thesis has given me an opportunity to expand my knowledge in a direction of my own choice, a challenging, but very fun and enlightening part of my education.

Trondheim, June 9, 2021

Anne Sophie S. Ness

Anne Sophie Sagbakken Ness

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First, I would like to thank my supervisor Professor Stein Ove Erikstad from NTNU for guidance throughout the process of writing this master thesis. I would also like to thank my co-supervisor Øyvind Endresen from DNV for providing guidance and insightful information for the prospects of ammonia as a marine fuel.

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Lastly, I am grateful for my office mates for a great environment throughout the year.

Thank you,
Anne Sophie Sagbakken Ness

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Abbreviations

CAPEX	Captial expenditures
CO_2	Carbon dioxide
CCS	Carbon capture and storage
ETS	Emissions Trading Scheme
EU	Europen Union
GWP	Global warming potential
GHG	Greenhouse gas
HFO	Heavy fuel oil
ICE	Internal combustion engine
IMO	International Maritime Organization
LNG	Liquid natural gas
LCA	Life cycle analysis
NH_3	Ammonia
nm	nautical miles
NO_x	Nitrogen oxides
OPEX	Operational expenditures
PEMFC	Proton exchange membrane fuel cell
PM	Particulate Matter
ppm	parts per million
SBSD	System based ship design
SDG	Sustainable Development Goals
SOFC	Solid oxide fuel cell
SO_x	Sulfur oxides
UN	United Nations
VOYEX	Voyage expenditures

1

Introduction

This chapter will first introduce the background for the subject of this thesis. Second, the objectives of the thesis are presented with corresponding sub-objectives. Third, the scope and the limitations of the thesis will be introduced. Fourth, the thesis structure is presented.

1.1 Background

The pressure and regulatory urgency towards decarbonization of shipping are increasing and the subject is taking center stage. In 2018, the International Maritime Organization (IMO) presented its initial strategy to reduce greenhouse gases (GHG) emissions from international shipping by 50% within 2050 compared to 2008 levels. Figure 1.1 presents the relative goals as well as their absolute goals, with a 40% reduction in carbon intensity by 2030 and a 70% reduction by 2050.

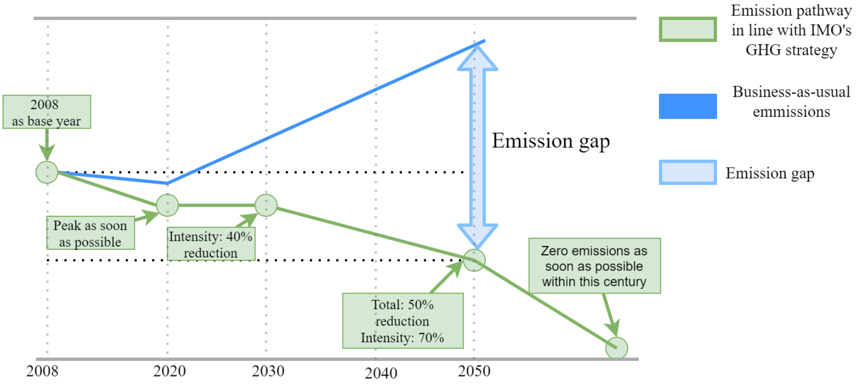


Figure 1.1: IMO GHG strategy modified from DNV-GL [1]

Deep-sea shipping is responsible for more than 80% of the CO_2 emissions from shipping [2]. To reduce emissions from this shipping segment, it is essential to find feasible and cost-effective solutions. For short sea shipping, the required stored energy is lower which gives flexibility in choosing possible zero-carbon solutions for power generation, like batteries.

Most deep-sea vessels today have large two-stroke combustion engines and travel over long distances. The amount of energy required for onboard storage makes the volumetric energy density of the fuel important. An issue for most current potential zero-carbon fuels is the lower energy density compared to conventional fuels, hence larger volumes are often required for fuel storage. This is one of the main challenges for the decarbonization of the deep-sea segment.

Short sea shipping and deep-sea shipping can require different solutions to reach the goals set out by the IMO. While battery-electric propulsion could be a valid option for short sea shipping routes, the current energy density properties of batteries make the technology unsuitable as the main energy source for deep-sea shipping. To reach the goals in the IMO GHG strategy in Figure 1.1 to decarbonized shipping, carbon-free or carbon-neutral fuels with sufficient energy density is needed. Hence, questions regarding future propulsion systems and choice of fuel for deep-sea shipping are being raised more frequently, both among ship owners, regulators, financiers, yards and the capital markets.

In recent years, many different renewable and green fuel options have been proposed and introduced. Hydrogen and ammonia are increasingly highlighted as the preferred medium and long-term solutions. However, both ammonia and hydrogen need to pass several technological, logistical and regulatory hurdles before becoming commercially available for shipping. Regulatory risk and technological uncertainty are important aspects shipowners are facing today. A ship built today will, during its lifetime, need to comply with new rules and regulations related to emissions and GHG performance, both from international agencies (IMO) and regional agencies, like the European Union (EU). Finding solutions that allow vessels to “sail through” or to be modified during their lifetime is business-critical for ship owners. With global ambitions of lowering emissions, the motivation and purpose for stakeholders in the entire shipping industry are converging towards a joint effort of finding the right solution for future propulsion and fuel type.

Literature regarding the use of ammonia as fuel in shipping presents challenges connected to the energy density, toxicity and cost, among others. In order to make the literature more applicable to different business cases using ammonia as fuel in shipping, a dynamic and visual presentation of the design could increase its informative value.

1.2 Objectives

The main objective in this master thesis is to investigate how using ammonia as fuel in deep-sea shipping will affect the competitiveness for selected technical and economical KPIs (key performance indicators); cost and volume allocation, compared to conventionally fueled vessels.

To meet the main objective, the first sub-objective is to make a conceptual design platform based on available literature and with relevant methods which allow a user to apply their business case and assumptions and get an estimate of how their case will perform in terms of total lifetime cost and design for different designs using ammonia as fuel. While the relevance of literature could be limited to a specific business case, this platform can be applied to a range of business cases. The design alternatives in the conceptual design platform will include a baseline heavy fuel oil (HFO) fueled vessel and some of the most promising energy converter technologies for using ammonia as fuel in the following list:

1. Internal combustion engine
2. Proton exchange membrane fuel cell
3. Solid oxide fuel cell

The second sub-objective is to use the design platform in a case study where the different design alternatives using ammonia as fuel will be compared to the conventional fueled vessel. The inputs will include different market values for HFO fuel price, ammonia price and CO_2 taxation rate to illustrate different future scenarios.

1.3 Scope and Limitations

In this thesis, the use of ammonia as fuel in deep-sea shipping with the onboard processes, design and costs related to the vessel build and operation will be the main focus. Other, important factors in the value chain of using ammonia as fuel will not be covered to the same extent.

Emissions from shipping in this thesis will mainly focus on CO_2, hence ammonia-fueled shipping will be regarded as carbon-free although other emissions can be present. The emission perspective will be tank to wake.

In the thesis, a baseline vessel is used on several occasions. Results will be most applicable to this ship segment and size type and using the results for other segments and sizes should be done with caution and reasonable modifications.

The main engine or energy converter will be the main focus regarding ammonia-fueled technology, hence auxiliary engines are not focused on. Propulsion and maneuvering components are likely to be different for internal combustion engine designs and fuel cell designs, however, it will be assumed to be the same for all the generated designs in this thesis.

A simple model for calculating costs will be used to compare design options. The relative costs will be the main purpose of the cost calculations and not the absolute costs.

1.4 Thesis Structure

This section introduce the thesis structure, where Chapter 2, Chapter 3, Chapter 4 and Chapter 5 form the literature base for the thesis. Chapter 6 then introduce the general methods used, while Chapter 7 describes the method used for the development of the conceptual design platform before Chapter 8 show the application of the conceptual design platform in a case study. Chapter 9 presents the results from the case study and lastly, Chapter 10 discusses the conceptual design platform and the case study results and Chapter 11 concludes the thesis. Figure 1.2 illustrates the overall path of the thesis. The following list includes more details on the contents of the chapters.

Chapter 2 presents some of the key drivers for decarbonization. The market and regulatory drivers are both important on the path towards shipping decarbonization and will be described in this chapter.

Chapter 3 describes some of the characteristics of ammonia as fuel and some of the introduced technologies using ammonia as fuel.

Chapter 4 describes the existing regulations and the safety measures affecting the design of an ammonia-fueled vessel.

Chapter 5 introduces the conceptual design phase in ship design and how the total life cycle costs are in a large degree set in this stage of design.

Chapter 6 introduces the methods used in the thesis including design methods, software tools, data collection methods and calculations algorithms used.

Chapter 7 describes the development of the conceptual design platform. This includes the choice of system breakdown and the description of the modules as well as how they interconnect with a cost model. The resulting conceptual design dashboard is also presented.

Chapter 8 presents the case study operational profile, the chosen main dimensions and a set of future scenarios for fuel prices and carbon pricing. These will be applied to the conceptual design dashboard.

Chapter 9 presents the case study techno-economic results from the conceptual design platform.

Chapter 10 discuss the results from the case study as well and the conceptual design platform in general.

Chapter 11 concludes the thesis and present suggestions for further work.

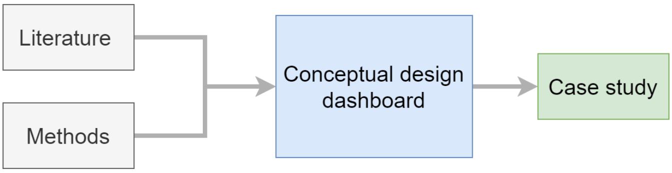


Figure 1.2: Overview of the thesis path

2

Key Drivers for Decarbonization

This chapter investigates the key drivers for decarbonizing shipping. Included in this chapter are regulatory and market drivers.

The Paris agreement temperature goals require lowering GHG emissions across many sectors, including shipping. There are several drivers pushing this change, categorized as regulatory and market drivers in the two next sections with subcategories illustrated in Figure 2.1.

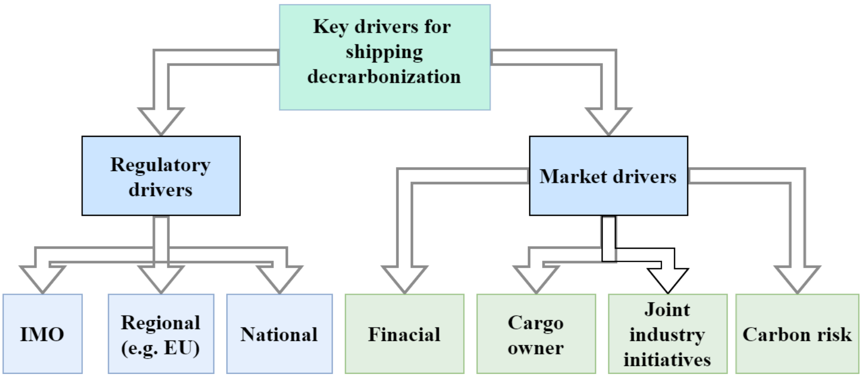


Figure 2.1: Key drivers for decarbonization in shipping, (figure made by author)

2.1 Key Regulatory Drivers for Shipping Decarbonization

This section introduces some of the most significant regulatory drivers for decarbonizing shipping.

2.1.1 International Maritime Organization

The IMO is a specialized agency of the United Nations that supports the sustainable development goals (SDG) with responsibilities for safety and security of shipping and protecting the environment from pollution from ships [3]. In 2018, the IMO came with an initial strategy to reduce GHG emissions from shipping. This strategy includes the intention of reducing CO_2 emissions per transport work from shipping with at least 40% by 2030 and by 70% by 2050 compared to the levels from 2008 [4]. In addition, another level of ambition is to reduce the annual GHG emissions from all international shipping by at least 50% by 2050. Being the international shipping regulator, IMO has a lot of power and responsibility and they are arguably the most important driver towards lowering emission from the shipping industry. Recent initiatives from the IMO will see energy efficiency design indexes extended(EEXI) to the existing fleet, as opposed to only having energy efficiency indexes on newbuilds(EEDI).

The Energy Efficiency Design Index(EEDI) is one of the measures for promoting energy-efficient equipment and engines and requires a minimum energy efficiency level per capacity mile (e.g. tonne mile). This level is different for each ship segment and size type[5]. The Energy Efficiency Existing Ship Index (EEXI) is an extension of the EEDI which includes ships built before 2013 and will contain similar requirements as the EEXI [6].

Carbon intensity indicator (CII) is a new measure to reduce carbon intensity by 40% by 2030 and is based on an operational approach. The system give the operation of ships a rating based on their carbon intensity on a scale from A to E as in Figure 2.2, where A is the better performing vessel. The CII will most likely enter into force in 2023[7]. Performance levels of D or E will require submitting a plan on how to improve the carbon intensity of the vessel.

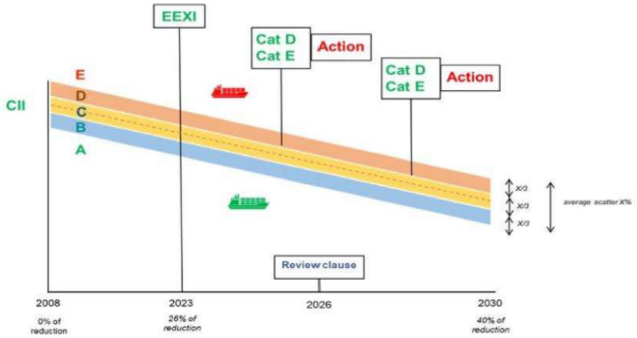


Figure 2.2: Carbon intensity index rating system [8]

2.1.2 Regional - EU

In 2013, the EU set in motion a climate strategy to reduce GHG emissions from the maritime industry [9]. The plan consists of three steps:

- → A system for monitoring, reporting and verification (MRV) of CO_2 emissions for all ships visiting ports in the European Economic Area. Vessels calling into these ports must annually deliver the aggregated data to be verified and published by the European Commission [10].
- → Defining GHG reduction targets for shipping. Guided by the collected data from the first step, updated emission targets are set, both at the global and EU level.
- → The last step includes setting medium and long-term marked-based measures for reducing maritime GHG emissions. The aim is to create incentives that achieve GHG emission reductions while being economically sensible.

The strategy is aligned to meet the United Nation's 2°C temperature goals which later materialized in the 2015 Paris agreement [11].

The EU climate strategy of 2013 was followed up by a new roadmap in 2019, The European Green Deal [12], which aims to make Europe the first climate-neutral continent within 2050. This comprehensive deal encompassed all sectors and areas, including the maritime sector.

2.1.3 National

National regulations vary, but a common denominator is that they expand the regulations set by both the IMO and regional authorities. In 2019, the Norwegian parliament issued strict requirements on SO_x and NO_x thresholds in the Norwegian world heritage fjords [13]. In addition, the parliamentary resolution states that all tourist ships in the world heritage fjords must be low- or zero-emission no later than 2026. Initiatives like these help accelerate the means against polluting ship systems, paving the way for greener alternatives.

2.2 Key Market Drivers for Shipping Decarbonization

2.2.1 Financial

Green financing could work as an accelerator towards decarbonization. Poseidon Principles is one important player for green financing and an increasing number of large shipping lenders are signing up to the principles. They define themselves as: "The Poseidon Principles establish a framework for assessing and disclosing the climate alignment of ship finance portfolios. They set a benchmark for what it means to be a responsible bank in the maritime sector and provide actionable guidance on how to achieve this" [14]. Poseidon Principles follow the ambitions of

IMO to reduce GHG emissions and enable financial institutions to also align with IMO strategies. A large group of banks has committed to the Poseidon Principles. Banks play a significant role in the financing of new projects and therefore have the power to choose which projects to support. The banks signing the Poseidon Principles agree to measure the carbon intensity of their loans and to report the results publicly.

Green bonds are another financial market driver and are a key element of environmental, social and governance (ESG) investing. It is an instrument to finance climate positive projects.

2.2.2 Cargo Owners

The focus on decarbonization is increasing also among cargo owners. Some cargo owners are choosing to charter less carbon-intensive vessels, with chartering departments working under increasingly stringent CO_2 budgets. Sea Cargo Charter is an example of an initiative with the intention of aligning chartering with the environmental goals set by IMO [15]. Many charterers have signed to follow the framework and to report how their activities perform in terms of emissions. Initiatives like this contribute to the acceleration of the energy transition for shipping.

2.2.3 Joint Industry Initiatives

Other private and public initiatives are also contributing to speeding up the energy transition. An example is the Green Shipping Programme's initiative for fleet renewal. They assist shipowners wishing to invest in green ships and cargo owners who wish to lower their emissions can be assisted in establishing green transportation contracts [16]. Other initiatives include Green Maritime Forum, Sustainable Shipping Initiative and Global Industry Alliance and the Zero-Emission Shipping Mission, among others.

2.2.4 Carbon Risk

Carbon risk is a term used to combine the regulatory-, charter- and financial risks due to future uncertainties for a shipowner. Regulatory risk, the risk of new regulations, can affect the market value of the assets or requiring costly investments, resulting in financial risks as well. Charter risk, the possibility that cargo owners will choose contracts with emissions in mind in addition to cost, will also result in financial risks for the shipowner.

A vessel ordered today will in most cases take a few years to finish. We imagine a vessel that is delivered in 2025. Typically, the vessel has a long lifetime, between 25-30 years. If the GHG strategy of IMO succeeds, this vessel will live through a time where carbon intensity is intended to be decreased by 70%. This means the vessel will be subject to many new regulatory requirements on emissions. This future uncertainty makes it very hard to predict which vessels to build and flexibility in terms of easy retrofits or fuel, or robustness in vessel design will be very important.

Regulatory and technical risk is also increasingly being used to explain the low newbuild contracting figures seen over the last two years, especially in the dry bulk, tanker and container segments. Carbon risk makes decisions regarding fuel and engine converter technology a very hard task. These decisions are often made in the conceptual design phase which makes the conceptual design phase more important now than before.

3

Ammonia as Fuel for Deep-sea Shipping, Characteristics and Energy Converter Technologies

This chapter is a literature review concerning the use of ammonia as fuel in deep-sea shipping. Included in the chapter is some history of the use of ammonia as fuel and the production, characteristics of ammonia as a fuel, production of ammonia as well as technologies for using ammonia as fuel in deep-sea shipping.

3.1 A Brief History of Ammonia

The history of ammonia as fuel begins with world war II when it was used as fuel in vehicles to prepare for a shortage of diesel fuel. After world war II, the united states was the largest producer of ammonia and had a steep incline in production. Later, China replaced the United States as the largest producer with its main use as fertilizer in agriculture [17].

In regards to the production of ammonia from renewable energy sources, there have been production plants located in Norway, in Notodden, Rjukan and Glomfjord [18]. All of which had about 40 years of operation. These examples prove the feasibility of producing ammonia from renewable energy.

Ammonia as fuel in vessels has sparked interest across the maritime industry a part of the solution of IMO's GHG strategy and the need for alternative fuels to lower carbon emissions from shipping.

3.2 Energy Density

The attention ammonia has lately received is mainly due to features that are preferable to those of pure hydrogen, a proposed zero-emission fuel candidate. The volumetric energy density of ammonia is significantly higher than that of hydrogen.

A higher volumetric energy density is advantageous in deep-sea shipping as less volume is needed for fuel, leaving room for more payload. The storage technology for ammonia ensures that the conditions in the tanks stay below the boiling point for ammonia, at $-33°C$, while hydrogen requires $-253°C$ to stay liquid [19], [20]. This large difference in boiling temperature will result in a large cost gap between ammonia and hydrogen in terms of storage. The amount of boil-off gas can also be more easily managed for ammonia due to the higher boiling temperature.

3.3 Toxicity

Ammonia is a toxic substance. Safe operation, storage and transportation are essential for fuel to be commercialized. In addition to standard safety requirements on board a vessel, safety strategies responding to ammonia leakages can be expected for ammonia-fueled vessels.

Ammonia in tanks, fuel supply and power generation system on a vessel presents a safety risk for the crew on board. It is toxic and fatal to humans subjected to a leak in a confined area over a longer or shorter time, depending on the concentration of ammonia in the air. Maintenance and repairs can be problematic.

Low concentrations of ammonia in the air may cause coughing, while higher concentrations can lead to blindness or even be fatal. This is a considerable barrier for the use of ammonia as fuel. Due to its distinct smell humans can detect the gas at low concentrations.

There are several different suggested exposure limits for ammonia. Table 3.1 is the suggested new exposure limits by Occupational Safety and Health Administration in the United States [21]. Time-weighted average (TWA) usually describes the average concentration that is acceptable during an 8-hour work shift. Short-term exposure limit (STEL) describes the concentration acceptable in short term, usually 15 minutes of exposure. Immediately dangerous to life or health (IDLH) is the concentration that is dangerous to life or health immediately during exposure.

Table 3.1: Exposure limits of ammonia [21]

Time weighted average (TWA)	25 [ppm]
Short term exposure limit (STEL)	35 [ppm]
Immediately dangerous to life or health (IDLH)	300 [ppm]

3.4 Flammability

Ammonia has a narrow flammability range and is hard to ignite although flammable. It presents a relatively low explosion risk compared to other alternative fuels like for example LNG. Ammonia requires a lot more energy to ignite compared to LNG and especially compared to hydrogen. In open air, ammonia burns with difficulty and needs a supporting flame for continuous burning[22].

