Evaluating emissions of offshore transportation vessels

V.P.M. Peeten 4375637

Report Number: MT.22/23.012.M

TU Delft

ULSTEIN®

Evaluating Emissions of Offshore Transportation Vessels

by

V.P.M. (Vino) Peeten

to obtain the degree of Master of Science in Marine Technology
at the Delft University of Technology,
to be defended publicly on Tuesday November 29, 2022 at 15:00 PM.

Document number:	MT.22/23.012.M	
Student number:	4375637	
Project duration:	February, 2022 – November, 2022	
Supervisors:	Dr. A. A. Kana,	TU Delft
	Ir. J. D. Stroo,	Ulstein Design & Solutions B.V.
	Ir. B. Daman,	Ulstein Design & Solutions B.V.
Thesis committee:	Dr. A. A. Kana,	TU Delft, chair
	Ir. J. J. Zwaginga,	TU Delft
	Ir. J. D. Stroo,	Ulstein Design & Solutions B.V.
	Dr. D. Fiscaletti,	TU Delft

Preface

Dear reader,

The thesis is finished, although the work is not yet done. With this thesis I complete my final project on the evaluation of emissions from alternative fuels in offshore transportation vessels.
Having delved into numerous climate reports, I feel that the work on this topic has just begun. Alternative fuels can facilitate the transition to a more sustainable world, but are not yet an obvious choice due to a lack of incentives for companies I hope that through this work I can convince you of the relevance of choosing alternative fuel systems in ship design.

First of all, I would like to express my gratitude to Austin Kana. Thank you for the guidance, the structuring, restructuring, discussions and feedback during the writing of this thesis, and thank you for scouring my work looking for awkward English.

Ko Stroo's ever-critical eye helped elevate my work to a higher level. During the weekly meetings you were able to immediately identify the problem and steer me in the right direction to solve it. Thank you for your time, help and expertise, I appreciate that immensely.

I would also like to thank Jesper Zwaginga for entrusting me with your tool. I hope I have enriched it well with my environmental parts. Thank you for having me around when I got stuck in Python related bugs and issues or had questions.

Also a big thanks to Jeroen Taen. Thank you for your on-demand assistance with the *Blended Design* tool as well when I was at Ulstein. Together we crushed some bugs and learned a lot in the process.

A big thanks to everybody at Ulstein for the nice time I've had. I really felt part of the team when joining the after-work activities. I'll never forget the *teamuitje* where I was surprised by the dance skills of some of my colleagues. I would also like to thank everybody for the support, advice and encouragement throughout the thesis.
A special thank you to Desmond Eisinger, thanks for being my go-to colleague when a Python interpreter broke or the GIT connection was lost. Thank you very much for all your developer-related support!
And I also would like to thank Kenneth Vonk for all the beautiful renders of ships which don't exist yet, but hopefully will soon make their first voyages.

At the end of my thank you list, I would like to thank all my friends, family, roommates and fellow Froude board members. Thank you for the support, the comfort when I got stuck, but also for the non-academic distraction I needed from time to time.

Vino Peeten
Rotterdam, November 2022

Abstract

The offshore wind market is growing rapidly, and new offshore wind projects are being launched more than ever [27]. To keep up with demand, parts for these wind turbines are being produced all over the world. To get all the parts needed to their destination on time, they must be transported on heavy transport vessels (HTVs).

Today, business cases focused on maximizing profits dictate the design of these vessels. Despite the upcoming energy transition, the environmental impact of these vessels is usually neglected. Therefore, there is a need for a method to evaluate the economic and environmental performance of HTVs.

One basis for such a method is *Blended Design*, as developed in a graduation research by Zwaginga et al. [91]. This method is able to cope with market uncertainties in the early stages of ship design by expanding knowledge when design freedom is still high. This is achieved by combining market forecasts for offshore wind farms with multiple vessel designs. An uncertainty model then evaluates the financial performance of the vessels in the market, allowing designers to explore the performance on basic main dimensions of an offshore wind installation vessel.
The main limitations of this method are that it is not able to optimize on environmental performance and evaluate the financial impact of alternative fuels.

Due to growing concerns about climate change, Ulstein has seen an increase in requests for the use of alternative fuels in ship designs. For this research, HFO, methanol, ammonia and liquid hydrogen are being investigated as these alternative fuels are considered future-proof.

The use of alternative fuels in ship design involves some adjustments to the *Blended Design* method Due to the different gravimetric and volumetric densities of these alternative fuels, this has implications for the endurance of the ship design and the amount of cargo the ship can carry.
Changing system and installation requirements and varying fuel costs also drastically alter the financial performance of alternative fuels on ship designs.

The proposed methodology accounts for these changes and quantifies alternative fuel emissions by converting them to CO_2-equivalent emissions. In this way, other greenhouse gases such as CH_4 and N_2O are also included in this metric. The environmental performance is then expressed in the EEXI-equivalent: the amount of CO_2-e emitted by the ship design per tonmile. The EEXI-e index makes it possible to compare the various alternative fuels in terms of their environmental performance on the same basis.

In this work the EEXI-e method is combined with the original *Blended Design* method and the method is adapted to include alternative fuels. This makes it possible to evaluate the environmental performance and associated financial impacts of different alternative fuels.

Because financial and environmental performance are now linked, it is possible to examine the impact of different ranges of carbon taxes. The case study results presented in this thesis show that the carbon tax has a large impact on the financial performance of the ship when it is applied. When enforced, the choice of an alternative fuel system becomes more attractive.

The proposed method has provided a guide to ship designers to make better decisions about the main dimensions of a ship at an early stage of ship design. In addition, the method can provide much needed insight in the selection of alternative fuels by evaluating the financial and environmental performance of alternative fuel systems.

List of acronyms

American Bureau of Shipping	**ABS**
Beam	**B**
Capital Expenses	**CAPEX**
Block coefficient	**Cb**
Carbon Capture and Storage	**CCS**
Carbon Intensity Indicator	**CII**
CO2 equivalent	**CO2-e**
Draught	**D**
Dynamic Positioning	**DP**
Deadweight	**DWT**
Emission Controlled Area	**ECA**
Energy Efficiency Design Index	**EEDI**
Energy Efficiency Operational Indicator	**EEOI**
Energy Efficiency Existing ship Index	**EEXI**
EEXI-equivalent	**EEXI-e**
Energy Storage Device	**ESD**
Early Stage Ship Design	**ESSD**
Fuel cell	**FC**
Greenhouse Gasses	**GHG**
Gross Tonnage	**GT**
Global Warming Potential	**GWP**
Hazard Identification	**HAZID**
Heavy Fuel Oil	**HFO**
Heavy Transport Vessel	**HTV**
International Council on Clean Transportation	**ICCT**
Internal Combustion Engine	**ICE**
International Eenrgy Efficiency Certificate	**IEEC**
International Maritime Organisation	**IMO**
Key Performance Indicator	**KPI**
Length	**L**
Liquified Natural Gas	**LNG**
Maritiem Research Instituut Nederland	**MARIN**
International Convention for the Prevention of Pollution from Ships	**MARPOL**
Markov Chain with Rewards	**MCR**
Maximum Continuous Rating	**MCR**
Marine Diesel Oil	**MDO**
Marine Gas Oil	**MGO**
Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping	**MMMCZCS**
Newbuild Costs	**NC**
New York	**NY**
Operational Expenses	**OPEX**
Offshore Wind Farm	**OWF**
Particle Matter	**PM**
Power Take-In	**PTI**
Power Take-Off	**PTO**
Required Freight Rate	**RFR**
Return On Investment	**ROI**
Set-Based Design	**SBD**
Selective Catalytic Reduction	**SCR**
Systems Engineering	**SE**
Ship Energy Efficiency Management Plan	**SEEMP**
Specific fuel consumption	**sfc**
State of the Art	**SoA**
Tank-to-Wake	**TtW**
United Statess of America	**USA**
Voyage Expenses	**VOYEX**
Speed	**Vs**
Well-to-Tank	**WtT**
Well-to-Wake	**WtW**

List of Figures

List of Tables

Contents

Part 1
Introduction & Problem Analysis

’The time of picking winners is already gone’
Fiona Wild - BHP Vice President Climate Change & Sustainability

1 Introduction

With the ever-growing world population and the rising quality of life of every individual [62], energy demand is peaking like never before [88]. This exploding demand for energy must be met somehow. One promising way to meet this growing demand for energy in the least polluting way is by transitioning to green and sustainable solutions as much as possible, like using the sun, tides, water or wind as energy sources. The latter is one of the solutions that has been gaining momentum lately: offshore wind. Installing massive wind energy farms off the coast can accommodate part of the growing energy demand. To further increase the generative capacity of each wind turbine and thus maximise energy production, the size of the turbine is expected to increase. According to an article by Durakovic [22], the swept area of a wind turbine could be almost the size of 5.5 standard football pitches in area by the end of 2024.

In March 2022, the Dutch government - *de Rijksoverheid* - confirmed this suspicion by announcing that it has agreed to double the production of offshore wind energy by building five new wind farms with a total capacity of 21 GW by the end of 2030 [69]. This creates a huge increase in demand for offshore wind energy contractors.
The idea of meeting part of the world's energy needs in a sustainable way sounds very tempting, but the wind farms first have to be built before generating wind energy.

An internal study done by Ulstein Design & Solutions B.V. (hereinafter referred to as Ulstein) in collaboration with Clarckson Offshore & Renewables and Platau [81] figured that the transshipment from the production site to a marshalling port is a possible bottleneck. A marshalling port is a place where big pieces of cargo are temporarily stored, waiting until being transported to the installation site. Currently, there are not enough vessels available to transport these components quickly, reliably and safely from A to B, especially considering the growing demand of the offshore wind turbine market.

To respond to this growing demand for offshore wind turbines, Ulstein has developed the HX120 Heavy Transport Vessel (HTV). This type of vessel is characterized by its big, flush main deck capable of transporting big and bulky cargo. Based on the research from Clarckson & Platau it is expected that the demand for this type of ships increase a lot these days, making it a very interesting market for companies to tap into.

The way ships are being designed nowadays is mainly cost-driven, often the most profitable design is selected. Since 2020 Ulstein incorporates alternative fuels in ship designs. With the upcoming energy transition and due to the purpose of the HX120 - transporting goods which are used for generating green energy - Ulstein requested a research to measure the effects of sustainability in the design of the ship as well.

1.1. Status Quo of the HTV

This section aims to explain the design of the heavy transport vessel (HTV), the main characteristics, what it is used for and the way it is being designed at this point. It concludes with limitations of the current design methods.

1.1.1. What is an HTV

An HTV is a heavy transport or feeder vessel which combines long transit efficiencies, beneficial payload and proper financial performance for heavy and bulky cargo which doesn't fit in a standard TEU container [82]. The displacement and stability are carefully tuned to minimise vessel motions, being mostly heavy and versatile cargo. Ulstein's answer to this type of vessel is called the HX120, shown in figure 1.1. This ship - which is still a concept - is comparable to a floating pontoon with its very large, unobstructed deck area, on which the various parts (monopiles, towers, topsides, nacelles, blades) can be loaded and transported efficiently and safely over very long distances. The main advantage of this vessel is the high transit efficiency and a low risk of cargo loss since the main deck is especially designed for bulky cargo parts as it is flush with a lot of space inside the hull. The ship design can be equipped with Ulsteins signature X-BOW for higher speeds while maintaining a stable seagoing resulting in lower accelerations during transit.

Figure 1.1: A rendered image of a heavy transport vessel (HTV)

The initial concept design of the HX120 design parameters are shown in table 1.1 below.

Table 1.1: Initial concept design dimensions of the HX120 design by Ulstein

Parameter	Value	Unit
Lenght	170.8	m
Beam	42.0	m
Draught (design)	8.0	m
Speed (max)	12	kts
Accomodation	20	POB
Deck area	6100	sqm

Propulsion propellers	2 x 3,100	kW
Tunnel thrusters	3 x 500	kW
Main generator sets	3 x 3,150	kW
Deck length	145.6	m
Deck strength	15	t/m^2
Depth to main deck, moulded	13.3	m
Draught (summer)	9.4	m
Deadweight (summer draught)	35,400	mT

1.1.2. How are HTVs currently designed?

Ulstein has developed a tool which is able to evaluate a ship design while encounting for market uncertainty. This enables them to put the costs of a ship into perspective to the ever-changing market of offshore wind.

Since the HTV market is limited, there are not a lot of companies involved in designing these kind of vessels. Examples of companies who are able to design HTVs are Vuyck, Gusto MSC, C-Job and Ulstein Design & Solutions B.V. to name a few.

A lot of design companies more or less follow the same kind of steps in order to design a vessel according to the needs and wishes of the customer. The different phases are shown in figure 1.2.

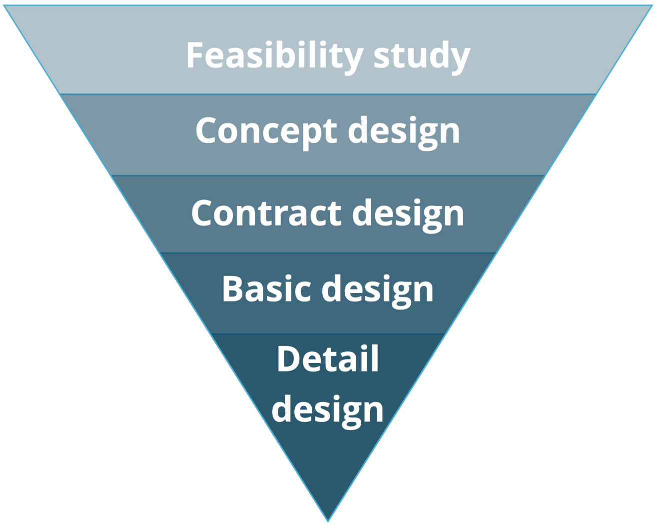


Figure 1.2: The initial design phases of design companies

During the **feasibility study** the customers wishes and ideas are formulated and those are being researched to match with reliable facts and figures. Often this is a critical factor for the future success of a project [26].
In the **concept design** phase, the initial design is being set up and revised to come to a point where a feasible design with main dimensions is sketched out. This results in a General Arrangement (GA) with a specification that is detailed enough for a shipyard to be able to tender an estimate. Ship-owners can use this to consider if the investment fits their business case, since the cost estimations are still about 10 to 20% off.
During **contract design**, the customer gets an adequately detailed basic for new-building contract with the shipyard to be signed. Previous work and results can be established and the shipyard can quote a fixed price.
Then the **basic design** is next. This is the point where authorities and classification societies will interfere in the design process. All stability calculations are being done, necessary projections and documents are set up and the required authorities are engaged.
Lastly, the **detail design** phase the complete design is being produced, together with calculations and complete design visualizations and construction drawings.

Each designing company advertises with the fact they do anything to reduce the environmental footprint and use environment-friendly fuels and designs as much as possible, but in the end all design companies have one thing in common; they design the ship to be as efficient and cost effective as possible.

Cost optimization & profit maximization
Due to the heavily commercialized world, the main incentive for each company is to maximize their profits and operate as cost-effective as possible, cutting down operational and capital costs to a minimum. This means when a big investment - like a ship - is scheduled, a comprehensive financial analysis is done beforehand, turning each and every dime in order to synthesize the optimal, most profitable design of a ship.

In order to support decision making with a business case of a design of a ship, Ulstein has developed a new design method called *Blended Design* over the past two years. This method is programmed into a software tool that can be used to design thousands of different versions of the basic dimensions of a complex offshore installation vessel, depending on which type of vessel the software is configured for. The method takes into account the ever-changing market for offshore wind farms, as not only the demand but also the size of the wind turbines changes during the years. After combining all configurations of sizes, speeds and crane capacities, the method can be useful to help make early stage design choices based on economical performance. The past year this design method has already been used in the design of three ships.

1.2. The problem

With the energy transition coming up, optimizing on costs is no longer adequate. A growing number of shipping firms are seeking to improve on this point [85], since intergovernmental organizations like the IMO are gradually pushing towards more environmental friendly solutions when evaluating emissions. This makes the environmental performance of ships becoming an increasingly important key focus point when designing ships.
Also Ulstein Design & Solutions B.V. is looking for ways to improve the environmental impact of ships. Therefore this thesis aims to

> **develop a method that assesses both the economic and environmental performance of HTVs, specifically for future offshore wind**

1.2.1. Subquestions

To split the problem into bitesize parts, the following sub-questions are being researched:
- What are the State of the Art ship design methods and how do they cope with the unique characteristics of HTVs? What are the limitations in the way HTVs are currently designed?
- What are established environmental performance indices and how can they be applied to HTVs?
- How can emissions of alternative fuels be quantified?
- To what extent do alternative fuel systems have an impact on the design of a HTV?
- How does taxing the environmental impact of a ship change the ROI and other financial benchmarks? How are they influencing each other?

1.3. Structure thesis

The thesis is split up into three different parts, as can be seen in figure 1.3. Part I presents the introduction and problem analysis where the reader is brought up to speed with the topic. In the second part the method setup is discussed as well as the case study in order to test the method is formulated. In the last part the results are presented and analysed and a conclusion is drawn.

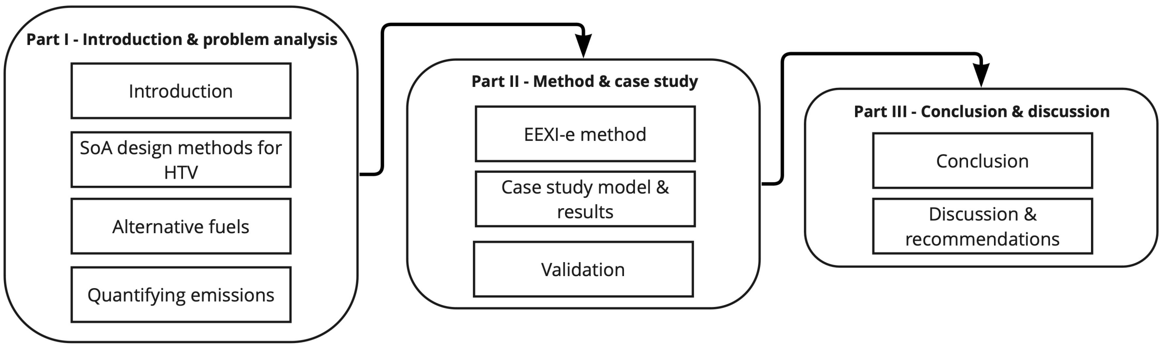


Figure 1.3: The structure of the thesis split up into parts

2

State of the Art of HTV design

This chapter elaborates on the State of the Art (SoA) design methods used when designing ships, how they are relevant to the design and what to look out for when applied to the unique characteristics of an HTV. This chapter ends with a discussion of their limitations.

2.1. Design methods

This section several approaches for a shipbuilder or ship design bureau to come to an established ship design are discussed. These methods help to systematically design a ship from scratch and give structure to the design process by keeping overview on the entire process. Each discussed design method is commonly used and has its own pros and cons.

2.1.1. Point Based Design

Many naval architects are familiar with the 'design spiral' of Evans [30]. It shows the iterative nature of the design process of ship design. Because ship designs are too complex to be described by a set of equations set up beforehand, the iterative nature is necessary. This means in first instance, educated guesses are made for a lot of dimensions, like hull size, displacement etc. which are modified when more precise information is available after an iteration, increasing detail in each iteration. This method is also known as point-based design, since it seeks to reach a single point in the design space [47]. In figure 2.1 this spiral is visible [30].

Although this is a very useful way to set the first sketches of a design, this is also very time consuming method to work with, since it involves close communication between different parties. Each department has its own view and wishes on how the ship design should look and function.
The point based design method results in a more detailed design of one ship design, not a set of ships within a global optimum. This means it is hard to optimize in terms of the ship design measure of merit, such as the Required Freight Rate (RFR) [47] since each iteration of the loop can modify this optimization parameter.

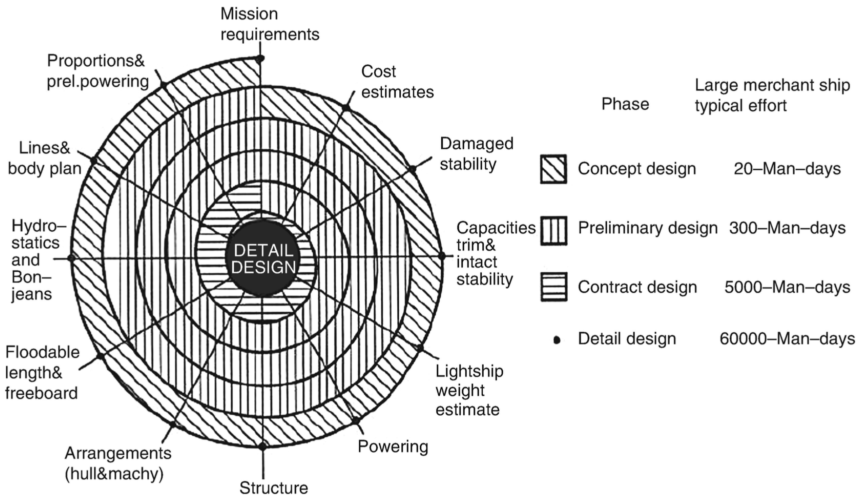


Figure 2.1: The iterative design method, showing the design spiral

2.1.2. Set-Based Design

To speed up the design process, and lower the costs during the design phase, Set-Based Design (SBD) can be used. It sounds counter intuitive, but by delaying big and important decisions, it is possible to save time in the end and boost quality.

A study done by Singer et al. [76] stated three reasons why Set-Based Design is less expensive, time saving and higher in quality. The first one is SBD tries to reduce the committed costs, also called incurred costs, of a project and keep this as low as possible.

Secondly, in the beginning of a project very few details concerning the design are well defined nor developed or understood. A big design decision in the beginning is often difficult, since it is based on little knowledge due to incomplete data. The knowledge increases over time, making it easier for engineers, managers and customers to better understand the implications.

The last area that SBD beats other design methods is the stakeholder influence. In initial design, the stakeholders have the greatest impact on design. By delaying big design decisions and the commitment of costs until later in the design process, the time stakeholders have influence on a design is increased. This can be seen in figure 2.2.

To implement SBD, there are three principle concepts: 1) consider a large number of design alternatives by understanding the (feasible) design space, 2) allow specialists to consider a design from their own perspective, and 3) use the intersection between individual sets to optimize a design and establish feasibility before commitment [6]. The different steps of this process is depicted in figure 2.3.

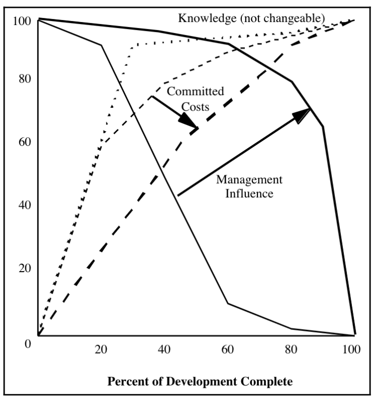


Figure 2.2: Advancing product development practices [6]

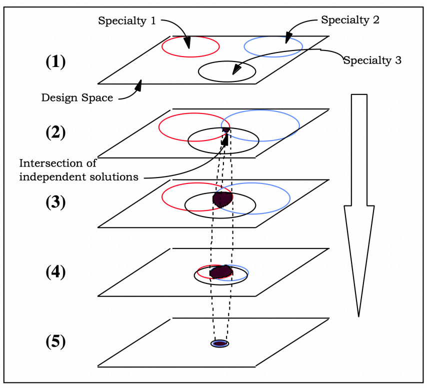


Figure 2.3: The Set-Based Design process Bernstein [6]

Ultimately a smaller set of unified global concepts is created by integrating the sets of designs completed by different functional groups. The integration process is facilitated by conceptual robustness, which is achieved when engineering decisions concerning one aspect of a design remain valid in the face of design decisions made in other aspects of the design. Engineers in a SBD environment are required to increase the fidelity of their options as the design timeline progresses. This ensures reducing the set of options based on additional information and not on arbitrary decisions.

2.1.3. Systems Engineering

Systems Engineering is a design method which focuses on the design of large and complex systems. Since ships became increasingly more complex, this method found its way to ship design [8], [54]. The method combines the increased complexity of the logistic chains, structures regulatory systems on more aspects and makes room for computer-based design tools at the same time. It allows the evaluation of different concepts and concurrent design processes [54].
According to the International Council on Systems Engineering (INCOSE), Systems Engineering is a ”transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods.” [75].

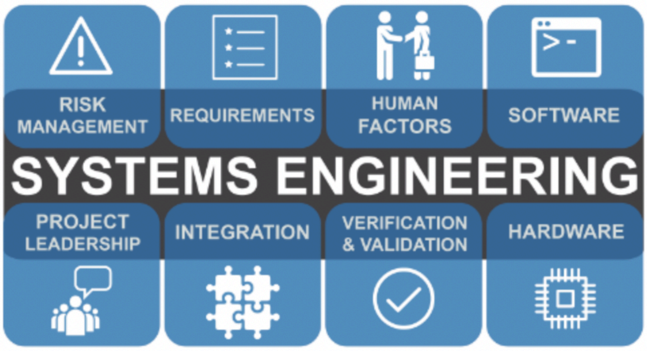


Figure 2.4: The basics of Systems Engineering, adapted from [**71 in lit report**]

Many Dutch hi-tech industry and major businesses in civil and maritime engineering now use Systems Engineering as their standard operating procedure [70], [86]. Systems engineering makes sure the tools, techniques, methods, knowledge, standards, principles and concepts are all intertwined in such a way a complex structure is successful. In figure 2.4 this concept is visualized. This inter- or multidisciplinary approach is not only meant for designing, building and operation of a system, it also tries to account for the recycling or reuse (of the system) at the end of its lifetime. To have a complete, holistic view on the project, it is important to know all the different stakeholders (or departments) involved in the project.
Systems Engineering is not limited for designing vessels, but can be used when designing intricate traffic networks [70], complex machines like satellites [68] or even the implementation of software with it [4].

2.1.4. Limitations design methods

The presented design methods discussed in this chapter are traditional methods to help design large, complex projects. Each of them having a different focus; point-based design is iterative, set-based design helps to design in parallel and systems engineering includes multiple context levels.
Because the design methods presented are versatile and not mainly focused on designing one specific object, they don’t take into account something as specific as the changing market of offshore wind. Since the offshore wind farm (OWF) market is a part of the sector where Ulstein actively designs for, the company developed a new design method called *Blended Design*. This method includes the changing market of offshore wind, and is therefore able to design if markets are uncertain but shift over time.
The next section will dive into the details of the *Blended Design* method.

2.2. Blended Design

Blended Design is a design method developed at Ulstein Design & Solutions B.V. in 2020, as a result of a graduation project of Jesper Zwaginga (MSc) [91]. Although the method being quite new, there are already two ship designs generated based on outcomes of this design method. This section will explain the basic and working principles of the design method, hereafter referred to as *Blended Design 1.0*.

To grasp the *Blended Design* method in one sentence, it aims to to explore a ship's basic dimensions based on life time costs. It does this by varying some basic design parameters and calculating meaningful financial indicators like the operational expenditures (OPEX), capital expenditures (CAPEX) and the return on investment (ROI) of each design in accordance to predetermined market which is modelled with an uncertainty modelling method.

The OPEX - or the operational expenses - are ongoing costs to have a ship operational.
CAPEX - or the capital expenditures - are the costs involved in buying and improving a ship.
The ROI - the return on investment - is the ratio of income over the period a ship is operational and the investment costs of the ship. The higher this number, the more the investment's gains compared to its costs. It relates profits to capital invested and is therefore an interesting measure.

Blended Design can be split up into three main parts; the market simulation, ship model and the uncertainty modelling. The aim of these modules is to collaboratively calculate optimal ship design parameters in order to operate as profitable as possible. By combining the data of these three parts, the model is able to plot economical performance on various parameters, like ROI versus length, breadth or ship speed. In this way, a ship designer can use this as guidance to alter the ship design to outcomes of the model, thereby making the ship more commercially interesting. A high level of the working principle of the *Blended Design* method is shown in figure 2.9.