3.5 Corrosiveness

Ammonia is corrosive towards brass, titanium, copper and zinc alloys. It is also destructive towards neoprene and rubber [23]. These materials are therefore unsuited for use with ammonia. Fuel tanks, fuel supply and power generation have to be designed without the materials that are corrosive to ammonia

3.6 Ammonia Production

Ammonia production today is split into the process of producing hydrogen and nitrogen and the process of producing ammonia [23]. Most ammonia production today uses reformed hydrogen from natural gas and nitrogen from the air. Coal gasification, water electrolysis, steam iron reaction are other production methods [23]. The processes are split into gray, blue and green ammonia production based on what source of energy is used as the basis for the production. Gray ammonia is produced with fossil fuels without carbon capture and storage. Blue ammonia produces the ammonia with natural gas and the CO_2 emissions from production are captured through a carbon capture and storage system. Lastly, the third way of producing ammonia, called green ammonia, is produced with electricity from renewable energy to split hydrogen from water particles and nitrogen from the air [24]. Figure 3.1 shows a simple illustration of the production pathways.

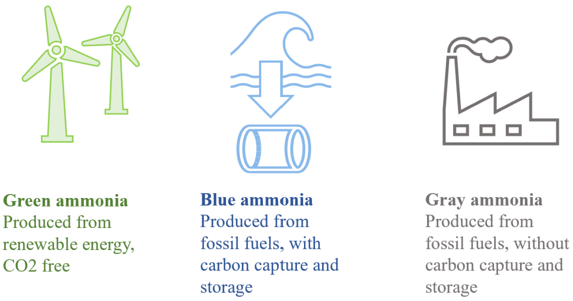


Figure 3.1: Alternative ammonia production pathways, green, blue and gray ammonia (inspired by DNV[25])

Ammonia is mostly produced with fossil fuels through the Haber-Bosch process in Equation (3.6.1). To achieve carbon neutral shipping in the long term, the production of fuels also has to be carbon neutral. As gray ammonia is produced in a large scale, the first ammonia-fueled vessels can be fueled with gray ammonia. Blue ammonia could then be a transition phase before green ammonia production, facilitated by increased renewable energy could be the primary production method in the long term, enabling emission-free shipping.

$$N_2 + 3H_2 \rightleftarrows 2NH_3 \tag{3.6.1}$$

Green ammonia is only produced in insignificant amounts today, while 180 million tons of gray ammonia is produced annually [26]. The majority of this is used for fertilizers. Ramping up the ammonia production to also include fuel production will require significant investments in renewable energy and/or carbon capture technology. If 30% of the future marine fuel demand is going to be covered by green ammonia, about 400 GW of renewable energy is needed [27].

Figure 3.2 illustrates the process of producing green ammonia from renewable energy. The required resources for green ammonia production are water, air and renewable energy. As air and water resources are plentiful, renewable energy would be the limiting factor in order to scale the ammonia production enough to cover all shipping activity.

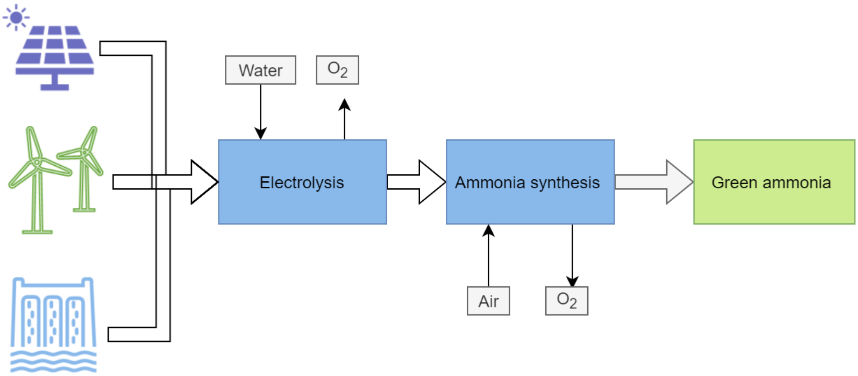


Figure 3.2: Green ammonia production chain, adapted from [28]

Yara has as of June 2021 signed an intention agreement with Trafigura to cooperate in the development and marketing of ammonia as a fuel in shipping[29]. This includes the intent to produce green and blue ammonia.

3.7 Ammonia-fueled Energy Converters

In this section, proposed technologies for energy converters in ammonia-fueled deep-sea vessels will be assessed. “Energy converter”, covers both fuel cells and internal combustion engines in this thesis. These promising technologies for using ammonia as fuel will define different design alternatives in a conceptual design platform in Chapter 7.

Extracting energy from ammonia for power generation currently has no commercialized solution. Potential technologies include combustion engines, fuel cells and gas turbines, with the two first options indicated as most suitable for ship propulsion systems. Ammonia can be direct fed to the power generation system or it can undergo cracking beforehand. Cracking is a process that extracts hydrogen from ammonia. Several projects with different approaches are launched.

The desired result of combustion or energy conversion of ammonia is steam and nitrogen as well as heat [30]. However, some oxidation of the ammonia may occur which is not desirable.

Two-stroke combustion engines are the most applied technology for deep-sea shipping and is currently expected to be the most cost-effective and technically mature option of the suggested ammonia power generation systems for vessels for the first movers.

3.7.1 Fuel Cells

Fuel cell (FC) technology is one of the suggested solutions for converting ammonia to energy for shipboard propulsion. Today, fuel cell technology is not a common option for deep-sea shipping. Nevertheless, with considerable development and cost reductions, fuel cells could be a contender for deep-sea shipping in addition to short sea shipping.

A fuel cell directly generates electrical power through a chemical reaction. All FC types consist of three main sections: anode, cathode and electrolyte [31]. Fuel cell technologies can potentially give a higher efficiency of the ship service power system than internal combustion engines [32]. Fuel cells are sensitive to rapid changes in power, affecting the lifetime which makes it critical to operate the fuel cell correctly.

Load management by peak load shaving is a method that aims to reduce the peak demand for variable loads. This can be accomplished by supporting the main energy provider by other energy sources, e.g. batteries, with a faster dynamic response. During low energy demand, the fuel cell can utilize excess energy to charge the battery. When the demand is high, the battery provides the peak load, allowing the fuel cell to generate a lower, more stable output. As fuel cells are still a costly technology, using them in a way that lengthens the lifetime will potentially save significant amounts of expenditures.

There is a large selection of fuel cell technologies, yet not all are suited for vessel power generation. Solid oxide fuel cells (SOFC) and proton exchange membrane fuel cells (PEMFC) are frequently selected as options for maritime use. PEMFC is more commercialized than SOFC, yet SOFC has the advantage of fuel flexibility. The potential of these two will be described in more detail.

Proton Exchange Membrane Fuel Cell

Proton exchange membrane fuel cells (PEMFC) have an electrolyte composed of a solid polymer film of acidified Teflon conducting hydrogen ions. Operation temperature is rather low, ranging between 70°C and 90°C [33]. This improves safety and decreases start-up time. A drawback is its cost due to the expensive materials.

The cost of the PEMFC has on the other hand dropped in recent years due to the scaling of the production. A further drop in the cost of these fuel cells can be expected but is dependent on the uptake of the technology for marine use.

The PEMFC requires purified hydrogen supplied and cracker will therefore have to split the ammonia before it is supplied to the fuel cell. This will require that some of the energy is used for cracking instead of propulsion, reducing the efficiency. The benefits of this fuel cell are that the technology has already been applied to full scale vessels and the technology might be more mature than the SOFC.

The total process in Figure 3.3 follows Equation (3.7.1) in the anode and Equation (3.7.2) in the cathode. The total reaction is shown in Equation (3.7.3) [34].

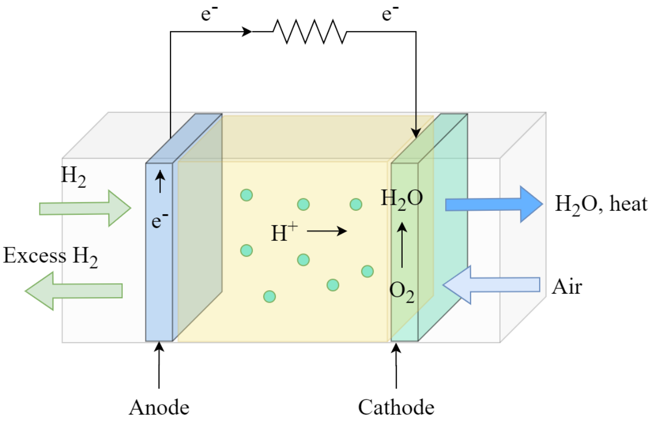


Figure 3.3: Proton exchange membrane fuel cell illustration, figure adapted from [35]

$$H_2 \rightarrow 2H^+ + 2e^- \tag{3.7.1}$$

$$\frac{1}{2}O_2 + 2e^- + 2H^+ \rightarrow H_2O \tag{3.7.2}$$

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + heat \tag{3.7.3}$$

Solid Oxide Fuel Cell

The solid oxide fuel cell can use ammonia directly. Compared to the other fuel cell types, the efficiency in power generation is high [31]. A high operating temperature of $500 - 1000°C$ gives a long start-up time. The SOFC requires additional volume compared with PEMFC and combustion engine and is also heavier [32]. SOFCs can use a waste heat recovery system to increase the efficiency of the system.

The process in a solid oxide fuel cell anode is as follows [31]:

$$2NH_3 + 5O_2^- \rightarrow 2NO + 3H_2O + 10e^- \tag{3.7.4}$$

$$2NH_3 + 3NO \rightarrow 5/2N_2 + 3H_2O \tag{3.7.5}$$

There are variations of the solid oxide fuel cell, one is called SOFC-H and another is called SOFC-O [31]. The two has different qualities which will be explained next:

SOFC-H

The fuel cell in Figure 3.4 has a proton conduction electrolyte. Theoretically, this has higher maximum efficiency than SOFC-O.

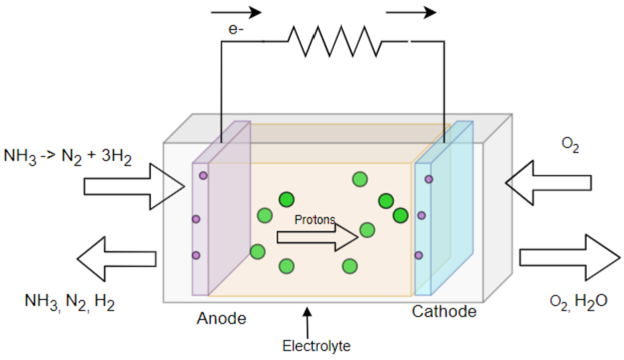


Figure 3.4: Solid oxide fuel cell illustration, figure adapted from [36]

SOFC-O

This version has an oxygen-ion conduction electrolyte. The principle here is to indirectly take the path to oxidation of fuel by decomposing the ammonia to extract hydrogen that then will be electrochemically oxidized in the fuel cell [31]. The process is shown in Figure 3.5.

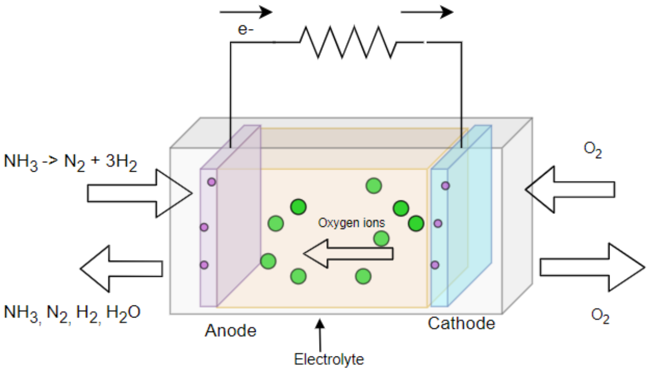


Figure 3.5: Solid oxide fuel cell illustration

3.7.2 Internal Combustion Engine

Internal combustion engines (ICE) are thermal power machines converting energy from fuels like diesel and gas to mechanical energy through internal combustion [37]. For deep-sea shipping, large, two-stroke engine is most commonly used.

The internal combustion engine has a high degree of technical maturity from many decades of operation and improvements with conventional fuels. ICE run on ammonia is however a relatively new concept and is not per today tested in full-scale vessels. Many characteristics will be the same for an ammonia combustion engine, though with some important differences.

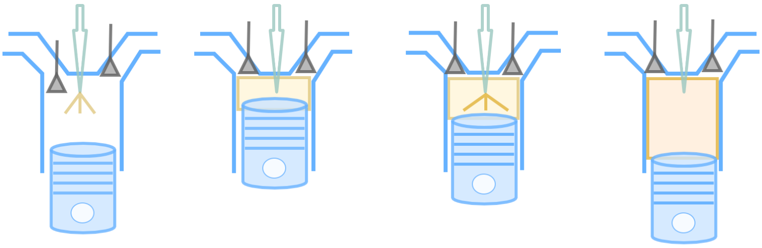
MAN energy has presented one of their dual-fuel engines as a possible combustion system for ammonia and claims that only a few alterations have to be made for it to be possible [38]. Wärtslia has also started testing of an ammonia combustion engine and will work to test the technology in collaboration with ship owners [39]. These concepts will be described in more detail in the following sections.

Combustion Process

The combustion process of ammonia follows the process in Equation (3.7.6). Fuel and air is the input in the combustion, producing nitrogen, water and heat.

$$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O + heat \tag{3.7.6}$$

Characteristics of ammonia combustion are still a research subject. NO_x and ammonia slip is a likely by-product of the combustion and strategies to reduce the emissions of this gas are also under research. An example combustion strategy is illustrated in Figure 3.6. The strategy includes fuel mixture and pre-combustion.



Pilot injection and formation of pre-mixed mixture

Pre-combustion of the ammonia-air mixture

Spray combustion of ammonia

Expansion stroke

Figure 3.6: Suggested combustion strategy of ammonia, adapted from [13]

Due to the narrow flammability range of ammonia, the combustion can benefit from a pilot fuel injection of a more flammable fuel. Fossil fuels could be an option, however as the goal is to lower carbon footprint as much as possible, hydrogen might be a better option.

3.7.3 Prime Mover: MAN Dual-fuel Combustion Engine

MAN Energy solutions announced their intentions to prepare a retrofit package for their two-stroke dual fuel engine “MAN B&W ME-LGIP”, shown if Figure 3.7, running on LPG and the similar ME-LGIM running on methanol to be able to use ammonia as fuel. The solution is said to be ready in 2024 [40].

The engine is tested through a large number of hours of operation in full scale. The concept is said to have no visible differences between the ammonia engine and the ME-LGIP/LGIM engine [38].

Shipowners naturally wish to build new vessels which require low future investments to remain compliant. A retrofit option would therefore be a good and commercial solution to make the vessel as future-proof as possible.

Figure 3.7: MAN B&W ME-LGIP engine [41]

3.7.4 Prime Mover: Wärtsila Engine

Wärtsila is currently conducting tests of ammonia four-stroke combustion engines. A research unit is the test subject as of March 2020, but full-scale tests in collaboration with ship owners are expected from 2022 [39]. The tests will be conducted for both dual fuel and spark ignition gas engines. The aim is to produce a complete system of an engine, fuel supply and storage.

3.8 Fuel Supply and Storage

Ammonia has similar characteristics to LPG which makes some technologies for LPG transferable to the use of ammonia. LPG storage tanks can also be used to store ammonia. These tanks are usually type C tanks at 18 bar pressure [42]. When the pressure in the fuel tanks gets higher than desired, a ventilation mechanism will be necessary. Due to toxicity, the location and configuration of the vent will be important.

Fuel supply systems for low-flashpoint fuels can be modified to suit ammonia fuel supply. The materials that corrode in contact with ammonia mentioned in Section 3.5 should be avoided in the fuel supply system. For example, rubber can be substituted by Teflon for sealing rings [42].

The toxicity of ammonia will mean special safety requirements for all systems onboard connected to the fuel, supply included. Double-walled pipes and limitations for where the pipes are placed could be expected. This will be further discussed in Chapter 4.

The volumetric energy density for ammonia is less than half of the volumetric energy density of conventional fuels. Other additional volumes could be needed for storage and handling. This can affect the overall available volumes in the vessel including fuel storage, crew compartments, payload and so on. For ammonia to be an option for deep-sea shipping, enough energy has to be kept on board to travel long distances. Determining optimal tank size for different routes could be more important than for conventional fuels. It could also be relevant to build bigger vessels to compensate for lost payload volume or have more frequent bunkering.

4

Regulations and Safety Regarding Ammonia as Fuel

Excising regulatory framework regarding ammonia as fuel will be presented in this chapter as well as design implications for ammonia-fueled ships. This chapter is largely influenced by the “Ammonia as a Marine Fuel Safety Handbook” by DNV[22]. Regulations with the purpose of ensuring safety are a large part of vessel design regardless of the segment, fuel, or cargo in question. Ammonia adds some safety challenges due to its characteristics. Using ammonia as fuel is uncharted territory and has not yet a complete regulatory framework. This is therefore one of the important barriers for using ammonia as fuel.

Current rules and regulations as well as the potential for future regulations are becoming an increasingly important part of a ship design process. For alternative designs, the process of design approval is more extensive. Today, several classification societies are in the process of developing a set of rules for ammonia-fueled vessels. In a press release, Bureau Veritas presents the release of an “Ammonia Prepared ” notation which certifies that a ship has been designed and constructed to later be converted to use ammonia as fuel[43]. DNV will also release class rules for ammonia in July this year and also a Fuel ready (ammonia) class notation. RINA announced in May 2021 that they published a first edition of Ammonia and Ammonia Ready rules[44]. Classification society rules can be developed relatively quickly in cooperation with pilot projects. Classification society rules can form a basis, but to make a fuel commercially available for vessels, IMO regulations would also need to be developed. This is a process that can span over several years.

4.1 SOLAS

The International Convention for the Safety of Life at Sea (SOLAS) regulates the safety of merchant ships internationally[45]. This also includes the use of fuels.

Ammonia is considered a low flashpoint fuel, which is a fuel with a flashpoint lower than 60°C. The use of low flashpoint fuels has historically been prohibited by SOLAS due to the risk of tank explosions and fires. The SOLAS convention was amended in 2015 to allow the use of low flashpoint fuels for vessels complying with the IGF code.

4.2 IGF Code

"The International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels", the IGF code, provides a standard for vessels not covered in the IGC code that operates with gases or other low-flashpoint liquids as fuel [46]. The IGF code has specific design requirements for LNG, but the other fuels have a set of functional requirements. As the IMO develops a set of design requirements for ammonia or the other low-flashpoint fuels in the IGF code, this will also be added to the code.

Before this happens, designs using any of the fuels in the IGF code other than LNG can be used provided that an equivalent level of safety is demonstrated. This requires an extensive risk-based approval process with a high degree of uncertainty in order to approve the design.

4.3 IGC Code

"The International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk" or IGC-code for short applies for gas carriers constructed after July 1986. It states a standard for safe transport of liquefied gases and some other substances by defining a set of rules for design and construction to minimize the risk to ship, crew and the environment [45]. The IGC Code includes a separate chapter on the use of cargo as fuel but does not permit the use of cargoes identified as toxic products like ammonia for this purpose. This means that the Code, in its current form, does not permit gas tankers to use ammonia as fuel.

The IGC-code also states that the outlet from ammonia tank pressure relief valves (vent mast) shall have a 25 meters safety zone around it [45]. This is an important design feature that will affect the area around this vent outlet. The toxic area requires no openings like doors or windows in the zone. The area also requires no crew access. This could be limiting for many ship segments. Another issue with ammonia slipping into the air could be that the gas is reactive with water particles and could make a toxic fog or toxic fluids on the deck of the vessel [21]. Extra systems for processing the ammonia slip could also be relevant. In general, it will be very important to have double safety barriers and shut down mechanisms in situations with potential leaks. All potential leakage points should be under control and observation. Personal protection equipment like masks and suits for the crew during bunkering and maintenance will also be necessary.

4.4 Implications to Design and Operations

The use of ammonia as fuel presents some challenges. The list below presents some safety concepts which will be important[22]:

Segregation: Due to the toxic qualities of ammonia and potential harm to the environment as a result of leaks, it will be important to keep the fuel tanks away from areas that can be damaged in a grounding or collision incident.

Double barriers: Safe handling and supply of fuel can require leakage control and double barriers to prevent leakages.

Leakage detection: Detecting leakages will also be an important safety measure to prevent crew and/or passengers to come in contact with the toxic gas.

Automatic isolation of leakages: In an event of ammonia leakage detected by the leakage detection system there should be automatic isolation of the leak.

Avoiding materials corrosive to ammonia: Materials subject to the corrosive qualities of ammonia must be avoided in fuel supply, storage and preparation

The next subsections will describe in more detail what this means for some of the vessel systems and operations.

4.4.1 Fuel Storage, Preparation and Supply

The IGC code defines accepted cargo tanks for the storage of ammonia. These are likely to be accepted as ammonia fuel tanks as well. They need to be either fully refrigerated at $-33°C$ or semi or fully pressurized.

Fuel Storage

Some design considerations which will be important for fuel storage are listed below:

- Tank location should be carefully considered in regards to collision and grounding accidents due to the toxicity of the fuel.
- Fuel preparation and supply systems will need double barriers, automatic leakage detection systems and automatic isolation of leakages.
- Preventing tank vapors as much as possible.

Fuel Preparation

A selection of the design considerations for fuel preparation rooms:

- Arranged to provide a secondary barrier to leaks, gas-tight boundaries towards other areas.
- Water curtain outside the entrance of fuel preparation rooms.
- Ventilation outlets should be placed in areas where the risk of exposure to personnel is low.
- Catastrophe ventilation starting automatically in leakage situations.
- Protective gear for personnel working in such spaces.

Fuel Supply

Some design considerations for fuel supply system:

- Secondary enclosure surrounding the fuel supply pipes.
- Connected to a vent pipe for relieving pressure.
- Materials able to handle low temperatures and withstand corrosive characteristics of ammonia.
- Minimum design pressure of 18 bar to avoid vapor.

4.4.2 Bunkering

The bunkering operation can be a situation where the risk of exposing the crew to ammonia is present. For this reason, the bunkering system should be designed in a way to make the operation as smooth as possible. Both bunkering station and coupling onboard should be designed in a way to make the risk of leaks as low as possible.

If possible the operation should be overseen remotely by the crew and people involved should wear extensive protective gear. Design features reducing the risk of leaks during bunkering can include: mechanical shielding of leakage points, leakage detection and automatic isolation, manual emergency stop among other features.

4.4.3 Machinery Space

The machinery space will also need secondary barriers against gas leaks. There should be no access from the spaces containing ammonia to the machinery room. During maintenance and repairs, it should be possible to isolate equipment from the fuel system.

The technologies introduced in Chapter 3 will need different solutions as the equipment is different, however, the main principles for ensuring safety in the machinery space will be the same.

4.4.4 Hazardous Areas

The ventilation of toxic ammonia gas should be prevented as much as possible, however as it will not be possible to eliminate the need for ventilation, pressure relief vent masts have to be present. The area around these vents will be possible toxic zones which makes it important to prohibit any possible exposure to the crew from these vents. Therefore a safety distance to any accommodation air intakes, outlets, or openings of 25 meters or the vessel breadth, whichever is less[22].

The hazardous area zone can make a large area of a vessel unavailable. For many ship segments, this presents a design challenge.

5

Conceptual Design Phase

This chapter presents the conceptual design phase of ship design and the significance of the decisions made in this stage of vessel design.

The conceptual design phase of a vessel design process includes decisions affecting the vessel's performance. Decisions include a mission statement where the ship or fleet operational profile is decided as well as capacity, speed and restrictions. The functions of the vessel and the system description can then be determined[47]. The system is affected by factors of which many are uncertain. Taking these factors into account and properly map between form and function is the design task. Figure 5.1 show the conceptual design domain where the left side is the objects, while the right side is the factors to be considered when analyzing the performance of the system [48].

The biggest challenges for shipowners wishing to acquire new vessels today occur already in the conceptual design phase. Choosing the right fuel and power generation system for propulsion can for many seem like an impossible task due to carbon risk as presented in Section 2.2.4. Emerging factors like uncertain future regulations, technology development and carbon risk affect the vessel design and presents risks when building new vessels today.

A small portion of the costs are expended during the conceptual design phase, about 6-8%, yet it can be assumed that between 60%-80% of the total lifecycle cost is determined during the conceptual design phase[48]. An illustration of committed costs and expended costs during vessel design is shown in Figure 5.2. From the figure, the light gray area illustrates the committed costs while the dark gray bars represent the accumulated costs. A wrong decision in the conceptual design phase can give significant economic consequences. Worst-case scenarios could be no contracts, very high fuel costs, or a rebuild of significant costs.

Ammonia is singled out by many as a likely zero-carbon alternative to fossil fuels.

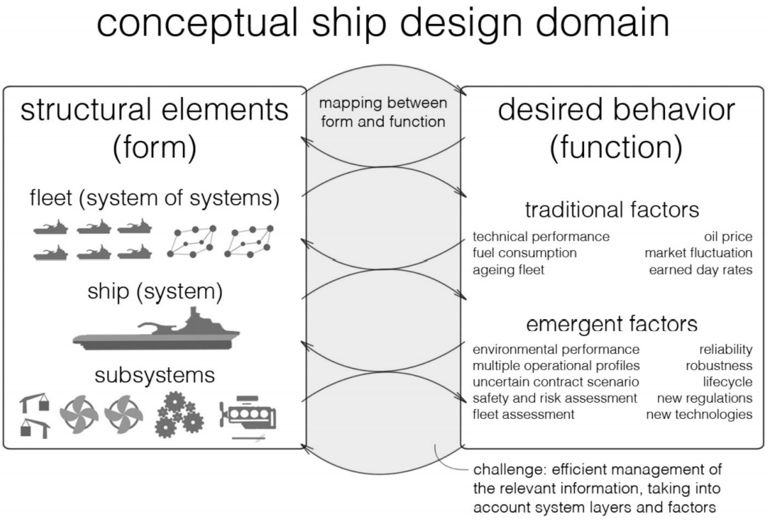


Figure 5.1: Conceptual ship design domain [48]

There are several different alternatives for main energy converter systems using ammonia as fuel. Choosing the correct main energy converter technology plays a large role in the conceptual design process and perhaps even more so today and in the future than in the past. The alternatives have some different qualities and one solution could be suited for one operational profile and not the other. Therefore it would be beneficial to see how the different designs compare in an operational profile.

A common mistake for ship designers in the conceptual design phase is to use too much detail in a visualization of a possible concept to the client. This can in some cases take the focus away from the most important decisions like fuel choice and energy converter choice during the conceptual design phase.

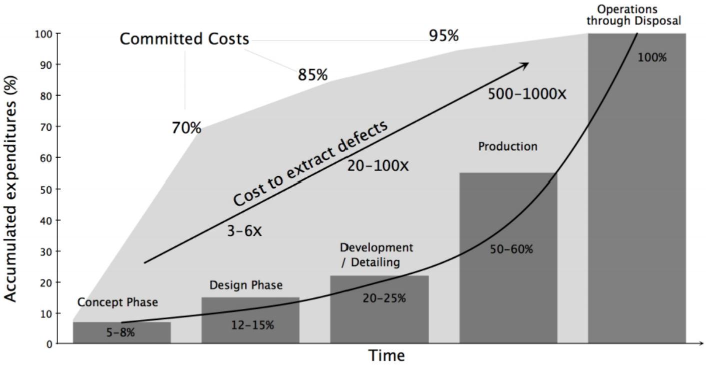


Figure 5.2: Total committed life cycle costs and accumulated expenditures, light gray area illustrates the committed costs, dark gray bars represent the accumulated costs [48]

6

Methods and Tools

This chapter and Chapter 7 presents the methods used in this thesis. Firstly, the methods used for conceptual design are presented. Included are methods for breaking a vessel into modules based on function and location which will be used in a conceptual design platform. Then, a method for deciding the dimensions of a vessel based on the desired cargo volume is presented and will be used to decide the dimensions of a generic vessel in a case study performed in Chapter 8. Next, software tools used and assessed are presented and how they are used. Then, the method used for finding relevant data will be presented. Lastly, this chapter presents the methods used for cost estimation of total life cycle costs.

6.1 Design Methods

This section introduces methods for deciding the main dimensions of a vessel and methods for breaking a ship structure into subsystems. The method will be used in the thesis to set a generic ship for a case study and to decide modules for visualizing subsystems of a vessel.

Methods to divide a vessel into subsystems reflect different aspects of the vessel systems. One way is to focus on the functional aspect of the systems, what each part of the ship actually does. Another way is to focus on the product aspect of the systems, concerning what the product actually does. Thirdly there is the location aspect of the system, focusing on spaces and location relative to other subsystems.

The benefit of using a location-based system breakdown is that it can be practical in a conceptual and visual design phase which for this master thesis is the most relevant part of the design phase. The two other methods are superior when it comes to communicating detailed elements in the ship during manufacturing or operation especially.

One of the most used ship subdivision systems is the SFI system, which is a functional subdivision system. Another, which is introduced in some courses at Marine Technology is System Based Ship Design[47]. These are used as inspiration for a ship system breakdown and will be presented in short in Section 6.1.1 and Section 6.1.2.

Deciding vessel dimensions will be done to illustrate a generic ship in a case study in Chapter 8. Choosing the optimal main dimensions for hydrodynamic performance will not be the purpose of the main dimensions, hence the method chosen for deciding this will be a simple, approximate method, based on statistics from System Based Ship Design by Levander (2006)[47].

6.1.1 SFI

The SFI Group System is a commonly used standard for functional subdivision of a vessel. It ties together important functions of the ship, improving communication related to procedures in shipping like production, maintenance and repairs, etc.[49]. Eight primary groups are used in the SFI system, listed below:

1. General
2. Hull systems
3. Cargo equipment
4. Ship equipment
5. Crew and Passenger Equipment
6. Machinery Main Components
7. Systems for Machinery Main Components
8. Common Systems

For each primary group, there are 10 secondary groups and 10 tertiary groups for each secondary group. In addition to this, there are detail and material codes.

The benefit of the SFI system is that there are many users, and ideally if used by all, it creates a common language for communication related to vessels or rigs.

For a visual presentation of a vessel as is intended for this thesis, there are some disadvantages. Most prominent is that it is difficult to divide the primary groups into locations as several of them are located in several places on the ship, like ship equipment.

6.1.2 System Based Ship Design

System based ship design (SBSD) is a ship design method that uses a mission definition to generate a functional system description that defines all systems needed in the ship to perform the desired tasks. SBSD proposes a functional breakdown of a tank vessel as shown in Figure 6.1 [47]. The benefit of this method is that it can quite easily be transferred to location-based breakdown and the method includes an approach for deciding some of the main dimensions of the vessel. System based ship design presents this approach for several ship segments including tanker vessels.

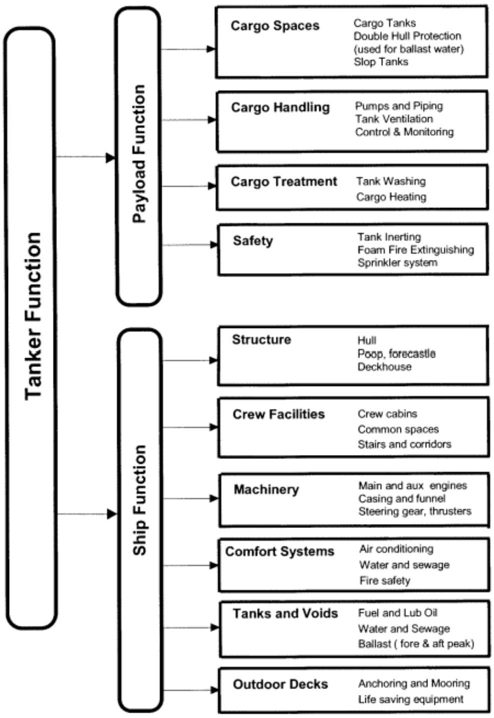


Figure 6.1: System based ship design ship breakdown system[47]

The SBSD approach for finding main dimensions uses the stakeholder needs and use existing vessel statistics. In Figure 6.2 a tanker volume distribution is presented. The ballast tank capacity is around $20 - 30\%$ of the cargo tank capacity according to system based ship design [47], other volumes like machinery, bunker tanks and crew spaces take up around 10% of the volume.

Other graphs with statistics and regression analysis of the common main dimensions for deciding length, breadth, depth and power similar to Figure 6.2. By starting

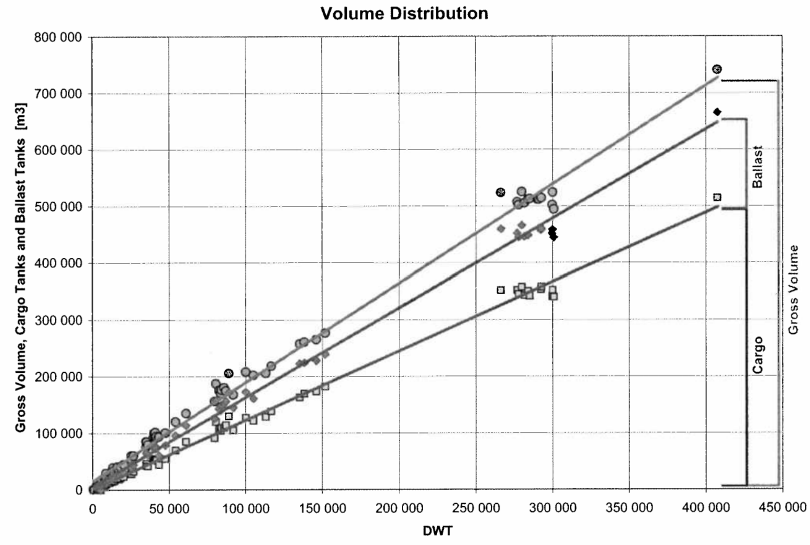
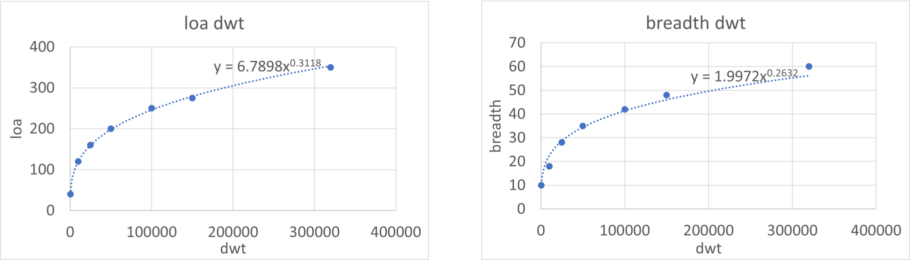


Figure 6.2: System based ship design dimensioning of tank vessels [47]

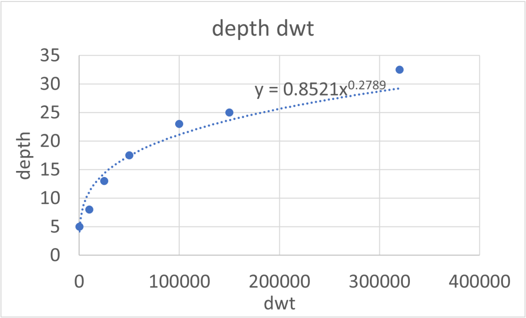
with for example a cargo volume, all the main dimensions of the vessel can be found using the graphs. This method could restrict creativity, however, it is a good starting point, and for the purpose of this thesis it is sufficient.

The statistics from SBSD are reproduced to excel where a new regression analysis is made and the resulting trend line is used in the conceptual design platform. These graphs are shown in Figure 6.3.

In this thesis, the functional breakdown system from SBSD will inspire the functional breakdown chosen for this thesis. The selected system breakdown will be described in Section 7.2. For the main dimensions, the approach suggested by SBSD will be used in Chapter 8.



(a) loa vs dwt (b) breadth vs dwt



(c) depth vs dwt

Figure 6.3: Regression analysis from system based ship design statistics [47]

6.2 Software Tools

In a conceptual design process, some of the most important decisions of the vessel design are chosen and will in a large degree affect the economics. To illustrate how physical form, the chosen business case and future market assumptions are connected to each other and affect the cost-effectiveness of a vessel, a conceptual design dashboard is created. Software for computer aided design, “Rhinoceros”, is the chosen platform to make this dashboard, combined with scripting with plugins “Grasshopper”, “Human UI”, “ShapeDiver” and “Python”. The result is a conceptual ship design dashboard aimed at a range of users like ship owners, yards and ship designers.

6.2.1 Rhinoceros

Rhinoceros is a computer aided design software used to visualize a simple 3D model of a vessel. Combined with the software Grasshopper and Python, the visual model is programmed and not drawn directly in Rhinoceros. This way, the model can be more easily modified.

Figure 6.4 illustrates a box made in Rhinoceros. Each square shows the visual object from a different plane.

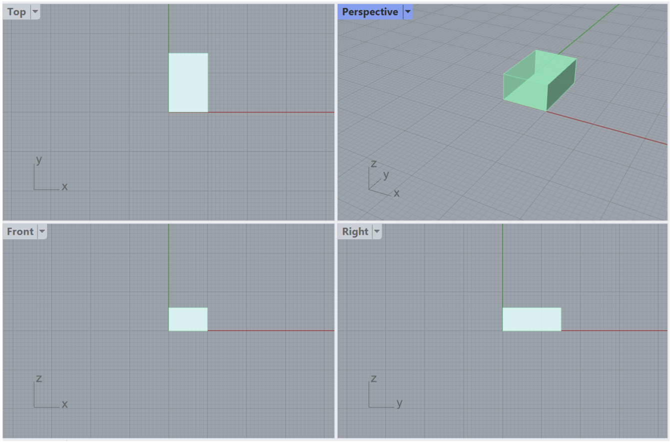


Figure 6.4: Box in Rhinoceros

6.2.2 Grasshopper

Grasshopper is a visual programming language used with Rhinoceros[50]. Visual objects are created by dragging and connecting components on a canvas.

Figure 6.5 show an example of what grasshopper components put together make a box. The sliders decide the dimensions while the boxes perform different actions like making a rectangle from input dimensions and then creating a box from the rectangle surface with a given height and lastly deciding the color of the geometry.

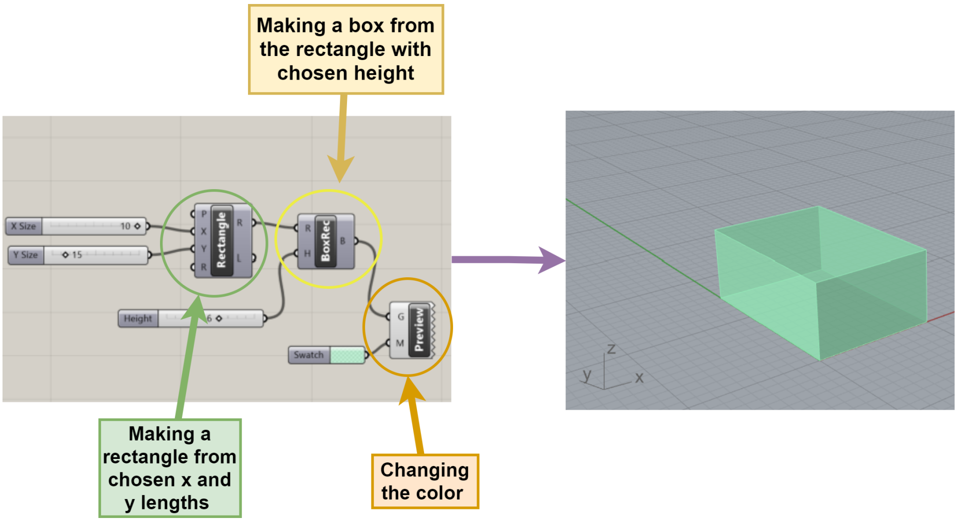


Figure 6.5: Illustration of scripting visuals for Rhinoceros in Grasshopper

To make a complex structure like a ship, many different components has to be put together in the Grasshopper canvas. Figure 6.6 shows how the canvas looks when a more complex structure is made.

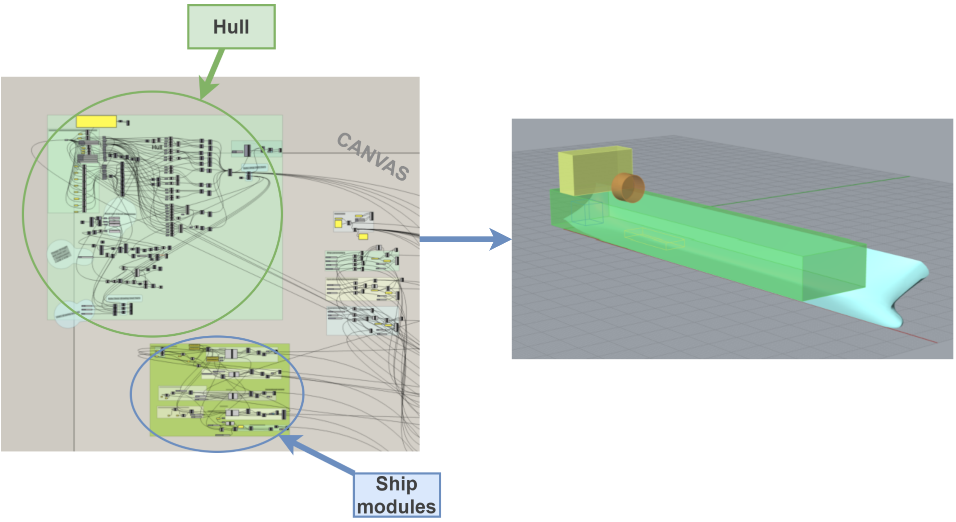
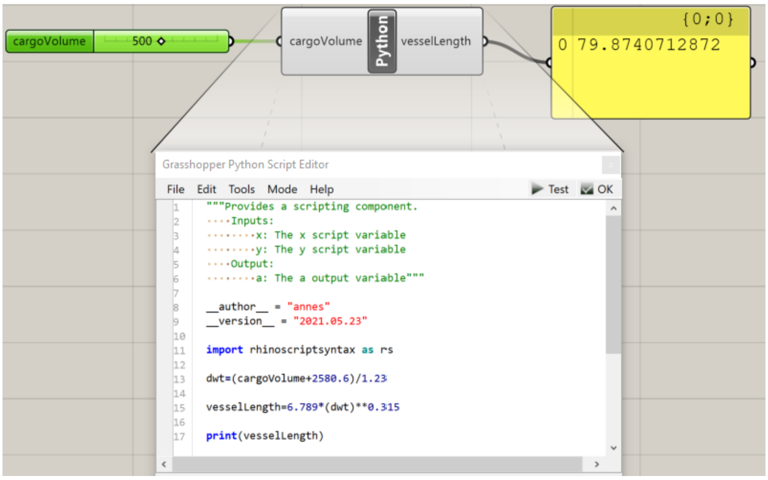


Figure 6.6: Grasshopper canvas

6.2.3 Python

Python is a high-level, general-purpose programming language[51]. It is used in this thesis to calculate volumes used in the visualization of a vessel and to calculate costs related to building and operating a vessel. Python programming can be used in Grasshopper which makes it possible to apply the code in the Grasshopper network model to define the visualized volumes. The code can also be used by itself or it can be modified to be applicable to other ship segments.