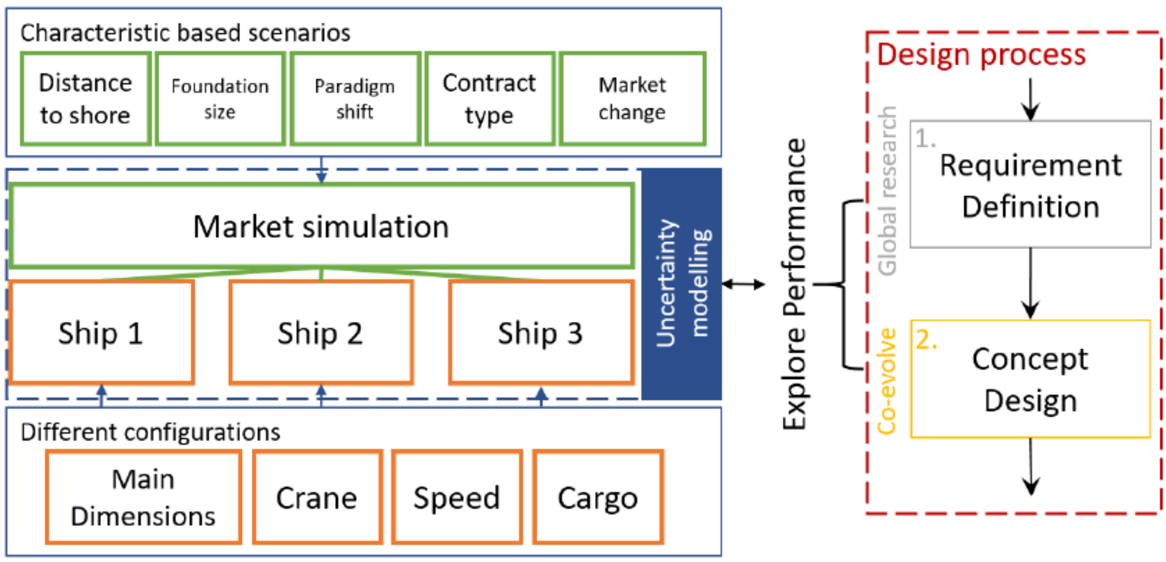


Figure 2.5: The working principle of the Blended Design method and how it fits in the design process, from [91]

The next sections will elaborate on each of the three parts. A detailed run through the script which will demonstrate the working principles of *Blended Design* is presented in appendix A.

2.2.1. Market model

Simulating the offshore wind farm market can account for an up-to-date overview of the current market and establish expected trends if done correctly. The trends should be able to cover the projected market demand for at least the economic lifetime of a vessel as well as the future sizes and dimensions of offshore wind farm parts like monopiles and jackets [91] .

In *Blended Design 1.0* data from market intelligence organisation *4COffshore* is used to forecast this, since this company has the most extended data set of offshore wind farms, including distance to shore, build year, CAPEX per wind farm and even planned wind farm projects up to five years in advance is included in this data.

To make an estimation of the growth of the wind farms, large amounts of data is used to distill projecting trends in order to estimate future dimensions and weight of wind farms.
By forecasting trends from the available data, a prediction is made on how the future market could behave and grow. These forecasts are used in the *Blended Design 1.0* version in order to be able to calculate various interesting economical figures, like OPEX, CAPEX and ROI based on the amount of cargo the ship is able to transport and how much profit it yields. Spearman's rank coefficient is used to check the correlation of data in the database since this correlation coefficient is able to discover the strength of a link between two sets of data. In this way, the Spearman's correlation coefficient for turbine, foundation and environmental parameters is calculated and are used to better estimate basic dimensions of future OWF parts when scaling due to size growth of each part occurs. When all the correlation coefficients are calculated, the forecast of size growth is made using a probability density function which uses the mean, upper and lower bounds for each year.
The results of this analysis are the expected growth of the market and the corresponding growth of the monopiles and jackets itself.

2.2.2. Ship model

This part of the method sets up a wide range of different ship design configurations. The user can set a number of input values which the method combines to make configurations of all possible connections. All these connections are visualized in figure 2.6.

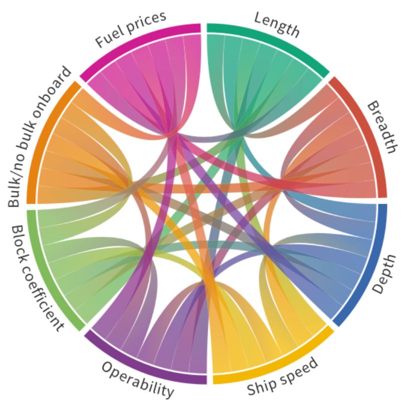


Figure 2.6: All possible combinations of ship designs parameters are linked with each other to generate all ship configurations

Figure 2.7: All possible configurations of design parameters are combined in a dataframe

It is possible to set constraints on these parameters: i.e. to limit the model to only vary the length from 175m to 194m with steps of 5m for example. This is done since some of the configurations or dimensions are not interesting or viable to calculate, ensuring to only perform calculations for realistic values while also limiting computing time.

Another measure to prevent the method from calculating unrealistic ship designs, is that each design configuration is checked to have realistic values by various functions. The ship model can be divided into five different modules in which each design is passed trough in the following sequence:

1. Scaling
2. Power and propulsion
3. Weight estimate

4. Mission
5. Cost and income

After all these functions are computed, each ship design is subjected to a series of functions to calculate various important values to evaluate each design on economical performance per given market.

2.2.3. Uncertainty modelling

This module tries to combine the market and ship configurations by calculating the amount of cargo can possibly fit on the deck determined for different 'cut-off diameters' and verifying it with the market demands. The amount of piles that can be transported for different diameters can be linked to the cumulative probability density matrix from the market simulation. This calculates the probability of the number of contracts during a period will occur with that specific amount of piles on deck, as shown in figure 2.8. In this figure the number of contracts that will result in the formation of three piles on the deck will be 85% in 2030 for example. In 2040 this number will likely drop to 40%. This number of piles the ship design can load can be used to calculate cost, income, and profit of the design.

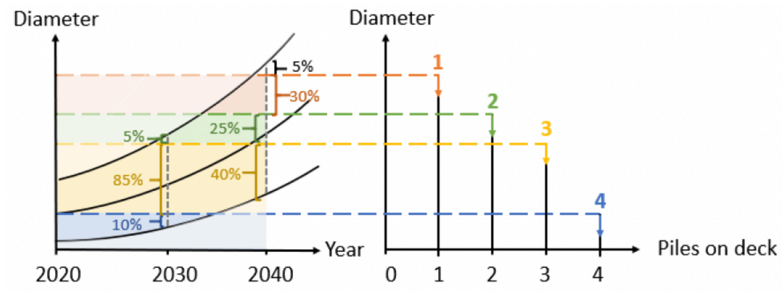


Figure 2.8: The amount of piles which fit on deck, the values are simplified. From [91]

The uncertainty of the market is modeled by using a discounted Markov Chain with Rewards (MCR) with a finite horizon from Sheskin [74], since these processes are very useful to calculate these kind of finances for managerial decisions. Since vessels are regularly expressed in monetary value, discount rates need to be included. This method describes both the depreciation and the possible interest rate gained by other investments, which is described in more detail in Zwaginga et al. [91].

After this, the financial performance of the vessel's design can be computed. This is done with the help of other interesting values, of which the percentage of contracts that a vessel is able to complete in a given time span and the amount of foundations that a vessel is able to complete over its lifetime.

To see how these three parts exactly aggregate in each other, appendix A explains on the basic principles. In the thesis of Zwaginga et al. [91] the exact inner workings are explained in depth.

2.2.4. Output Blended Design

The output of the *Blended Design* method is the financial performance of each generated design simulated on various markets. For every iteration the new build costs, the profit, costs, revenue, ROI and other financial performance indicators are calculated. Combining these numbers with the parameters which change every iteration like ship speed, length or other dimensions, insightful plots can be set up where an optimum can be found. *Blended Design* is able to analyse for a bound market, in other words having a cap on the minimum and maximum capacity of wind turbines, as well as calculating the financial performance of a design for the unbound market.
In figure 2.9 an example of the results of the *Blended Design 1.0* method are visible, showing for a wide range of design parameters their financial performance. Arguably, the figures show the optimal and most financially interesting length, breadth, depth and crane capacity for different future market projections. For example lowering the depth with 1 meter does not affect the offshore wind construction nor the profit of the ship that drastically, but the figure should help identify the ranges in which it is dangerous to choose them.

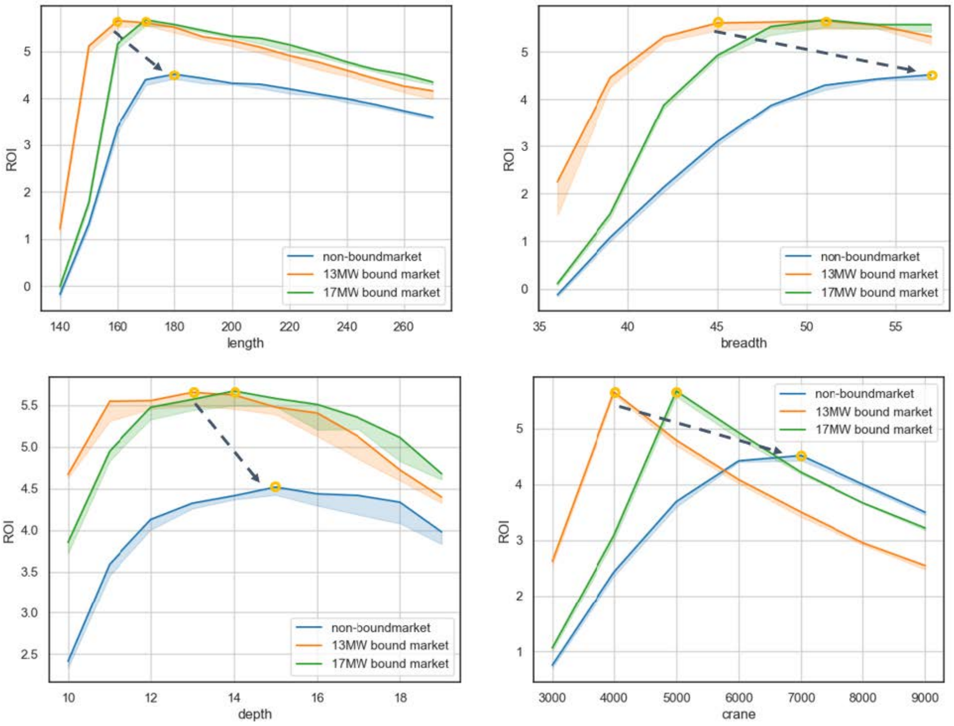


Figure 2.9: An example of the results of the *Blended Design* tool

In each of the example plots shown in figure 2.9 the y-axis plots the return on investment, whereas the x-axis shows a different main dimension which is analysed for each plot. The optimum for each of these dimensions for the simulated markets is the highest point in the graph, indicated with a yellow dot in figure 2.9. The arrows indicate that if there is an unbound market, the results change in the direction of the arrows.

2.3. Limitations of Blended Design 1.0

At this point ships are almost always optimized on costs only. This also yields for the *Blended Design 1.0* method, which is also able to comprehend and optimize for the financial side of a ship.

Ulstein noticed an increasing number of their customers want to take a more pro-active role in combating climate change, and therefore are asking what impact alternative fuels are having on the design of a ship and if the design still remains feasible. Therefore Ulstein Design & Solutions B.V. is looking for a method to expand the existing *Blended Design 1.0* tool by making it able to also optimize a ship design on emissions rather than only getting the business case right.

For now, the *Blended Design 1.0* tool is not able to quantify emissions by any means. In order to do so, the tool has to be equipped with some kind of emission index to calculate the amount of emissions. The *Blended Design* method as initially developed by Jesper Zwaginga is developed for offshore installation vessels, meaning it is not optimized for HTV type vessels. In order to evaluate HTVs in the tool, some parts of the tool need to be redeveloped to comply with the HTV's design.

There are a number of ways to reduce emissions from heavy transportation vessels. Switching to cleaner-burning fuels, installing scrubbers on smokestacks, and using more efficient engines are all options. Operators can also take measures to slow down vessels or route them around areas with sensitive air quality. But according to DNV [18] the best way to cut down on emissions, is to use alternative fuels. Currently it is not possible to model the effect of alternative fuel systems in the *Blended Design* tool yet.

Thus, this thesis aims to extend the current *Blended Design* method to include HTVs, and to include

emissions calculations in order to also optimize on environmental performance together with financial performance.
The foundation of the method for optimizing on emissions will be *Blended Design 1.0* as developed by Ulstein Design & Solutions B.V.. The illustration in figure 2.10 shows overlapping areas of different relevant topics of the proposed version of the *Blended Design* method. The blue area with costs aims to optimize on the financial side, whereas the orange circle intents to do the same for emissions.

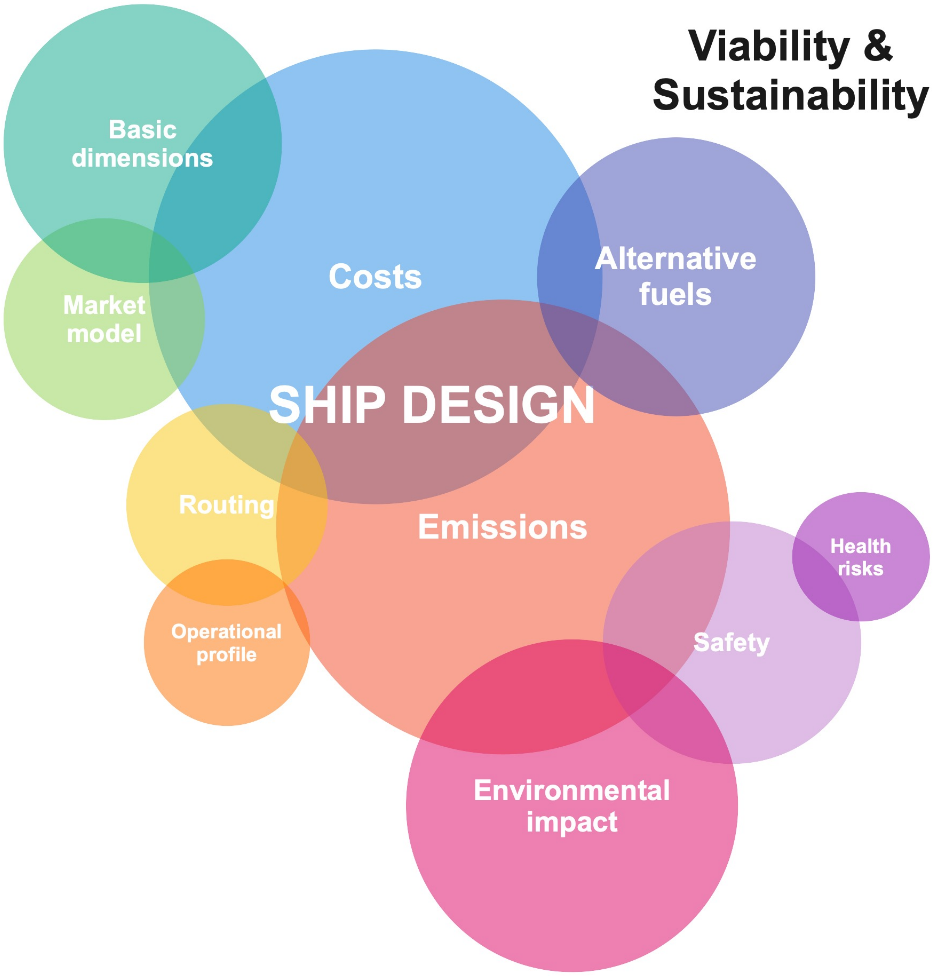


Figure 2.10: The overlapping areas of the *Blended Design*

2.4. Evaluation of solutions

To summarize all the capabilities and things which can't be accomplished with the selected design methods elaborated on in this chapter in one overview, figure 2.11 has been set up.

A green box means the method or index is capable of evaluating the given requirement, orange means that it is possible but not especially meant to do so. A red box means it is not possible to calculate or get the desired key performance indicator (KPI).

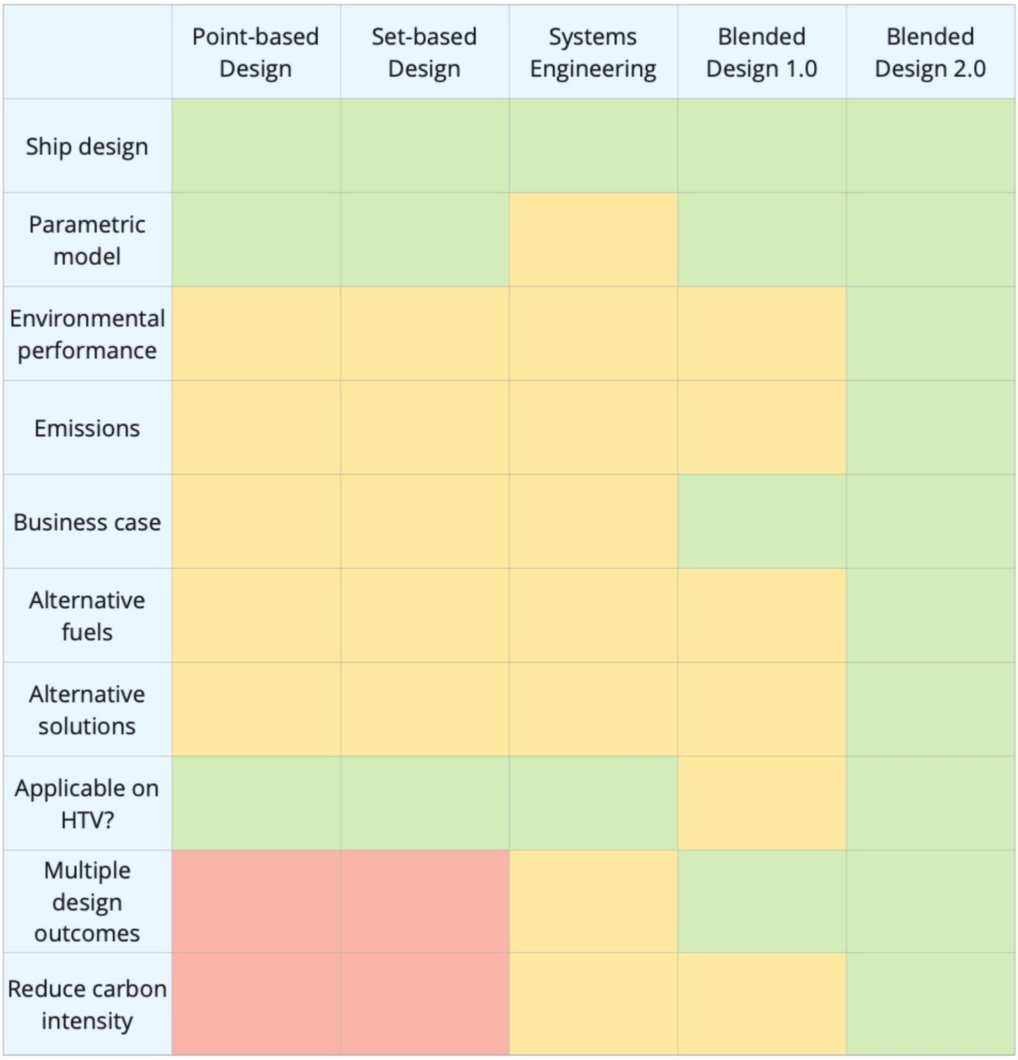


Figure 2.11: The capabilities of selected design methods

As can be seen in figure 2.11, the main shortcoming in the current *Blended Design 1.0* method is that it is not able to properly evaluate environmental emissions nor alternative fuels. A first list of requirements for the next version of *Blended Design* has been made in the last column named *Blended Design 2.0*.

3

Alternatives and emissions

As discussed previously, many of the design methods presented were not primarily focused on the environmental performance of a vessel. To develop a method which can comprehend emissions, first a thorough understanding of what's out there has to be build. This chapter will set out the details about alternatives and emissions, the distinction of harmful (greenhouse) gasses, how they can be compared, what alternative fuels exist and other impact reducing solutions for the environment.

3.1. Environmental impacts

As stated earlier in chapter 2, at this point the financial performance of a ship is leading when making design choices. Especially since the ships are becoming larger to still be able to compete in the growing market, the risk of investing in a ship increases as well. The larger ships have a severe impact on the climate, often because bigger ships emit more greenhouse gasses (GHGs) since more weight has to be moved.
It is estimated that 2.7% of the total global CO_2 emissions is emitted by the shipping sector [14]. In order to combat the changing climate, the United Nations (UN) set up 17 different sustainable development goals of which a few of them have the focus on improving the climate as can be seen in figure 3.1 [83]. By providing this blueprint for peace and prosperity for people and the planet, the UN hopes to stimulate sustainable developments. Each progress in these goals is one step closer to a better, improved world.

Figure 3.1: The 17 sustainable development goals set up by the United Nations, [83]

Ulstein thinks their clients should care about a better environment, that is why they design with an option for alternative fuel since 2020. An increasing number of their clients also want to take a pro-active role in combating climate change. They are interested in solutions to cut down emissions, like alternative fuels or other emission mitigating solutions.

This chapter presents a few of the environmental beneficial solutions, like the option for dual-fuel engines and alternative fuels, as well as environmental performance measures like design indices and emission index approaches.

3.2. Dual fuel

The conventional fuels which are mainly bunkered by the maritime industry are Heavy Fuel Oil (HFO), Marine Diesel Oil (MDO) and Marine Gas-oil (MGO). None of the conventional fuels, HFO nor MDO, are capable of providing emission-free shipping unless the carbon capture and storage (CCS) technology advances majorly in the coming years [57]. In addition to that, the shipping sector emits approximately nearly 15% of global NOx emissions, and around 13% of global SOx emissions per year, making the sector unsustainable [50].

It is clear that looking from an environmental viewpoint HFO or other conventional fuels don't hold as a future fuel. In order to make a ship less polluting a transition solution like a dual-fuel system could be interesting.

According to research by Nair and Acciaro [60] three factors are of major importance when adopting an alternative solution; (1) fuel characteristics and physical requirements, (2) fuel prices and (3) fuel availability. Especially the availability of a fuel could be problematic and can therefore be decisive for a shipowner, since it could delay operations when the desired fuel is not available in the arrival port, resulting in downtime for the operator. This makes the choice for HFO a lot more obvious and convenient, since it is worldwide available.

Installing a dual-fuel system on board of a ship could help making the transition to an alternative fuel become more fluent. Especially when considering not every port has the necessary infrastructure in order to be able to bunker each alternative fuel immediately.

It is possible to install a propulsion system in the ship which runs on a combination of conventional and alternative fuel. Another form of hybrid propulsion is a combination of an internal combustion engine (ICE) and batteries as a energy storage device (ESD). Another form of 'hybrid' propulsion is achieved with a dual fuel engine, this means that the engine can run on both liquid and gaseous fuels [51], for example an engine which can run on diesel and LNG. A paper written by Wang et al. [87] looked into hybrid propelled ships. According to this paper it is possible to achieve an emission reduction of about 10% with a hybrid propulsion system instead of using only an ICE.

Having dual fuel enabled makes it difficult to compare performance of different ships with each other. It is hard to say for what ratios the fuels are going to be used when operating the ships, since this depends on many different factors, like fuel price and fuel availability worldwide which are hard to estimate.

3.3. Alternative fuels

A recent report by DNV [18] noted that the most impactful way to decarbonize by 2050 is by reevaluating fuels. This means when changing to an environmentally friendly alternative fuel, the biggest effect towards low-carbon or even carbon-free sailing can be achieved, as can be seen in figure 3.2.

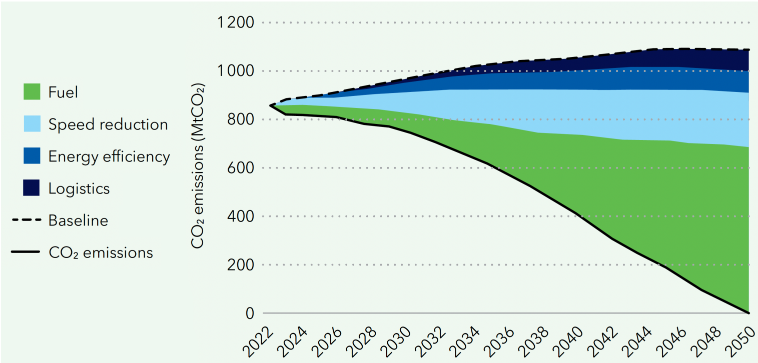


Figure 3.2: The expected impact of various measures to reduce emissions in order to fully decarbonize by 2050, adopted from [18]

If a ship would only be optimized on emissions, the decision for choosing for an alternative fuel system could become obvious since alternative solutions often have a less severe impact on the environment compared to conventional fuels. There are alternative fuels which have no harmful emissions at all when being combusted.

When making a design for a ship, choosing for such an installation is best done as quickly as possible since an alternative fuel installation can have a big impact on the design of a ship. Alternative fuel installations often have other requirements, additional safety qualifications, specific operational features, they take up more space onboard and additional systems need to be taken into account before such system is operational. This section will elaborate on several promising alternative fuels to be used for the shipping industry.

Alternative fuel criteria
According to a paper from Gray et al. [28], an ideal future marine propulsion technology has to meet as many of the following criteria to be successful:

- High volumetric and gravimetric density, (MJ/L) and (MJ/kg) respectively, to minimize fuel volume and mass which is beneficial for long-distance voyages
- Low level of local emission production, such as SOx, NOx and PM, to ensure compliance with IMO ECA regulations
- Low energy costs (€/MWh) to be competitive with low-quality residual fossil fuels such as HFO, MDO and MGO.
- Low lifecycle GHG emissions (gCO2-e/MJ), to meet the IMO goals from 2050
- It has to be easily scalable to make sure that large volumes of fuel are available to meet the demands of the shipping sector
- Widespread bunkering infrastructure to increase the availability, enabling vessels to refuel at ports worldwide
- Compatibility with existing infrastructure, which allows decarbonisation of current vessels and future retrofit projects

A selection of promising alternative fuels which meet many of the criteria explained in the list above is made. This section elaborates on if these alternatives are being used throughout this research. A couple of popular and promising alternative fuels are:

- LNG
- Methanol
- Ammonia
- Hydrogen (liquid & gas)
- Biofuels
- Batteries
- Nuclear (Thor)

Not every alternative fuel is suited for the use-case of the HTV, therefore it is researched which options can be implemented and which not. What is also important is carefully balancing all the pros and cons of each alternative solution since there are various safety issues with alternative fuel solutions. In table 3.1 the main hazards are shown of various alternative fuels.

Table 3.1: Main hazards of popular alternative fuels, adopted from [48]

	Main Safety Issue
Ammonia	Highly toxic
Methanol	Fire hazard, low toxicity
Hydrogen	Fire hazard
LNG	Fire hazard
(Bio/synthetic) diesel	Small fire hazard, low toxicity
Nuclear	Dangerous handling

3.3.1. Liquefied Natural Gas

To start with liquefied natural gas (LNG), this is a liquid gas consisting of mostly methane (CH_4) with a bit of ethane (C_2H_6) in it that has been cooled to its liquid form for storage [44]. While still being categorized as fossil fuel, using LNG as an alternative fuel means the CO_2 emissions are approximately 20-30% less from tank to propeller compared to conventional fuels like HFO [10] due to its cleaner burning behavior. The SO_x and NO_x gasses can count on even more reduction, since LNG does not contain sulfur meaning SO_x emissions are completely eliminated [10]. At this moment LNG is the most used alternative fuel, since the technology is very developed and it is a relatively clean alternative to HFO [2]. This makes it commercially interesting to service low-sulfur areas like the Baltic Sea and North Sea [53].

LNG can be burned in two different engines; in high-pressure and low-pressure engines. Using LNG in a high-pressure engine produces a lot of NO_x emissions as a result of the high pressures. In order to reduce these NO_x emissions, these engines often have a selective catalytic reduction (SCR) installation equipped. Low-pressure engines on the other hand experience methane slip [32]. This phenomenon is caused due to unburned methane since it is challenging to achieve complete combustion, resulting in methane emissions literally 'slipping' in the air. When a ship sails at lower power modes to save fuel, the methane slip often becomes worse.

This means the advantages of using LNG from a GHG emission perspective is controversially uncertain. Some sources like Transport & Environment [80] even claim that the vast majority of ships running on LNG are worse for the environment than their conventional counterparts due to methane slip. When factoring in higher upstream emissions LNG doesn't even provide a climate benefit at all according to the International Council on Clean Transportation (ICCT) [44] because the production pathways can be relatively energy intensive compared to conventional fuels. Pavlenko et al. [63] even stated that GHG emissions resulting from LNG are 20% higher than those of HFO, due to the methane slip of LNG.
Some other sources debunk these claims by reflecting the slip is drastically cut back in some engines throughout the years with the introduction of advanced combustion techniques [44]. Another breakthrough is the fact that the LNG technology is perfectly suited for burning low-carbon, bio- and synthetic fuels that will help the industry to lower its GHG emissions to levels targeted by the IMO by 2050.

To summarize, at this point LNG is a good transition fuel, but it is not the most sustainable fuel solution in the long term since LNG powered vessels and gas production facilities still emit a notable amount of CO_2 and methane (CH_4) compared to other alternatives. Especially considering it is not a zero-carbon solution and the risk of methane slip it is not future-proof enough.