Figure 6.7 shows how a Python scripting component looks in grasshopper. The left side of the box is the input parameters while the right side is the output parameters. When the component is double-clicked, the user is able to write Python script to decide the relationship between the inputs and outputs.



cargoVolume 500

cargoVolume vesselLength

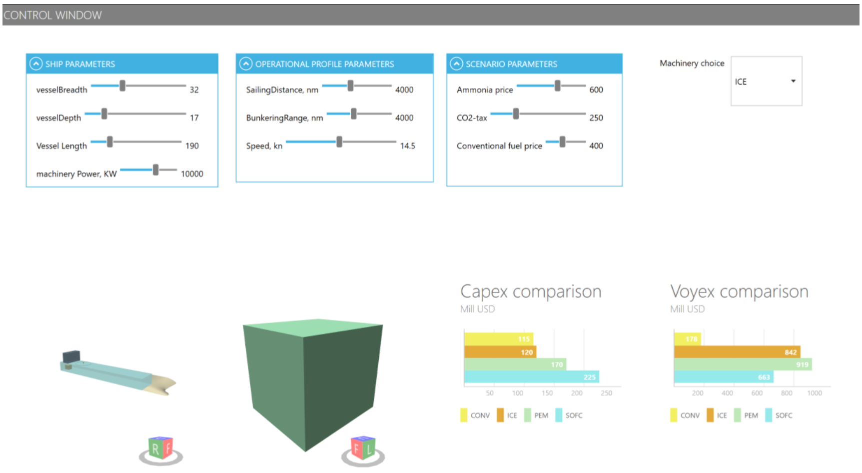
```
{0;0}
0 79.8740712872
```

```
"""Provides a scripting component.
    Inputs:
        x: The x script variable
        y: The y script variable
    Output:
        a: The a output variable"""

__author__ = "annes"
__version__ = "2021.05.23"

import rhinoscriptsyntax as rs

dwt=(cargoVolume+2580.6)/1.23

vesselLength=6.789*(dwt)**0.315

print(vesselLength)
```

Figure 6.7: Grasshopper Python component

6.2.4 Human UI

Making a complicated structure in Grasshopper generates a complicated canvas. The canvas can be tidied to make it look less messy, though with limited success in making it user-friendly. A simpler user interface would be beneficial to decrease the time spent to understand the model. An improved visual presentation of the design platform would also be favorable. For this reason, another plugin for Grasshopper is used, called Human UI. The result is a more user-friendly dashboard, where the creator of the dashboard can decide which parameters will be possible to change by the user. Figure 6.8 illustrates an example of the Human UI dashboard.



vesselBreadth 32
vesselDepth 17
Vessel Length 190
machinery Power, KW 10000

SailingDistance, nm 4000
BunkeringRange, nm 4000
Speed, kn 14.5

Ammonia price 600
CO2-tax 250
Conventional fuel price 400

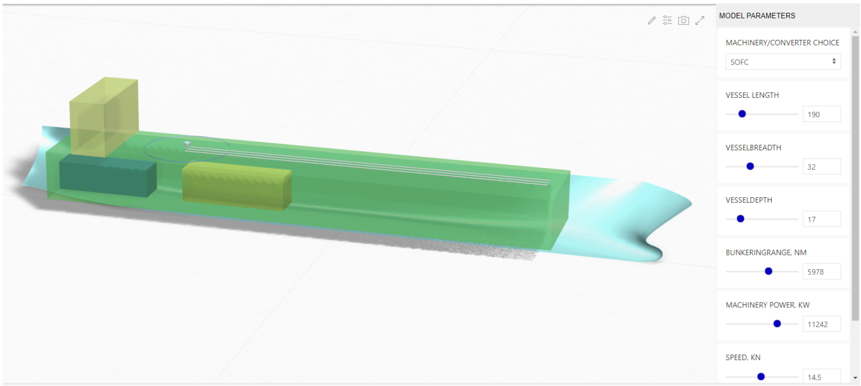
Machinery choice ICE

Figure 6.8: Human UI example

As shown in Figure 6.8, several different elements are available to view in the dashboard. There are sliders to variate the inputs, there are 3D models and there are graphs.

6.2.5 ShapeDiver

The conceptual design dashboard made in Human UI can include the desired inputs, visuals and graph components. However, the dashboard is only available through Rhinoceros which makes using the model slightly complicated. For this reason, a way to show the model online was searched for. A plugin for Grasshopper called ShapeDiver was found which partly solves this problem. The model is uploaded to their website and includes the desired visualization and inputs. It does not however present graphs.



MACHINERY/CONVERTER CHOICE: SOFC
VESSEL LENGTH: 190
VESSELBREADTH: 32
VESSELDEPTH: 17
BUNKERINGRANGE, NM: 5978
MACHINERY POWER, KW: 11242
SPEED, KN: 14,5

Figure 6.9: ShapeDiver visualization example

It is however deemed a useful tool anyways as the visualization is a very important part of this thesis, and having this available online presents some opportunities.

To use ShapeDiver, the Grasshopper file is uploaded to ShapeDiver where it is possible to select which sliders, toggles and so on should be available to change by the user.

6.3 Data Sources

This section presents how data for this thesis was found. Cost data is used in the conceptual design platform to estimate the costs of designs while AIS data is used to inspire the construction of an operational profile for a case study.

6.3.1 Cost Data

There are several inputs regarding costs in this thesis concerning capital expenditure, operational expenditures, voyage expenditures among others for vessel design and operations. The costs of building and operating ammonia-fueled vessels are vital to the competitiveness of the fuel and its related technologies, which makes it important to base it on accurate data.

As there are currently no ammonia-fueled vessels in operation, the data on the subject is scarce. Cost data in this thesis is therefore based on available literature. Kim et al. (2020)[32] and Stopford (2009)[52] inspired several of the inputs used in the thesis.

Numbers used in this thesis will be presented with the source in the applied chapter or section.

6.3.2 AIS Data

Automatic identification system (AIS) is an automatic tracking system used to track vessel traffic. The IMO requires all vessels with more than 300 gross tonnage to have AIS tracking systems[53]. AIS data can be used for many purposes, like calculating fuel consumption for individual vessels or ship groups, but will in this thesis be used to plotted geographically to inspire an operational profile.

To better illustrate a case study with a realistic operational profile, it was desired to use AIS data from existing vessels. AIS data for 2020 from existing vessels were retrieved by DNV.

6.4 Calculation Methods

This section presents the general calculations used in this thesis. These will be used in the conceptual design platform to define volumes and calculate costs in Chapter 7. Calculations specific to the conceptual design platform or case study will be presented later in the thesis.

6.4.1 Fuel Tank Volume

Fuel tank volume is calculated using the following equations. Firstly, the specific fuel consumption is calculated from lower heating value and energy converter service efficiency in Equation (6.4.1)

$$specFuel = \frac{1}{LHV \cdot \eta} \cdot 1000 = [\frac{g}{kWh}] \tag{6.4.1}$$

Where *specFuel* is specific fuel consumption in g/kWh, LHV is lower heating value for the fuel in question in kWh/kg and η is energy converter service efficiency. The result is given in g/kWh. This is then used to calculate the fuel consumption per nm in Equation (6.4.2)

$$fuelCons = \frac{power \cdot specFuel}{designSpeed} \cdot \frac{1}{1000000} = [\frac{t}{nm}] \tag{6.4.2}$$

where *fuelCons* is fuel consumption per nautical mile (nm), *specFuel* is the specific fuel consumption calculated from Equation (6.4.1), *designSpeed* is the vessel design speed in knots (kn). The result is given in *tonnes/nm*. When calculating costs, the fuel consumption is calculated like this, though when calculating total fuel tank volume, the fuel consumption is converted to m^3 per nm using the density of the fuel in question. This is then used to calculate the fuel tank volume in Equation (6.4.3). Fuel consumption changes with speed, however, design speed is used here to find the fuel consumption per nautical mile. In reality, the fuel consumption would change with service speed.

$$fuelTankVolume = range \cdot fuelCons = [m^3] \tag{6.4.3}$$

Where *fuelTankVolume* is the minimum required fuel tank volume for the given operational profile in m^3, *range* is the range in nautical miles between bunkering stations and *fuelCons* is the calculated fuel consumption in m^3/nm. The result is given in m^3.

6.4.2 Energy Converter Volume

The main energy converter space volume is calculated by using a number defining the amount of kW per volume and the energy converter power.

$$M.E.Volume = \frac{power}{PowerPerVolume} = [m^3] \tag{6.4.4}$$

Where *M.E.Power* is the set total power of the main machinery or energy converter in kW and *PowerPerVolume* is the kW per volume for the energy converter in question. The result is given in m^3.

In addition to this volume, there are additional equipment needed for the complete energy converter volume. This will be specific to the technology in question and will be described for each of the design alternatives in Chapter 7.

6.4.3 Cost Calculations

The costs related to acquiring and running a vessel are introduced in this chapter. The costs will be individual for the ship in question, however, there are some similarities. Figure 6.10 shows how the total costs are classified in a bulk carrier[52].

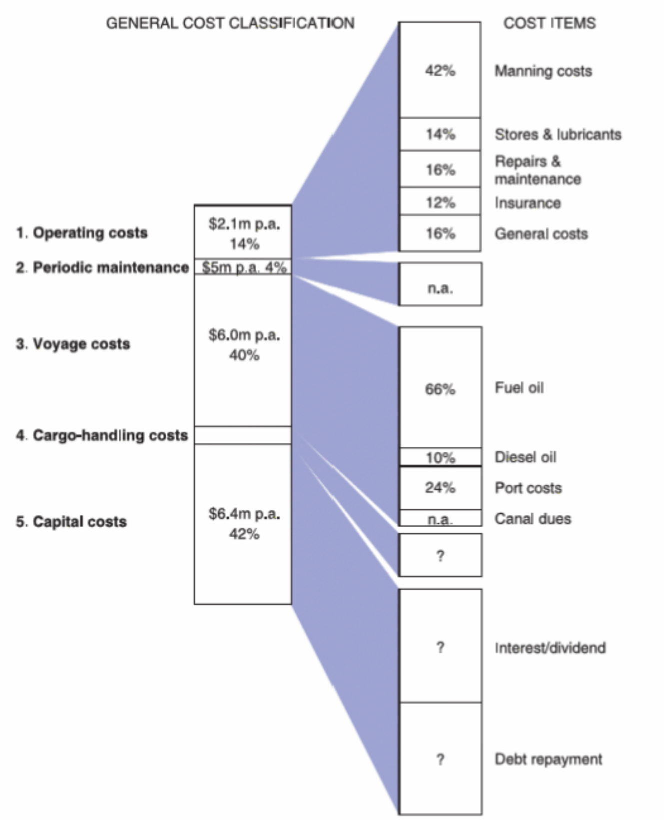


Figure 6.10: General cost classification [52]

In addition to the costs presented in Figure 6.10, some other relevant costs are calculated. Lost opportunity cost is calculated to compare different design alternatives based on their cargo capacity. Lastly, carbon pricing will be calculated as this is likely to become a part of voyage expenditures in the future for CO_2 or other CO_2-equivalent emissions.

OPEX

Operational expenditures usually include costs like crew wages, lubricants, maintenance and repair. This usually makes up 14% of the total costs of a ship[52]. This is only a rough estimate. Within operational costs, the different costs are listed below with a rough estimate of the % of the total operational costs[52].

- Crew costs: 42%
- Stores and consumables (lubricants): 14%
- Maintenance and repair: 16%

- Insurance: 12%
- General costs: 16%

VOYEX

Voyage expenditures include voyage-related costs like fuel, port charges and canal fees.

Total lifetime fuel costs are calculated from the fuel consumption calculation per nautical mile shown and the fuel price as shown in Equation (6.4.5). The fuel consumption represents an average fuel consumption of the vessel lifetime, although the fuel consumption will in most cases variate.

$$C^{fuel} = FuelPerYear * P^{fuel} * lifetime \tag{6.4.5}$$

where C^{fuel} is the total fuel cost for a vessel lifetime, *FuelPerYear* is the fuel consumption per year and P^{fuel} is the fuel price, and *lifetime* is the total lifetime of the vessel. Fuel price will in this calculation represent an average fuel price over the vessel lifetime.

Carbon Pricing

Carbon pricing is suggested as one way to close the cost gap between fossil fuels and zero-carbon fuels and accelerate the uptake of zero-carbon fuel technologies.

Carbon pricing is calculated from the fuel consumption, carbon factor and CO_2 taxation rate. In this thesis, CO_2 tax will only be calculated for CO_2 emissions and not other GHG emissions which give CO_2-equivalent emissions.

The CO_2 tax is calculated as follows:

$$CO_2Tax = CarbonFactor \cdot TaxRate \cdot FuelConsumptionPerYear \cdot lifetime \tag{6.4.6}$$

Carbon pricing could potentially also increase the cost of blue and gray ammonia. However, as mentioned in Section 1.3, tank to wake is the main focus. It will be up to the individual user to base the input values on their own assumptions.

Lost Opportunity Cost

Designs using ammonia as fuel will be different from conventional vessels. Especially volumes related to energy converter and/or fuel will be increased for ammonia-fueled vessels.

It is assumed that the increased volume compared to a conventional design will substitute possible cargo volume and hence reduce the income for the vessel per trip. Here, the lost income is accounted for as lost opportunity cost. The lost opportunity cost will depend on the cargo price and will be calculated with the following equation:

$$LostOpp = (CargoVol^{conv} - CargoVol^{ammonia}) \cdot voyages \cdot lifetime \cdot P^{cargo} \quad (6.4.7)$$

where LostOpp is the lost opportunity cost in USD, $CargoVol^{conv}$ is the conventional vessel cargo volume in m^3, $CargoVol^{ammonia}$ is the ammonia-fueled vessel design cargo volume in m^3, voyages is the number of voyages per year for the operational profile chosen, lifetime is the expected lifetime of the vessel in years and P^{cargo} is the average cost of the cargo carried by the vessel in USD.

6.5 Development of Conceptual Design Platform

This chapter has presented the methods used in this thesis which are collected from literature. In addition to these methods, a conceptual design platform has been developed which is also a part of the methods used, although it is produced by the author. This is presented in its own chapter in Chapter 7.

7

Development of Conceptual Ship Design Platform

This chapter presents the development of a concept design platform developed with the software Rhino and Grasshopper, presented in Section 6.2. In the platform, the visual model and variable design parameters are directly connected to a cost model developed in Python. This chapter describes how the model is developed using methods presented in Chapter 6 as well as describing the components and their interconnections.

7.1 Vessel Type Selection

It is desirable to choose a segment type for the sake of having a clear business case. Several of the deep-sea segments could be a good choice for this thesis to illustrate the consequence of different choices in vessel design when using ammonia as a fuel for deep-sea shipping.

The deep-sea segment of shipping contributes to the majority of the emissions related to shipping, especially the larger vessels. For example, would it be effective to have a large 18 000+ TEU container vessel use ammonia as fuel. However, ammonia tankers have already many of the necessary design specifications and classifications for using ammonia as fuel. This makes the segment a more likely first mover for using ammonia as fuel like the example with LNG carriers being first movers for using LNG as fuel. An ammonia tanker will therefore be the chosen segment for this conceptual design platform.

The conceptual design platform will be created for an ammonia tanker of a certain capacity but will be possible to modify to study other similar deep-sea segments with some adaptions. Those include, but are not limited to bulk carriers, tankers, etc.

7.2 Selected Ammonia Tanker System Breakdown

This section describes the selected ammonia tanker system breakdown, based on the system breakdown methods presented in **??**. For the purpose of this master thesis, a location-based approach to module breakdown is selected. Each module represents an area or volume as well as a function. Figure 7.1 below illustrates the chosen breakdown hierarchy of the designs for this master thesis. The model is relatively general to allow several ship types without too many alterations to the model.

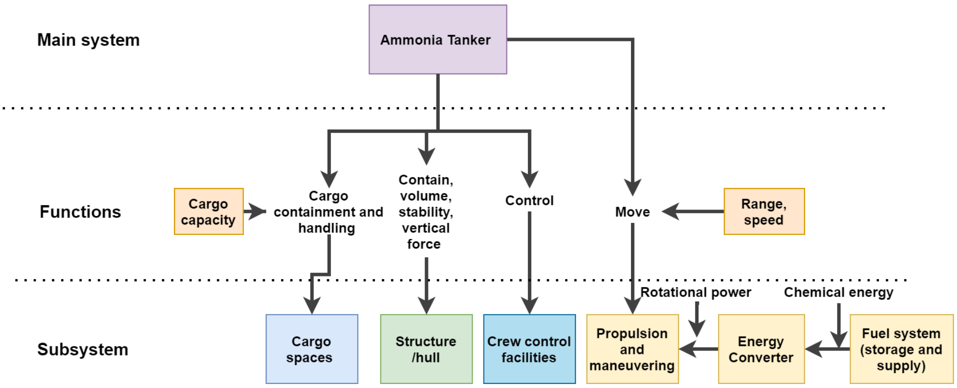


Figure 7.1: Ammonia tanker system breakdown (figure made by author)

Cargo space: Cargo spaces include cargo storage, cargo handling and cargo treatment. For this conceptual design platform, the cargo is ammonia.

Energy converter space: Including main energy converter and supporting equipment. Depending on the technology used as the main power generator for propulsion, the energy converter room will have different layouts. In this thesis, a selection of different technologies is assessed.

Fuel system: Including bunkering system, fuel storage and fuel supply.

Crew control Facilities: This module includes crew accommodation, the bridge and other crew areas.

Ship structure/hull: Ship structure includes the ship hull.

Propulsion and maneuvering Including propulsion and maneuvering systems and supporting systems. This module will not be included in the visualization but is an important subsystem.

7.3 Visual Model Elements

The model breakdown structure presented i Section 7.2 is used in the conceptual design platform. Figure 7.2 presents how the modules are connected to the system breakdown. The subsystem volumes are calculated using a variety of inputs which will be presented in this chapter.

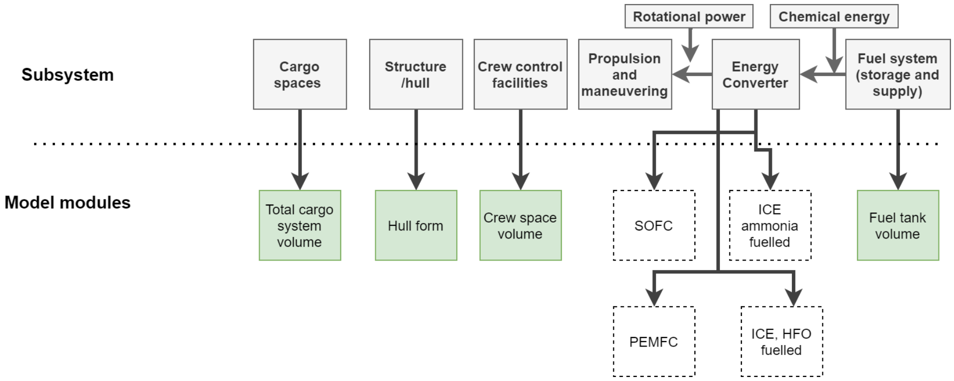


Figure 7.2: Ammonia tanker subsystems modules, green color for common volumes for all designs, dashed line for design choices (figure made by author)

There are five major modules in this model, the energy converter, the fuel tank, the cargo space and crew space as well as the hull. In addition to this, the energy converter space has four different technologies which will be presented individually.

7.3.1 Energy Converter Volume General Description

Different energy converter technologies are suggested for the use of ammonia as fuel. A set of four of these will be used for this case study. The chosen designs include a baseline HFO-fueled vessel with a two-stroke internal combustion engine and scrubber as well as variations of ammonia-fueled energy converters; internal combustion engine (ICE), proton exchange membrane fuel (PEMFC) as well as solid oxide fuel cell cell (SOFC).

The volume of each energy converter technology is based on the power per volume for the energy converter in question like the calculation in Section 6.4.2. The additional equipment volumes are added to this volume. The extra equipment is set with a rigid cost and volume. Which equipment is included in each design is inspired by Kim et al. (2020)[32].

Figure 7.3 presents the inputs and outputs for the energy converter space.

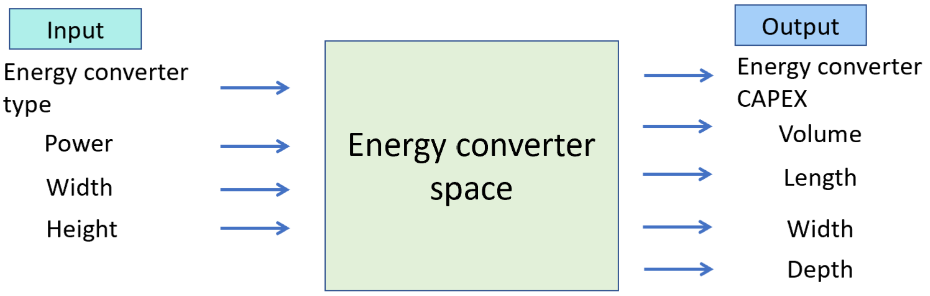


Figure 7.3: Energy converter space input and output in conceptual design platform

7.3.2 Design 1: HFO-fueled Two-stroke Engine Module with Scrubber

The design alternatives is an HFO-fueled design with a scrubber. This will be a benchmark for the other design alternatives with ammonia as fuel to be able to compare them to a more familiar design.