3.3.2. Methanol

Methanol is used in thousands of everyday products ranging from plastics to paints and from furniture to fuels [5]. Methanol is considered as one of the main promising alternative fuels, due to its beneficial environmental potential. It is the simplest alcohol structure (CH_3OH) and because it is already broadly used in the chemical industry it is a mature and well-known chemical [71]. It is also non-toxic for humans, which means it does not requires more monitoring systems than current fuels, which is favorable for costs [38].

The main reason to look at methanol when reducing emissions is that it has the property of clean burning [15]; depending on the carbon and sulfur content it has next to less CO_2 and SO_x emissions and it significantly reduces the emissions of NO_x and particle matter (PM) in comparison with LNG.

Due to the fact it is possible to synthesize methanol from several feedstocks, the fuel is widely available throughout the whole world [38]. Together with its practical advantages in comparison to other alternative fuels, these are two reasons methanol is particularly interesting as an alternative fuel [1].

However not all methanol has a positive impact on the environment, it depends on how it is synthesized. Methanol can be produced cheaply from coal gasification, causing a highly negative GHG impact [78]. Natural gas can also serve as a feed stock for producing methanol. Especially when renewable feed stocks are used during production such as municipal or industrial waste, biomass and carbon dioxide, methanol is a low-carbon alternative fuel [38]. Methanol completely produced from renewable energy sources on the other hand is not commonly available and if so, often in low volumes since this is expensive to make.

Lastly the technology needed for safely storing and deploying methanol are considered mature [57]. The fuel can be stored in liquid form in standard fuel tanks, since it does not require a cryogenic installation like other alternative fuels do [71]. The combustion engines and structural tanks are comparable to proven conventional converter and storage technology as used for MDO. This makes the step to actually implement this alternative fuel smaller. Another advantage of storing methanol is that it completely dissolves in water, making it less environmental polluting than MDO in the case of leakage [71].

To sum up, due to the clean burning property of methanol it is a promising fuel regarding the mitigation of GHG emissions. It is relatively easy to produce and widely available. The storage of the fuel does not require a lot of extra safety or cryogenic installations, making it a financially interesting fuel compared to other alternatives.

3.3.3. Ammonia

Ammonia is gaining popularity in the last few years as it has been increasingly proposed as a potential zero-carbon maritime fuel due to its lack of CO_2 emissions [3]. Due to the relatively high liquefaction temperature of -33°C it makes the fuel easy to store and distribute throughout the ship [20].

In contrast with an alternative fuel like hydrogen, ammonia is already available over the whole world due to the international fertilizer industry since it is also used as a fertilizer. Although this is beneficial for the availability of the fuel, the ammonia is often produced from fossil fuels and therefore having little to no beneficial effect for the environment if used as a shipping fuel. The main challenge is to synthesize ammonia using only renewable energy in order to make it a fully zero carbon fuel, since the generation of ammonia takes up a lot of energy.

Furthermore ammonia is relatively energy-dense as a liquid which makes it applicable for long-distance voyages lasting several weeks. This also saves space on board of the ships, cutting down distribution costs.
Since ammonia as an alternative fuel is very corrosive and toxic to humans [43], additional safety and health measures and extra safeguards for the system onboard need to be in place. Ammonia in liquefied gas state requires to be stored in specialized, insulated tanks. Also each crewmember has to undergo specialized training (HAZID) in order to detect and react to problems or possibly dangerous situations.

Concluding, ammonia can be a zero-carbon fuel if produced using renewable energy. The storage of this alternative fuel does not require cryogenic tanks when in liquid form. As of safety, ammonia is highly toxic to humans.

3.3.4. Hydrogen

Hydrogen is an alternative fuel without any GHG emissions. In a hydrogen-oxygen fuel cell the energy released from the chemical reaction of hydrogen and oxygen, electricity is generated together with the byproducts of water and heat [23], making it a true zero-carbon fuel.

The technology around hydrogen systems is still fully in development and is not mature enough to already be commercially available. This means that a considerable amount of research and development efforts have still to be made in order to overcome the current technical and economic considerations that hinder the emergence of a hydrogen-based economy [23].
Due to the low technology readiness of hydrogen, the availability of this alternative fuel in ports lacks behind since there is low demand [9].
Since it is still very expensive to produce hydrogen, it has to gain momentum in the economy of scale in order to be economically competitive to other fuels. Especially in bulk transportation and storage since these costs are still very high since it has to be transported and stored cryogenic. This means that on a ship it also has to be stored in a cold tanker under high pressure, making it very costly and dangerous to have a ship equipped with such a system [23].

Liquid vs. gas
There are two ways of storing and transporting hydrogen on a ship; liquid and gaseous. The critical temperature of hydrogen is -240 °C, this means the it is gaseous at ambient temperature. If hydrogen is stored as a gas, it needs to be stored in high pressure tanks up to 700 bar in order to accomplish a decent energy density between 1.4 and 2.1 MWh/m^3 [57].
If hydrogen is stored as liquid, the energy density could be increased to somewhere between 2.2 and 2.8 MWh/m^3. Doing this requires a consistent temperature between (13.8 K and 33.2 K), which is very low and result in a 30% higher energy demand to maintain this temperature [57]. When dealing with a cryogenic fuel there is a certain level of 'boil off' where some liquid begins to evaporate. To re-liquify the boil off gas, extra systems are needed. This results in more complex infrastructure on board the ship and energy demand in order to keep these installations running.

To summarize, hydrogen still has a long way to go to become interesting for the industry since the technology is not developed enough, therefore troubling availability around the world. Also the storage costs of hydrogen are high due to the cryogenic nature of the fuel. Being a zero-carbon fuel, hydrogen has a high potential in decreasing GHG emissions.

3.3.5. Biofuels
Biofuels really gained interest the last couple of years. Although biofuels don't foresee a complete zero-emission future, they can become quite powerful as a transition fuel the coming years since below the line they are carbon neutral, making them more sustainable than conventional fuels [9]. Biofuels come with the advantage they can be used in conventional ICEs often without making adaptations. This makes there is no need for a refit of the ships engine system, making the transition instant. Biofuels can be a way of transitioning to a net-zero-emission future.

There are dozens of different biofuels, each with their own advantages and disadvantages [90]. This makes it impossible to have every type of biofuel available at each port.

The reason why biofuels are considered net-zero alternative fuels is because they consist of already captured carbon. So the carbon emissions are captured before it is released in the environment again when the fuel is being burned, making it a carbon-neutral fuel while still emitting CO_2 emissions.

Concluding, biofuels can serve as a transition fuel since the engine installation does not require a refit, making it easy to transition to. Since biofuels still emit GHG, they are not considered zero-carbon fuels.

3.3.6. Battery systems
One interesting alternative energy source is a battery bank. This can be charged in the harbor and when fully charged it can be used to operate a ship fully electric. During the use it discharges the battery without emitting any GHG, therefore making this alternative power source as polluting as the power being used during charging.

Due to the relatively low energy density of battery banks compared to other alternative fuels it is mainly used on short voyages preferably with multiple port calls to be able to recharge [9]. It requires a lot of batteries and thus a lot of space in order to have the ship sailing.

An interesting use of battery banks on ships is using them as a hybrid system to cut down on emissions. When combining conventional generators and lithium-ion batteries as a type of energy storage system (ESS) an overall reduction of 8.6% to 20.7% of CO_2 emissions can be achieved [42]. This effect is mainly researched in medium-sized oceangoing ships as well as small-sized coastal ships.

For the safety aspect, battery banks have the risk of thermal runaway, which can lead to battery failure and increased risk of explosion or fire, which means fire protection systems are required. The crew therefore needs additional training regimes and the system requires complex monitoring equipment to manage the systems extensively [65].

To summarize, battery systems are a way of emitting no GHG at all when they are charged with renewable power. Due to the low power density and high weight of batteries, this makes them suited for short haul trips, but not ideal to be used in longer voyages. Batteries can be deployed as a form of hybrid propulsion. The crew needs extra training and there needs to be a monitoring system in place to prevent thermal runaway.

3.3.7. Nuclear (THOR)

Recently, Ulstein Group presented another way of cutting down emissions by using alternative fuels, namely going nuclear [77]. The concept is called Thorium and it is according to Ulstein the solution to the zero emission challenge. The concept ship design is equipped with a Thorium Molten Salt Reactor (MSR) to generate vast amounts of clean and safe electricity, in order to propel the ship carbon free.

One extra interesting fact is the Ulstein SIF concept. This vessel is a 100m long zero-emission expedition cruise ship able to welcome 160 guests on board. The vessel will run on next-generation batteries and can be recharged with the Thor ship while at sea, making operations safer since the Thorium MSR is kept at a distance, while also being sustainable and convenient.

Due to the fact this is still a very early concept and too less information is because it is still being developed, this alternative fuel solution is not considered in this thesis.

3.4. Energy density

The energy density is the capability for an (alternative) fuel of how much energy it is able to store per defined volume or mass. Every alternative fuel has its own, unique value. Energy density can be expressed in two ways, namely the volumetric and gravimetric density. Volumetric energy density is how much energy per liters an (alternative) fuel has. How much energy per kilograms a fuel is able to generate is expressed by the gravimetric energy density. It is desirable to have both of these measures as high as possible, making the fuel volume and weight efficient to carry.

A paper from Law et al. [50] researched several alternative fuels on their relative weight and volume compared with HFO. In figure 3.3 an overview of the alternative fuels is plotted. Ideally an alternative fuel is lighter in weight and/or smaller in volume than the base fuel (HFO), which is indicated with the green arrows in figure 3.3. It stands out that none of the alternative fuels researched is located in this area.

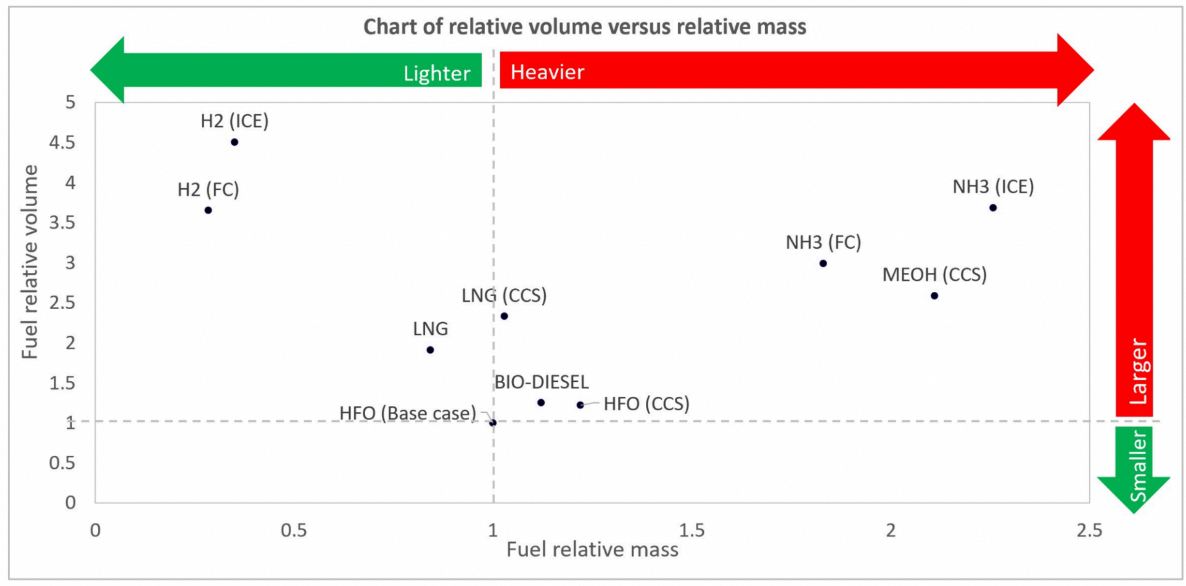


Figure 3.3: The relative volumetric and gravimetric densities of several alternative fuels with base case HFO, adopted from [50]

Since the energy density of an alternative fuel impacts the amount of fuel the ship can to bunker due to the size of the fuel, this also has an impact on bunker intervals. The bunker intervals in their turn can influence the total time of a voyage if a vessel needs to stop extra to bunker the ship for example. In figure 3.4 the bunkering intervals for several alternative fuels is visually represented.

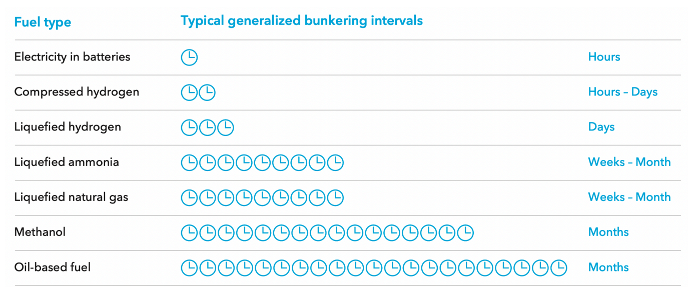


Figure 3.4: A generalized illustration of bunkering intervals for different type of fuels, adopted from [21]

In the coming years, DNV expects the following alternative fuel solutions increase in popularity and usability based on their most recent report [19]:

- LNG
- Methanol
- Ammonia
- Hydrogen
- Batteries

Although batteries is still listed by DNV as an interesting alternative solution, this thesis will not incorporate it in the case study, since batteries are for short haul voyages as can be seen in figure 3.4. This is something the HTV is not intended to be used for, due to the global operational area of the HTV and thus longer endurance a fuel has to deal with.

The scope of the thesis will therefore focus on the remaining alternative fuels; methanol, ammonia and hydrogen. This means some alternative fuels discussed in section 3.3 are not considered since these are not expected to become relevant in the coming years.

3.5. Emission design indices

One of the aims of this thesis is to quantify emissions. The last couple of years, regulation agencies like the International Maritime Organization (IMO) developed indices to be able to formulate environmental performance of a ship design. Making this insightful it helps shipbuilders and shipowners thrive to design and operate their ship more sustainable. Each of the indices has its own purpose and intention, like expressing emissions, evaluating carbon saving solutions or operating more efficient. In this section, several existing and established indices are discussed. Most of the indices are currently in force or come into force within the near future. The working, basic principle is covered, as well as the limitations when applying these design indices to an HTV.

3.5.1. Design methods and indices

There is a difference between design methods and design indices. A design method helps generate a new design or design concept, while a design index helps evaluate a key performance indicator of a design.
Since *Blended Design* is a design method, an index needs to help evaluate the designs generated by the method. This section therefore analyses a limited number of design indices to see if they are able to evaluate the environmental performance of HTVs.
The basic principles of the EEDI, EEOI, SEEMP, CII and EEXI will be explained and the limitations and applicability to the HTV will be elaborated on.

EEDI

The Energy Efficiency Design Index (EEDI) is a measure of a ship's CO_2 emissions in grams per ton transported nautical mile [7] and is obligatory for mainly general cargo and passenger ships [25], but not mandatory for HTVs. The idea behind the EEDI is to easily calculate the impact on the environment offset by the benefit to society by calculating the amount of CO_2 emissions per tonmile transported. Therefore it can be used to compare the carbon performance and therefore the efficiency of a ship.

Basic principle

The equation for calculating the EEDI is developed by the IMO in 2011 and is able to quantify emissions by evaluating the installed power with the specific diesel engine characteristics, as shown in equation 3.1. The complete equation with full explanation can be found in the documentation of IMO and MARPOL [39].

$$EEDI = \frac{P * sfc * C_f}{dwt * v} \tag{3.1}$$

Where P is the installed power measured at 75% of the engine's Maximum Continuous Rating (MCR), sfc is the engine specific fuel consumption at 75% power in grams per kilowatt-hour, C_f is the grams of CO_2 emitted per gram of fuel consumed, which is about 3.114 for most of the marine carbon fuels and dwt is the ship's deadweight, v is the ship's calm water speed at power P [16]. The index is mandatory for a wide range of ships being built from 2011 on and the outcome has to be formally checked by a classification bureau. Every few years the index gets adjusted to be slightly stricter to still have a meaningful and positive impact on the climate, as can be seen in figure 3.5 [25], [34].

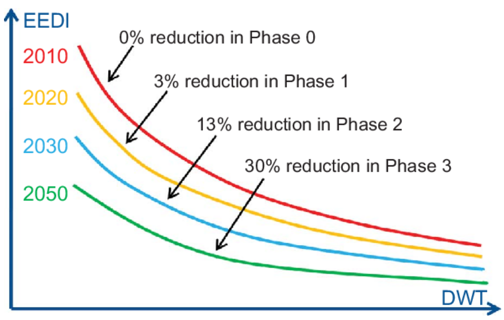


Figure 3.5: The four reduction phases of the EEDI

If the EEDI value of a ship is calculated, it is compared to a curve representing an average index value fitted on a set of individual index values for a defined group of ships [40], after which the EEDI has to be verified in a sea trial [25]. In this way the obtained value can be benchmarked with similar ships according to their size and efficiency. For each type of ship, a reference line (baseline) is set up $Referenceline = a * capacity^{-}c$ where a and c are constants determined from a regression curve fit of that specific type of ship.

Since the engine specifics and power estimates are often already known upfront, this index can already be calculated during the design phase of a ship. It uses basic information to evaluate environmental performance of a ships design. Different designs could therefore be compared to each other.

EEOI

The Energy Efficiency Operational Indicator (EEOI) was put forward by the IMO in 2009 indicating the ratio of CO_2 emissions to the actual cargo or passenger turnover given a specific period of time or one voyage [89]. Since the fuel consumption and the conversion from fuel to CO_2 factor is used in this method, the EEOI score very much depends on technical and logistical factors - the operational performance - rather than the design of the ship [79]. The benchmark for this index can therefore perfectly be used by companies internally to keep an eye on the operational efficiency of each voyage by comparing it to previous voyages.

Basic principles

The IMO [37] set up an equation to calculate the annual, average EEOI as shown in equation 3.2:

$$EEOI_{avg} = \frac{\sum_i \sum_j (F_{i,j} * C_{F\,j})}{\sum_j (m_i * d_i)} \tag{3.2}$$

Here j is the fuel type, i is the sequence number of a voyage, $F_{i\,j}$ is the consumption of fuel type j at voyage i; $C_{F\,j}$ is the conversion factor (unitless) of fuel type j when converted from fuel consumption to CO_2 emission; m_i is the weight of cargo carried at voyage i (in tonnes or other measurement); and d_i is the distance travelled (in nautical miles) corresponding to the cargo carried.

The unit of the EEOI depends on how the measurement of cargo carried or work done is expressed, depending on evaluating cargo or guests on board for example. In the equation given it is tonnes CO_2/(tonnes * nautical miles), but it can also be tonnes CO_2/(TEU * nautical miles), tonnes CO2/(person * nautical miles) [37]. It is possible with the EEOI to establish a rolling average of the value, since it takes into account the property of 'time'. When calculating the EEOI over a suitable time period this can be achieved. Like stated, the EEOI is more of a operational performance measure, which makes it hard to apply in the design stage of a ship.

SEEMP

The Ship Energy Efficiency Management Plan (SEEMP) is also an operational measure which aims to improve the energy efficiency of a ship in a cost-effective manner [36]. The ship owner is encouraged to continuously evaluate new technologies for the SEEMP at each of the four steps; planning, implementation, monitoring and evaluation. It is intended to improve the energy use of the ship, eventually leading to less energy use and therefore decreasing emissions. If a ship is equipped with a SEEMP, the ship can qualify for an International Energy Efficiency Certificate (IEEC), which is mandatory for all vessels of 400 gross tonnage (GT) and above [67]. This also includes vessels built before the EEDI was enforced.

Basic principles

The working mechanism of the SEEMP is by optimizing energy efficiency through the fleet management of a company or ship owner, so it is not ship specific but fleet wide. Some examples of increasing efficiency of the fleet are frequent propeller and hull cleaning or making more advanced voyage plannings (just-in-time arrival in ports). Upgrading the propulsion system on board, installing a waste heat recovery system or making hydrodynamic adjustments, like installing a bulbous bow, are also options to make the fleet or a ship within the fleet more efficient.

CII

In 2023 the IMO wants to introduce a Carbon Intensity Indicator (CII) together with the EEXI. Ships get rated on their energy efficiency in a categorical system. Just like a car or a house are obliged to have an energy label, the ship now also gets one. The rating will be from A to E, with A being the best. In this way different ships can be easily compared to each other. The CII measures how efficiently a ship transports goods or passengers by calculating the grams of CO_2 emitted per cargo-carrying nautical mile. The CII is calculated again every year and the rating thresholds will become gradually stringent towards 2030, so the ship has to become increasingly efficient. Since it is evaluated each year, this also makes it kind of an operational measure, since it doesn't have to be approved in preliminary stage of the ship design.

Basic principles

In combination with the EEDI and the SEEMP which address the technical efficiency and the management system of a ship respectively, the CII rating scheme addresses the operational efficiency. From 2022 onward the reduction factor of the CII is planned to increase with 2% each year up until 2026 in order to stay within the set boundaries of the IMO [11].

3.5.2. EEXI

The Energy Efficiency Existing ship Index (EEXI) is a slightly updated index that was amended in June 2021 and applicable to all vessels over 400 GT under MARPOL Annex VI from 2023 onward. It looks very similar to the EEDI, only with a few updated parameters. Contrary to the EEDI, this measure has a retroactive effect, meaning all ships within specific categories ever built are immediately applicable to this measure. The index is intended to evaluate the environmental performance with a technical approach by looking at the installed power and other design indicators, similar to the EEDI.

The EEDI and EEXI indices measure the same in practice, namely the amount of CO_2 per tonmile transported. EEXI regulation is one of the most significant measures by the IMO to promote more environmentally friendly technologies and reduce the shipping industry's carbon footprint.
The complete formula for calculating the EEXI is shown in equation 3.3.

$$\frac{\prod f_j \sum P_{ME(i)} * C_{FME(i)} * SFC_{ME(i)} + P_{AE} * C_{FAE} * SFC_{AE} + \prod f_j \left(\sum P_{PTI(i)} - \sum f_{eff(i)} * P_{AEeff(i)}\right) * C_{FAE(i)} * SFC_{AE} - \sum f_{eff(i)} * P_{eff(i)} * C_{FME} * SFC_{ME}}{f_i * f_c * f_l * capacity * f_w * V_{ref} * f_m} \tag{3.3}$$

In the equation, different parts are colored to indicate the main parts of this equation. The red box is to evaluate the CO_2 emissions of the main engine part. The yellow part does the same as the red one, only for the auxiliary engines. The blue part evaluates the use of a power take-off (PTO) and power take-in (PTI), since there will be some efficiency loss when the ship is equipped with these systems, but also evaluates innovative energy efficiency technology which the main engines are equipped with if there are any in place. The green part is set up to incorporate innovative energy efficiency technologies for reduction of auxiliary engines. Lastly the black box, the denominator, depicts the amount of tonmile multiplied with several performance coefficients. In table B.1 presented in appendix B a short description of each of the variables is shown.

With the EEXI being future proof and well established due to the fact that the EEDI is well adopted within the industry, the EEXI is an interesting measure to be able to calculate the amount of CO_2 per ton-mile.

3.6. Limitations and relevance to HTV

All the addressed indices in this chapter have one thing in common: they are not specifically applicable to an HTV, since it simply is not categorized in the ship types the indices are meant to be used for. This means during the design, building and operation of the HTV, none of these indices are mandatory to calculate, so the HTV does not have to comply with these indices according to regulatory organizations.

Other limitations of the selected design indices are shown in figure 3.6 below. What stands out is that all of them try to improve the environmental performance of a ship in some way. By calculating the emissions or improving environmental performance by using alternative fuels. Their qualities are evaluated with different colors, where a green box means the method or index is capable of evaluating the given KPI, orange is that it is possible but not especially meant for and a red box means it is not possible to calculate or get the desired KPI.

Figure 3.6: Limitations of each of the selected design indices

To conclude, the goal of every environmental design index is to map out environmental performance in some way and help design a ship which has as low as possible CO_2 emissions, therefore being as environmental friendly as possible. Looking at the CO_2 emissions of alternative fuels, some options don't emit CO_2 at all. This does not automatically mean they are sustainable, since they still emit some pollutants.

To be able to compare the environmental performance of alternative fuels with each other, it is vital to be able to quantify the emissions in one way or another. Since alternative fuels often emit less to no CO_2 at all, looking at the GHG CO_2 alone is not a good measure. The alternatives have to be compared on other GHGs as well. Next section will review several types of GHG, and elaborate on a selection where this thesis will focus on. After that, a way of comparing them is presented.

3.7. Distinction GHG emissions

With the main question concerning the quantification of emissions, first the distinction of interesting GHG emissions has to be made. One of the most common and recognized GHGs is CO_2. This is a global emission, which means its influence on the environment spreads all over the world.
Because not all alternative fuels discussed in the previous section 3.3 emit CO_2, it does not make sense to only look at CO_2emissions alone. There are other greenhouse gasses (GHGs) as well which are

just as or even more harmful to the environment. In this chapter the distinction of GHGs is explained in more detail.
According to a presentation from IMO [35], the most significant emissions can be roughly split up into three different categories; greenhouse gasses, air polluting gasses and ozone depleting substances. In the overview in table 3.2 below this distinction of the most important greenhouse gasses is already made and listed within each category, according to MARPOL Annex VI; the prevention of air pollution from ships.

Table 3.2: Distinction of the most impactful GHGs, adopted from IMO

Greenhouse gasses	CO_2, CH_4, N_2O	global
Air polluting emissions	NOx, SOx, particulate matter (PM)	local
Ozone depleting substances	CFC, HCFC	local

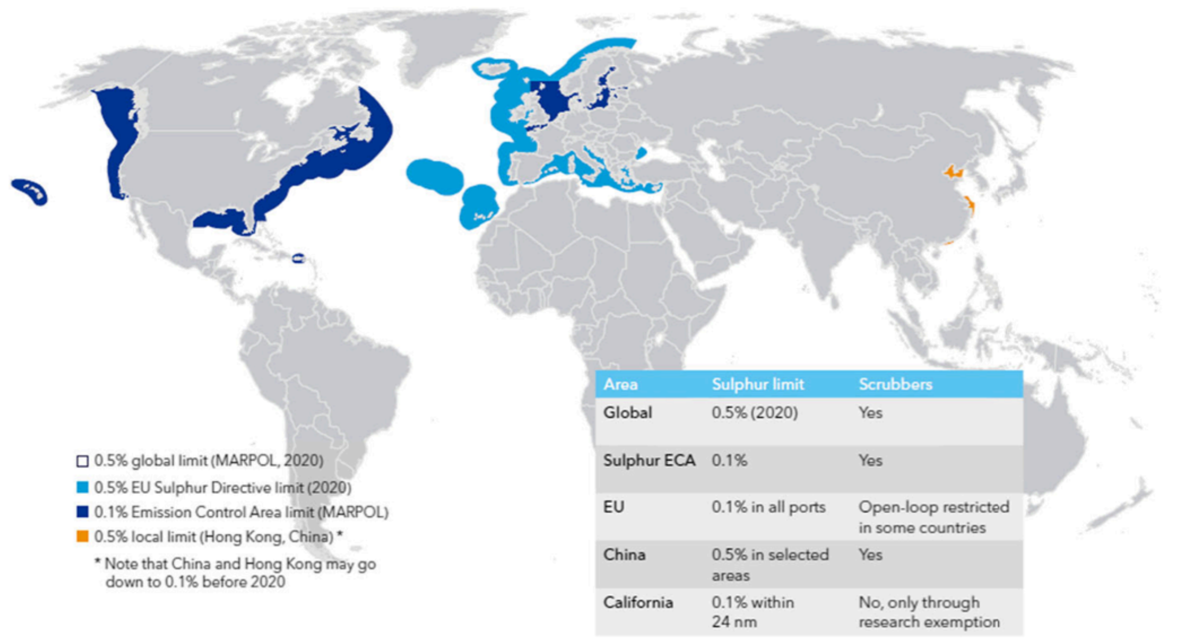
3.7.1. CO_2, $CH_4$and N_2O

Climate change is mainly driven by too large quantities of CO_2, $CH_4$and N_2Oemissions, since these gasses are responsible for 72%, 19% and 6% respectively to the global total GHG emissions [61]. N_2O; nitrous oxide and CH_4; methane are even more harmful emissions compared to CO_2. These emissions are generated by incomplete combustion due to incorrect timing. For example if the fuel is not fully mixed with oxygen or a pilot fuel is needed for combustion and it isn't properly mixed, these emissions emerge. Since some of the selected alternative fuels in section 3.3 can emit these two emissions more than other harmful emissions, these are important to keep track of as well.

The remaining 3% is mainly accounted for by F-gasses (like Fluorinated gases) [17]. Fluorinated gases is a group of fluorocarbons, hexafluoride and other syntetic gases are considered ozone depleting gasses. These substances do not play an immediate role of having an effect on the changing climate nor being dangerous to people. They are mostly emitted from a variety of household, commercial and industrial applications and processes making the effect negligible. Therefore this research only focuses on the GHG and air polluting emissions, since reducing these account for the biggest, positive environmental impact.

3.7.2. Air polluting emissions

SO_x (SO_2), NO_x and PM emissions contribute to acid rain and can have negative impacts on human health. Particle matter (PM) emissions can cause respiratory problems and other health issues. The air polluting emissions are mostly hazardous when coming into contact with, playing a role in the safety and human health on board of the ship but also on shore. These emissions are harmful, butt very locally. Since most of these pollutants don't directly cause global warming, they are not considered as GHGs but as air polluting emissions [35]. That is why the IMO set up some low SO_x and NO_x regions, especially in coastal regions. In figure 3.7 these ares are highlighted.



Area	Sulphur limit	Scrubbers
Global	0.5% (2020)	Yes
Sulphur ECA	0.1%	Yes
EU	0.1% in all ports	Open-loop restricted in some countries
China	0.5% in selected areas	Yes
California	0.1% within 24 nm	No, only through research exemption

Figure 3.7: The different ECAs are highlighted, The ECAs in 2018 under MARPOL Annex VI, adopted from DNV [53]

The consequences of GHGs are already discussed; they warm up the earth. NO_x , SO_x and PM on the other hand are a little less recognised, so a brief description of each harmful emission, together with some human health risks is given in the next couple of paragraphs.

NO_x
Due to the high temperature when combusting fuel (more than 1300 °C) some of the nitrogen is oxidised in the air to NO_x gasses. Especially when using biofuels made from plant material the NO_x emissions can be higher compared to Diesel, since all plants contain nitrogen. NO_x emissions can cause health problems in the respiratory system, having a negative impact on human health.

SO_x
Most of the times this refers to sulfur dioxide (SO_2) and in some cases to sulfur trioxide (SO_3). It is produced within a combustion engine from the oxidation of sulfur which most fuel-oils contain. SO_x can cause acid rain, sea and soil acidification and general human health issues.

PM
Particulate matter (PM) is produced due to incomplete combustion of fuel. The formation is closely linked to the fuel sulfur level, meaning a reduction of sulfur in fuel will reduce both SO_x and PM. Particulate matter is correlated to respiratory illness, cardiovascular and cardiopulmonary disease, and lung cancer in recent studies [45].

The HTV will operate globally, since the OWF market acts as a global market. Also because the HTV will cover long distances mostly on open seas, the focus of this research is not on SO_x , NO_x or PM pollutions since they are most harmful near populated areas. The focus of this thesis will be on the greenhouse gasses CO_2, $CH_4$and N_2O.

3.8. Global Warming Potential

As discussed in the section 3.7 above there are other significant GHGs in addition to CO_2, namely methane (CH_4) and nitrous oxide (N_2O) for example. These emissions contribute to the greenhouse effect too but to a different extent since they remain in the atmosphere for different periods of time [59].

To make the effects of different GHGs comparable, the the Intergovernmental Panel on Climate Change (IPCC) of the United Nations has defined the so-called 'Global Warming Potential' (GWP). The GWP is a multiple of the heat absorbed by any GHG in the atmosphere compared to the heat same mass of CO_2 would absorb over a given time period. This enables comparing emissions other than CO_2 to be compared to CO_2 by expressing the warming effect of a certain amount of GHG over a set period of time. Usually a time period of 100 year is being used, but the GWP of GHG emissions can also be measured in a 20 year time frame. In the next paragraph the different time horizons are explained.

3.8.1. The difference between GWP20 and GWP100

The values 20 and 100 refer to number of years. The global warming potential is a measure of how much energy the emissions of 1 ton of gas will absorb over a given period of time - the 20 or 100 years - compared to CO_2. The larger the GWP, the more that a given gas warms the earth compared to CO_2 over that time period. For example the effect of methane CH_4 for 20 years in the atmosphere is 84 times more severe than CO_2, but it does not stay as long in the atmosphere than CO_2 does according to the ICPP [41] which results in a lower GWP (of only 28) when looking at a time span of 100 years.

Time horizon matters

How high the capability for a gas is to warm the earth depends on the number of years over which the potential is calculated. If the gas is quickly removed from the atmosphere it may have a large effect at the beginning, but for longer time periods it becomes less poignant.

The number of years over which the GWP is calculated is often denoted by a subscript. Thus methane CH_4 has a potential of 25 over 100 years (GWP_{100} = 25) but 86 over 20 years (GWP_{20} = 86). The GWP value depends on how the gas concentration decays over time in the atmosphere. This is often not precisely known and therefore the values should not be considered exact. For this reason when quoting a GWP it is important to give a reference to the calculation [29].

Due to the difference in short- and long term effects, it is better to regulate fuels based on their GWP_{20} emissions according to Comer et al. [12]. For example; the 20-year GWP of methane is nearly three times higher than its 100-year GWP. When looking at the CO_2-20 emissions intensity for LNG powered ships, the incentive would be to minimize methane slip and promote the use of LNG in low-methane-slip engines, such as HPDF. It would also induce is to phase out the use of fossil LNG as a marine fuel at all and encourage using alternative fuels faster than if it continues to regulate based on GWP_{100} due to the higher GWP.
Commonly, also the case in this thesis, a time horizon of 100 years is used.

3.8.2. CO_2-e, the CO_2 equivalent

The global warming potential will come into use when comparing different alternative fuels, since not all alternative fuels emit CO_2, but other types of emissions as well. By converting every GHG emission to the CO_2-equivalent (CO_2-e) emission, it is suddenly possible to compare the GHG emission performance based on CO_2 emissions of these alternative fuels.

Since the GWP takes CO_2 emissions as a base case, the conversion for other GHGs to CO_2-e emissions is done by multiplying with the GWP value. In this way, the CO_2-e global warming potential can be obtained, enabling calculations based on CO_2 emissions.

An overview of current CO_2-e values for the selected emission types is shown in table 3.3 below. Like stated earlier, they are susceptible to change.

Table 3.3: The global warming potential and CO_2-equivalent values of the selected emission types, from [29]

	Lifetime (yr)	GWP_{20}	GWP_{100}
CO_2		1	1
CH_4	12.4	84	28
N_2O	121.0	264	265

As discussed in section 3.7, the most important GHG emitted by the shipping industry next to CO_2 are $CH_4$and N_2O. With the help of the GWP, these emissions can now be converted to CO_2-e values, making their impact proportional to CO_2 emissions and making them fit for calculations that are based on CO_2 emissions.

3.9. Approach quantifying emissions

In order to quantify emissions, this chapter presented and reviewed several design indices to research if they could enable quantifying emissions of alternative fuels. In figure 3.6 the overview of the limitations of the design indices is shown.
Quantifying emissions can be complicated since it depends on the approach which is used to evaluate the emissions. In the next two paragraphs, different lifecycles of alternative fuels are discussed and approaches of the pathway of alternative fuels are elaborated on.

3.9.1. Color coded lifecycles

With different colours a distinction is be made between the different lifecycles of alternative fuels. Green ammonia for example does not mean the ammonia is coloured green, the color refers to the way it is generated. The three most used colors in literature are green, blue and gray [50].

Green fuels are the cleanest fuels of these three colours. Green fuels are generated using electricity coming from renewable sources like wind and solar energy. This means there was no carbon involved during the production of these fuels. In some cases, fuel generated from biomass is also categorized as a green fuel.

Blue fuels could indicate that the fuel is generated with the use of natural gas, but most often the color refers to the fact that these fuels rely on carbon capture & storage to reduce their carbon intensity [24]. The reduction in GHGs is very sensitive to the effectiveness of the CCS.

Gray fuels are fuels produced using traditional fuels, generated in a carbon emitting way without any form of capturing or compensating for the fact it emits CO_2. These fuels are the most polluting ones and therefore have the most impact on the environment.

In figure 3.8 the different pathways are shown per color.

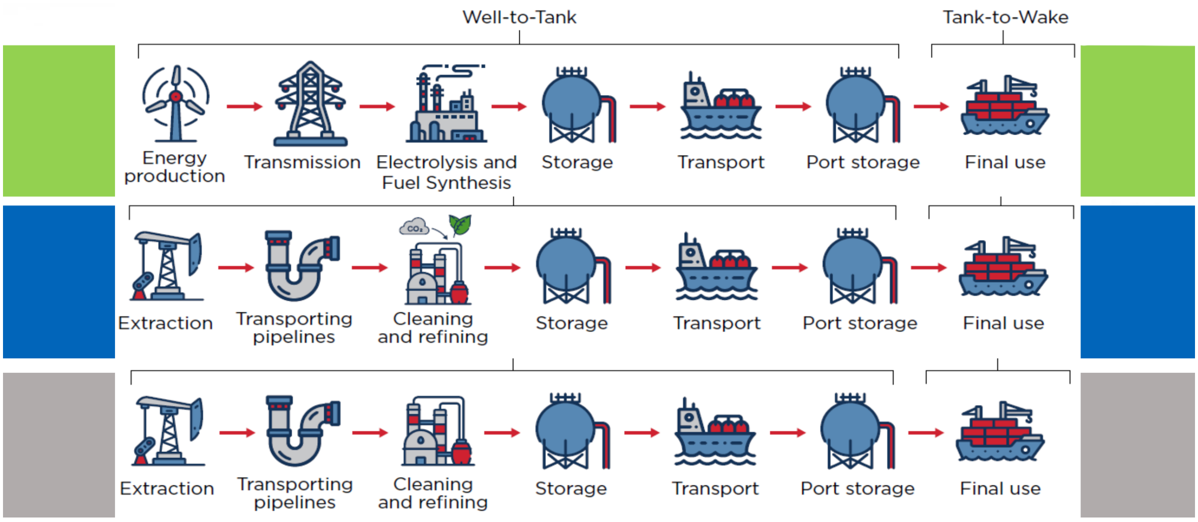


Figure 3.8: Different pathways of generating alternative fuels, the color is shown on the side of each pathway. From [49]

3.9.2. Well-to-wake, well-to-tank & tank-to-wake pathway

When discussing the alternative fuels it already came by briefly, but there is a difference on how the environmental impact of alternative fuels can be measured.

Measuring the environmental impact can be done in three ways; the well-to-wake (WtW), well-to-tank (WtT) and the tank-to-wake (TtW) approach. The different approaches refer to include the fuel production or not.

Well-to-wake covers the whole production process, from the extraction or generation of the (alternative) fuel up to the point the fuel is used to generate energy to propel a ship. This approach is preferred nowadays since it accounts for all emissions generated before and when using the fuel [73] and therefore captures the whole emission impact.

Well-to-tank, also called the upstream [73], involves the energy and emissions generated by extracting and processing the fuel, transporting the fuel up to the point it is being bunkered in a ship and ready for use.

Tank-to-wake lastly is also called the downstream, or tank-to-propeller pathway [73]. This only accounts for the emissions created by burning the fuel in the engine of the ship, excluding the upstream.

In figure 3.8 the distinction is made between WtT and TtW. Combining these two value-chains it is called the well-to-wake process.
With the growing concerns on the environment, many classification societies and regulators more often refer to the WtW approach as being the most promising one. According to recent research, the well-to-wake approach is believed to be the best in order to decarbonize the shipping industry [13], [49].
Especially since alternative fuels often don't emit many GHGs during their use on the ship, the tank-to-wake pathway, it does not make a lot of sense to compare alternative fuels on their TtW pathway.

The last reason to choose for the WtW pathway is that GHG emissions are a global problem. It does not matter where or at which stage the emissions are generated, they spread across the world, therefore the well-to-wake approach makes much more sense.
That is the reason why this thesis only considers the well-to-wake emissions for all alternative fuels, to create a level playing field for all alternatives.

3.10. Conclusion: Alternatives and emissions

To conclude, optimizing on emissions seems to be one of the most promising ways to cut down on emissions.
To decrease emissions, alternative fuels can be used on board of ships. Ammonia, methanol and hydrogen seem to be promising alternative fuels since they have little to no GHG emissions and are becoming more commercially available, making them more interesting for the industry.
There are several indices in place to measure and evaluate the environmental performance in some way, which can help monitoring of emissions of specific types of vessels.
One downside of alternative fuels is their energy density compared to conventional HFO, which often scores low resulting in worse endurance. Another disadvantage of alternative fuels is they may not emit CO_2, but they do emit other harmful GHG like $N_2O$and CH_4. Therefore conventional design indices can not be used to compare and evaluate their environmental performance.
With the global warming potential, these GHG can be converted back to the same benchmark as HFO. In that way they can be easily compared since they are expressed as the impact of CO_2, named CO_2-equivalent.
Converting the emissions of alternative fuels in this way only has little effect, since the fuels tend to be very sustainable when looking from a tank-to-wake perspective. Since the extraction and generation of these fuels currently emits lots of GHGs, the well-to-wake approach is an idea supported by increasingly more literature nowadays.

Part 2
Method & Case Study

’All models are wrong, but some are useful’
George Box - British mathematician and statistician

4

Blended Design 2.0

This chapter will present the solution proposed in this thesis. The technical background gained in previous chapters will be combined in this chapter into the new design method.

4.1. Solution approach

In order to address the limitations described in chapter 2.3, a plan of approach is made upfront as shown in figure 4.1. This chapter will outline the basics which have to be researched and understood to be able to give answer on the main- and sub questions of this research. In order to get everything working for designing HTVs, some adaptations of the *Blended Design* tool are addressed and explained in section 4.2

Alternative fuels can drastically change both the business case and the design of a vessel, while having a positive impact on the vessel's environmental performance. Often alternative fuels occupy more space onboard, or are heavier than conventional fuels, leaving less space for cargo. The fuel system itself often requires more space on board and has to deal with more safety systems.
Alternative fuel systems also can avoid future conversion costs or carbon taxes for example. This makes the design of a HTV even more complicated, as it is important to design an economically feasible vessel while also considering the environmental impact of the design.
It is advantageous to make these design decisions as early in the design process as possible, because at that point such an arrangement can be realised quite easily. There is more freedom in the initial phase of the Early Stage Ship Design (ESSD) of a ship than in the final phase.

From section 4.4 onward, the quantification method for emissions is explained.

In figure 4.1 the steps towards the solution presented in this thesis, *Blended Design 2.0*, are shown.

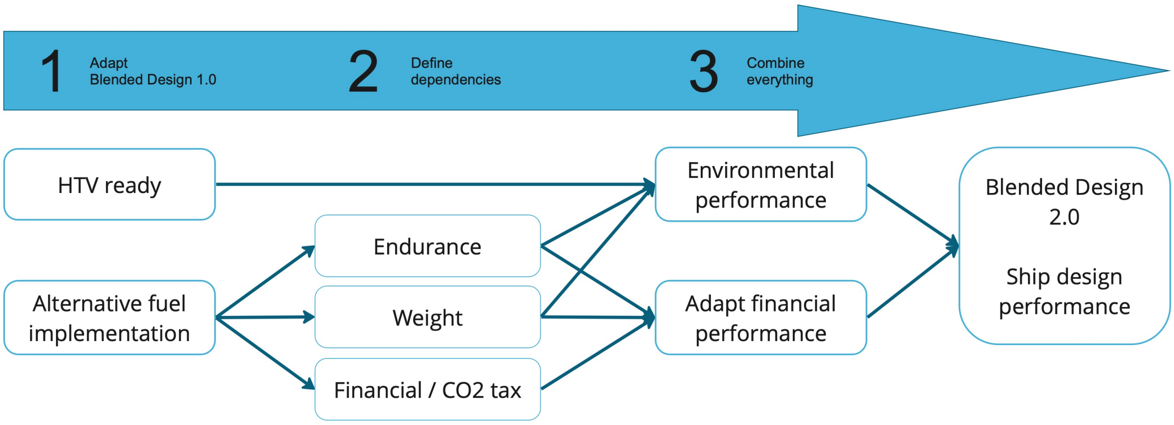


Figure 4.1: The steps towards the solution

4.2. Fitting the HTV in Blended Design

The previous version of the *Blended Design* tool as presented in the thesis of Zwaginga et al. [91] was developed to be used for designing Offshore Wind Installation Vessels, more specifically for the Ulstein HX118 type. These heavy lift crane vessels offer a well-balanced combination of carrying payload, a flush work deck area but most importantly a lot of lifting capacity. This was the signature design of the vessel, since the vessel is designed for installing wind farms offshore. This means the vessel has to be very good at position-keeping, so it is equipped with a powerful DP2/DP3 system and 8-point mooring capability. Due to the high main crane, typically 5,000 mT, the design is capable of handling any type of XL monopiles and jacket foundations.

Since the HX120 has a different use profile, some of the principles and programmed characteristics within the previous *Blended Design* tool were modified to adapt to the characteristics of the HX120, like the following:

- Dynamic Positioning (DP) is not needed for HTVs since they do not have to float in the same position in (rough) sea states
- There is no need for a crane onboard the ship, leaving room for more cargo
- Some (main)dimensions are changed in order to be more in line with the design of the HTV, like the length of the deck house for example
- Reference values, corrections and coefficients are changed in order to comply with the future design

In figure 4.2 and 4.3 the designs of the HX118 and HX120 are shown side-by-side. It stands out that the HTV is not equipped with a large crane on board. On the HX118 the thrusters are more prominent, since these have better DP capabilities. Since the purpose of the HX120 is mainly transporting goods, the DP systems is comparable to the DP capability of a cargo vessel.

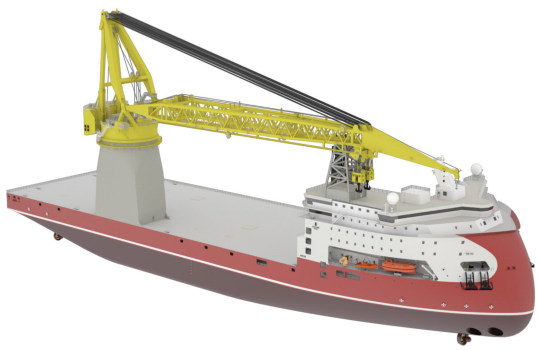


Figure 4.2: The design of the HX118

Figure 4.3: The design of the HX120

In chapter 5 the numerical adaptations are being presented and explained in more detail in order to have the model tailored to the design of a HTV.

4.3. Implementing alternative fuels

To implement the option of evaluating alternative fuels in the *Blended Design* tool, several existing functions and calculations need to be altered. In this section, each of the functions which were changed are discussed.

There are three main dependencies that are addressed: the impact an alternative fuel system has on the weight, on available volume and on endurance of the ship and the costs of the ship. This section points out what and how these capabilities are changed. The following dependencies are particularly important by using alternative fuel systems in a vessel. In the next paragraphs their dependencies and the found solution are explained and how it is worked around.

- Endurance
- Cargo weight & volume
- Costs

In order to calculate how much fuel can be bunkered, the model calculates the maximum amount of energy what can be stored based according to three separate constraints; demand, volume and weight constraints. Of these three values, the lowest outcome is taken for further calculations, since this will likely be the limiting factor on the amount of fuel which can be bunkered.

4.3.1. Endurance calculation

How long the ship is able to be operational in order to complete the transit without having to be refueled is one of the concerns, since it determines the endurance of a ship. Especially when considering that due to the long voyages on the open sea of a HTV, it does not encounter a port for a very long time. This means that the vessel doesn't have the occasion to simply refuel.

The endurance mainly depends on two factors namely the gravimetric and volumetric density of a fuel [56]. When considering each alternative has its own specific weight and volume it becomes clear that endurance could cap the viability of an alternative solution. Based on the total time defined the ship has to be self supporting in order to complete the mission, the desired energy storage capacity is calculated.

Blended Design 2.0 assumes that a ship can be refueled at every port, which means it only calculates the energy demand for a single journey for each mission. This also implies that each and every alternative fuel selected should be available at every port.

The maximum amount of fuel the ship has to be able to bunker to meet the specified endurance is therefore calculated with equation 4.1. To convert the amount of energy to the number of liters of that specific fuel, it can be divided with the fuel specific energy, which is expressed in [MJ/l].

$$MJ_{endurance} = \frac{3.6 * perc_{enginerunning} * P_{inst} * t_{selfsup}}{\eta_{conv,engine}} \tag{4.1}$$

With this, the fuel demand for the selected mission is calculated and the tool can evaluate how much space and weight there has to be free in order to actually carry this amount of energy.

Calculating volume and weight alternative fuel

Calculating the volume and weight of the alternative fuel, the fuel density is very useful. In figure 4.4 below the uncontained volumetric and gravimetric fuel density is shown for several common alternative fuels.

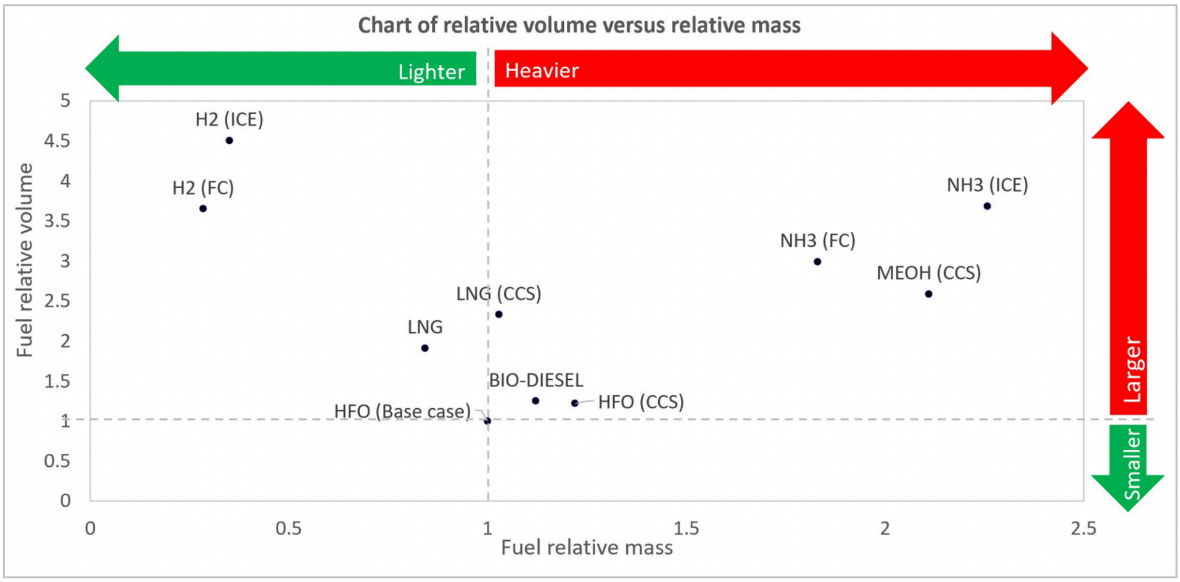


Figure 4.4: The relative, uncontained volumetric and gravimetric densities of several alternative fuels with base case HFO, from Law et al. [50]

The volumetric fuel density can be a limiting factor when bunkering alternative fuel. Similar to the gravimetric fuel density, volumetric fuel density is expressed in MJ/m^3. The lower this metric, the more space the alternative fuel needs per megaJoule.

In figure 4.4 the volumetric fuel density is shown for several common alternative fuels. With the volumetric fuel density, the amount of MJ of alternative fuel which can be stored in total in the storage tanks is calculated with equation 4.2 for each design. The volume of these tanks vol_{hold} is different per ship design and depends on the main dimensions of the ship.

$$MJ_{vol} = vol_{hold} * 1000 * \rho_{vol,altfuel} \tag{4.2}$$

Because the accommodations are built on the front of the ships flush main deck and the rather empty hull of the HTV, there is plenty of volume available to fit all the systems and engines in the ships design. It is therefore assumed that the left over space can be used to bunker the alternative fuel.

Like the different volume of alternative fuels influences the total fuel bunker capacity, the different weight can also be a limiting factor. The ship has to remain afloat during the transit, meaning the ship can only bunker as much fuel as there is deadweight available. Since the tool is able to compute the amount of deadweight, this is multiplied with the gravimetric density of the alternative fuel in MJ/kg in order to define the maximum amount of fuel by weight constrain can be bunkered. The principle is similar to when calculating the volume of the alternative fuel, as shown in equation 4.3.

$$MJ_{DWT} = DWT_{cargo} * 1000 * \rho_{grav,altfuel} \tag{4.3}$$

Now the amount of MJ which is needed to complete the voyage in one go, the number of MJ which can maximally be loaded in order to keep the ship floating and the amount of energy which physically fits in the storage tanks of the ship design are calculated. The minimal value of these three calculations acts as the constraint for the ships design. This number is used to calculate the amount of alternative fuel the ship can bunker and is used throughout the method to evaluate other performance indicators.

An alternative fuel installation often requires specialized equipment, like extra insulated piping to be able to transport the cooled alternative fuel or withstand the enormous pressures of a gaseous alternative fuel. Also the internal combustion engine or fuel cell (FC) can be equipped with extra safety features, making them heavier than common ICE's. The weight of these installations can impact the cargo the ship is able to transport, since this is less to still remain afloat. This dependency is not incorporated in the current *Blended Design* tool, since some alternatives are not yet commercially available, resulting in too little data on this. Due to this lack of data, it is assumed that the weight of alternative fuel engines and systems is similar to a conventional ICE.

4.3.2. Impact on cargo weight

Since some of the alternative fuels have a higher gravimetric density compared to HFO, this can have an impact on the cargo which can be transported, since a part of the freeboard is reserved for that extra weight of the fuel. Now the interrelated dependencies arise; volume and weight of alternative fuel solutions can be limiting factors on the cargo performance of a ship. The heavier the fuel per MJ, the less spare weight for cargo is left.

The weight dependency is incorporated in the *Blended Design* tool by recalculating the amount of cargo the ship is able to transport. This is accomplished by subtracting the weight of the alternative fuel from the available cargo deadweight, as shown in equation 4.4.

$$DWT_{cargo} = DWT_{cargo} - W_{altfuel} \tag{4.4}$$

Having less space for cargo on board has an effect on the income the ship design is able to generate. This effect is studied in the next paragraphs.

4.3.3. Financial implications on alternative fuels

Since the purchase costs of an alternative fuel installation often are higher than for a conventional fueled engine, choosing for an alternative fuel system is not as straightforward, since these choices can have a severe impact on the business case of a ship. Three aspects are of main importance when choosing an alternative fuel; the purchase costs of the engine plus the system as a whole, the maintenance costs and lastly the alternative fuel price.

This section aims to address the changes made in order to incorporate the financial consequences of alternative fuels in the *Blended Design* tool. It is divided into three paragraphs, each elaborating on an important financial parameter; the CAPEX, OPEX and VOYEX. Each of the paragraphs explains how the costs adapt to the alternative fuel systems.

The CAPEX is depended on the newbuild costs since this is a percentage of the depreciation and the interest of the ship (tax, repay, loan interest, RoE).
The OPEX is a function of the maintenance, storage costs, installation costs and management costs and the number of people working on board of the ship, since they have to be paid when the ship is operational.
Lastly the VOYEX captures the expenses per voyage; per trip of the design. In this metric things as fuel costs and the revenue of the cargo are used.

CAPEX - Engine & Storage costs

The CAPEX are the costs of owning a ship and are most influenced by build costs, depreciation and interest rates, which are set as a percentage of the investment in the ship [91]. The equation of calculating the CAPEX is shown in equation 4.5.

$$CAPEX = Loan_{interest} + Loan_{repayment} + Equity_{return} \tag{4.5}$$

The total costs for the investment of a ship is expressed in the new build costs (NC), the costs of components needed to build a ship. The height of the NC depend on a lot of variables and often it is depending on the scale. A bigger ship will be more expensive than a smaller one. *Blended Design 1.0* scales the following components in order to make an estimation of the new build costs:

- Steel costs (EUR/ton), dictated by steel weight
- Engine/generator costs (EUR/kW), dictated by propulsion power
- System costs (thruster, retractable, tunnel thruster EUR/kW)
- Electric system (EUR/kW), dictated by the installed power

- Accommodation costs (including systems, EUR/pp), dictated by the number of crew members

Since the CAPEX is based on the new build costs, it means if the NC changes, the CAPEX automatically changes with it. The engine and system costs are part of the NC, and thus CAPEX of a ship. So in order to calculate the CAPEX for alternative fuel systems, a well founded estimate has to be made on the engine and system costs.

As stated earlier, an alternative fuel system has a different price tag than a conventional fuel system, resulting in higher new build costs. Since the costs of the system and engine account for a big part of the total new build costs, it is important to correctly incorporate the price of alternative fuel installations in the *Blended Design* tool since it can have a noticeable influence on the costs and financial performance of the ship.