It has a two-stroke, low-speed engine which is usually the most efficient combustion engine on the market. Table 7.1 lists the characteristics used for this thesis in the visual model and cost model of the conventional two-stroke engine.

Table 7.1: HFO-fueled internal combustion engine data

Characteristic	**Value**	**Unit**	**Reference**
Engine type	Two stroke	$[-]$	-
Specific fuel consumption	186	$[g/kWh]$	calculated
Cost per kW	300	$[\$/kW]$	[32]
Specific power	36	$[kW/m^3]$	[32]
$\eta_{service}$(Service effect)	0.48	$[-]$	[32]

Table 7.2 presents the additional equipment for the HFO-fueled internal combustion engine design.

Table 7.2: Equipment HFO-fueled combustion engine [32]

Equipment	**Volume** $[m^3]$	**Price** [$]
Genset	107.7	1,575,000
Scrubber	150	3,400,000
Selective catalytic reduction (SCR)	90	792,000

7.3.3 Design 2: Ammonia-fueled Internal Combustion Engine

Design 2 is an ammonia-fueled combustion engine and is arguably the most mature of the technologies suggested for ammonia-fueled vessels. Although internal combustion engines are a mature technology, fuelling them with ammonia is relatively new. Table 7.3 below lists the inputs for the ammonia-fueled internal combustion engine. This design alternative will need a cracker to produce hydrogen to use as pilot fuel in the combustion. A battery of 300 kWh is included to run the cracker used for pilot fuel[32].

Table 7.3: Ammonia-fueled internal combustion engine vessel data

Characteristic	**Value**	**Unit**	**Reference**
Engine type	Two stroke	$[-]$	-
Specific fuel consumption	402	$[g/kWh]$	calculated
Cost per kW	300	$[\$/kW]$	[32]
Specific power	36	$[kW/m^3]$	[32]
$\eta_{service}$(Service effect)	0.48	$[-]$	[32]

Table 7.4 presents the additional equipment for the ammonia-fueled internal combustion engine.

Table 7.4: Equipment ammonia-fueled combustion engine [32]

Equipment	**Volume** $[m^3]$	**Price** [$]
Genset	107.7	2,475,000
Lithium ion battery	4.2	150,000
Cracker	19.4	670,000

7.3.4 Design 3: Ammonia Fed Proton Exchange Membrane Fuel Cell Vessel

The proton exchange membrane fuel cell is as mentioned in Section 3.7.1 the more mature fuel cell technology for marine use compared to the SOFC. As it has to be fueled by pure hydrogen, a cracker and a purifier are needed before being fed to the fuel cell. Table 7.5 below lists the inputs for the PEM fuel cell design. A battery of 3550 kWh is included to run the cracker for the PEMFC and for heating at cold start-up [32].

Table 7.5: Ammonia Fed Proton Exchange Membrane Fuel Cell vessel data

Characteristic	**Value**	**Unit**	**Reference**
Energy converter type	PEMFC	$[-]$	-
Specific fuel consumption	439	$[g/kWh]$	calculated
Cost per kW	300	$[\$/kW]$	[32]
Specific power	36	$[kW/m^3]$	[32]
$\eta_{service}$(Service effect)	0.48	$[-]$	[32]

Table 7.6 presents the PEMFC additional equipment used in this thesis.

Table 7.6: Equipment proton exchange membrane fuel cell [32]

Equipment	**Volume**	**Price** [$]
Cracker	19.5	2,690,000
DC converter	111.4	1,200,000
Lithium ion battery	73.26	1,775,000
VFD (variable frequency drive)	61.8	1,400,000
Prop. motor	56	904,500

7.3.5 Design 4: Ammonia Fed Solid Oxide Fuel Fell Vessel

The solid oxide fuel cell is a favorable technology for ammonia-fed fuel cells in terms of efficiency. On the downside, the cost of the technology is high. For deep-sea vessels, however, the efficiency of the energy converter is of high importance as it affects the volume needed for fuel. This could be a significant benefit for the SOFC design. Table 7.7 presents some of the characteristics of the SOFC design. A battery of 1600 kWh is included for peak load shaving and cold start-up [32].

Table 7.7: Ammonia fed solid oxide fuel cell vessel data

Characteristic	**Value**	**Unit**	**Reference**
Energy converter type	SOFC	$[-]$	-
Specific fuel consumption	317	$[g/kWh]$	calculated
Cost per kW	300	$[\$/kW]$	[32]
Specific power	36	$[kW/m^3]$	[32]
$\eta_{service}$(Service effect)	0.48	$[-]$	[32]

Table 7.8 lists the volumes of the equipment for the SOFC design.

Table 7.8: Equipment solid oxide fuel cell [32]

Equipment	**Volume** $[m^3]$	**Price** [$]
DC converter	99.8	1,200,000
VFD (variable frequency drive)	61.8	1,400,000
Lithium ion battery	66.6	800,000
Prop. motor	57.4	904,500

7.3.6 Fuel Tank Volume

The fuel tank is an important factor of the model as it illustrates how the fuel tank volume is affected by variables in the operational profile like the sailing distance between bunkering as well as the fuel consumption for the different design alternatives. Bunkering range is defined as the distance in nautical miles between bunkering ports.

Bunkering range and fuel consumption per nautical mile are used to calculate the total fuel consumption per trip which determines the required fuel tank volume. This makes the calculation very dependent on the chosen operational profile, which should be considered when using the model.

Figure 7.4 shows the inputs and outputs of the fuel tank module. The outputs give the dimensions for the fuel tank which defines the visualization of the fuel tank, while the fuel tank CAPEX is used in the cost model.

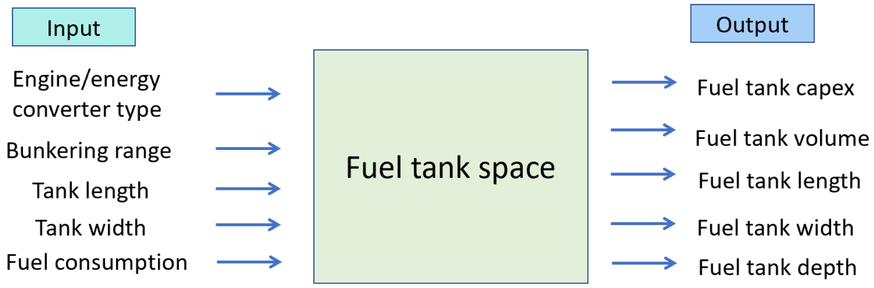


Figure 7.4: Fuel tank space input and output in conceptual design platform

The fuel tank volume defines two different fuel tank configurations in the visualization, the first is a box which represents the volume used from the cargo tanks in the case where fuel is supplied from the cargo like would be possible for an ammonia tanker. This configuration is used in the cost model. The volume also defines a second fuel tank configuration where the fuel tank is cylindrical and placed on the top of the cargo deck areas. This last configuration is used to visualize this fuel tank selection, but will not be used in the cost model. This would be possible to change if deemed necessary. For example, when modifying the platform to other segments, the cylindrical tank configuration might be more suited. Table 7.9 presents the fuel tank CAPEX per volume.

Table 7.9: CAPEX fuel tank per volume

Component	**Cost**	**Unit**
Ammonia fuel tank	720 [54]	$[USD/m^3]$
HFO fuel tank	313 [54]	$[USD/m^3]$

7.3.7 Cargo Volume

In the conceptual design phase, a part of the process is usually to set the main dimensions. Often, the dimensions are set from a list of requirements from a main stakeholder, like a shipowner. It is common to derive the main dimensions from the desired cargo volume.

In the design platform, the user can input the desired cargo volume to get a set of main dimensions, but can also choose a set of main dimensions independently. The cargo volume will be affected by the chosen dimensions as well as the chosen energy converter as the volumes from the fuel tank and the energy converter substitutes cargo volume and hence leads to less cargo volume when these volumes increase. The more voluminous technology is then “punished” with lost opportunity cost for lost cargo volume as described in Section 6.4.3. Figure 7.5 illustrates the input and outputs of the cargo space volume.

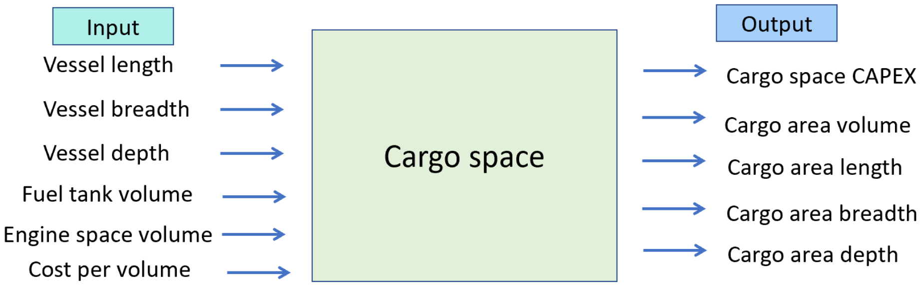


Figure 7.5: Cargo area input and output in conceptual design platform

In a case where the cargo is used as fuel, the cargo volume will be affected by the fuel tank volume, but with a type c tank on the vessel deck, the cargo volume would only be affected by the energy converter volume. Table 7.10 presents the cargo area CAPEX per volume.

Table 7.10: CAPEX cargo tank

Component	Cost	Unit
Ammonia cargo tank	720 [54]	$[USD/m^3]$

7.3.8 Crew Area Volume

The crew area volume is mainly present to illustrate a familiar look of a vessel, but also adds to the CAPEX of the vessel. The input parameters are fed from the vessel specifications and from the number of crew. The output parameters give the inputs for the visualization of the model and the CAPEX function of the cost model.

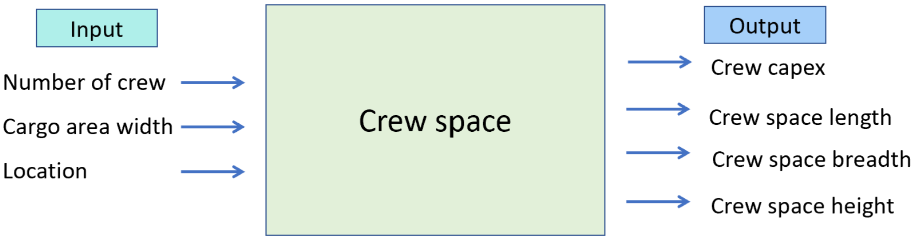


Figure 7.6: Crew area input and output in conceptual design platform

7.3.9 Hull

The hull is mainly added to illustrate how a ship of the given dimensions can look, giving the ship a more familiar appearance. In the conceptual design phase, too much detail in the conceptual design drawing can distract the customer from the most important aspects of the concept. For this reason, only half the hull is included in the conceptual design model. This way, the contents of the ship, the cargo are, fuel tank and energy converter space are more easily observed and how these modules change with different input parameters.

Ballast tanks take up a lot of the ship volume, though is not illustrated in the model to be able to view the ship contents. However, the ballast tanks are represented by voids between the hull and the cargo volume box.

The hull visualization is made by RhinoCentre and is edited to fit the model made by the author of this thesis[55].

7.3.10 Regulatory/Safety Measures Visualization

Some of the safety measures related to having ammonia on board a vessel will be possible to visualize. These measures will be needed whether the fuel is HFO, ammonia, or other for an ammonia tanker as the substance is already on board. However, for other segments, they could be very important.

The safety measures visualized will be a safety zone, around a ventilation tower. The requirements for this area are described in Section 4.4.4. The safety zone occupies a relatively large area and is therefore useful to visualize.

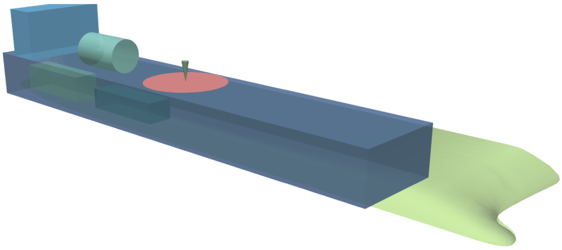


Figure 7.7: Example picture of safety zone around BOG vent, red circle illustrates safety zone

7.4 Cost Model

This chapter describes costs that will be calculated in the conceptual design platform developed in this thesis. The general calculations described in Section 6.4 will be used in addition to the calculations which are more specific to this model which will be presented in this section.

The complete conceptual design platform built in Rhino includes a visual model of a vessel with a set of different design alternatives defined by the chosen energy converter for propulsion. The costs for each design alternative will variate with the chosen main dimensions and operational profile. The visual model and cost model are linked.

Some market parameters will be of special importance when calculating costs for ammonia-fueled shipping. In this thesis, these market parameters included are HFO fuel price, ammonia fuel price and potential CO_2 taxation rate.

This cost model is intended to give an estimate of the costs related to the building and operating of a ship. The most important result of the cost model is to illuminate the differences in cost and/or income for different design choices and will for this reason not focus on costs that are the same for the intended design alternatives.

CAPEX

The CAPEX calculations are different for the selection of design alternatives as they include different power generation technologies which require different fuels and/or equipment. The individual costs for each of the different design components were presented in Section 7.3.

CAPEX is calculated individually for each of the design alternatives and is the sum of the CAPEX for the fuel tank, crew area, cargo tank and energy converter.

OPEX

Crew wages will for all the design alternatives be the same. However, maintenance, repairs and lubricants will vary for each alternative. Crew wages are included in the model as well to get a wider user experience in case of different business cases and vessels.

The operational costs varying with each design alternative are also included in the calculation of OPEX. For example will the internal combustion engine, both HFO-fueled and ammonia-fueled needs lubricants in a larger amount than the fuel cell alternatives as there are more moving parts. The OPEX components are shown in Table 7.11 with example values. Operational costs are somewhat inspired by Stopford (2009)[52], while some costs like maintenance for fuel cell maintenance based on rough estimates.

Table 7.11: OPEX components

Component	**Applicable design alternative**	**Cost**	**Unit**
Crew wages	ALL	50,000	$\$/crew/year$
Lube oil	CONV[1], ICE[2]	400,000	$\$/year$
Maintainance ICE	CONV, ICE	500,000	$\$/year$
Maintainance FC	PEM[3], SOFC[4]	250,000	$\$/year$
Other OPEX (Insurance etc.)	ALL	800,000	$\$/year$

VOYEX

Voyage expenditures include voyage-related costs like fuel, port charges and canal fees. The two latter will be the same for each operational profile, and will hence not present a difference in costs for design alternatives with the same operational profile. Both port charges and canal fees can be added to the conceptual design platform.

VOYEX will be calculated based on the fuel consumption per year for each of the design alternatives and multiplied with the chosen fuel price and then multiplied

---

[1] CONV= HFO-fueled ICE design

[2] ICE= ammonia-fueled ICE design

[3] PEM= ammonia-fueled PEMFC design

[4] SOFC= ammonia-fueled SOFC design

with the lifetime of the ship to get the total voyage expenditures.

Carbon pricing is a part of the voyage expenditures and will be calculated for the HFO-fueled design.

Replacement Cost

The selected design alternatives include fuel cells which have additional costs related to the replacement of the fuel cell stacks as their lifetime is limited.

For each replacement of the stacks, the life expectancy of the fuel cell is expected to increase due to the improvement of the technology and the cost is expected to decrease due to scaling and maturing of the technology. Table 7.12 presents an estimation of the replacement costs for the PEMFC and SOFC designs. The internal combustion engine designs are assumed to last the lifetime of the vessel.

Table 7.12: Lifetime and cost expectations for fuel cells [32]

Item	**Expected lifetime**	**Increasing rate of lieftime for each replacement**	**Decreasing rate of cost for each replacement**
PEMFC	6 years	25%	42%
SOFC	5 years	25%	42%

7.5 Fuel Price and Carbon Taxation Values

Many market aspects will affect the costs of each design alternative, however not all will be included as that would increase the complexity perhaps without increasing the quality of the results. The chosen variables are among the assumed most important factors in the decarbonization pathway and more specifically for the use of ammonia as fuel. These are parameters that are difficult to predict, it is, therefore, desirable to create scenarios including different value combinations for the following three market value variables:

- Ammonia price
- HFO price
- CO_2 tax rate

These can be changed to test the effect of possible future values and how it affects the costs of each design alternative.

7.6 Conceptual Design Dashboard

The conceptual design dashboard is made in Rhinoceros, scripted in grasshopper with the plugin Human UI. It is configured with a flow suited for the conceptual design process.

The design alternatives will have a shortened name in the model, listed below. These names will follow the designs throughout the rest of the thesis.

CONV: Design 1- HFO-fueled internal combustion engine powered ammonia tanker

ICE: Design 2- Ammonia-fueled internal combustion engine powered ammonia tanker

PEM: Design 3- Ammonia fulle PEMFC powered ammonia tanker

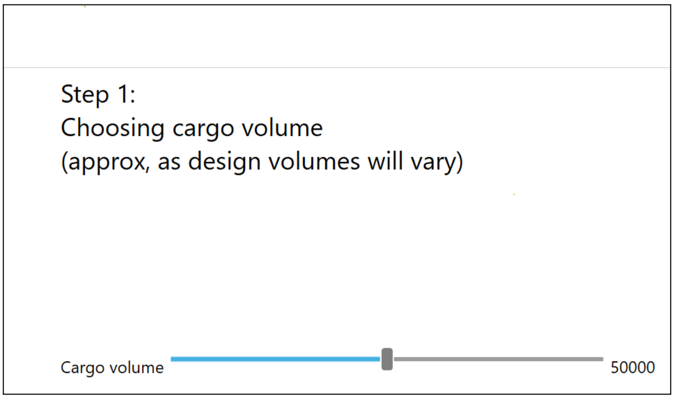
SOFC: Design 4- Ammonia-fueled SOFC powered ammonia tanker

The conceptual design dashboard in its entirety can be viewed in Appendix A. The Grasshopper canvas can be found in Appendix B. A link to an introduction video to the conceptual design dashboard can be found in Appendix C while the online visualization dashboard in ShapeDiver can be found in Appendix D.

The following will explain the steps of the conceptual design dashboard.

Step 1: Choose Cargo Volume

Often the conceptual design process begins when a shipowner sees an opportunity in a market and which to purchase a vessel to perform services in this market. This mission statement usually includes a cargo and a cargo volume. Ammonia tankers are the chosen segment in this design platform, however, the cargo volume is decided by the user. This is step 1 in the dashboard.

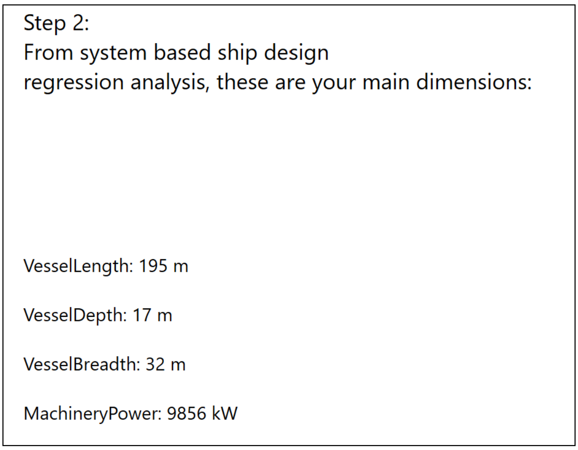

Step 1:
Choosing cargo volume
(approx, as design volumes will vary)

Cargo volume 50000

Figure 7.8: Step 1 conceptual design dashboard

Step 2: Output loa, breadth, depth

Using the correlation between dwt and loa, breadth and depth from Section 6.1.2, the vessel length, breadth, depth and main energy converter power is found.



Step 2:
From system based ship design
regression analysis, these are your main dimensions:

VesselLength: 195 m

VesselDepth: 17 m

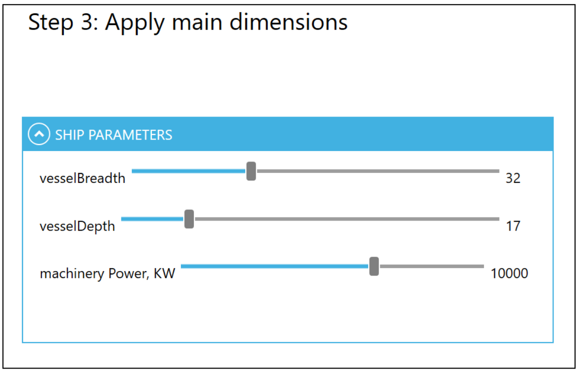
VesselBreadth: 32 m

MachineryPower: 9856 kW

Figure 7.9: Step 2 conceptual design dashboard

Step 3: Apply Main Dimensions

The user can choose to use the main dimensions from the system based design approach in step 1 and 2 or choose their own. These parameters include length, breadth, depth and machinery/energy converter power.



Step 3: Apply main dimensions

vesselBreadth 32

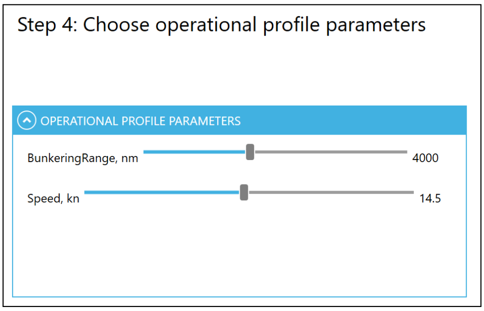
vesselDepth 17

machinery Power, KW 10000

Figure 7.10: Step 3 conceptual design dashboard

Step 4: Choose Operational Profile Parameters

The operational profile parameters are then set, choosing the speed and the bunkering range. The bunkering range is the used parameter for sailing distance as this will be the determining factor for fuel volume. Speed will in this model mainly affect how many trips the vessel is able to take per year.