A study has been carried out to find values for the different costs of machinery which has to be installed for each alternative fuel. An overview of these costs for the HTV is presented in chapter 5, the case study, since these costs may vary per ship type and alternative fuel. The engine and system related costs can be found in table 5.4.

Therefore equation 4.6 is changed in such a way that the red parts of the equation are dependant on the alternative fuel. Since a major part of the CAPEX depends on the NC of the ship, equation 4.6 has to be understood first.
The engine costs, $C_{propulsion}$, are tailored to the alternative fuel engine which is selected when calculating the NC. In table 5.4 the values for the alternative fuel engines are shown. A storage part $Storage_{CAPEX}$ is added to cover the extra costs of (safety) systems and installations on board, like all the (pressurized) tanks, pipes and extra design costs. In comparison with the *Blended Design 1.0* method, the costs for the crane and crane systems are removed since the HTV doesn't have a crane on board.

$$\begin{aligned} NewbuildCost = C_{class}(Lwl) + C_{steel}(W_{steel} + C_{propulsion}(P_B) + C_{gen}(P_B) + \\ C_{electric-system}(P_B, P_{DP}) + C_{accommodation}(Crew) + Storage_{CAPEX}(W_{altfuel}) \end{aligned} \tag{4.6}$$

As stated earlier, alternative fuels need different systems and installations in order to transport and use these fuels safely and efficiently on board of the ship. For example Ammonia has to be stored in extra enhanced C-type tanks, making the storage of this fuel more expensive. This effect is calculated in the variable $Storage_{CAPEX}$ and scales with the amount of energy which is stored on the ship in order to compare alternative fuels with each other.

OPEX - Maintenance costs
A shipowner also has to consider the operational expenses when operating a ship, which are reflected in the OPEX [91]. These consist of loan costs for the crew, maintenance costs, insurance costs, stores & supply costs and management costs.

Since the OPEX costs are running costs over the lifetime of a ship, these costs can vary every year. In the list below, the OPEX costs and the dictating factors on which the costs are depending on can be found.

Table 4.1: Different dictating factors of the OPEX

Costs	Dictated by	Default value
Crew costs	Amount of crew per day	600 USD/crew
Maintenance & Repair costs	A percentage of newbuild costs per year maintenance & repair	1.15 %
Stores & supplies costs	A percentage of newbuild costs per year stores and supplies	2 %
Insurance costs	a percentage of newbuild costs per year insurance	0.5 %
Management costs	A percentage of newbuild costs per year management overhead	1 %

Alternative fuel systems again tend to be more expensive, due to extra maintenance costs, but also higher storage costs, changing the business case of a ship design when eventually operational. Therefore the equation which calculates the OPEX as shown in equation 4.7.

$$OPEX = Crew_{wage} + maintenance + stores\&supplies + insurance + management_{overhead} \quad (4.7)$$

The red parts are altered in such a way that it iterates different input values for different alternative fuels. Maintenance costs are different for each of the alternative fuels, they are presented in chapter 5, the case study, since these costs may vary per ship type. The overview is shown in table 5.5.

VOYEX

The voyage expenses (VOYEX) are based on the amount of trips, the used fuel and the port fees paid; all the expenses involved with the actual voyages the ship makes. The equation to calculate the VOYEX is shown in equation 4.8, again the red parts showing the iterative variables for alternative fuels.

$$VOYEX = trips_{yr}(P_{inst} * t_{tot} * sfc * Perc_{use}) * C_{fuel,tonne} \quad (4.8)$$

Since the price of the alternative fuel itself is different than for conventional fuels, this mainly affects the VOYEX of each alternative fuel & ship design configuration.

When analysing the costs for alternative fuel prices years in the future, the projections become more and more inconsistent. Many research institutes and companies try to estimate the future fuel prices as accurately as possible, but it still remains a projection based on guesses.
To find representative values for future alternative fuel costs, research institute MARIN set up a database where scientific estimations can be found [55]. These projections are used in the *Blended Design* tool to construct a poly fit through a discrete number of input values of fuel price points in order to set up a smooth, continuous value of fuel price variations to ensure the fuel price can be calculated for every year. In figure 4.5 the fuel price development of several alternatives is shown. This poly fit gives a rough estimate on how the fuel price will evolve over the years. Different fuel price projections can be entered to calculate the financial and environmental performance for different fuel price scenarios. By entering these different price scenarios into the model, the uncertainty of the alternative fuel price can be accounted for.

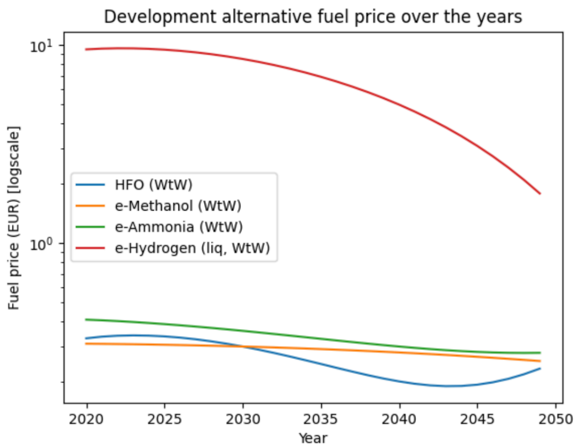


Figure 4.5: The development of the fuel price over the years

The price estimates are projections since the price can differ heavily on where you bunker the ship for example. Currently *Blended Design* does not incorporate different alternative fuel prices at different ports. Availability and scalability are often problems of ports they have to cope with. Not at every location it is possible to bunker the preferred alternative fuel.

4.4. Evaluating performance of alternative fuels

One of the aims of this thesis is how to quantify the environmental performance of alternative fuels, therefore enabling a comparison between different alternative fuels based on GHG emissions. This section will combine all the information presented in previous chapters and merge it into a new method for comparing the environmental performance of several alternative fuels.

4.4.1. EEXI-e module

The EEXI is a future proof, well established way to calculate the total emitted grams of CO_2 per ton-mile. Supported by the IMO, the veracity of this index is high and broadly known within the industry. Especially when the index comes in force from 2023 onward.

To expend the capabilities of the EEXI to also capture the $CH_4$and N_2Oemissions instead of only CO_2 emissions, the formula for calculating this index needs to be modified.
In order to make a logical comparison, all types of GHG emissions need to be incorporated in this formula. As seen in chapter 3 this can be done with the CO_2-equivalent of different GHGs. In order to capture the environmental performance of the alternative fuels, the GWP of the emissions other than CO_2 needs to be incorporated in the EEXI equation to include the impact these GHGs have on the environment.

In order to incorporate the CO_2-equivalent emissions, it has been altered with an added $C_FME, added$ factor, the so called *fuel emission factor*, as shown in red in equation 4.9.

$$EEXI{-}e = \frac{\begin{array}{r}(\prod_{j=1}^{n} f_j)(\sum_{i=1}^{nME} P_{ME(i)} \cdot (C_{FME(i)} + C_{F,added(i)}) \cdot SFC_{ME(i)}) + (P_{AE} \cdot (C_{FAE} + C_{F,added}) \cdot SFC_{AE}) \\ +((\prod_{j=1}^{n} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{n_{eff}} f_{eff(i)} \cdot P_{AEeff(i)})(C_{FAE} + C_{F,added(i)}) \cdot SFC_{AE}) \\ - (\sum_{i=1}^{n_{eff}} f_{eff(i)} \cdot P_{eff(i)} \cdot (C_{FME} + C_{F,added(i)}) \cdot SFC_{ME})\end{array}}{f_i \cdot f_c \cdot f_j \cdot capacity \cdot f_w \cdot V_{ref} \cdot f_m} \tag{4.9}$$

The added part in the equation is the total added global warming potential expressed in CO_2-e which originate from the $CH_4$and N_2Oemissions. With equation 4.10 the CO_2-equivalent values, the added GWP, can be calculated for these emissions, resulting in an EEXI-equivalent (EEXI-e) index. The value for $C_{FME,CH4,i}$ and $C_{FME,N2O,i}$ are multiplied with their corresponding GWP as found in table 3.3. For each alternative fuel, the amount of $CH_4$and N_2Oit emits is calculated and multiplied with the CO_2-e value, resulting in different EEXI-e values.

This means the EEXI-e now yields a result in [gCO_2-e/tonmile] instead of only calculating for CO_2 emissions, making it possible to not only evaluating the environmental performance of carbon emitting fuels, but also alternative fuels.

$$C_{FME,added} = C_{FME,CH4,i} * 25 + C_{FME,N2O,i} * 298 \tag{4.10}$$

As stated, the values which are used for the $C_{FME,CH4}$ and $C_{FME,N2O}$ differ per alternative fuel. The exact values used are clarified in the case study chapter, section 5.2.

To check if the presented EEXI-e method is consistent in output, it is studied if the information flow remains similar from input to output. To graphically show this, figure 4.6 is set up. What can be seen is that the nature of the output does not change, it still is something the original EEXI index was intended for ($gCO_2/tonmile$), but now added with extra functionality ($gCO_2 - e/tonmile$).

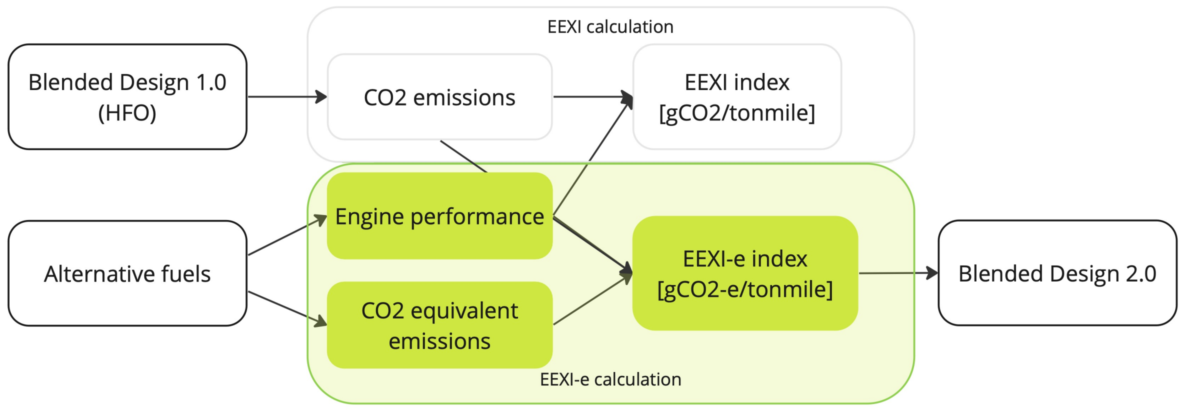


Figure 4.6: The consistency of the EEXI-e method

Specific fuel consumption
One of the inputs for the EEXI-e index is the specific fuel consumption (sfc). This is a value which changes depending on the engine type, since the engine dictates how much fuel is used at a certain power of the engine. The sfc tells something about how much fuel is converted into energy in the engine, since it is a measure with unit [gfuel/kWh]. With the sfc the method is able to calculate the amount of fuel which is used during a trip. For alternative fuel engines some estimations were made in order to fit into the index. More on the estimations is explained in section 5.2 in the case study chapter.

Measure of merit
The EEXI-e equation calculates the amount of CO_2-equivalent gasses which are emitted per ton mile depending on the type of cargo. The $capacity$ variable in the denominator can be interpreted in several ways, like the total amount of cargo weight or number of passengers a vessel can transport.
Since the cargo an HTV transports is a discrete number of monopiles or jackets, it is possible to calculate the EEXI-e index by dividing the the amount of CO_2-equivalent emitted with the number of cargo pieces it is able to transport. However this would be unfair for bigger ship designs, since they are able to move more and heavier monopiles/jackets, leading to more cargo weight which increases the amount of GHG emitted during transport.

In order to prevent penalizing bigger ship designs from scoring worse, the total weight of the cargo what the ship design is able to transport is calculated and is taken as a measure of merit. In this way all ship designs are evaluated on their cargo weight performance, and therefore can be compared fairly.

4.4.2. Carbon tax
An extra incentive for shipbuilders and especially shipowners is the introduction of a carbon tax [58].

Currently there are several instruments in place to tax carbon emissions. These so called emission trading systems (ETS), also referred to as cap-and-trade system, vary per location in the world. Entities which exceed their allowed emissions need to purchase extra allowances from entities which fall short on their allocation, creating a carbon market [65]. This puts a cap on the total carbon emissions, but does not aim to reduce them proactively.

Therefore ABS [65] foreshadows that in the future a ship operator will be burdened for the total CO_2 emissions they produce. An overview of different carbon tax policies is shown in figure 4.7.

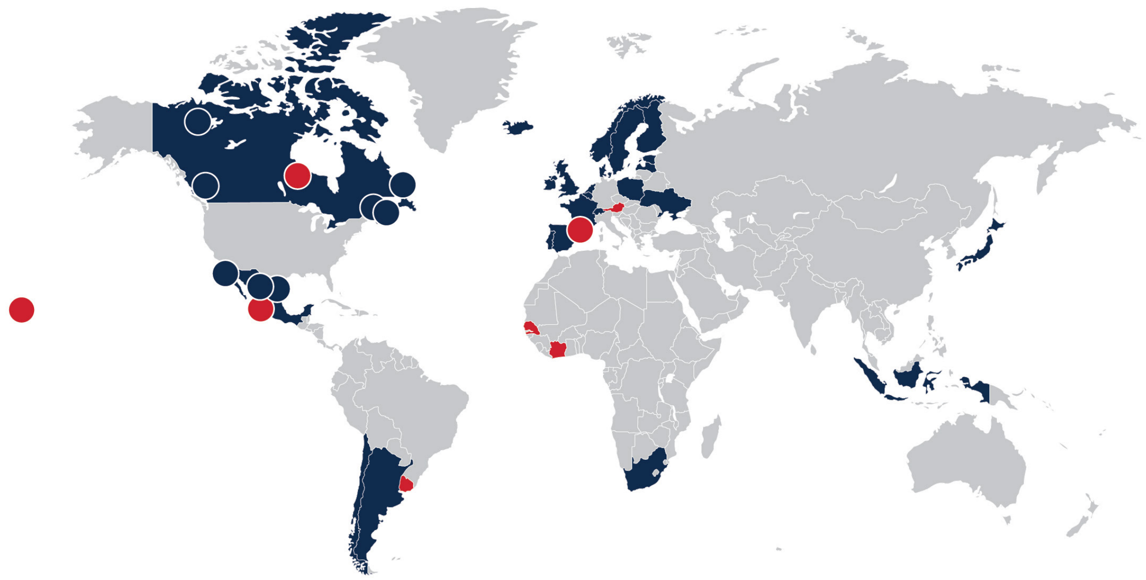


Figure 4.7: A worldwide overview of carbon tax policy, adopted from [65]

To make the *Blended Design* method even more future proof and be able to model the effect of such a tax, a carbon tax function is implemented.

The carbon tax module is split up in two approaches; one where the carbon tax is applied as a range to the design, for example from 0 to 500 EUR/ton of CO_2 emitted. The other method the carbon tax is defined as a budget, to answer the question what the height of the carbon tax maximally can be in order to still break even during operations, based on the profits.

Carbon tax range

Since the EEXI-e module is able to calculate the CO_2-equivalent emissions for each ship design, the CO_2-e value can be used in order to apply to the carbon tax. By multiplying the annual CO_2-e emissions with the value of the carbon tax and feeding this number back to the cost-income calculation, it is possible to see what effect the carbon tax has on the business case of a ship design.

Since the carbon tax is related to the amount of voyages the vessel makes annually, the costs for the carbon tax are added in the VOYEX equation, as can be seen in the red part of equation 4.11.

$$VOYEX = trips_{yr}(P_{inst} * t_{tot} * sfc * Perc_{use}) * C_{fuel,tonne} + CarbonTax \tag{4.11}$$

Carbon tax budget

To calculate the carbon-e tax budget - the amount one ton of CO_2-equivalent emissions cost before running into the red - the following equation 4.12 is used.

$$CO_{2,budget} = \frac{profit}{CO_{2,emitted}} \tag{4.12}$$

The carbon tax budget is mainly interesting for regulators, since it can help determine what the price for carbon tax could be when it will be introduced. For a ship owner this value could be an indication for the maximum price for carbon the business case of the ship design still holds.

4.4.3. Overview implementations

The way the next generation of *Blended Design* is interwoven with the original tool is made visible in figure 4.8 below. The three main functions of *Blended Design* - ship model, market model and uncertainty model - are still visible, as well as the added green blocks in order for the EEXI-e module to function properly.

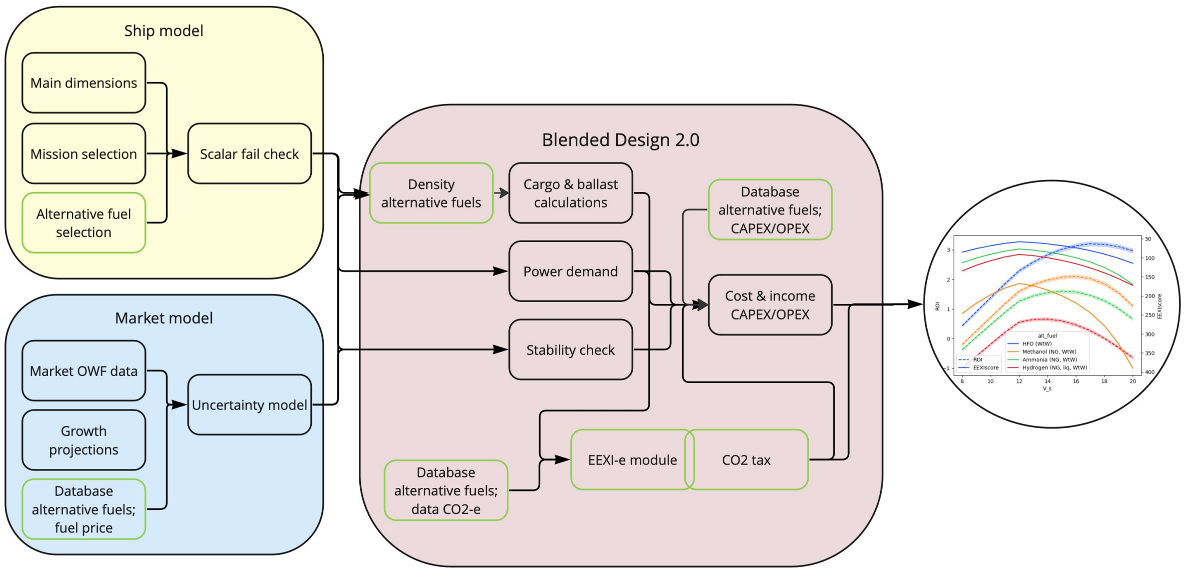


Figure 4.8: A schematic overview of the interwoven Blended Design tools

In figure 4.8 the carbon tax is visible merged with the EEXI-e module, because it only functions when an EEXI-e value is calculated since it is based on emitted CO_2-equivalent GHGs. What stands out is that the CO_2 tax function links back to the cost & income function, which can be explained that due to the added costs of GHGs-tax, the business case of a ship changes and therefore needs to be recalculated. From now on, the added developments of the initial *Blended Design* will be referred to as the *Blended Design 2.0* method.

4.5. Assumptions method

To make the method work, numerous assumptions were made. The assumptions are split up in two parts; the ones which are made in order to develop the method, and the assumptions made for the input. In this section, the most important assumptions to make the method work are presented and elaborated on.

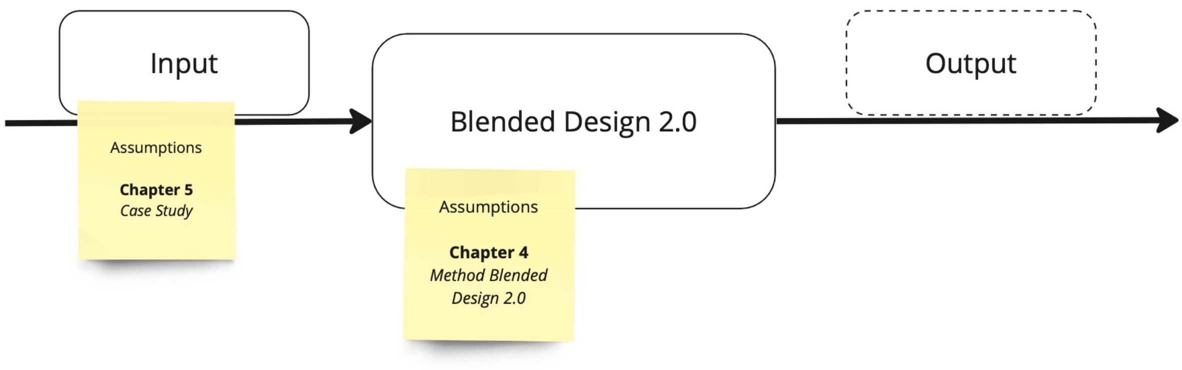


Figure 4.9: The assumptions are split up into two parts

Refueling
Blended Design 2.0 assumes that a ship can be refueled at every port, which mean each type of alternative fuel should be available at every port. In reality this will not be the case for a long time since availability is one of the main challenges for alternative fuels.

Installed power
The EEXI-e index is based on the installed power of the ship design. The power of the main engine P_{ME} is 0.75 times the installed power, the power of the auxiliary engines is the installed power minus the power of the main engine.

GWP100 used
As explained in chapter 3, the global warming potential is used in this thesis, since this is commonly chosen in most literature.

Extra weight alternative fuel systems
It is assumed that the weight for alternative fuel engines and systems is the same as conventional ICE. Since some alternative fuel engines are not even commercially available there is too little data on this characteristic, therefore this decision is made.

Utilization HTV
One thing that makes the HTV not comparable with other cargo vessels, is the utilization factor. When taking the selected missions as starting point, in the best case the load factor of the HTV will be close to 100% half of the time in transit, and the other half the ship will be empty due to a lack of cargo. This means the averaged load factor of the vessel will be at max 50% due to the fact the supply and demand are in other continents.

Missions
The missions are based on some assumptions as listed below:

- The sea route planning website https://classic.searoutes.com/routing is used and is expected to yield reliable and realistic routes
- The ships speed is kept constant during the voyage
- The vessel can pass through the Suez-canal
- The port of departure is chosen to be Rotterdam
- For the USA West-coast 'New York port' is chosen and for Asia the port of Beijing is chosen

DP time
As explained in a previous chapter, the DP time is manually set to 0, since the HTV does not need to have this capability due to the long distances it covers with deep sea shipping. Although being still incorporated in the *Blended Design* method, this part of the tool is skipped.

5
Case study

A case study is performed in this chapter in order to test the *Blended Design 2.0* method and see how the tool reacts to input and if the output of the method makes sense. The output the method generates will be presented in graphs later in this chapter, and will be studied to see if the output is representative.

First interesting markets for the HTV are explored in order to set up a variety of real world, plausible missions. After that, all EEXI-e parameters and coefficients which are used in this case study are presented, followed by the different costs for having alternative fuels. Now everything is in place to get to the results of this case study based on the missions of the HTV. Lastly the assumptions which are made during the case study are explained, why and how several assumptions are made is elaborated on.

5.1. Possible transportation routes

The mission of a HTV is clear; transport the OWF parts from the fabrication site to a marshalling port near the installation site. In order to come up with more specified numbers for a mission like the distance, it is important to know where these ports are located.
Internal market research at Ulstein created a map on which all upcoming offshore wind farm (OWF) projects are shown, as can be seen in figure 5.1 where every red dot indicates one OWF project. The size of these project is not shown on this map. It stands out Europe is expanding its own wind farms, but North-America and Asia (mainly China) are picking up speed building renewable energy sources as well.

To determine the major routes the HTV has to sail, the locations of (major) marshalling ports near the installation site and the location of manufacturers of components have to be researched. This led to an examination of major wind turbine component manufacturers as well as places where new, upcoming OWFs are being built, as shown in the same figure 5.1. All countries where OWF part manufacturers are located are indexed. Blue countries indicate more manufacturers are located in that country, making it more probable that parts have to be transported from that location to one where new wind farms are planned on being built.

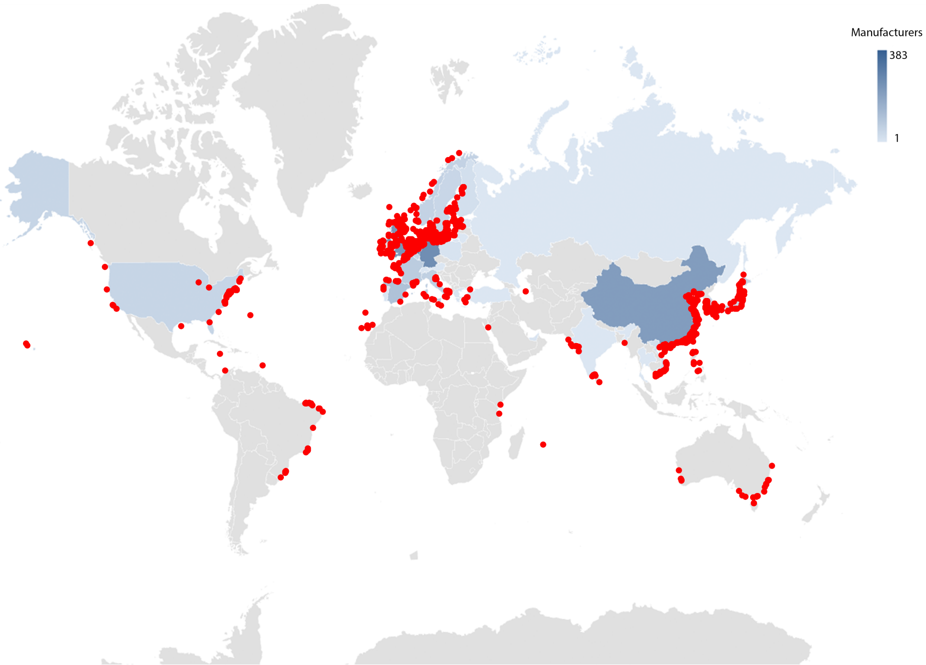


Figure 5.1: All OWF manufacturers and OWF projects shown on a worldmap

5.1.1. Mismatch supply and demand

To set up interesting routes for a HTV, data of 4COffshore and Ulstein is analysed using data processing software like Tableau and Excel. Now the supply and demand for each continent can be indexed by comparing the number of manufacturers of OWF parts (supply) with the number of OWF projects (demand). A mismatch in this supply and demand of Offshore Wind Farms projects and manufacturers can be discovered while analysing the data. In figure 5.2 this mismatch is visible by showing the number of projects versus the number of manufacturers per continent. By offsetting the supply and demand of each continent, it is possible to predict where interesting routes will likely be sailed.

A number of assumptions has been made in order to reach a conclusion about where demand is high.

- Since Turkey is based in two continents at the same time, the demand and supply of Turkey is added to Asia
- Sometimes one manufacturer can have multiple 'assignments' for one wind farm. This is added together, since that manufacturer has a higher demand
- There has not been looked at the size of each project, this is due to incomplete information about (installed) capacity. Therefore each project is assumed to be the same size

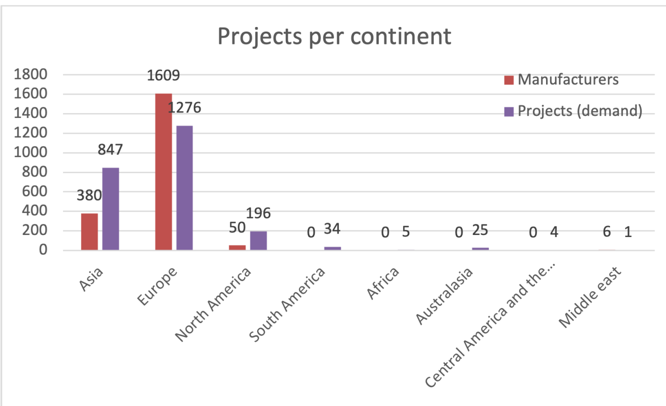


Figure 5.2: The number of projects versus the number of manufacturers on each continent

From this it can be concluded that a lot of wind turbine components are being manufactured in Europe and mainly have to be shipped to Asia and North America, since the demand is higher than the supply in those parts of the world. This means the most interesting routes will be from Europe to Asia (mainly China) and North America (mainly the United States of America).

5.1.2. The missions

The use of missions makes sense since it is easier to compare different alternative solutions with each other when modeled with a benchmark voyage. Based on the facts the main supply will be coming from Europe and the main demand will be in the USA and China, two scenarios are set up.

Europa - USA east-coast

For covering the route between Europe and USA, a trip has been set up between the port of Rotterdam and the port of New York. The distance between these ports is 3308NM on sea and the journey takes roughly 10 days 14 hours when sailing 13 knots according to Searoutes.com [72] and is mapped out in figure 5.3.

Europa - China

For delivering OWF parts to mainland China, a trip between the port of Rotterdam and the port of Shanghai is set up. The distance between these two ports is 10548NM on sea and journey time is 33 days 19 hours and is mapped out in figure 5.4. The port of Shanghai is taken as trade port since this is the largest, busiest and most industrialized port of China. The Suez-canal is sailed on during this trip, resulting in extra canal fees.

Figure 5.3: The route from Rotterdam to New York

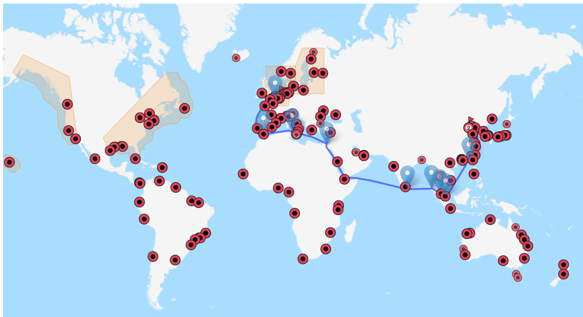


Figure 5.4: The route from Rotterdam to Beijing

These missions are used in this case study as benchmark missions to analyse the environmental and financial performance of the different ship designs for different voyages.

5.2. Adapting the EEXI-e

In order to use the EEXI-e module, some variables need to be calculated upfront. This section elaborates on the input of the EEXI-e method in this case study is and how it is altered to fulfil being a design indicator.

5.2.1. Power prediction

As explained in chapter 4, the EEXI uses the installed and brake power as an input. To estimate the required power of the ship, first the resistance is determined using the Holtrop & Mennen method [31]. The assumption is made that the ship designs fit into the bounds needed in order to use Holtrop & Mennen. When estimates of several types of resistance are combined, together with the hullprop interaction a calculation on how much power is needed is done. In section 2.2 the establishment of the total resistance and power demand is more in-depth explained.

5.2.2. Engines, efficiencies, specific fuel consumption and pollution

Conventional internal combustion engines always come with a performance data sheet. This is a document filled with tables in which all types of measurements of an ICE are shown, ranging from rated speed and power data to several fuel use rates and emission-data. This data can be used to calculate different emissions the engine produces. Every engine manufacturer is required to include this information when selling an engine. With this information, it is possible to calculate the fuel used for each speed in the operational profile if the speed-power curve of the ship is also known.

Since many of the alternative fuel type engines are still in development and not widely commercially available, this results in a data gap. Not much data is openly available about efficiencies or exact emission performance of these engines. Therefore, together with Ulstein some estimations were made based on internal documents, knowledge and available information on alternative fuel engines. In table 5.1 the outcomes are shown. It is possible to change these numbers as desired if updated data is available within the model.

Table 5.1: Efficiencies and specific fuel consumption of alternative fuels

Fuel	**Conversion efficiency**	SFC_{ME} (gfuel/kWh)	SFC_{AE} (gfuel/kWh)
HFO	0.50	190.0	215.0
Methanol	0.52	381.0	381.0
Ammonia	0.56	302.4	302.4
Hydrogen	0.45	30.0	30.0

As for the $C_{FME,CH4}$ and $C_{FME,N2O}$ for each of the alternative fuels, values from a recent Bureau Veritas report [9] are taken. In the report, the values are presented as WtW emissions in [gCO_2-e/kWh], by multiplying with the amount of alternative fuel per kWh it can be converted to [gCO_2-e/gfuel]. The results are shown in table 5.2. There has been made a distinction between green and gray fuels. Green fuels are generated using fully renewable energy sources, therefore the carbon-equivalent footprint is less. The gray fuels are produced with natural gas or other carbon emitting fuels, leading to a higher amount of CO_2-e emissions.

Table 5.2: The different values for emissions, adopted from [9]

Gray fuel (Gry)	**HFO & scrubber**	**Gry Methanol**	**Gry Ammonia**	**Gry Hydrogen (liq.)**
C_F [gCO_2-e/gfuel]	3.3526	5.2231	3.0159	36.1964
Green fuel (Grn)	No green alternative	**Grn Methanol**	**Grn Ammonia**	**Grn Hydrogen (liq.)**
C_F [gCO_2-e/gfuel]		0.0184	0.0331	0.0000

5.2.3. EEXI-e coefficients

Since the EEXI-e formula is composed with a lot of coefficients and parameters to account for various special cases like ice-class or energy efficiencies, these need to be justified. In this section each of the coefficients is elaborated and justified why the case study uses the specified value for it.

Table 5.3: The EEXI coefficients and their assumed values

Variable	**Unit**	**Value**	**Short description**
fj	-	1	Ship specific design elements
feff	-	0	Availability factor each innovative energy technology, waste energy recovery system is 1.0^6
fi	-	1	Capacity correction factor ice-classed ships, 1 for no ice class
fc	-	1	Cubic capacity correction factor if DWT/GTratio 0.35
fl	-	1	Factors for general cargo ships with cranes, $fl = f_{cranes} * f_{sideloader} * f_{roro}$
fw	-	1	Correction factor speed reduction at sea
fm	-	1	1 (or 1.05 for ice-classed ships)

The coefficients are implemented in such a way that these can be changed fairly easy per ship type. This means the values can be set per project, not per iteration.
Now everything is in place to calculate an EEXI-e index for a ship design equipped with an alternative fuel.

5.3. Alternative fuel system & use costs

To make the coupling between the environmental and financial performance of a ship design, some extra costs involved with an alternative fuel system need to be known. These can be split up in engine costs and the costs in order to have such a system up and running on board, which involves piping, extra safety measures or different storage tanks. These costs are captured in the $CAPEX_{Engine}$ and $CAPEX_{storage}$ respectively. The costs for the engine $CAPEX_{Engine}$ scale with the installed power of the ship. This means a bigger ship often needs more propulsive capacity in order to sail, which is reflected in the $CAPEX_{Engine}$ multiplied with the installed power. The costs of $CAPEX_{Engine}$ are therefore defined in [USD/kW].

The $CAPEX_{Storage}$ is expressed in a one time expense, since it only has to be purchased and installed once. These costs are different for for each alternative fuel and each ship design and scale with the amount of alternative fuel the ship is able to bunker. In a report from DNV-GL [20] an estimation of the different storage costs for different alternative fuels is made. In figure 5.5 these estimations are visible.

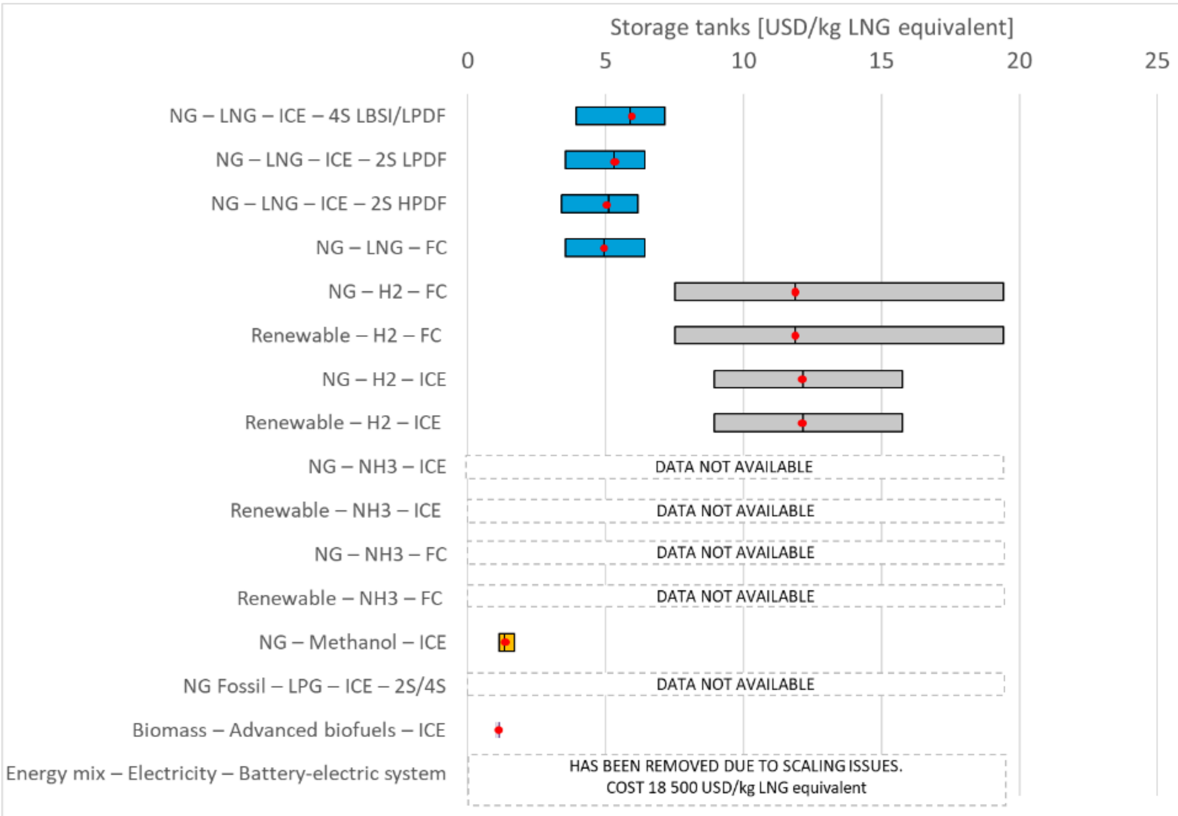


Figure 5.5: Storage costs of several alternative fuels, from [20]

For each alternative fuel the extra storage costs per kg are calculated in line with the DNV report [20] in the unit USD/kg. This makes it possible to easily scale the storage costs with the weight capacity of the alternative fuel the ship is able to bunker. Since the storage costs for ammonia are not available, it is assumed that these costs are comparable to the costs of storing one kg of LNG.
In table 5.4 the storage costs of the different alternative fuels are visible. The costs for the standard HFO engine and system are the same as the ones used in the initial *Blended Design* tool, the values for the alternative fuels are assumed and added to estimate the costs as good as possible.

Table 5.4: Accepted CAPEX costs for various selected alternative fuels

fuel	$CAPEX_{Storage}$ [EUR/kg]	$CAPEX_{Engine}$ [EUR/kW]
MDO/HFO/Biofuel	0.94	471
Methanol	0.57	655
Ammonia	2.17	1500
hydrogen_liq	32.72	2000

For the operational costs, it is found that mainly the maintenance $OPEX_{Maintenance}$ is the most significant for alternative fuels and therefore play a noticeable role in the value of the OPEX. The maintenance costs $OPEX_{Maintenance}$ is influenced as a percentage of the build costs of the ship as an insurance. This means the shown values for this are presented as a percentage.

Table 5.5: Accepted OPEX costs for various selected alternative fuels

fuel	$OPEX_{Maintenance}$	$VOYEX_{Fuelcosts}$ [EUR/kg]
MDO/HFO/Biofuel	0.0115	0.33
Methanol	0.03	0.31
Ammonia	0.03	0.41
hydrogen_liq	0.04	9.5

For the alternative fuel prices, table 5.6 shows the projections which have been used. The numbers origin from the database MARIN has set up [55], with fuel price projections for alternative fuels towards 2050. The price difference between green and gray generated alternative fuels, although being present, is not made in this case study due to too little available data.

Table 5.6: Projected fuel prices for alternative fuels [EUR/kg]

Year	**HFO**	**Methanol**	**Ammonia**	**Hydrogen**
2020	0.33	0.31	0.41	9.5
2030	0.30	0.30	0.36	8.5
2040	0.20	0.28	0.30	5.0
2050	0.25	0.25	0.28	1.5

To visualize the alternative fuel price development throughout the years, figure 4.5 in the previous chapter has been created.

5.4. Results

This section will elaborate on the outcomes of the case study and discuss some notable findings to study if the presented method produces reliable and representative output. Each paragraph will outline a result accompanied with the input the *Blended Design 2.0* method was given.

Plots

Since this graduation project is a follow-up of the project by Zwaginga et al. [91], much attention has already been paid to set up interesting plots. Therefore the result plots in this thesis are based on the previous graduation project ones, to ensure consistent results.

Like discussed in chapter 3 the results are presented from well-to-wake (WtW) approach, this to stimulate the green fuels the best. But comparing fossil generated fuels with alternative fuels who have their origin in green electricity is not fair. It is therefore intentionally chosen to compare the WtW from fossil originated fuels separately from the alternative fuels which are generated using electricity.

5.4.1. Gray vs. green fuels

Since the EEXI-e index of each of the ship designs has been calculated, the environmental performance of the green and gray alternative fuels can be compared with each other. In figures 5.6 and 5.7 this is shown for various case studies.

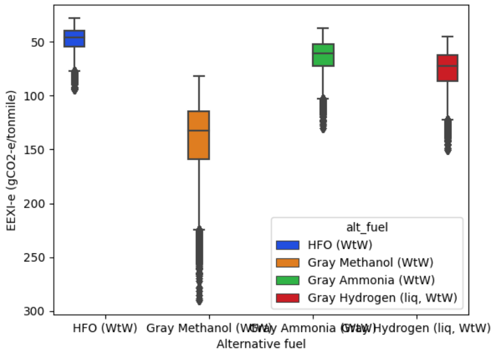


Figure 5.6: The EEXI-e index for gray WtW fuels

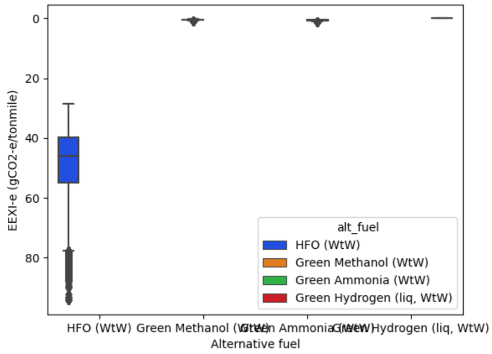


Figure 5.7: The EEXI-e index for green WtW fuels, hydrogen is abscent due to the fact this has an EEXI-e index of 0

In both cases, green and gray, the range of EEXI-e values for HFO remains the same, which is logical since in both cases the same input is used to calculate these values.
What stands out is that the way the fuel is produced has a severe impact on the EEXI-e index, when looking at the WtW approach. Some gray fuels are a worse choice compared with HFO when looking at EEXI-e index, on average HFO has a better environmental performance. Looking at the green fuels on the other hand, they score better than HFO. One other thing what is noticeable is that there is no hydrogen visible between the green fuels plot. This is due to the fact that liquid hydrogen does not emit any kind of polluting emissions at all, resulting in an EEXI-e index of 0 [gCO_2-e/tonmile].

5.4.2. Speed vs. EEXI-e index

In figures 5.8 and 5.9 various speeds are plotted together with their corresponding financial and environmental performance.

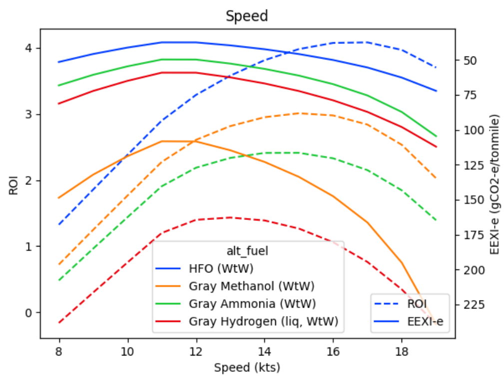


Figure 5.8: The financial and environmental performance with varying speeds for gray WtW fuels

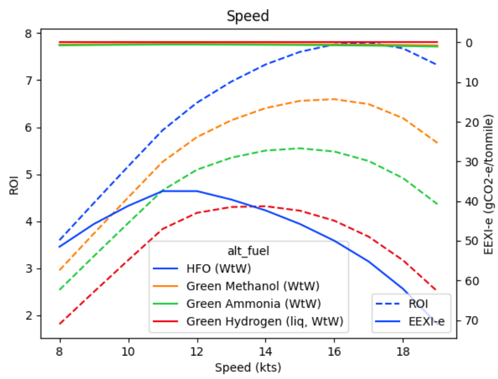


Figure 5.9: The financial and environmental performance with varying speeds for green WtW fuels

What is noticeable is that next to a preffered speed for having a profitable ROI, there is also an optimal speed to sail environmentally wise. For each of the alternative fuels this is slightly different, but it ranges from 11 to 13 knots, depending on which fuel looked at. This effect is best visible for gray fuels shown in figure 5.8, since these fuels have more variance in EEXI-e index. At speeds around 12 knots it is possible to have the best environmental performance while having as much space for cargo on board. The environmental performance is decreases after this range since sailing faster means more fuel use, resulting in more emissions. The fuel weight also has a negative effect on the EEXI-e index, since this value decreases due to the extra weight of alternative fuels.

This could be valuable information for a shipbuilder, since this plot shows that the most financial return could be sailing at a higher speed, but when slowing down the environmental performance could increase significantly. Therefore this plot could help to raise the discussion what the optimal sailing speed for a HTV could be, which probably will be somewhere between the two optimal speeds for ROI and EEXI-e.

5.4.3. Impact on cargo DWT

It is obvious that different alternative fuels have different effects on the available cargo weight which can be loaded on the ship. This is due to the different gravimetric densities of the alternative fuels, as explained in chapter 4.3.2. A clear way to show this effect of decreased bulk weight due to the weight of the used alternative fuel is to plot these two values against the ship speed, since a higher speed requires more fuel. This plot is shown in figure 5.10.

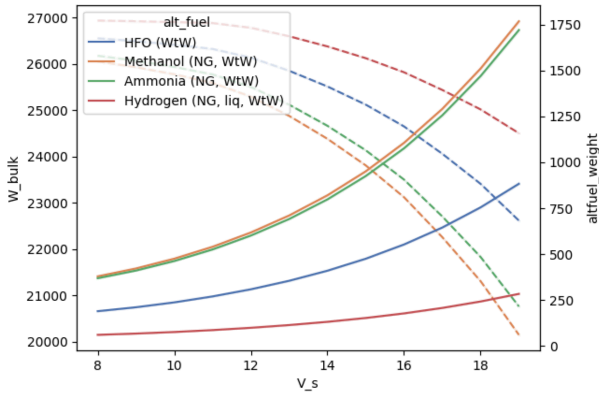


Figure 5.10: The alternative fuel weight and available weight for cargo vs. ship speed

As expected the weight of the alternative fuel increases as the speed goes up. Therefore the loading capacity decreases, expressed in the amount of weight what can be loaded on the ship. Since the gravimetric densities are different for each alternative fuel, the alternative fuel chosen dictates how much cargo can be transported.

5.4.4. Length & beam vs. EEXI-e index

For this result the financial and environmental performance are evaluated on two basic dimensions; the length and beam of the ship design.

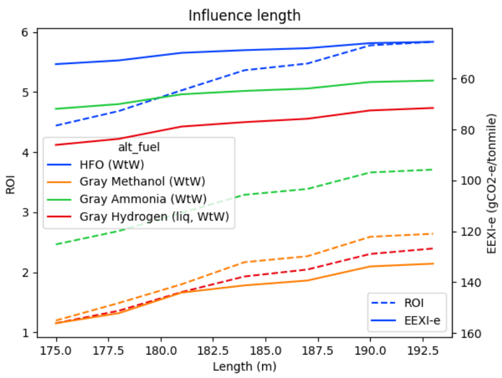


Figure 5.11: The financial and environmental performance with varying length for gray WtW fuels

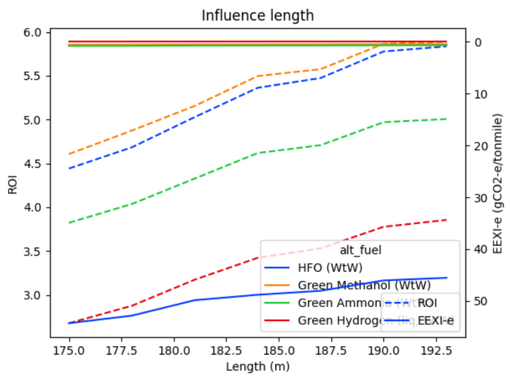


Figure 5.12: The financial and environmental performance with varying length for green WtW fuels

As can be seen in figures 5.23 and 5.12, it looks like a greater length results in a better performing ship environmentally as well as financially. The influence tends to decrease around 185 meters for this ship design. This probably has to do with the fact that the length of the design does not have a large influence on the cargo which is loaded on the vessel anymore, resulting in a bend of both of the performance curves.

In order to check if the tendency that a longer ship automatically results in a better EEXI-e index, a run is done with ship designs with a length up to 250m. The result is shown in figure 5.13, the plot looks blocky since the step size is increased to 10 meters. As can be seen the EEXI-e index increases with the length of the ship, peaking around 220 meters. The reason that the score drops after the lengths get larger than 220 meters is that the cargo which can be transport increases this much resulting in a lower EEXI-e index.

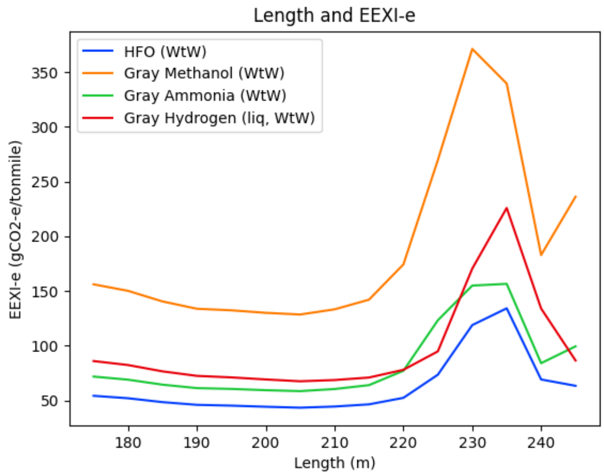


Figure 5.13: The EEXI-e index for gray fuels plotted against varying length of ship designs

To analyse the influence of the beam on the EEXI-e index, the following plots in figures 5.25 and 5.26 are set up.

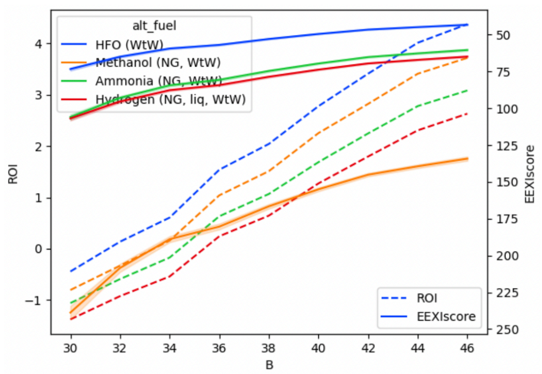


Figure 5.14: The financial and environmental performance with varying beam for gray WtW fuels

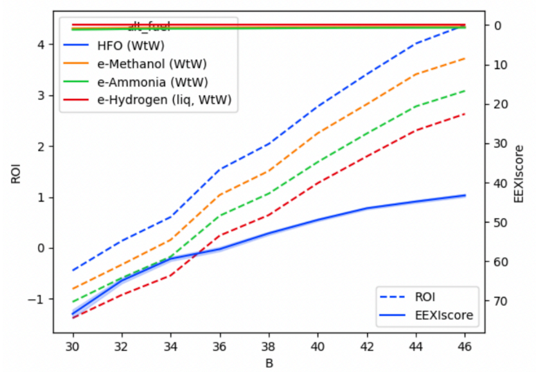


Figure 5.15: The financial and environmental performance with varying beam for green WtW fuels

As well the case with the length, the environmental performance also becomes better when increasing the beam, as shown in figures 5.25 and 5.26. This can be explained since the vessel design is able to transport more cargo since a bigger beam often means more deck area. Since the EEXI-e module also takes into account the amount of cargo it moves, this index obviously gets better. The shaking shape of the plots are a result of the shape of the cargo, at a certain beam the ship design suddenly is able to load more cargo on deck, which increases both financial and environmental performance, therefore resulting in a bump in the plot.

5.4.5. Different missions

This section will focus on differences between missions, since the case study derived two different missions from the market research done. In figures 5.16 and 5.17 the economical and environmental performance of the vessel designs for each of the missions is shown.

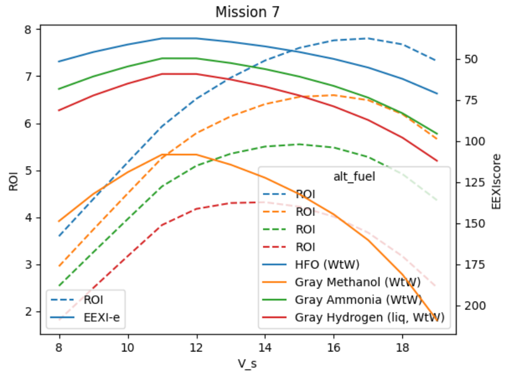


Figure 5.16: Vessel performance on route Rotterdam - New York

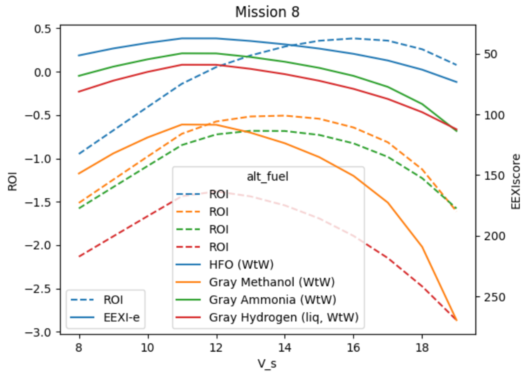


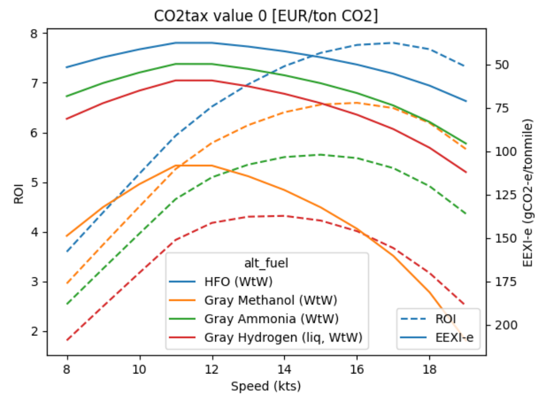
Figure 5.17: Vessel performance on route Rotterdam - Shanghai

What can be seen is that the financial performance for the last mission - from Rotterdam to Shanghai - is worse compared to the performance of the first mission from Rotterdam to New York. This is because the distance for the last mission is much longer than the first one, resulting in more fuel use and therefore more fuel costs. Since the earnings per voyage is not altered and the same for the two missions, this results in a bad ROI since the revenue per trip is simply too small. This can be counteracted by charging each cargo piece more to generate more income per voyage.

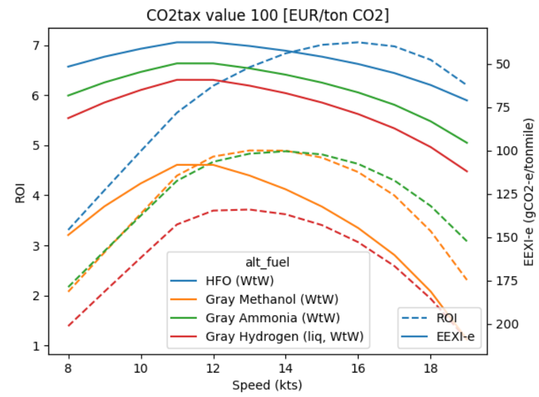
Another noticeable difference is the best performing sailing speeds for each mission. This has again to do with the difference in distance the vessel has to cover, since this can account for more fuel and therefore more fuel weight, resulting in less cargo what can be loaded on the ship. Since the EEXI-e also evaluates the amount of cargo per trip, this results in an altered optimal sailing speed.

5.4.6. Different prices for the carbon tax

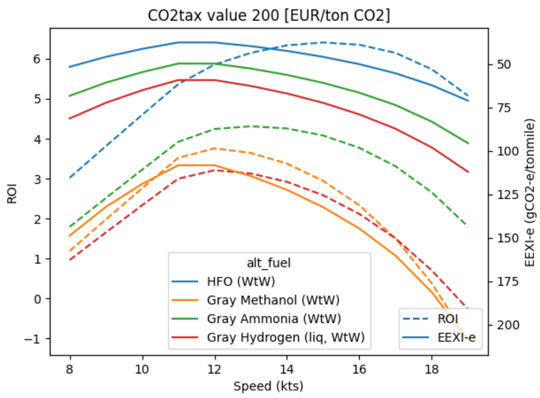
In figure 5.18a to 5.18d several values for the carbon tax are shown. Please note that the figure is shown on the next page.
As can be seen in figure 5.18, the carbon tax drastically influences the financial performance of a ship design. As can be seen when a tax of 0 EUR/tonCO_2-e is applied, the ROI is positive, but as soon as the value for the carbon tax increases, these figures become less positive.
Notable is that the figure of ROI shifts towards the EEXI-e when the carbon tax increases in value. This is easy to explain as it becomes more profitable to sail at a low fuel consuming speed. With a carbon tax of about 400 EUR/tonCO_2-e the figures match almost, as shown in figure 5.19.