Step 4: Choose operational profile parameters

BunkeringRange, nm 4000

Speed, kn 14.5

Figure 7.11: Step 4 conceptual design dashboard

Step 5: Study Design Alternatives

From the main dimensions and operational profile parameters, the vessel designs can then be observed and compared. Cylindrical fuel tanks included to amplify the visualization of the fuel tank volume.

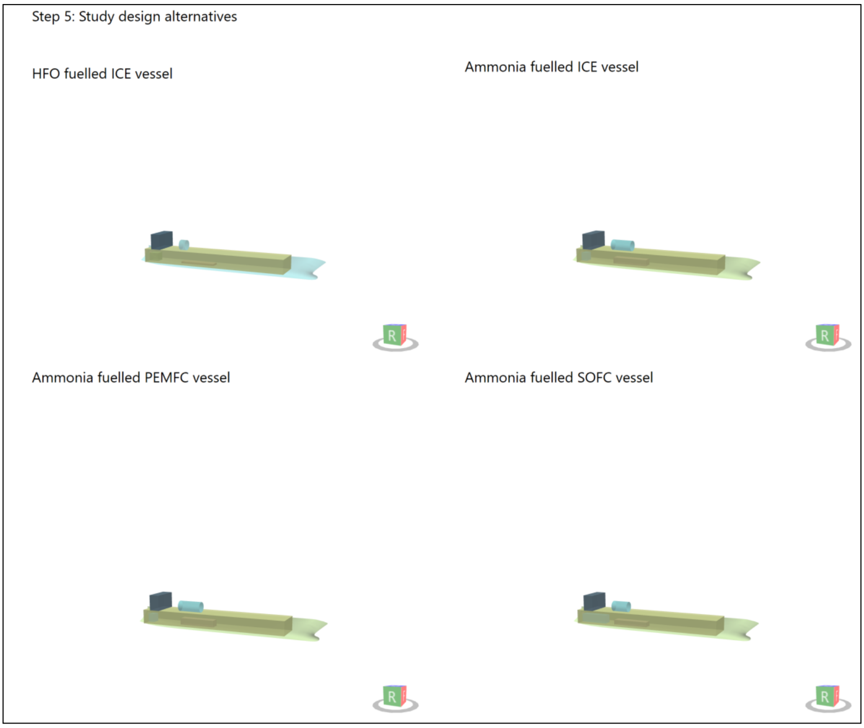
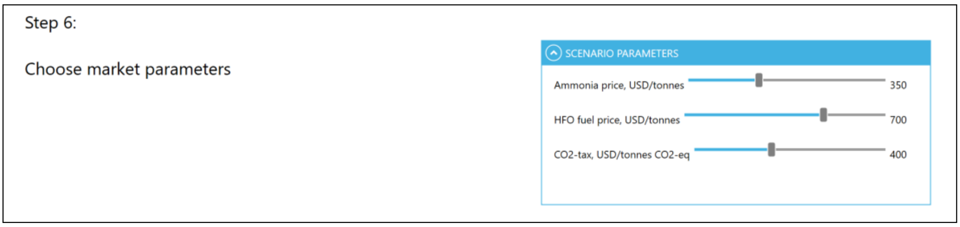


Figure 7.12: Step 5 conceptual design dashboard

Step 6: Choose Market Parameters

The market parameters, ammonia fuel price, HFO fuel price and CO_2 tax rate are then chosen. This will affect the results to a large degree, considering fuel costs are the main cost factor for VOYEX.


Step 6:

Choose market parameters

Ammonia price, USD/tonnes 350

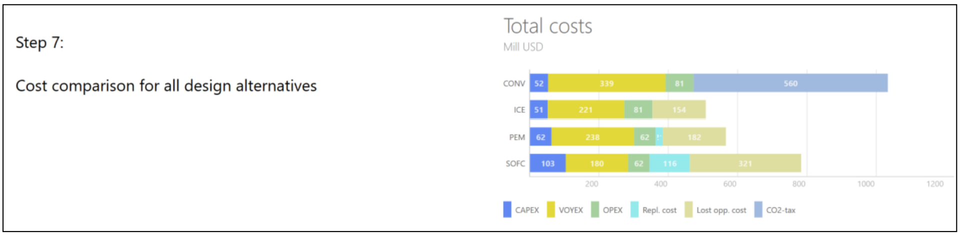
HFO fuel price, USD/tonnes 700

CO2-tax, USD/tonnes CO2-eq 400

Figure 7.13: Step 6 conceptual design dashboard

Step 7: Cost Comparison for All Design Alternatives

A large part of the decision process will be to compare the costs of the design alternatives. All costs for the chosen ship-, operational- and market parameters are collected in one graph to be able to view the total for each design alternative and compare them together. These costs include CAPEX, VOYEX, OPEX, replacement costs, lost oppurtunity cost and CO_2 costs.

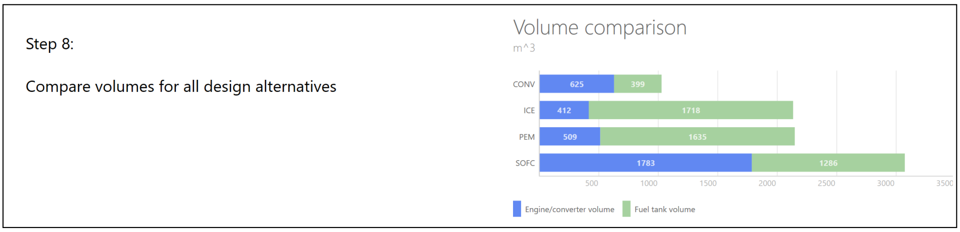

Step 7:

Cost comparison for all design alternatives

Figure 7.14: Step 7 conceptual design dashboard

Step 8: Volume Comparison for All Design Alternatives

One of the challenges with using ammonia as fuel is the decreased energy density of the fuel which increases the fuel tank volume compared to a conventionally fueled vessel. Step 8 presents a volume comparison for all design alternatives.



Step 8:

Compare volumes for all design alternatives

Figure 7.15: Step 8 conceptual design dashboard

Step 9: Choose Design Alternative

Based on the visualization of the design alternatives and the costs connected to each design alternative, the user of the conceptual design platform can decide which design alternative to choose.

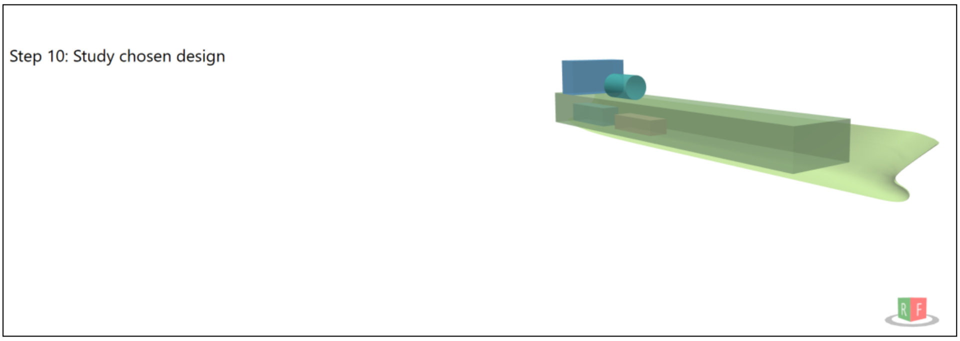
Step 9: Choose design alternative

Machinery choice: CONV

Figure 7.16: Step 9 conceptual design dashboard

Step 10: Study Chosen Design Alternative

The user is then able to view the chosen design in a bit more detail during the next steps. The step presented in Figure 7.17 presents the chosen design on a larger scale.



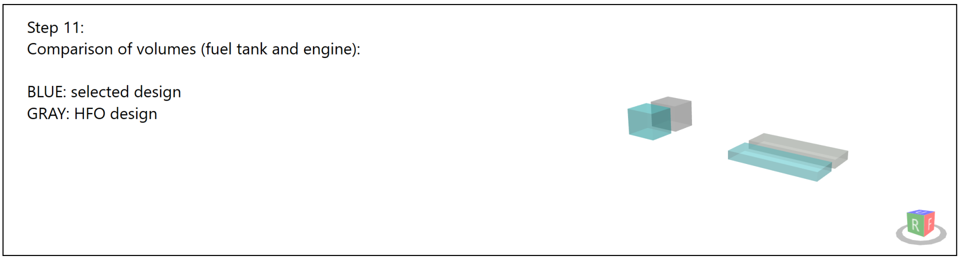
Step 10: Study chosen design

Figure 7.17: Step 10 conceptual design dashboard

Step 11: Comparing Volumes to Conventional Vessel Volumes

The next step in Figure 7.18 visualizes the volumes for the main energy converter for the chosen design alternative in comparison to the HFO-fueled design. The user is then able to see how the chosen design alternative differs from a conventional and perhaps more familiar design.

The volumes are shown as a total volume, regardless of the configuration chosen for either the machinery space and fuel tank.



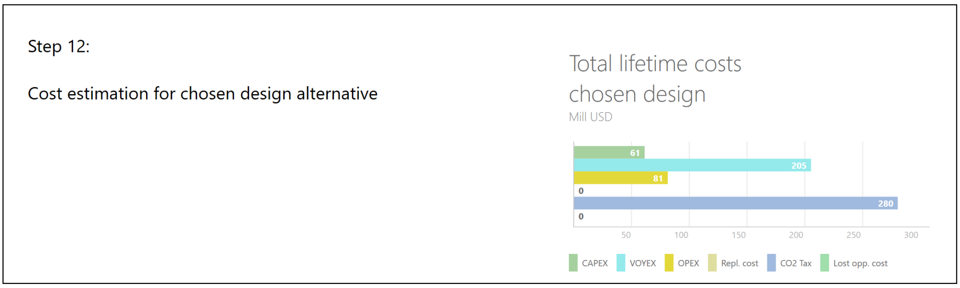
Step 11:
Comparison of volumes (fuel tank and engine):

BLUE: selected design
GRAY: HFO design

Figure 7.18: Step 11 conceptual design dashboard

Step 12: Cost Estimation for Chosen Design Alternative

Lastly, the cost estimation related to the chosen design alternative can be viewed. This includes CAPEX, VOYEX, OPEX and if applicable; CO_2 tax, replacement costs and lost opportunity costs.



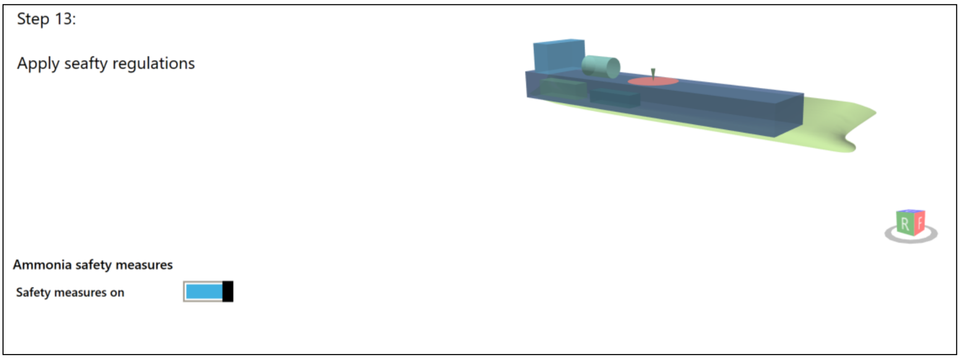
Step 12:

Cost estimation for chosen design alternative

Figure 7.19: Step 12 conceptual design dashboard

Step 13: Apply Safety Regulations

The last step allows the user to view the chosen vessel with safety zones around a pressure relief ventilation mast connected to the fuel tank and/or cargo tank which is one of the regulations affecting the vessel design to a large degree.



Step 13:

Apply seafty regulations

Ammonia safety measures

Safety measures on

Figure 7.20: Step 13 conceptual design dashboard

8

Case Study

This chapter presents an operational profile and business case for an ammonia tank vessel used to assess different technologies using ammonia as a fuel for deep-sea shipping to use as input in the conceptual design platform presented in Chapter 7. The operational profile is decided using AIS-data for existing ammonia carriers and their routes while the ship's main dimensions will be decided using system based design from Chapter 6.

8.1 Operational Profile Description

To compare different technologies for using ammonia as fuel, a baseline ship will be chosen. A known owner of ammonia tankers is ammonia-producing company Yara. Among their fleet is tankers with a cargo capacity of about $37000m^3$. However this thesis assumes the potential to use ammonia as fuel in the future, increasing the demand for ammonia. For this reason, a larger vessel is desired, width a cargo capacity of about $50000m^3$.

The following describes the mission statement:

> *"An ammonia tank vessel fueled by ammonia, with a cargo capacity of between 40 000 and 55 000* m^3 *sailing an existing ammonia transportation route to benefit from existing infrastructure "*

The main dimensions will be found using system based ship design introduced in Section 6.1.2, while the sailing route will be inspired by existing ammonia carriers transporting ammonia for agriculture.

Figure 8.1 shows the sailed routes in 2020 for 5 ammonia carrier vessels. This will inspire the route selection as the desire is to take advantage of existing infrastructure for ammonia transportation.

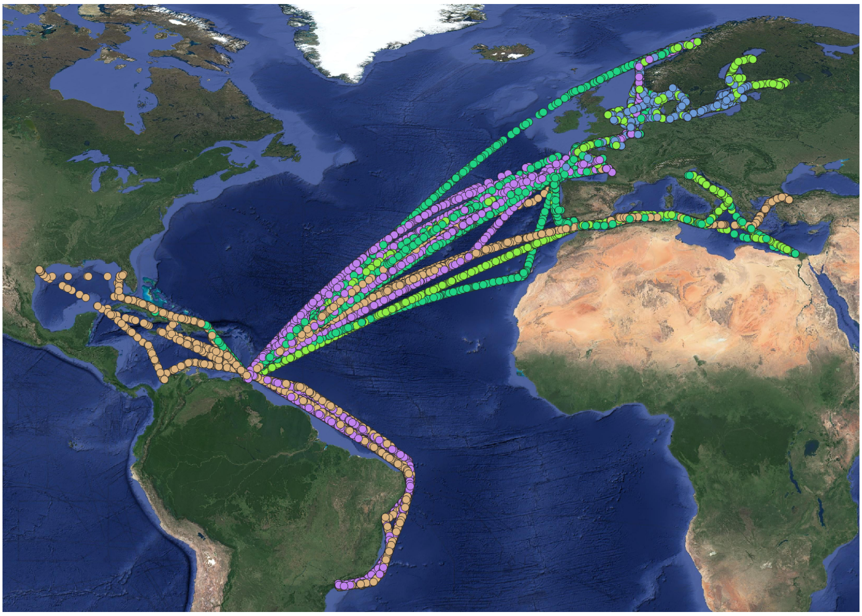


Figure 8.1: Map of 5 ammonia carrier routes in 2020 made from AIS data provided by DNV

One of the ports that are singling out among the visited ports by the ammonia tankers is Trinidad in South America. There is also a lot of activity in Europe to a variation of ports in different sizes. To make ammonia fuelling available to as many shipping routes as possible one of the most visited ports is chosen, the port of Antwerp. Table 8.1 presents the chosen ports for this case study and the sailing distance.

Table 8.1: Operational profile, ports and sailing distance

Port 1	**Port 2**	**Sailing distance**
Antwerp	Trinidad	4000 $[nm]$

8.2 Baseline Ship

The main dimensions of the vessel including the overall length, breadth and depth as well as energy converter installed power will be set for all the design alternatives. This is one way to make the consequences of the different design decisions easily comparable.

With a cargo volume of $50000m^3$, system based ship design estimates $40000dwt$ with the approach described in Section 6.1.2.

This is not among the larger tanker vessels but resembles the studied existing ammonia tankers which increases the relevance of this case study.

8.2.1 Chosen Main Dimensions for Case Study

Table 8.2 presents the vessel main dimensions set using an approach from system based ship design introduced in Chapter 6. The vessel lifetime is assumed to be 30 years.

Table 8.2: Vessel data, *distance from top of keel to top of deck beam at midship

Attribute	**Value**	**Unit**
Vessel type	Ammonia tanker	[−]
Vessel length	195	[m]
Vessel breadth	32	[m]
Vessel depth*	17	[m]
Power	10	[MW]
Speed	14.5	[kn]
Bunkering range	4000	[nm]

Figure 8.2 illustrates the baseline vessel.

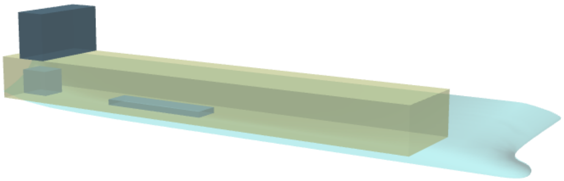


Figure 8.2: Baseline HFO-fueled vessel case study

8.3 Choosing Fuel and Carbon Pricing Rates

The cost model in the conceptual design platform uses input values for ammonia price, HFO fuel price and CO_2 tax rate. Which values to use in the case study will be decided in this section.

Decarbonization of shipping has several different pathways and presents a lot of uncertainties. Predicting when and which regulations, technologies and market variables will be present in the future is a very difficult task to predict.

To illustrate how different futures give different outcomes for the competitiveness of ammonia, a set of future scenarios has been constructed. Each scenario contains the same set of variables, but with different values.

8.3.1 HFO Fuel Prices

Predicting what the future HFO prices will be is a difficult task. Historic HFO prices can on the other hand provide a range of prices with which the conceptual design cost model can be tested. Figure 8.3 shows the historical HFO prices from the year 2000 until 2020. The prices have ranged from $ 100 per tonnes to above $ 700 per tonnes.

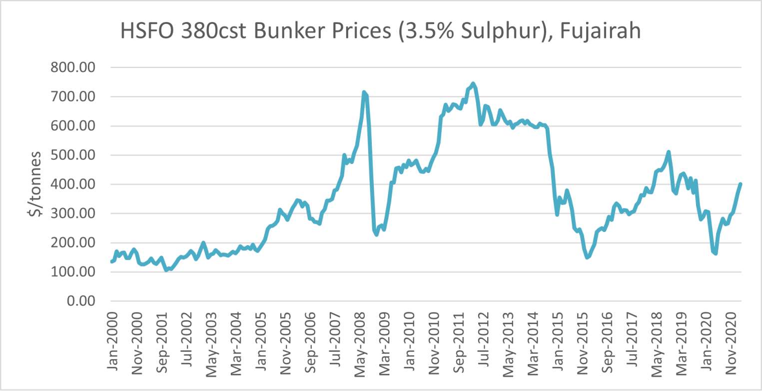


Figure 8.3: HFO fuel prices from 2000-2021 [56]

8.3.2 Ammonia Prices

Most ammonia trade is today related to agriculture. Using ammonia as fuel in shipping would increase the worldwide demand according to the uptake of ammonia-fueled technologies. This would require large investments in the scaling of the production and if the ammonia production plants are producing green ammonia, renewable energy sources to power the production would also have to be available. Scaling the ammonia production to produce fuel will most likely affect the ammonia price in the future.

Firstly, ammonia is commonly divided into 3 different types representing which power source is used to produce it as mentioned in Section 3.6. Naturally, the price for using this primary energy source will directly affect the price of ammonia.

Figure 8.4 show the historic (gray) ammonia prices from 2000 to 2021. The ammonia price has been close to $ 900 per tonnes and as low as $ 100 per tonnes.

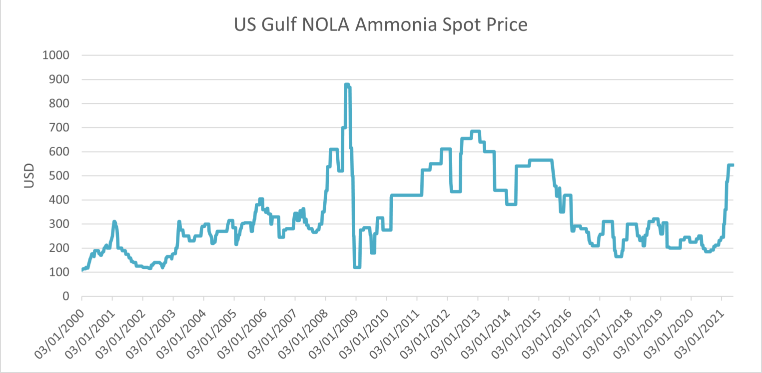


Figure 8.4: Ammonia prices from 2000-2021 [57]

8.3.3 CO_2 Tax Rate

Alternative fuels are currently more expensive than conventional fuels, to make carbon-neutral fuels more competitive, incentives like CO_2 tax could be necessary[58]. Carbon pricing could together with operational and design requirements mean a faster shift towards green shipping. This is currently not implemented for international shipping, though some countries implemented it.