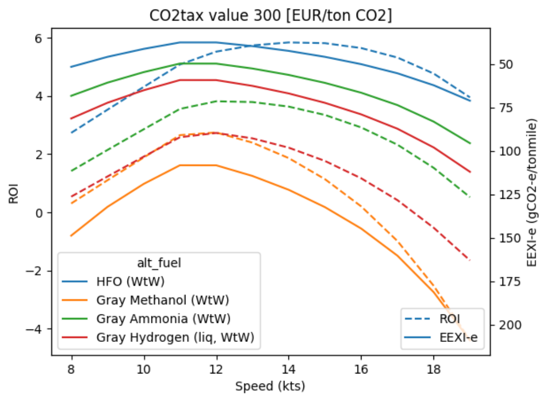
(a)]
ROI & EEXI-e for carbon tax 0 [EUR/tCO_2-e]



(b) ROI & EEXI-e for carbon tax 100 [EUR/tCO_2-e]



(c) ROI & EEXI-e for carbon tax 200 [EUR/tCO_2-e]



(d) ROI & EEXI-e for carbon tax 300 [EUR/tCO_2-e]

Figure 5.18: ROI and EEXI-e for several values of carbon tax

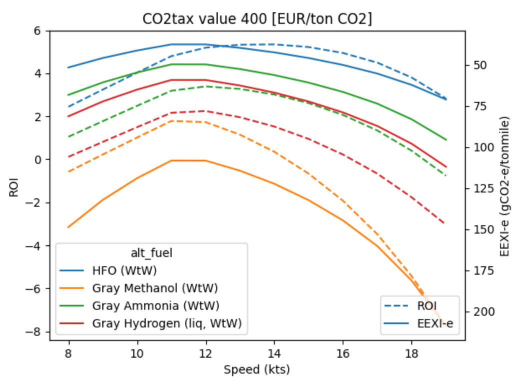


Figure 5.19: A carbon tax of 400 EUR/tonCO_2-e implemented

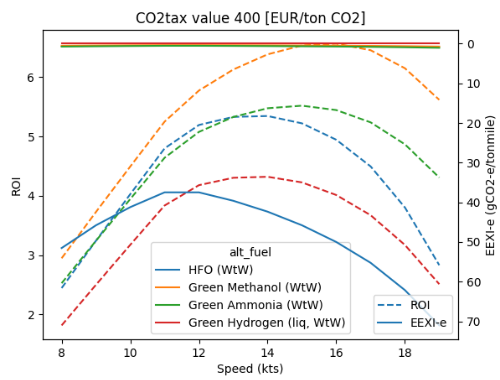


Figure 5.20: The same carbon tax of 400 EUR/tonCO_2-e applied to green fuels

In order to compare this with applying a CO_2-e tax of 400 EUR/tonCO_2-e when using green fuels, figure 5.20 has been set up. This shows that the ROI for HFO is much worse than the ROI for the alternative fuels, therefore making it interesting to switch to an alternative fuel system.

Sensitivity carbon tax

When altering the carbon tax, the ROI starts to show drastic changes, even changing in far negative numbers. This shows that carbon tax has great effect on the ROI. In figure 5.21 in the appendix the different financial components for mission Rotterdam - New York are shown. What stands out is that the VOYEX drastically increases at higher speeds, which can be explained by the fuel use which goes up.

5.4.7. Financial performance for alternative fuels

The financial performance parameters CAPEX, OPEX and VOYEX relate different to each other, as shown for the HFO case in figure 5.21. What stands out is that the VOYEX is very depending on the speed of the ship. This makes sense since the VOYEX involves the fuel costs, which drastically increase when the speed goes up.
Also the costs for the OPEX and CAPEX slightly bend upwards when the speed increases. For the OPEX this has to do with the increased maintenance costs. The CAPEX are higher due to the fact that the engines required for a higher speed are more expensive.

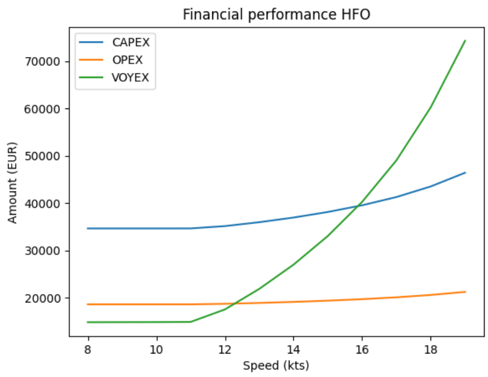


Figure 5.21: The order of magnitude difference of the OPEX, CAPEX and VOYEX plotted against speed

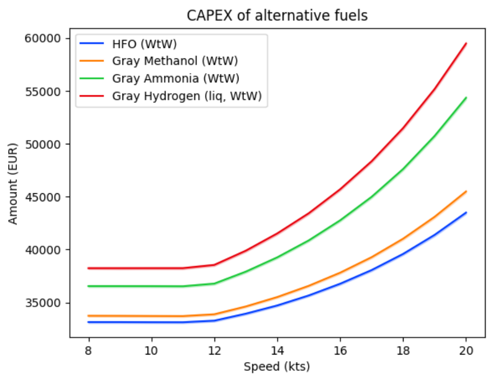


Figure 5.22: Calculated CAPEX of alternative fuels

To check if the storage and engine costs, which both are part of the CAPEX, are different for each alternative fuel, a CAPEX plot for all fuels is set up. In figure 5.22 the different CAPEX are shown for each of the researched alternative fuels.
What stands out is that the CAPEX for hydrogen is highest, which makes sense when knowing the engine costs per kW are highest for this alternative fuel, as well as the storage costs due to the fact it has to be stored in cryogenic tanks. Therefore this fuel scores fairly high on the CAPEX compared to other fuels. HFO seems to be the most financially appealing option, which also makes sense since the associated engine system is fully developed and the fuel is easy to handle on board.

5.4.8. Influence block-coefficient on EEXI-e index

Ship designs with a high block coefficient close to 1 often have more loading capacity. To analyse if these kind of ships also have a lower, more preferable EEXI-e index, the plots in figures 5.23 up to and including 5.26 are set up. The goal is to analyse if a higher block coefficient automatically results in a better environmentally performing design.

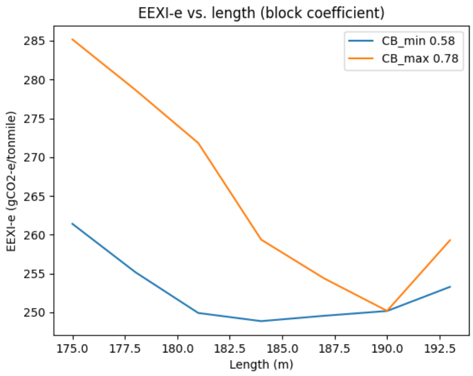


Figure 5.23: The influence of different lengths on the EEXI-e score for gray fuels

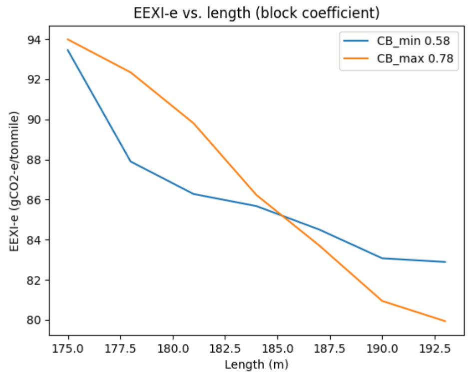


Figure 5.24: The influence of different lengths on the EEXI-e score for green fuels

The length-block coefficient relation shows that for ships with a high block coefficient equipped with gray fuels tend to have a higher EEXI-e index, making them more polluting for the environment. Interesting to see is that when using green fuels, shown in figure 5.24, the two lines intersect. This means that the ship with a high block coefficient at that length has a better environmental performance than the ship with a lower block coefficient.

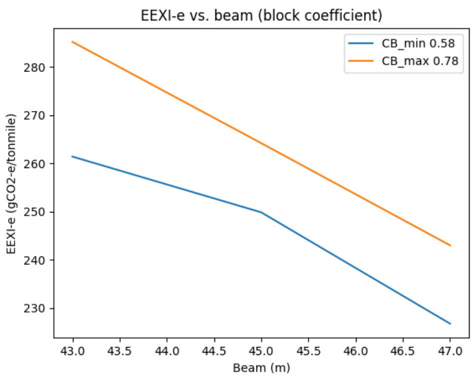


Figure 5.25: The influence of different beams on the EEXI-e score for gray fuels

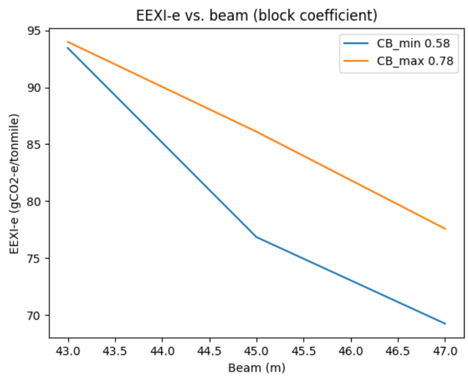


Figure 5.26: The influence of different beams on the EEXI-e score for green fuels

For the influence of the beam per block coefficient on the EEXI-e index the same can be concluded as the length: ships with higher block coefficients tend to have a worse environmental performance than ships with a lower block coefficient. This is the case for both gray and green fuels. The influence of the block coefficient and beam therefore seems to be less sensitive to the green and gray fuels.

Methanol

What stands out is that gray methanol as alternative fuel results in a rather high EEXI-e index compared to the other alternative fuels. This is because the specific fuel consumption of methanol at running speed of the engine is very high compared to other alternatives. The base case of HFO has 190.0 gfuel/kWh where methanol uses up to 381.0 gfuel/kWh [84]. The fuel consumption is inseparable linked to the amount of GHG resulting in a high EEXI-e index.

5.5. Assumptions case study

During the research of this thesis, many assumptions were made in order to have the model running and arrive at stable, useful and *true to nature* results, to come as close as possible to reality. Often these assumptions were made in compliance with the expertise of Ulstein internal knowledge base or with the best approximations as found in literature. The most important assumptions of this case study are elaborated on in this section. In the section 6 validation, the assumptions are tried to be validated.

Well-to-wake pathway
The research only considers the well-to-wake pathway of alternative fuels, since most of the alternatives aren't that environmentally polluting when only looking at the fuels combustion process. The way the alternative fuel is generated could therefore play a major role in how it is evaluated in the *Blended Design* method.

Fuel costs
To model the changing fuel price over the years, a poly fit has been set up through a discrete number of fuel price projections. The fuel price is then averaged and used to calculate with. This does not affect the ROI over the lifetime of the ship, since the effect of the changing fuel price is still incorporated in the poly fit function. This could however have an effect on the cash flow or profit when only looking at yearly results, since the price is kept constant. Since the tool is mainly used to analyse the results of the performance over the lifetime of a ship, it is assumed that this does not influence the main results.

Another important note to make is that there is not made a distinction in alternative fuel price of gray and green fuels. Currently it is more expensive to produce green fuels since they rely on more technological advancements than gray alternatives. This is reflected in their price, being more expensive.
This thesis assumes the price for gray and green alternative fuels is the same. When a higher price for green fuels is inserted, this will result in a lower ROI.

Extra power alternative fuels
Some alternative fuels are cryogenic, meaning they have to be extra cooled or kept under pressure. This accounts for extra energy demand, since the cooling and pressure systems have to be powered. To capture the extra energy needed in order to store these fuels, this effect is incorporated in the efficiency of the alternative fuels. If a fuel demands extra energy, the total fuel efficiency is adapted.

Costs green and gray alternative fuels
The costs for gray and green fuels are kept equal throughout the simulation. This assumption is not realistic, but made due to a lack of data. At this point in time, although worse for the environment, it is cheaper to produce alternative fuel with fossil fuels like natural gas. Different prices can result in different optimal alternative fuel choices.

Average weight cargo
To compare the number of transported monopiles and transition pieces fairly, the transported weight is calculated instead of number of pieces. This makes sure the smaller vessels are not burdened since they can not move the big pieces when calculating the EEXI-e index.

This means the total weight of the cargo is taken as a measure of merit instead of the number of piles the vessel design is able to transport. One problem with this is that during the years the market simulation is done, the amount of cargo pieces which fit on deck can change due to the size of the cargo increases due to market changes. This effect is visualized in figure 5.27.
Therefore it is assumed that the total weight of the cargo the ship is able to load stays roughly the same throughout the years of the market simulation. Research indicated this was the case, with the cargo weight fluctuating within acceptable limits. Therefore the mean weight of the cargo for each of the deck layouts is taken to account for the changing market in order to calculate an average EEXI-e index.
Since the weight of the cargo depends on the market at that point in time, and since the model always tries to maximize the amount of cargo it can transport, it is assumed that a mean would do for this instance. In figure 5.27 this principle is illustrated.

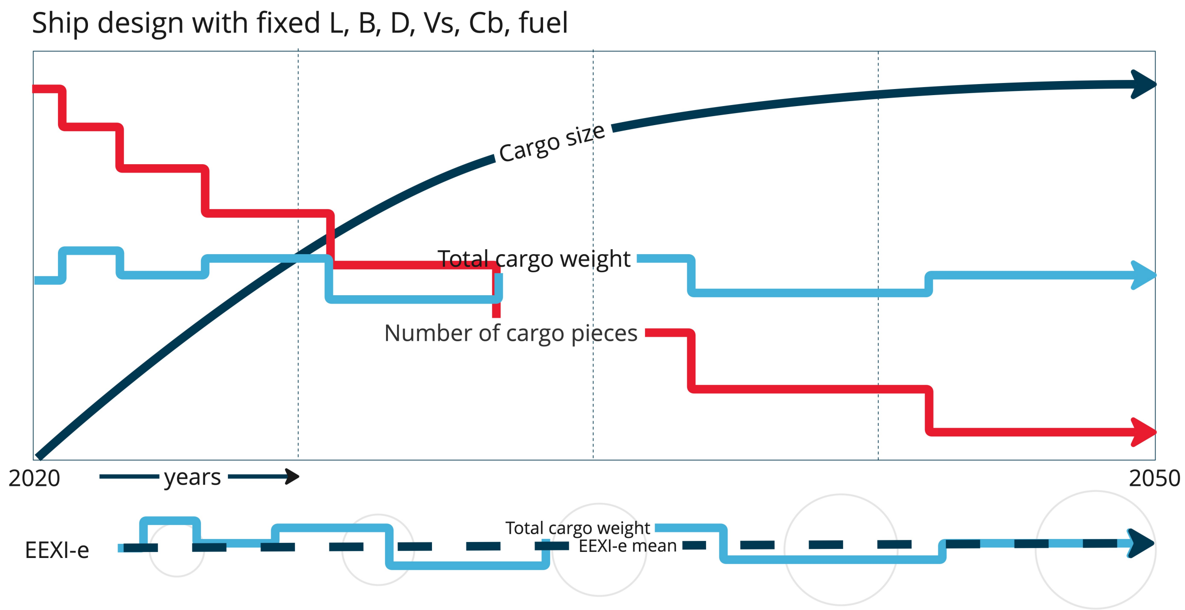


Figure 5.27: The principle of the averaged cargo weight to calculate the EEXI-e

Storage costs Ammonia
The storage costs for ammonia are assumed to be the same as the storage costs for LNG. Since both ammonia and LNG should be stored cryogenic and have similar properties, it is a plausible assumption. In the report of DNV-GL [20] the storage costs for ammonia are absent but the storage costs for LNG are estimated.

GWP100 & GWP20, new research
There are variations of the values for the global warming potential available since this is an ongoing research as explained earlier. Also some sources apply different measurement methods and therefore use different results, like Huijbregts [33], a comprehensive research done for the Dutch Government (de Rijksoverheid).

In this research the values of the IPCC are taken as a premise since these are internationally approved values. Different values for these numbers could be easily changed and adapted in the tool itself if necessary. As explained in chapter 3 this research used GWP20.

6 Validation

The validation of the *Blended Design 2.0* method is first elaborated on in preparation to the conclusions which is drawn in the next chapter.
Since this thesis is about the further development on the *Blended Design* tool as a result of research by Zwaginga et al. [91], part of the tool is already validated.

One part of the validation for the second version of the method is done by checking if the tool still yields the same results when fed with the same input data as the first version of *Blended Design*. This may be difficult since the type of ships which the tool is optimized for differs, but to some extend output can be compared with each other.

The second way of validating the method is done by the so called 'Validation square' according to literature from Pedersen et al. [64]. This is explained in the second section.

Lastly during the time span of this thesis, new literature became available which can be used to find similarities and discuss differences. This is done in the last section.

6.1. Verification using ship design

In order to check if the outcomes of the initial *Blended Design* tool match the output of the second version of the tool, a comparison is made by giving the same input to both models and study if they result in the same optimum found in an earlier study for an HX120 ship design.

Based on an Ulstein Concept Design Report, basic dimensions are matched with outcomes of the *Blended Design 2.0* tool. This involves the length, beam, draught and design speed. The exact numbers are enclosed in the confidential appendix D.

Noticeable is that some results do not fully coincide with each other, this could have various reasons:

- The market projection given as input is different, therefore this could lead to a different output
- Some functions are defined differently; the project involved DP2 capability whereas *Blended Design 2.0* does not incorporate this
- Some design choices can be made on a different ground; maybe the financial optimum is not used to make the specific decision

Speed-power curve
Also a speed-power curve is generated to see if it matches the speed-power relations the designed HX120. The relations of the design are also shown in appendix D. Both show similar results.

6.2. Validation square

The validation square from Pedersen et al. [64] is a method set up especially to validate things that can't be easily measured, something a lot of design methods have to cope with.

Since it is not possible to build each variation of a design and measure each of their individual performances and compare these with the predicted performances, this paper presents the validation square which aims to validate a design method as objectively and academically as possible. The validation square itself is shown in the gray box in figure 6.1 and tries to build confidence in usefulness [64].

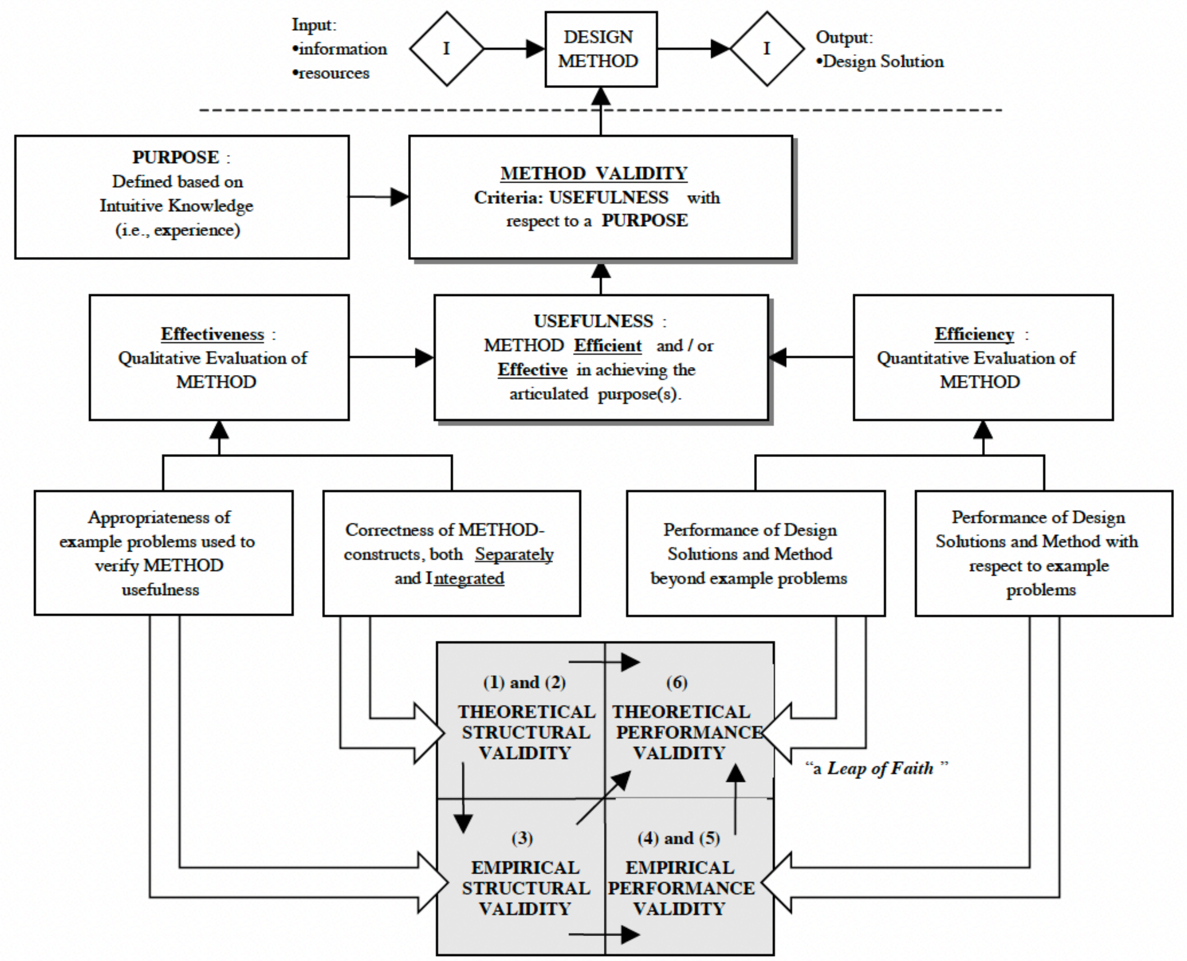


Figure 6.1: The validation square as presented by Pedersen et al. [64]

As can be seen in figure 6.1, the validation square tries to answer a few questions to the best knowledge possible. The following paragraphs each question is answered.

1. Is there internal consistency of each parent construct?

The method presented in this thesis is based on existing and already established equations. The EEXI index is a design index which is promoted and enforced by the International Maritime Organisation (IMO). Many shipping companies are preparing their fleet to have everything in place when this index comes into force in 2023, making the EEXI index an accepted measure.

The CO_2-equivalent is also something which is endorsed by the Intergovernmental Panel on Climate Change (IPCC). This organisation, which is part of the United Nations, is broadly recognized and a well respected body for assessing the science related to climate change.

2. Is the method internal consistent?

To verify the internal consistency of the EEXI-e method, a high-level flowchart of the information flow and input and output of the EEXI-e module is made, as shown earlier in figure 4.6. As can be seen the formation of the EEXI-e index value is based on the same principle as a EEXI index would be calculated. In this case it is combined with the CO_2-equivalent, making it also useful for alternative fuels. The calculations of the first *Blended Design* method are combined with the output of the EEXI-e module to create the results.

3. Are the example problems appropriate?
As covered in chapter 5, the case study is taken as an example problem. The three different missions presented are based on real data of offshore wind farms which are being built in the coming years. Also an indexation was made of all manufacturers of offshore wind farm products, i.e. blade, nacelle and monopile manufacturers. It is believed that this resulted in a complete view on supply and demand spread around the world, which is therefore considered to be relevant as an example problem.

4. Is the method useful for the chosen example?
The aim of the method was to enable quantifying emissions of alternative fuels in order to compare the environmental performance. With the addition of the EEXI-e method to *Blended Design*, it is possible to compare the environmental and financial performance of alternative fuels. During the research, many runs of the EEXI-e module have been executed in order to build a database of numbers and index values. Analysis of the results show an optimum for various design parameters, like ship length and speed. This strengthens the suspicion the method is also able to perform an optimisation based on environmental performance.

5. Is the demonstrated usefulness linked to the applying method?
It can be expected that the EEXI index is a well researched, fair method of calculating the CO_2 emissions. By applying the CO_2-e emissions to it, the foundation of the EEXI index is not altered. Due to the fact that the EEXI index becomes mandatory in the upcoming year, the method can be considered well established.
Implementing this in the *Blended Design* method, the method enables comparing alternative fuels on various parameters financially as well as environmentally.
As far as concerned, there is not a methodology published or other design methods known what is able to do this multi criteria analysis for a heavy transport vessel like the HX120. This makes it useful for this specific ship design.

6. Is the method useful for domains that are broader than the example problems?
The *Blended Design* method is intended to be used as an in-house software tool from Ulstein, currently used for helping design offshore installation vessels and the design of HTVs. The fact that the first version of the tool is converted to be applicable for HTVs shows that the tool can be deployed in a broader domain. Since the EEXI-e method is tried to keep as generically as possible, it is expected the method pursues usefulness in a broader domain. In the recommendations described in chapter 8 some future uses of the method are elaborated on.

6.3. Other literature - similarities & differences

One month before this research concluded, in October 2022, a report from Bureau Veritas came out which showed many similarities with the content of this thesis; alternative fuels from a well-to-wake perspective. This thesis aims to optimize on emissions of alternative fuels with the same WtW approach. A section of this research will therefore be dedicated to show the similarities and point out some differences found with this report.

Similarities
The report hints to the changing climate and presents alternative fuels as a valuable solution to combat this. It identifies the same GHGs as harmful emissions which contribute the most to climate change. It considers the well-to-wake approach to be the most complete solution in quantifying GHG emissions, and therefore presents it as a new way of measuring environmental impact of emissions.
BV agrees to assess alternative fuel options from a WtW basis, since only through a complete life-cycle analysis the environmental impact of fuels can be properly evaluated.

Differences

Where this thesis foremost focuses on the EEXI index as a solution to encourage design more environmentally friendly, the BV report focuses more on the CII which now not includes the upstream emissions. The CII is a valuable measure to determine the CO_2 emissions of existing ships by measuring them. By including the upstream emissions, a more realistic situation is created.

Next to main changes covered in this thesis, the BV report elaborates more on other shortcomings or obstacles with alternative fuels, like fuel characteristics, safety considerations, global availability and regulations.

Part 3
Conclusion & Discussion

’Five ships is not yet a fleet’
J.F. Taen - Naval Architect

7 Discussion & Conclusion

This chapter first discusses the findings of this thesis, the meaning of the results found and how the findings relate to other literature. Afterwards the main objective is paraphrased and the sub questions of the thesis are answered in the conclusion of this thesis.

7.1. Discussion

The findings in this thesis suggest there are points to be found where several main design parameters perform favorable when equipping an HTV with an alternative fuel system. The data also suggests that some ranges for these main dimensions have to be avoided when designing a ship, since the environmental or financial performance underperform.
The method presented combines the financial performance with the environmental, therefore it can help carefully balancing these two pointers when designing a ship, making a well informed consideration on numerous design parameters.
The results of the EEXI-e method are indicative since these are based on many assumptions as explained in earlier chapters. Since all calculations are done in the same way, the outcomes can still be compared with each other, making it still a quantitative method.

The societal relevance of the presented method is becoming increasingly important with the climate changing and the energy transition. The need for sustainable solutions is not a choice anymore, since regulation pushes towards a carbon-neutral future. Therefore the maritime industry has to adapt the design process to not only optimize on costs, but also take into account the environmental performance of a ship design.

7.2. Conclusion

The aim of this thesis was to develop a method that assesses both the economic and environmental performance of HTVs, specifically for future offshore wind.
The foundation for this method was the already available *Blended Design 1.0* method, capable of making a financial analysis with regard to the future offshore wind market.

With the EEXI-e methodology presented in this thesis, it is possible to quantify emissions of alternative fuels in a fair way with each other, by not looking at CO_2 emissions only, but also converting all GHG emissions to their CO_2-equivalent impact. This functionality is added to the already existing method of *Blended Design 1.0*, creating a new version of the method and tool.
Due to the merge of these two methods, the new method is able to evaluate the financial and the environmental performance for the entered ship designs. Enabling the method to a quantifiable analysis of emissions of alternative fuel and compare different HTV designs on their financial and environmental performance on different main design variables.

7.2.1. Sub-questions

Each of the chapters has tried to answer one of the sub-questions of this thesis.

- What are the State of the Art ship design methods and how do they cope with the unique characteristics of HTVs? What are the limitations in the way HTVs are currently designed?
- What are established environmental performance indices and how can they be applied to HTVs?
- To what extend does the quantification of emissions of alternative fuels have an impact on the design of a HTV?
- How does taxing the environmental impact of a ship change the ROI and other financial benchmarks? How are they influencing each other?