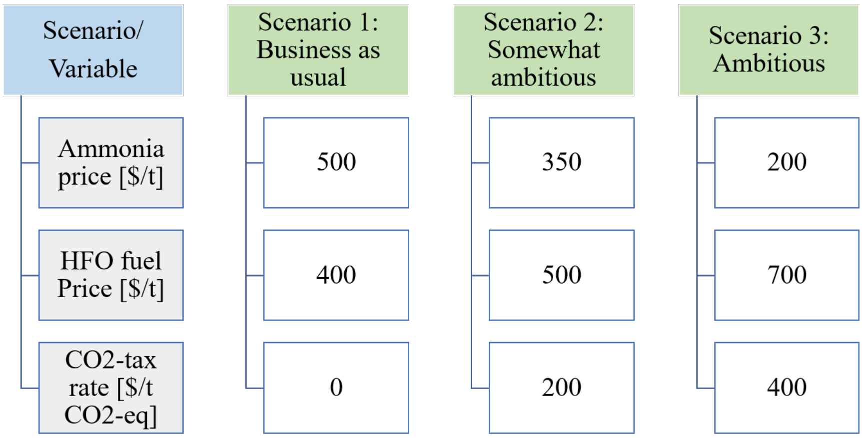
If the carbon pricing exceeds the differential between fossil fuels and carbon neutral fuels, the shift towards green shipping is likely to happen faster[58].

In this model, the carbon pricing is calculated based on the fuel consumption of the vessel, the carbon tax rate and the carbon factor. The tax rate is given in dollars per tonnes CO_2, fuel consumption is given in tonnes and carbon factor is given in CO_2-equivalents per tonnes fuel.

The IMO strategy to reduce GHG emissions can include introducing international carbon pricing. Suggested rates are 200 USD/tCO_2 by 2040 and 400 USD/tCO_2 by 2050 [58]. These values will be used in different scenarios in the case study.

8.3.4 Chosen Scenarios with Market Values

The three variables listed in the previous chapters; ammonia prices, conventional fuel prices and CO_2 taxes will contribute to the cumulative costs of the design alternatives. There are many external factors affecting these variables, for instance how electricity prices will greatly affect the ammonia price. To better understand how fuel price and CO_2 tax affect the cumulative costs of the designs, three different combinations of values for these variables are put together. One business-as-usual alternative with high ammonia price, no carbon pricing and low HFO price. The second is a somewhat ambitious combination with medium-low ammonia price, medium carbon pricing and medium HFO fuel price. The last combination is the ambitious scenario with ambitious scenario, with low ammonia price, high HFO price and high carbon pricing. These three alternative combinations are listed in Figure 8.5.



Scenario/ Variable	Scenario 1: Business as usual	Scenario 2: Somewhat ambitious	Scenario 3: Ambitious
Ammonia price [$/t]	500	350	200
HFO fuel Price [$/t]	400	500	700
CO2-tax rate [$/t CO2-eq]	0	200	400

Figure 8.5: Chosen future scenarios for fuel prices and carbon pricing rates

The conceptual design model can visualize the effects of any values for these variables. These combinations will present examples from different parts of the range for each of the variables.

9

Case Study Results

This chapter presents the techno-economic results from the case study using ship dimensions and operational profile presented in Chapter 8 applied to the conceptual design platform presented in Chapter 7. The results include graphs and figures as they appear in the conceptual design platform.

9.1 Visualization Results

The following images show the visualization of the four ammonia tanker design alternatives with the dimensions presented in Section 8.2.1. The vessel design will not be changed for the different scenarios. The cylindrical fuel tank located on the deck is included for a clearer illustration of the fuel tank volume.

Design 1: Two-stroke, Internal Combustion Engine Powered with Scrubber, HFO-fueled Vessel

Figure 9.1 show the visualization results of the HFO-fueled design. The different modules of the vessel are labeled. The internal combustion engine space is in this design 625 m^3 and the fuel tank volume is 399 m^3.

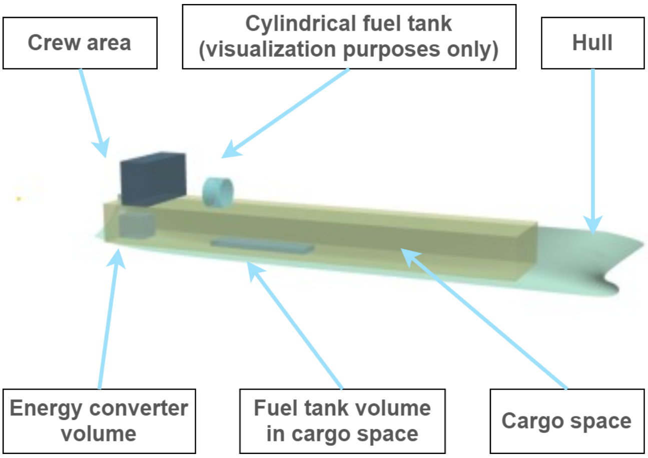


Figure 9.1: Visualization results, ICE HFO-fueled vessel

Design 2: Two-stroke, Internal Combustion Engine Powered, Ammonia-fueled

Figure 9.2 show the visualization results for the first ammonia-fueled design, the internal combustion engine. The same module labels as Figure 9.1 is applicable. The internal combustion engine space volume is here 412 m^3 and the fuel tank volume is 1781 m^3.

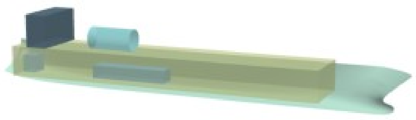


Figure 9.2: Visualization results, ICE ammonia fueled vessel

Design 3: Proton Exchange Membrane Fuel Cell Powered, Ammonia-fueled Vessel

Figure 9.3 show the visualization results for the second ammonia-fueled design, the proton exchange membrane fuel cell. The same module labels as Figure 9.1 is applicable. The fuel cell space volume is here 509 m^3 and the fuel tank volume is 1635 m^3.

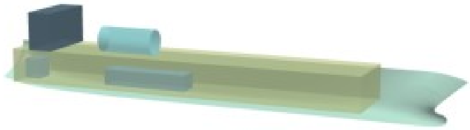


Figure 9.3: Visualization results, PEMFC ammonia-fueled vessel

Design 4: Solid Oxide Fuel Cell Powered, Ammonia-fueled Vessel

Figure 9.4 show the visualization results for the third ammonia-fueled design, the solid oxide fuel cell design. The same module labels as Figure 9.1 are applicable. The fuel cell space volume is here 1783 m^3 and the fuel tank volume is 1286 m^3.

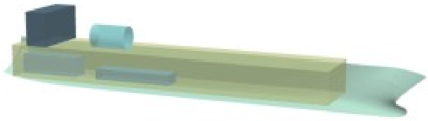


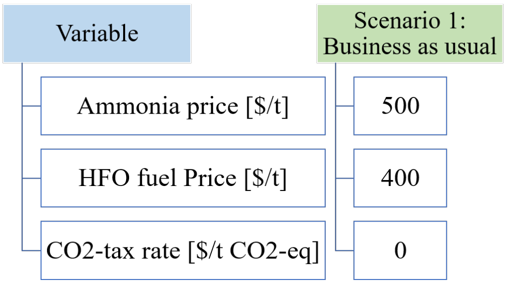
Figure 9.4: Visualization results SOFC, ammonia-fueled vessel

9.2 Economic Results

This section presents the economic results for the four design alternatives for the case study for three different future scenarios including market values for HFO fuel price, ammonia fuel price and CO_2 tax rate.

9.2.1 Cumulative Costs, Scenario 1: Business-as-usual

The business-as-usual market parameters is re-visualized in Figure 9.5 and give the results shown in Table 9.1 and Figure 9.6.



Variable	Scenario 1: Business as usual
Ammonia price [$/t]	500
HFO fuel Price [$/t]	400
CO2-tax rate [$/t CO2-eq]	0

Figure 9.5: Market values for HFO, ammonia and CO_2 tax rate, scenario 1: business-as-usual

Table 9.1 show that the lowest total costs are found for the HFO design with mUSD 340, next is the ammonia-fueled internal combustion engine with mUSD 1025, then the PEMFC design with mUSD 1151 and the SOFC with the total costs of mUSD 1490. Hence, the HFO-fueled design is the clear "winner" in terms of total lifetime costs in this scenario.

Table 9.1: cumulative costs results scenario 1: Business-as-usual

Design alternative	**HFO**	**ICE**	**PEM**	**SOFC**
Total cost of ownership $[mUSD]$	340	1025	1151	1490

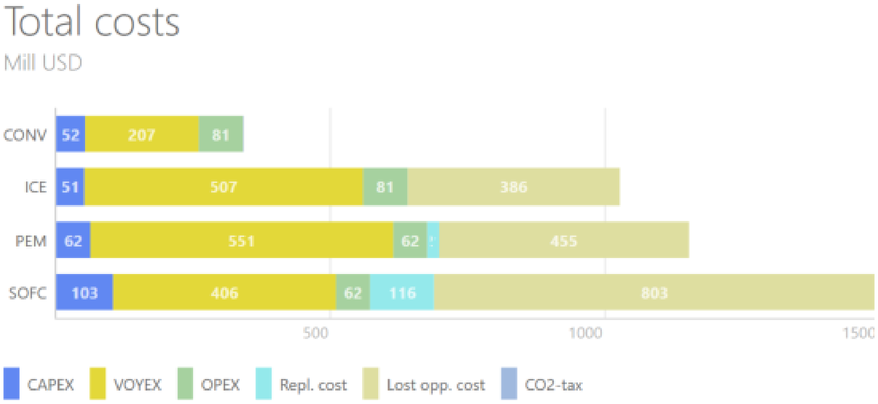


Figure 9.6: Cost results all design alternatives for scenario 1: business-as-usual

9.2.2 Cumulative Costs, Scenario 2: Somewhat Ambitious

This section shows the results for scenario 2: somewhat optimistic market values. The market parameters for this scenario are retold in Figure 9.7.

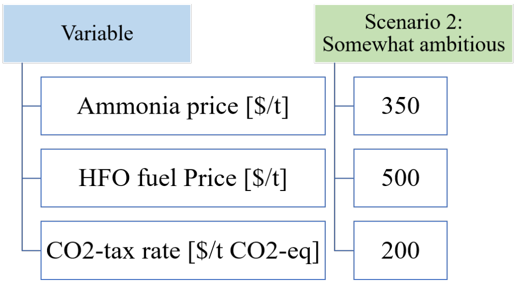


Figure 9.7: Market values for HFO, ammonia and CO_2 tax rate for scenario 2: somewhat ambitious

Table 9.2 and Figure 9.8 presents the results in scenario 2: somewhat ambitious. Here, the HFO-fueled internal combustion engine has the lowest total cost of ownership with mUSD 664, next is the ammonia-fueled internal combustion engine design with mUSd 766, then the PEMFC design with mUSD 859 and lastly the SOFC design with total costs of mUSD 1136.

Table 9.2: cumulative Costs, somewhat Ambitious

Design alternative	**HFO**	**ICE**	**PEM**	**SOFC**
Total cost of ownership $[mUSD]$	664	766	859	1136

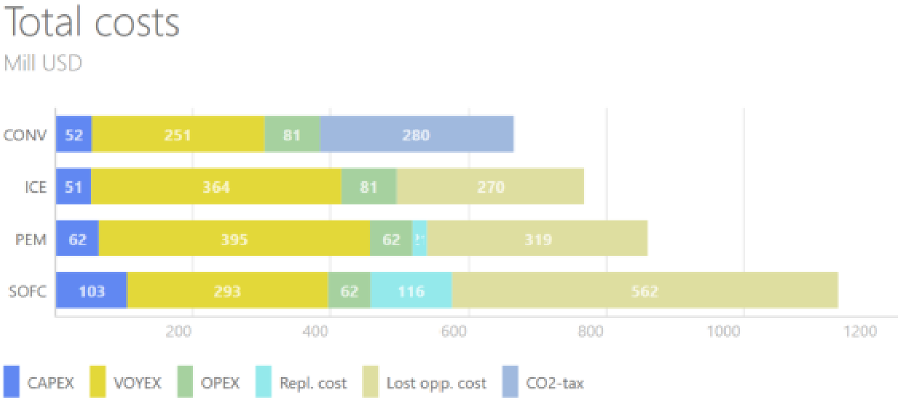
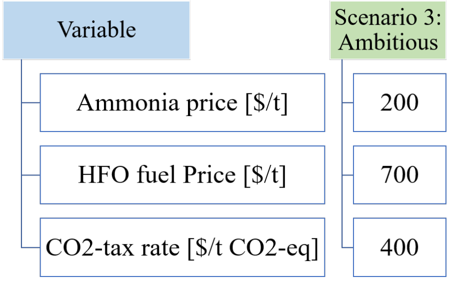


Figure 9.8: Cost results all design alternatives, scenario 2: somewhat ambitious

9.2.3 Cumulative Costs, Scenario 3: Ambitious

The ambitious scenario results portray a "best case scenario" with the market values for ammonia price, HFO price and CO_2 tax rate retold in Figure 9.9.



Variable	Scenario 3: Ambitious
Ammonia price [$/t]	200
HFO fuel Price [$/t]	700
CO2-tax rate [$/t CO2-eq]	400

Figure 9.9: Market values for HFO, ammonia and CO_2 tax rate for Scenario 3: ambitious

The results from the conceptual design dashboard for the ambitious market values are shown in Table 9.3 and Figure 9.9. The lowest costs in this scenario are found for the ammonia-fueled internal combustion engine with mUSD 507, next is the PEMFC design with mUSD 565, then the SOFC with mUSD 782 and lastly the HFO design with mUSD 1032. For this scenario all the ammonia-fueled design has lower total lifetime costs than the HFO-fueled vessel design.

Table 9.3: Optimistic cumulative costs results

Design alternative	HFO	ICE	PEM	SOFC
Total cost of ownership $[mUSD]$	1032	507	565	782

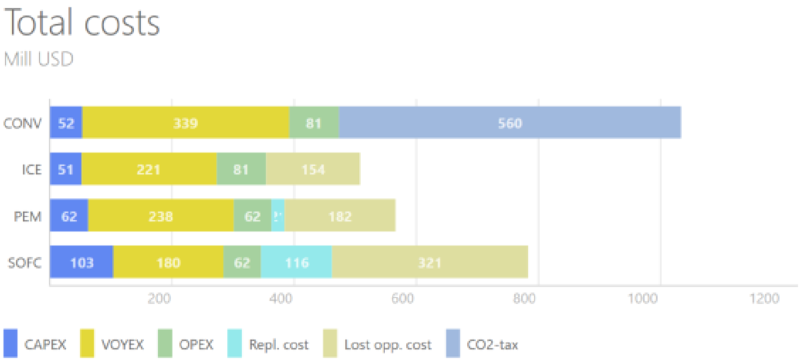


Figure 9.10: Cost results all design alternatives, scenario 3: ambitious

9.2.4 Cost Comparison Across Scenarios

Figure 9.11 shows a comparison of the results for all the scenarios. A general trend of decreasing costs for the ammonia-fueled designs can be seen from scenario 1 to scenario 3 while the HFO fueled design total costs increases.

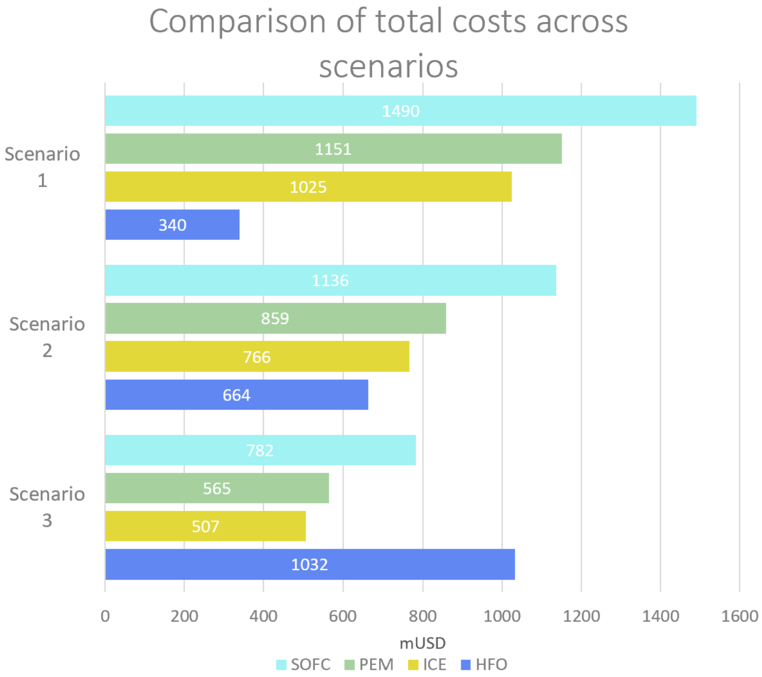


Figure 9.11: Cost results all design alternatives, all scenarios

9.3 Volume Comparison for Design Alternatives

Figure 9.12 presents the volume for the fuel tank and energy converter space for the different design alternatives. The cost model includes lost opportunity cost where more volume demanding energy converter space and fuel tank volume is “punished”. Low volume is therefore desired.

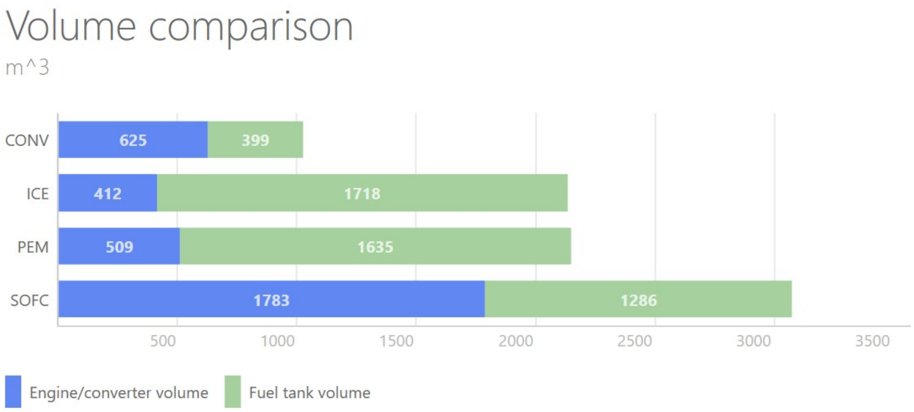


Figure 9.12: Test results ammonia-fueled vessel

Table 9.4 lists the volumes presented in Figure 9.12 as well as the total volume of the energy converter and fuel tank in % of the cargo volume without lost space to energy converter and fuel tank which is 51495 m^3 in the case study. The results show that the HFO design fuel tank and energy converter volume occupy 2 % of the cargo volume, the ammonia-fueled internal combustion engine design 3.9%, the PEMFC 4% and the SOFC 6%.

Table 9.4: Volume comparison for the design alternatives

Design alternative	**HFO**	**ICE**	**PEM**	**SOFC**
Volume of energy converter [m^3]	625	412	509	1783
Volume of fuel tank [m^3]	399	1718	1635	1286
Total volume energy converter and fuel tank [m^3]	1024	2130	2144	3069
% of cargo volume	2.0	3.9	4.0	6.0

9.4 Sensitivity Analysis

The scenario results show sensitivity to fuel price and carbon taxation. It is recognized that there can be several uncertain factors in the model, including both input data and methods. The sensitivity for the conceptual design platform will therefore be tested for two uncertain data inputs, listed below:

- SOFC service efficiency
- CAPEX SOFC

Efficiency

From the economic results in this chapter, it is observable that VOYEX is a very important factor of the competitiveness of ammonia-fueled designs. VOYEX includes fuel costs which make the results sensitive to the fuel price. The fuel price is varied as a part of the main results and the significance of the fuel price is an important finding. However, the amount of fuel used and hence fuel consumption, and further back, the efficiency of the energy converter will also very important as the fuel is such a large part of the total costs. Increased efficiency for either of the technologies can have a large effect on the results. To illustrate this, different efficiencies were tested. Although internal combustion engines are a mature technology, the efficiency can vary, however, the less mature technologies are likely to vary more in terms of efficiency and are likely to improve proportionately with the uptake of the technology. Three efficiencies were tested for the solid oxide fuel cell which is the least mature technology, the results are shown in Table 9.5. The somewhat optimistic market values for ammonia price, HFO price and CO_2 tax rate are used. Varying the other efficiencies will also have a similar effect.

Table 9.5: Sensitivity analysis of the total service efficiency for the SOFC design alternative

Efficiency	**Total costs of ownership** $[mUSD]$
0.59 (−3.3%)	1155 (+1.6%)
0.61	*1136*
0.63 (+3.3%)	1115 (−1.8%)
0.65 (+6.5%)	1097 (−3.4%)

Table 9.5 show that increasing the efficiency has an effect on the total costs of ownership, decreasing the total costs by 1.8% is the total efficiency is increased to 0.63 and decreasing the total costs with 3.4% when increasing the efficiency to 0.65. Comparing the costs with the results in scenario 2: somewhat ambitious, in Table 9.2, show that this improved efficiency does not change the order of the cost-effectiveness of the designs in scenario 2.

CAPEX SOFC

Uncertainties regarding cost for the SOFC converter are uncertain due to the relatively low level of technical maturity. The learning effect from the potential uptake of the technology could also affect the cost in a positive way. Table 9.6 shows how the total CAPEX for the solid oxide fuel cell and equipment changes with the cost per kW for the fuel cell. The price drops 42% from the original price each step as suggested by Kim et al. (2020) [32].

Table 9.6 show that the expected decrease of the costs for SOFC can have a large effect on the total costs of ownership for this design alternative. The first step decreases the total costs by 2.2%, the second step by 3.3% and the last step by 4.0%. The order of the total costs for the design alternatives does not change with these results either.

Table 9.6: Sensitivity analysis of the cost per volume for SOFC

Cost per kW	**Total costs of ownership** $[mUSD]$
5500	*1136*
3190 (−42%)	1111 (−2.2%)
1850 (−66.3)	1098 (−3.3%)
1073 (−80.5%)	1090 (−4.0%)

10

Discussion

This chapter firstly discusses the conceptual design dashboard, its value as well as the potential for improvement. Secondly, the chapter discusses the results from the case study.

10.1 Conceptual Design Platform

The conceptual design platform is a tool to assist a user such as a shipowner, ship designer, shipping analyst, etc., to understand the consequences and possibilities of using ammonia as fuel. The platform combines the information collected throughout the literature study to create a platform that can be adjusted to the users' needs. The platform uses an ammonia tanker as the segment can be a likely first mover for using ammonia as fuel. Much of the findings in the platform can be applicable to other segments, although more relevant for similar segments and size types. Including other tanker segments will be possible with just a quick adaption of the model, yet, the platform could also relatively easily be adapted to the bulk segment. Adapting the model to segments like cruise ships or container ships could require larger modifications of the model, however, the same general approach could be used.

Reducing emissions from shipping is the main motivation for writing this thesis. In the conceptual design dashboard and related case study, emissions are only accounted for with CO_2 tax for the HFO-fueled design while the ammonia-fueled designs are portrayed as emission-free. In addition, CO_2 tax is added only to CO_2 emissions and not to CO_2-equivalents. To get a more accurate representation of the emissions, the CO_2-equivalent emissions should also be calculated for both HFO designs and ammonia-fueled designs. A useful extension of the platform would therefore be to include calculations of different emissions related to all the design alternatives as well as their CO_2-equivalent emissions. This requires more research into the emissions from using ammonia as fuel.

Safety is important in vessel design, and ammonia presents challenges to preserve safety. How safety regulations for ammonia-fueled vessels will affect the design of vessels has been a topic in this thesis. There are several design implications, some of which are visualized in the dashboard like a pressure relief vent and a toxic zone around this vent. Others, like double leakage barriers and automatic detection of leaks, are more difficult to visualize and quantify at a conceptual design level.

The conceptual design dashboard uses the integrated fuel tank as default in the cost calculations as it is made for an ammonia tanker where it could be possible to supply fuel from the cargo. The model can be adapted to use a separate, cylindrical fuel tank which is a more likely configuration for other vessel segments. For an ammonia tanker, the whole deck of the vessel is categorized as a hazardous area. An ammonia fuel tank can therefore in principle be placed anywhere on the deck area, although not behind the wheelhouse according to the IGC code. Compliance with this regulation is rather simple for an ammonia tanker but represents a severe challenge for other vessel segments. If an adaption of the model is required in the future to include other segments, the problematics connected to the location of the fuel tank should be studied more closely.

When calculating the total volume of the machinery, the additional equipment to the main energy converter is set at a rigid number and cost. The cracker cost for example for the proton membrane fuel cell design alternative set as $2.4 million and is not dependent on the installed machinery power. The same goes for volume for the additional equipment. This means that the relevance of the calculated costs and volume might deviate if the conceptual design platform is used for very different business cases. The conceptual design platform also assumes all technologies are suited for any installed power, which might not be the case.

The cost model is only as good as its inputs. The model can be improved if more accurate inputs are used. The true costs of each design alternatives could deviate from the results in this thesis, however, they present an estimate and illustrates how the design might differ from each other. The purpose is to quantify and show differences between the design alternatives, which arguably makes the relative values more important than their absolute values[59]. The platform can relatively easily conduct a sensitivity analysis which made it possible to identify and investigate some of the uncertain parameters.

To use the dashboard, the user has to have the software Rhinoceros, Grasshopper and the plugin Human UI installed. With the former requiring a valid license for long-term use, the platform's accessibility is slightly limited compared to a complete open-source solution. The visualization of the dashboard is uploaded using another plugin for Grasshopper, called ShapeDiver. Then the user is able to access the dashboard online which is a lot easier and less time-consuming. It would be beneficial to find a way to implement the whole dashboard online for future use.

To calculate fuel consumption, design speed is used. A more accurate approach would be to use speed data from AIS. Often vessels do not sail at their design speed and therefore the actual fuel consumption could deviate from the calculations. On the other hand, it is difficult to predict which speed the vessels will sail in the future, hence could using design speed to calculate fuel consumption be a good base.

10.2 Results

The visualization results show the four designs where the energy converter and fuel tank volume are visibly different for each design. Requirements for both fuel tank and energy converter space are visibly different. The difference is best observable in the volume comparison. This comparison shows the least volume-consuming engine/converter is the ammonia-fueled internal combustion engine. The reason for the lower volume for the ammonia-fueled ICE is due to the scrubber added to the volume for the HFO-fueled ICE. The SOFC has distinctly the highest energy converter volume with 1783 m^3, occupying 6% of potential cargo volume while the PEMFC occupies 4.0%, the ammonia-fueled ICE 3.9% and the HFO-fueled ICE occupy 2.0% of the potential cargo volume. The SOFC design has the least mature technology and improvements can be expected as the maturity of the technology matures. The fuel tank volume is significantly larger for the ammonia-fueled designs. This is due to the lower volumetric energy density compared to HFO. It is also observable that the SOFC stands out among the ammonia-fueled designs with lower fuel tank volume. This is due to the increased efficiency of the fuel cell compared to the other ammonia-fueled designs.

The economic results show three very different graphs representing the three constructed scenarios. For the business-as-usual case, the HFO-fueled vessel performs best economically by around one third or more of the cumulative costs of the other designs. This is expected as there are currently insufficient incentives in place to make carbon-neutral fuels competitive in terms of total costs and the ammonia price alone is currently too high to make the technology favorable in terms of cost compared to conventional fueled vessels. Out of the ammonia-fueled vessels, the internal combustion engine vessel performs best economically due to the lower CAPEX and lack of replacement costs. The ammonia-fueled PEMFC is relatively close, while the SOFC has higher costs due to the large contribution to lost opportunity costs. Lost opportunity cost is a large cost contributor for all design alternatives, this shows the importance of the lost volumes due to the increased energy converter and/or fuel tank volume for the ammonia-fueled designs. Lost opportunity cost could be decreased by using the cylindrical fuel tank configuration placed on the deck of the vessel, however, this would require more research in the costs related to the configuration.

Already in the somewhat optimistic case, the effect of carbon pricing is observable. The total costs for the HFO-fueled design are almost doubled, much due to the carbon pricing, hence the ammonia designs are here almost able to compete, the ammonia-fueled ICE design is mUSD 102 more costly than the HFO-fueled ICE which in this case study is relatively close. The PEMFC design is close behind. The SOFC powered vessel is still the most costly out of the ammonia-fueled designs again much due to the large cost contribution from lost opportunity cost.

The optimistic scenario shows a change from HFO being the preferred option in terms of cost to having all the ammonia-fueled options being less costly than the HFO-fueled design. With high carbon pricing, the HFO design is not at all in the competition anymore. The HFO-fueled design has now mUSD 250 and higher total costs than the ammonia-fueled designs.

The sensitivity analysis illuminates how a potential increase in efficiency and predicted decrease of the costs for the SOFC fuel stack can affect the total costs for the SOFC design. Increasing the efficiency does not for this operational profile change the order of which designs are least and most cost-effective. The same goes for the decreased CAPEX of the sOFC.

11

Conclusion

This thesis has investigated how the use of ammonia in deep-sea shipping will affect the vessel design and how using ammonia as fuel influence the competitiveness of a vessel compared with conventionally fueled vessels. A conceptual design platform was created to study how different requirements (inputs) affect the design of ammonia-fueled vessels as well as the costs (outputs). Three different designs using ammonia and one using heavy fuel oil (HFO) as fuel were developed in a conceptual design platform using the software Rhinoceros with relevant plugins. In a conceptual design dashboard, these proposed designs can be modified for a specific operational profile and be compared with respect to their economic performance for chosen market values. The platform operationalizes important literature findings within an application in order to (interactively) provide the user with an understanding of the consequences of ammonia as a fuel in their (a specific) business case. Combining visualization of ammonia-fueled vessel designs with cost estimation communicates the findings in an intelligible way.

Discussions with stakeholders have shown that the conceptual design platform can be a good way to communicate important aspects like cost, volume allocation and safety regarding the use of alternative fuels. In this thesis, the platform is developed for ammonia tankers using ammonia as fuel, but the same approach could be useful for other segments and fuel types. The general idea of applying findings from literature to a platform like the one presented in this thesis will in many cases provide an important resource for communicating the potential for alternative fuels.

The conceptual design platform was successfully tested in a case study where four different designs were compared for one operational profile with three combinations of market values for ammonia price, HFO price and CO_2 tax rate. The case study results show how introducing carbon pricing can be an important incentive to generate a level-playing field for low-emission shipping solutions and the uptake of carbon-neutral fuels like ammonia. Carbon pricing is responsible for a very large part of the total costs for the HFO-fueled vessel in the ambitious and somewhat ambitious scenario used in the case study. For scenario 2 the ammonia fueled concepts are closer to competing with the HFO-fueled design while in scenario 3, the ammonia-fueled designs all outperform the HFO design in terms of total costs.

11.1 Suggestions for Further Work

This thesis shows the potential for ammonia-fueled technology in deep-sea shipping for certain market scenarios. The choice of market parameters and their values is in this thesis chosen from historic lows, highs and today's values and is likely to differ from the future values of these parameters. The model could therefore benefit from a more extensive study into the future values of these parameters.

There is an ocean of opportunities to expand the conceptual design platform. It would in particular be interesting to expand the model to include more alternative fuels as well as other ship segments. This will widen the applicability of the platform to cover a large part of the world shipping fleet and hence the emissions from shipping. With more options available within the platform, a more holistic representation of the situation for alternative fuels can be observed. This will give insight into the challenges towards zero-emission shipping and how the different pathways towards carbon-neutral shipping compare to each other.

The conceptual design platform is used with one ship design and operational profile for three different scenarios. It would be interesting to use the platform for several other designs and other scenarios and study the findings.

The conceptual design platform calculates the CO_2 tank-to-wake emissions, emissions from burning the fuel on board, for the HFO-fueled design related to carbon pricing. A useful extension of the platform would be to include calculations of different emissions like NO_x, SO_x and PM related to all the design alternatives as well as their CO_2-equivalent emissions. This would require more research into the emissions from using ammonia as fuel. In addition to this, it would be interesting to include well-to-tank emissions, e.g. emissions from fuel production. Decarbonizing shipping operations makes the building and scrapping of ships a larger part of the total life cycle emissions from shipping, it would therefore also be interesting to include these emissions in the conceptual design platform.

From the results in this thesis, it can be observed that costs related to fuel are of special importance for ammonia-fueled designs. There are technologies that can increase the efficiency of a vessel and hence decrease the fuel costs and fuel storage costs. This includes, but is not limited to, (rotor) sails and waste heat recovery systems. It would be a great addition to the conceptual design platform to include such technologies.

It is unarguable that an online version of the conceptual design dashboard would be more user-friendly. Therefore it will also be a suggestion for further work, to find a way to have the complete dashboards from Human UI online, including all the elements from the dashboard like it looks today as well as the expansions of the dashboard.

The cost model is simplified and tuning this further to have more precise costs would also improve the model. This includes making the equipment costs dynamic and related to the chosen installed machinery power for more precise cost estimation and volume estimation. For example, would it be an improvement to make operational costs dependent on the installed energy converter power and/or ship size and segment. Differentiated port costs based on for example carbon intensity index could reduce voyage expenditures for costs for zero-carbon vessels, including this in the conceptual design model would also be a useful addition to the cost model.

In terms of design, the main focus is on volumes for the main systems of the designs. Another useful addition to assess the designs is to include weight for the different designs and other design key performance indicators (KPI). Including an assessment of the stability of the different designs would then also be a useful extension. Including other KPIs like environmental KPIs would give the user more base for deciding the best performing design alternatives.

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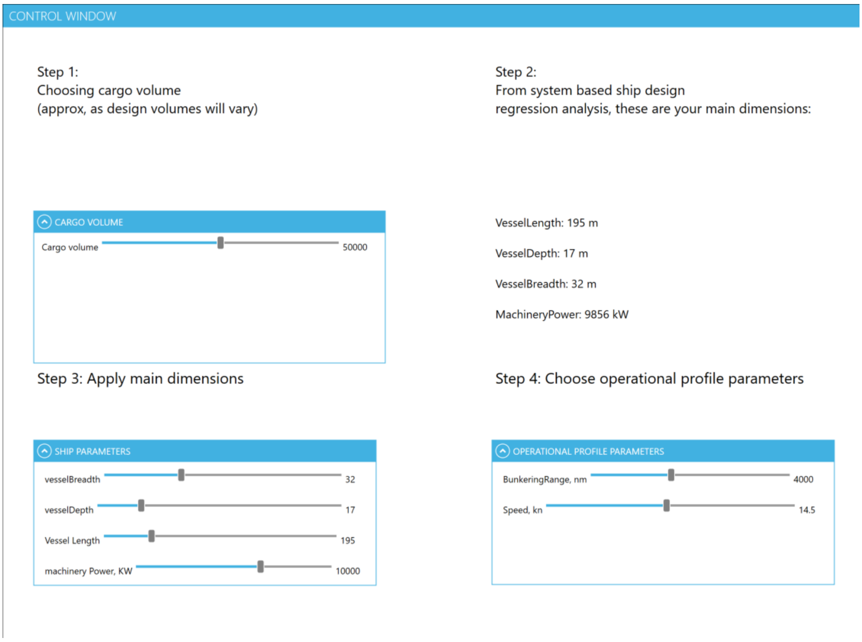
A

Conceptual Design Platform



Step 1:
Choosing cargo volume
(approx, as design volumes will vary)

Cargo volume 50000

Step 2:
From system based ship design
regression analysis, these are your main dimensions:

VesselLength: 195 m

VesselDepth: 17 m

VesselBreadth: 32 m

MachineryPower: 9856 kW

Step 3: Apply main dimensions

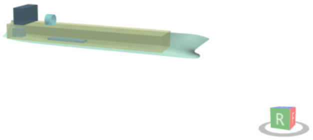
vesselBreadth 32
vesselDepth 17
Vessel Length 195
machinery Power, KW 10000

Step 4: Choose operational profile parameters

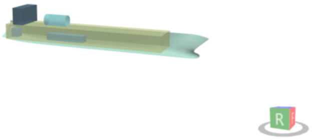
BunkeringRange, nm 4000
Speed, kn 14.5

Step 5: Study design alternatives

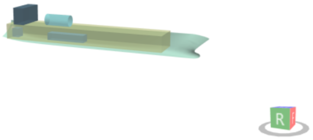
HFO fuelled ICE vessel



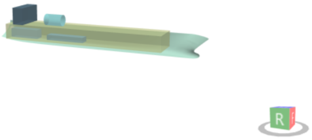
Ammonia fuelled ICE vessel



Ammonia fuelled PEMFC vessel

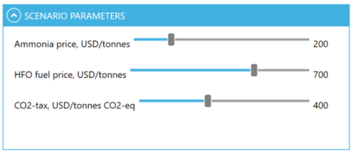


Ammonia fuelled SOFC vessel



Step 6:

Choose market parameters



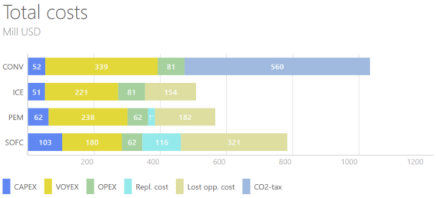
Ammonia price, USD/tonnes 200

HFO fuel price, USD/tonnes 700

CO2-tax, USD/tonnes CO2-eq 400

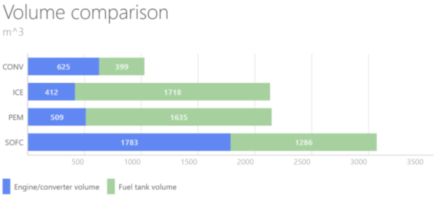
Step 7:

Cost comparison for all design alternatives



Step 8:

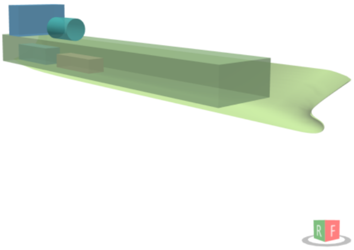
Compare volumes for all design alternatives



Step 9: Choose design alternative

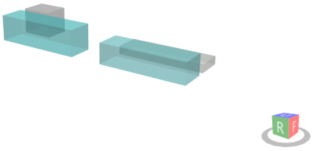
Machinery choice: SOFC

Step 10: Study chosen design



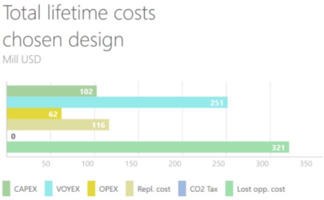
Step 11:
Comparison of volumes (fuel tank and engine):

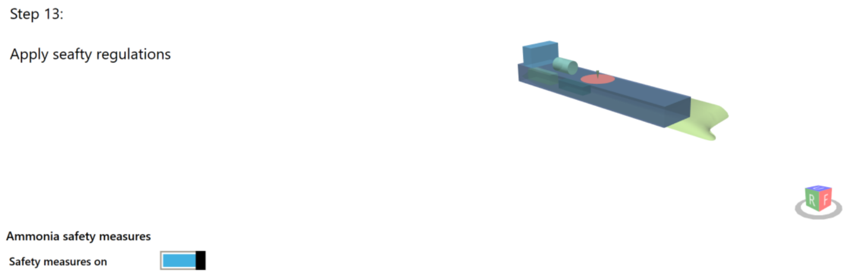
BLUE: selected design
GRAY: HFO design



Step 12:

Cost estimation for chosen design alternative





Step 13:

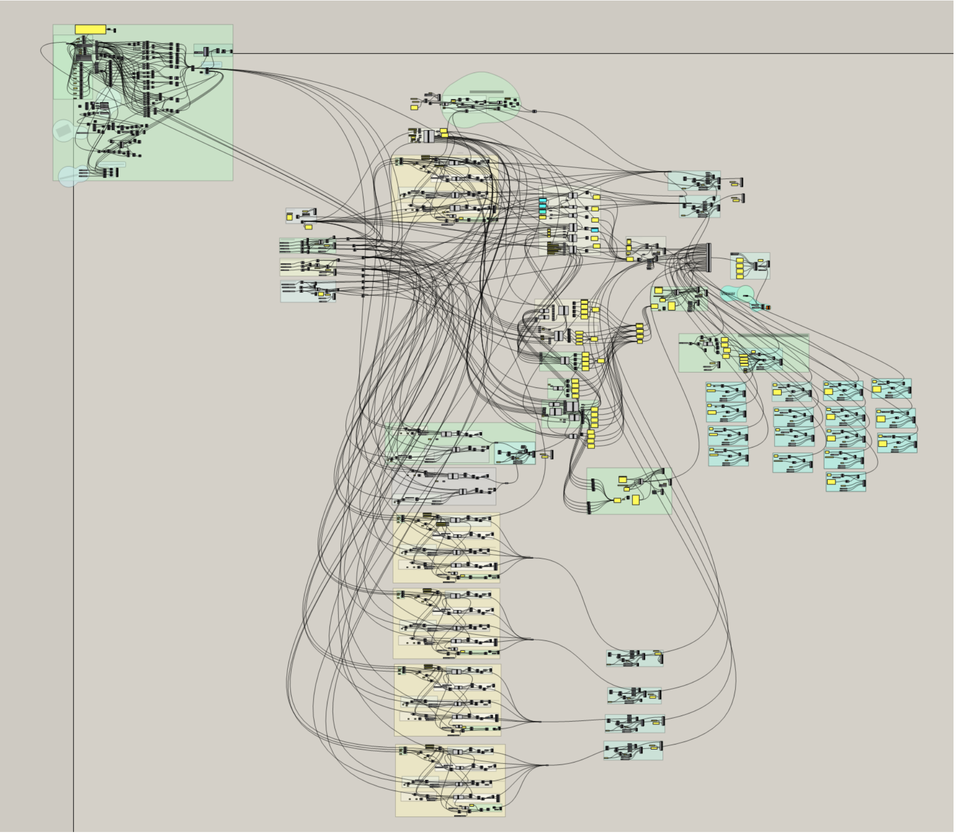
Apply seafty regulations

Ammonia safety measures

Safety measures on

B

Grasshopper Canvas



C

Conceptual Design Dashboard Illustration Video Link

Link to introduction to conceptual design dashboard video: https://youtu.be/t3ge8mGPDQU

D

ShapeDiver Visualization- Link and Instructions

ShapeDiver is a plugin for Grasshopper where a visualization made in Grasshopper can be uploaded online. The ShapeDiver visualization for the conceptual design platform can be found at the following link:

`https://app.shapediver.com/m/conceptual-design-of-ammonia-tanker-dasboard-2`

The link opens a web page where the ship visualization can be found. On the right side of the page is the inputs which can be changed. The following list describes these inputs:

1. Vessel length, breadth and depth: choose the dimensions of the vessel.
2. Energy converter power: choose installed power for the energy converter
3. Choose energy converter: choose either the conventional HFO combustion engine (CONV) design, the ammonia fuelled internal combustion engine design (ICE), the PEMFC design (PEM) or the SOFC design (SOFC)
4. Bunkering range: choose the distance between bunkering stations for the operational profile.
5. Safety zone on/off: choose to visualize an example of a safety zone around a pressure relief mast.