What are the State of the Art ship design methods and how do they cope with the unique characteristics of HTVs? What are the limitations in the way HTVs are currently designed?
Several State of the Art ship design methods are elaborated on in chapter 2. The most important one, as well as the foundation for this thesis, being the *Blended Design* method. This method aims to evaluate the design of an offshore installation vessel on its financial performance. This design method is altered to fit to design for HTVs. The most important limitation of this method is that it can not optimize on environmental performance of a ship design.

What are established environmental performance indices and how can they be applied to HTVs?
A lot of environmental performance measures are explained in chapter 3, the most important one is the EEXI index. This is a measure which comes into force in 2023 and evaluates the CO_2 emissions of a ship, relating it with the amount of cargo transported. This index is able to compare different cargo ships with each other and can be tailored to be applicable for HTVs.
To cut back on emissions, the use of alternative fuels is presented as the most impacting. HTVs can also be equipped with alternative fuel installations, but these fuels impact the endurance, cargo capacity and weight of the HTV.

To what extend does the quantification of emissions of alternative fuels have an impact on the design of a HTV?
Since not all alternative fuels emit CO_2 emissions but other GHGs as well, the conversion towards CO_2-equivalent emissions is presented. By optimizing the design of an HTV equipped with an alternative fuel installation on emissions, the CO_2-equivalent is used to compare the fuels in a fair way. In this way, a EEXI-e index can be calculated, enabling alternative fuels to be compared using the same unit. A way the quantification of GHG emissions leads to a different design is that it generally advices to lower the service speed of the vessel design in order to use less fuel and therefore generate less emissions. Different choices of alternative fuels lead to different environmental performances. This comparison method can therefore guide the choice of an alternative fuel system. The influence the alternative fuel system has on the weight, space, cargo capacity and endurance of the ship design is evaluated by the method, since each alternative fuel has its own characteristics. The tool also highlights areas in which the ship design probably underperforms, both environmentally as well as financially. This should help designers to avoid these areas of ship design and optimize ships which are financially interesting and perform better for the environment.

How does taxing the environmental impact of a ship change the ROI and other financial benchmarks? How are they influencing each other?
The environmental impact is mainly measured and compared by alternative fuel systems in the *Blended Design* method by means of the EEXI-e method. This results in a new version of the method; *Blended Design 2.0*. This new method is able to evaluate an enormous amount of different ship configurations and calculate their financial and environmental performance at the same time. The output can help ship designers with making design choices for basic dimensions and making a well-established decision for an alternative fuel system.
Since every alternative fuel system has its own additional costs; the engine & storage costs are often higher, the fuel costs increase and the cargo capacity of the ship design changes due to the weight of the alternative fuel, therefore resulting in less profitable cargo which can be loaded. The *Blended Design 2.0* method combines all these factors in an updated cost & income calculation to evaluate how the financial performance is impacted by the addition of alternative fuels.

8 Recommendations

This chapter concludes with recommendations for future research, development and topics which can be studied further. It concludes with a personal reflection on the thesis.

8.1. Recommendations

The recommendations aim to inspire further research on this relevant topic.

8.1.1. Verification with reference ship

It has proven challenging to calculate the emissions of a vessel before it is actually emitting GHG. This is especially true for ships employing alternative fuels, since little data is available. The method presented in this thesis aimed to approach reality as best as possible. However, it is based on assumptions as discussed in earlier chapters. The applied model can only be truly verified if a ship sailing on alternative fuel is built and operated. The emission measurements of this reference vessel can be compared with the expected GHG emissions from the presented method to verify the estimation. The tool can then be fine tuned by correlating these numbers.

8.1.2. Expanding markets and different ship types

At this point, the method models HTV ship designs for bottom founded structures, since this market is now upcoming. Because other markets - like the floating offshore wind structures market - is also gaining interest, it could be useful to have the method also design for this ship type and incorporate and model this market.

But even past the OWF market, it may be interesting to see how this method can be applied to other markets as well. For example the general cargo shipping market or the growing cruise market. One recommendation is to make the method flexible by incorporating more interesting markets. This can be achieved by analyzing more diverse market data to help build optimized ships for other segments as well. With this method, the design can be configured based on smarter decisions, financially but also environmentally wise.

This implies that the method also has to be suitable for other ship types as well. To make it available for a broad range of designs, it is interesting to first look into ships that have to deal with an uncertain market and have cargo which can be expressed as a value, since the EEXI-e thrives on this idea. For example cargo ships, passenger ships and cruise ships are all vessels which have cargo which can be described as a discrete value. For these types there could be looked into the implications and cargo handling of each of the designs, making the tool more flexible and adaptable for the different characteristics of each vessels needs.

8.1.3. Retrofits

It may be interesting to study the effects of including a retrofit of a ship design as explained in literature by Lagemann et al. [46]. Due to the fact the *Blended Design* method is developed for new build ship

designs, this thesis mostly studied to the financial and environmental effects of a design equipped with an alternative fuel system from the beginning. However, if a ship is retrofitted midlife, the business case and environmental performance could change.
For a ship that has to be retrofitted, most main dimensions and design parameters are already established. The effect of having alternative fuel systems on board of the ship could consequently lead to other combinations of engines and design configurations.

Recently the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS) published a report [52] in which the technical, economical and environmental aspects are analysed for the conversion of container vessels to alternative fuels. A detailed manual on how to prepare vessels, the total costs of conversion and how conversion timelines influence the total costs are presented in this report. The report aims to inform on the benefits of future retrofits by placing it in a costs and environmental perspective. Therefore, this report would be a good starting point to see what the beneficial effects of a retrofit could have on the environment of the ship design.

8.1.4. Alternative fuel price

The price function of alternative fuels can be improved in a next version of *Blended Design*. Currently the *Blended Design* method bases the price for alternative fuels on a poly fit through future price projections. This means it does not include fuel price fluctuations, uncertainties and other economical effects which causes the price to change.

Furthermore, *Blended Design* does not incorporate different alternative fuel prices at different ports. Since the fuel price accommodates for a different business case, it therefore could have an effect on the choice of alternative fuel system. It could be interesting to see what the effects of different alternative fuels prices across the world would be on the results of the method.

8.1.5. Battery modelling

In the method proposed in this thesis, batteries are not included. Mainly because battery systems are not ready as alternative energy storage for deep-sea trips. However, it also has to do with the way batteries work as an alternative fuel.

Normal (alternative) fuels decrease in weight and volume during the voyage, since they are being used. For batteries this is a different story. The volume and weight of a battery pack on board does not change during the trip. This means their behavior differs from (alternative) fuels in a way that is not modelled in the method.
Since batteries are not suitable to be used as alternative energy storage for long voyages, they still can be interesting to incorporate in a ship design. They may be utilised for peak-shaving during long voyages. When the energy demand suddenly peaks, a battery bank could jump in to meet the sudden demand spike. This can prevent another engine from powering on, therefore resulting in less fuel consumption. It would be interesting to see if and how much (alternative) fuel this could potentially save and therefore contribute to a beneficial environmental performance.

8.1.6. Investigate other emission types

SOx, NOx and particulate matter are local emissions; i.e. if these pollutants are emitted, they don't have a global effect, but mainly harm the local environment. That is why the regulation of these emissions is mainly local, like the emission controlled areas in the Baltic Sea, North Sea and the USA for example.

Therefore, the current regulation in place may play a role in the selection for an alternative fuel when designing a ship, since some of the alternatives may have a negative effect on the local environment when used in LSAs. It may be interesting to see how these emissions could impact the design, and especially the choice for an alternative fuel engine in the vessel. This would require an in-depth investigation into the operational profile of the ship, since (optimal) speeds change due to many circumstances; weather, seastate of ECAs for example. This can cause the engine to not always operate on its optimal running speed, resulting in a different environmental performance.
Furthermore, having the operational profile embedded more precisely in the method most likely yield more accurate results, since the emissions can be calculated more exact. This ensures even better

conclusions which can be drawn from the outcomes, resulting in ships with better environmental and emission performance.

8.1.7. Updated values

During the research it became clear that it is very challenging to find reliable, consistent and trustworthy data on alternative fuels. The financial numbers of the engines are speculations and the engine efficiencies and emission data of alternative fuels are often best guesses. This is due to the lack of commercially available data since there are not that many alternative fuel engines.

This thesis aims to explain how and why the presented solution is plausible and tries to prove that the method works like it is supposed to work. In order to become more helpful in the future, updated numbers and values for alternative fuels need to be found in order to make more precise predictions on their environmental performance.
The updated numbers:

- Global warming potential
- Alternative fuel efficiencies
- Alternative fuel engine specifics (amount of CO_2, N_2O and CH_4)

8.1.8. Structured collaboration

The *Blended Design* tool evolved during the duraiton of this thesis. Since the tool was still in development and more people were working on the tool at the same time, this sometimes resulted in conflicted versions.

During the research, more improvements were implemented to prevent this from happening again and at this stage the tool is more modular than when this thesis started. Transitioning the tool to GitLab, an online service where developers can collaboratively work on code together, helped with this. This makes the tool more flexible and robust when changes are made. Although being on the right track, there is still a lot of room to improve on this, setting up a more structured way of collaboratively working on the tool.

8.2. Personal reflection

”What would you do if you would win the lottery?”. A question frequently heard from those pesky commercials on the telly addressed to unsuspecting passersby. Often a summation of their wildest dreams follows. Make a big trip to a country far from here, spend more time with friends and family, buy a new car. In a way this question opens up a new reality for the people being interviewed, instantly triggering them to fantasize about the unthinkable becoming reality.

Now the end of my thesis is nearing, it kinda feels the same way. I find myself thinking about the way my life will evolve after this, what my new life after all those years of learning and studying will look like. I am fantasizing about what to do, where to go, who to work with, what to achieve.
At the time of writing this there are no concrete plans for after my graduation yet. It is the first time in a long while my agenda is as empty as a train at 5 o’clock in the morning (or 5 a.m. in Austin-time). Think I’m gonna enjoy that first.

Now what I learned from the thesis itself. The relevance and priority of the environmental challenges we are going to encounter is huge. During the making of this thesis I sometimes felt miserable, because of how things are the way they are in the world. I divided my weeks with my thesis’ topics, to research and work on them, resulting in two weeks of immersing myself into climate reports. After these two weeks I understood now is time to act and change, how cheesy that may sound.
Luckily I am not the only one who thinks this. More and more companies (in the Netherlands) are taking a proactive role in climate change, bettering their service and taking care of the ’small ones’, like recycling coffee cups or lowering meat consumption. Something I also want to be an ambassador of.

Thank you for coming to the end of my thesis. Cheers to a better, more sustainable world!

Bibliography

[1] ABS. *Setting the Course to Low Carbon Shipping*. Tech. rep. 2019.

[2] M. Adachi, H. Kosaka, T. Fukuda, S. Ohashi, and K. Harumi. “Economic analysis of trans-ocean LNG-fueled container ship”. In: *Journal of Marine Science and Technology (Japan)* 19.4 (Nov. 2014), pp. 470–478. ISSN: 09484280. DOI: 10.1007/s00773-014-0262-5.

[3] N. Ash and T. Scarbrough. *Sailing on Solar-Could green ammonia decarbonise international shipping?* Tech. rep. 2019. URL: https://www.researchgate.net/publication/332845713.

[4] Australian National University - School of Computing. “Software-Systems-Engineering”. In: *School of Computing* (2022). URL: https://comp.anu.edu.au/courses/comp3530/readings/Software-Systems-Engineering.pdf.

[5] S. Bengtsson, K. Andersson, and E. Fridell. “A comparative life cycle assessment of marine fuels: Liquefied natural gas and three other fossil fuels”. In: *Proceedings of the Institution of Mechanical Engineers Part M: Journal of Engineering for the Maritime Environment* 225.2 (May 2011), pp. 97–110. ISSN: 14750902. DOI: 10.1177/1475090211402136.

[6] J. I. Bernstein. *Design Methods in the Aerospace Industry: Looking for Evidence of Set-Based Practices*. Tech. rep. 1997.

[7] E. Bøckmann and S. Steen. “Calculation of EEDIweather for a general cargo vessel”. In: *Ocean Engineering* 122 (2016), pp. 68–73. ISSN: 00298018. DOI: 10.1016/j.oceaneng.2016.06.007.

[8] T. Bruinessen, F. Smulders, and H. Hopman. *TOWARDS A DIFFERENT VIEW ON SHIP DESIGN*. Tech. rep. 2016.

[9] Bureau Veritas. *ALTERNATIVE FUELS OUTLOOK FOR SHIPPING AN OVERVIEW OF ALTERNATIVE FUELS FROM A WELL-TO-WAKE PERSPECTIVE METHANOL LPG BIOFUEL LNG AMMONIA HYDROGEN*. Tech. rep. 2022.

[10] F. Burel, R. Taccani, and N. Zuliani. “Improving sustainability of maritime transport through utilization of Liquefied Natural Gas (LNG) for propulsion”. In: *Energy* 57 (Aug. 2013), pp. 412–420. ISSN: 03605442. DOI: 10.1016/j.energy.2013.05.002.

[11] ClassNK. *CII Presentation□Carbon Intensity Indicator□*. Tech. rep. 2021.

[12] B. Comer, J. O’malley, L. Osipova, N. Pavlenko, and S. 2022. *COMPARING THE FUTURE DEMAND FOR, SUPPLY OF, AND LIFE-CYCLE EMISSIONS FROM BIO, SYNTHETIC, AND FOSSIL LNG MARINE FUELS IN THE EUROPEAN UNION*. Tech. rep. ICCT, 2022. URL: www.theicct.org.

[13] B. Comer and L. Osipova. “Accounting for well-to-wake carbon dioxide equivalent emissions in maritime transportation climate policies”. In: *International Council on Clean Transportation* (Mar. 2021). DOI: 10.1002/jgrd.50171. URL: https://doi.org/10.1002/jgrd.50171..

[14] K. Cullinane and S. Cullinane. *Atmospheric Emissions from Shipping: The Need for Regulation and Approaches to Compliance*. July 2013. DOI: 10.1080/01441647.2013.806604.

[15] F. Dalena, A. Senatore, A. Marino, A. Gordano, M. Basile, and A. Basile. “Methanol Production and Applications: An Overview”. In: *Methanol: Science and Engineering*. Elsevier, 2018, pp. 3–28. ISBN: 9780444640109. DOI: 10.1016/B978-0-444-63903-5.00001-7.

[16] J. Devanney. *EEDI Absurdities*. Tech. rep. 2011.

[17] Dieselnet. *IMO Marine Engine Regulations*. URL: https://dieselnet.com/standards/inter/imo.php.

[18] DNV. *MARITIME FORECAST TO 2050*. Tech. rep. 2022.

[19] DNV. *MARITIME FORECAST TO 2050 - Energy Transition Outlook 2022*. Tech. rep. DNV, 2022.

[20] DNV-GL. "Comparison of Alternative Marine Fuels". In: *DNV-GL* (2019). ISSN: 2019-0567. URL: www.dnvgl.com.

[21] DNV-GL. *MARITIME FORECAST TO 2050*. Tech. rep. 2019.

[22] A. Durakovic. *Siemens Gamesa Cranks It Up to 15 MW with Offshore Behemoth*. May 2020.

[23] A. Al-Enazi, E. C. Okonkwo, Y. Bicer, and T. Al-Ansari. *A review of cleaner alternative fuels for maritime transportation*. Nov. 2021. DOI: 10.1016/j.egyr.2021.03.036.

[24] R. Energy, T. Scarbrough, M. Campbell, A. Davies, G. Maclean, C. Martin, M. Raugei, and H. Scammell. *Sustainable criteria and life cycle GHG emission assessment methods and standards for alternative marine fuels Report for IMO Low Carbon GIA Customer: International Maritime Organization Low Carbon Global Industry Alliance Contact*. Tech. rep.

[25] J. Faber and CE Delft. *Readily Achievable EEDI Requirements for 2020*. Tech. rep. 2016. URL: www.cedelft.eu.

[26] FKAB Marine Design. *Ship Design*. 2022.

[27] Global Wind Energy Council. *GLOBAL OFFSHORE WIND REPORT 2021*. Tech. rep. 2021. URL: www.gwec.net.

[28] N. Gray, S. McDonagh, R. O'Shea, B. Smyth, and J. D. Murphy. *Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors*. Feb. 2021. DOI: 10.1016/j.adapen.2021.100008.

[29] Greenhouse Gas Protocol. *Global Warming Potential Values*. Tech. rep. 2014. URL: www.ipcc.ch.

[30] J. Harvey Evans. "Basic Design Concepts". In: *Naval Engineers Journal* 71.4 (1959).

[31] J. Holtrop and G. G. J. Mennen. *AN APPROXIMATE POWER PREDICTION METHOD*. Tech. rep. 1982.

[32] C. Houston and Wärtsilä. *Mind the Methane Gap*. Oct. 2020. URL: https://www.wartsila.com/insights/article/mind-the-methane-gap.

[33] M. A. J. Huijbregts. "ReCiPe 2016 - A harmonized life cycle impact assessment method at midpoint and endpoint level Report I: Characterization". In: (2016). ISSN: 2016-0104.

[34] ICCT. *The Energy Efficiency Design Index (EEDI) for new ships*. Tech. rep. 2011. URL: https://theicct.org/sites/default/files/publications/ICCTpolicyupdate15_EEDI_final.pdf.

[35] IMO. *Alternative Fuels Online Slides*. 2021.

[36] IMO. *Energy Efficiency Measures (SEEMP)*. 2022. URL: https://www.imo.org/en/OurWork/Environment/Pages/Technical-and-Operational-Measures.aspx.

[37] IMO. *GUIDELINES FOR VOLUNTARY USE OF THE SHIP ENERGY EFFICIENCY OPERATIONAL INDICATOR (EEOI)*. Tech. rep. 2009.

[38] IMO. "USE OF METHANOL AS FUEL Methanol as marine fuel: Environmental benefits, technology readiness, and economic feasibility International Maritime Organization (IMO)". In: (2016). ISSN: 2015-1197. URL: www.dnvgl.com.

[39] IMO MEPC. *GUIDELINES ON SURVEY AND CERTIFICATION OF THE ENERGY EFFICIENCY DESIGN INDEX (EEDI)*. Tech. rep. 2014.

[40] Indian Register of Shipping. *Implementing Energy Efficiency Design Index (EEDI)*. Tech. rep.

[41] IPCC, H.-O. Pörtner, D. C. Roberts, M. M. Tignor, E. Poloczanska, and K. Mintenbeck. "Technical Summary: Climate Change 2022: Impacts, Adaptation and Vulnerability". In: (). DOI: 10.1017/9781009325844.002.

[42] K. Kim, K. Park, J. Lee, K. Chun, and S. H. Lee. "Analysis of Battery/Generator Hybrid Container Ship for CO2 Reduction". In: *IEEE Access* 6 (Mar. 2018), pp. 14537–14543. ISSN: 21693536. DOI: 10.1109/ACCESS.2018.2814635.

[43] Korean Register. *Guidelines for Ships using Ammonia as Fuels*. Tech. rep. 2021.

[44] K. Kouzelis. *Maritime fuels of the future A decision support tool for shipowners*. Tech. rep. 2021. URL: http://repository.tudelft.nl/..

[45] T. Kuwayama, J. R. Schwartz, R. A. Harley, and M. J. Kleeman. "Particulate matter emissions reductions due to adoption of clean diesel technology at a major shipping port". In: *Aerosol Science and Technology* 47.1 (2013), pp. 29–36. ISSN: 02786826. DOI: 10.1080/02786826.2012.720049.

[46] B. Lagemann, E. Lindstad, K. Fagerholt, A. Rialland, and S. Ove Erikstad. "Optimal ship lifetime fuel and power system selection". In: *Transportation Research Part D: Transport and Environment* 102 (Jan. 2022). ISSN: 13619209. DOI: 10.1016/j.trd.2021.103145.

[47] T. Lamb. *Ship design and construction*. Society of Naval Architects and Marine Engineers, 2003. ISBN: 0939773406.

[48] T. R. Lambregts, V. Peeten, M. De Haas, and E. Kooij. *What effect do future greenhouse gas regulations have on Transfennica? Shipping Management, MT44070*. Tech. rep. 2021.

[49] R. S. Laursen and ABS. *Presentation: Getting Ready for Clean-Produced, Carbon-Free Ammonia and Well-to-Wake Emissions*. Tech. rep. 2021.

[50] L. C. Law, B. Foscoli, E. Mastorakos, and S. Evans. "A comparison of alternative fuels for shipping in terms of lifecycle energy and cost". In: *Energies* 14.24 (Dec. 2021). ISSN: 19961073. DOI: 10.3390/en14248502.

[51] E. Lindstad, G. S. Eskeland, A. Rialland, and A. Valland. "Decarbonizing maritime transport: The importance of engine technology and regulations for LNG to serve as a transition fuel". In: *Sustainability (Switzerland)* 12.21 (Nov. 2020), pp. 1–19. ISSN: 20711050. DOI: 10.3390/su12218793. URL: https://www.scopus.com/record/display.uri?eid=2-s2.0-85094184933&origin=resultslist&sort=plf-f&src=s&st1=heavy+transport+vessel&nlo=&nlr=&nls=&sid=f5ecf58270c0067b60aafc08d1f5670b&sot=b&sdt=cl&cluster=scosubjabbr%2c%22ENGI%22%2ct%2c%22ENER%22%2ct%2c%22ENVI%22%2ct%2c%22EART%22%2ct&sl=37&s=TITLE-ABS-KEY%28heavy+transport+vessel%29&relpos=12&citeCnt=18&searchTerm=.

[52] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS). *A technical, environmental, and techno-economic analysis of the impacts of preparation and conversion*. Tech. rep. 2022. URL: https://cms.zerocarbonshipping.com/media/uploads/documents/Fuel-Options-.

[53] I. Mallidis, S. Despoudi, R. Dekker, E. Iakovou, and D. Vlachos. "The impact of sulphur limit fuel regulations on maritime supply chain network design". In: *Annals of Operations Research* 294.1-2 (Nov. 2020), pp. 677–695. ISSN: 15729338. DOI: 10.1007/s10479-018-2999-4.

[54] I. Malmgren and A. Ulfvarson. *Systems Engineering in Ship Design Education-is this the answer to changedindustry demands?* Tech. rep. 2006. URL: https://www.researchgate.net/publication/228891724.

[55] MARIN. *MARIN sustainable power database*. 2022.

[56] R. McGill, W. Remley, and K. Winther. *Alternative Fuels for Marine Applications*. Tech. rep. 2013.

[57] C. J. McKinlay, S. R. Turnock, and D. A. Hudson. "Route to zero emission shipping: Hydrogen, ammonia or methanol?" In: *International Journal of Hydrogen Energy* 46.55 (Aug. 2021), pp. 28282–28297. ISSN: 03603199. DOI: 10.1016/j.ijhydene.2021.06.066.

[58] G. Mundaca and J. Strand. *Carbon pricing of international transport fuels: Impacts on carbon emissions and trade activity Carbon pricing of international transport fuels: Impacts on carbon emissions and trade activity **. Tech. rep. 2020. URL: https://www.scopus.com/record/display.uri?eid=2-s2.0-85117793229&origin=resultslist&sort=plf-f&src=s&st1=heavy+transport+vessel&nlo=&nlr=&nls=&sid=f5ecf58270c0067b60aafc08d1f5670b&sc b&sdt=cl&cluster=scosubjabbr%2c%22ENGI%22%2ct%2c%22ENER%22%2ct%2c%22ENVI%22%2ct%2c%22EART%22%2ct&sl=37&s=TITLE-ABS-KEY%28heavy+transport+vessel%29&relpos=4&citeCnt=1&searchTerm=.

[59] myclimate. *What are CO2 equivalents?* 2022.

[60] A. Nair and M. Acciaro. "Alternative fuels for shipping : Optimising fleet composition under environmental and economic constraints". In: *International Journal of Transport Economics* 45.3 (Nov. 2018), pp. 439–460. ISSN: 17242185. DOI: 10.19272/201806703005.

[61] J. G. J. Olivier and J. A. H. W. Peters. *TRENDS IN GLOBAL CO 2 AND TOTAL GREENHOUSE GAS EMISSIONS 2019 Report*. Tech. rep. 2020. URL: https://www.pbl.nl/sites/default/files/downloads/pbl-2020-trends-in-global-.

[62] C. Pasten and J. C. Santamarina. "Energy and quality of life". In: *Energy Policy* 49 (Oct. 2012), pp. 468–476. ISSN: 03014215. DOI: 10.1016/j.enpol.2012.06.051.

[63] N. Pavlenko, B. Comer, Y. Zhou, N. Clark, and D. Rutherford. *The climate implications of using LNG as a marine fuel*. Tech. rep. 2020. URL: www.theicct.org.

[64] K. Pedersen, J. Emblemsvag, R. Bailey, J. K. Allen, and F. Mistree. *Validating Design Methods and Research: The Validation Square*. Tech. rep. 2000.

[65] G. Plevrakis, P. Koutsourakis, S. Stamopoulos, J. Sarvaiya, I. Soultanias, S. Vaidhyanathan, N. Seward, T. Shen, A. Zhu, R. Koliniati, A. Kalamidas, D. Barcarolo, I. Dimakopoulos, A.-N. Zhang, H. Daiyan, A. Bose, S. Bell, L. Bass, S. Crisafulli, and J. Lashbrook. *ZERO CARBON OUTLOOK - ABS*. Tech. rep. 2022.

[66] S. M. N. Prakash. *A Computational Method for Determination of Open Water Performance of a Marine Propeller*. Tech. rep. 12. 2012, pp. 975–8887.

[67] K. Prill and K. Igielski. "Calculation of Operational Indicator EEOI for Ships Designed to Other Purpose Than Transport Based on A Research – Training Vessel". In: *New Trends in Production Engineering* 1.1 (Oct. 2018), pp. 335–340. DOI: 10.2478/ntpe-2018-0041.

[68] RHEA. *Parallelle ontwikkeling en engineering*. 2022.

[69] Rijksoverheid. *Kabinet verdubbelt productie windenergie op zee*. Mar. 2022. URL: https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/nieuws/2022/03/18/kabinet-verdubbelt-productie-windenergie-op-zee.

[70] Rijkswaterstaat. *Systems Engineering Rijkswaterstaat*. 2022. URL: https://www.rijkswaterstaat.nl/zakelijk/zakendoen-met-rijkswaterstaat/werkwijzen/werkwijze-in-gww/systems-engineering.

[71] J. M. Rozendaal. *Methanol Hybrid Offshore Working Vessels A technical, environmental and economic assessment*. Tech. rep. 2020. URL: http://repository.tudelft.nl/..

[72] Searoutes.com. *Route between Rot and NY*. 2022.

[73] G. J. Seithe, A. Bonou, D. Giannopoulos, C. A. Georgopoulou, and M. Founti. "Maritime transport in a life cycle perspective: How fuels, vessel types, and operational profiles influence energy demand and greenhouse gas emissions". In: *Energies* 13.11 (June 2020). ISSN: 19961073. DOI: 10.3390/en13112739. URL: https://www.scopus.com/record/display.uri?eid=2-s2.0-85085860225&origin=resultslist&sort=plf-f&src=s&st1=heavy+transport+vessel&nlo=&nlr=&nls=&sid=f5ecf58270c0067b60aafc08d1f5670b&sot=b&sdt=cl&cluster=scosubjabbr%2c%22ENGI%22%2ct%2c%22ENER%22%2ct%2c%22ENVI%22%2ct%2c%22EART%22%2ct&sl=37&s=TITLE-ABS-KEY%28heavy+transport+vessel%29&relpos=14&citeCnt=7&searchTerm=.

[74] T. J. Sheskin. *MARKOV CHAINS and DECISION PROCESSES for ENGINEERS and MANAGERS*. Tech. rep. 2011.

[75] H. Sillitto, J. Martin, D. Mckinney, R. Griego, D. Dori, D. Krob, P. Godfrey, E. Arnold, and S. Jackson. *Systems Engineering and System Definitions*. Tech. rep. 2019. URL: https://www.incose.org/docs/default-source/default-document-library/incose-se-definitions-tp-2020-002-06.pdf?sfvrsn=b1049bc6_0.

[76] D. J. Singer, N. Doerry, and M. E. Buckley. "What is set-based design?" In: *Naval Engineers Journal* 121.4 (2009), pp. 31–43. ISSN: 00281425. DOI: 10.1111/j.1559-3584.2009.00226.x.

[77] L. Ståle Skoge. *SHIP DESIGN CONCEPT FROM ULSTEIN CAN SOLVE THE ZERO EMISSION CHALLENGE*. 2022.

[78] M. Svanberg, J. Ellis, J. Lundgren, and I. Landälv. “Renewable methanol as a fuel for the shipping industry”. In: *Renewable and Sustainable Energy Reviews* 94 (Oct. 2018), pp. 1217–1228. ISSN: 18790690. DOI: `10.1016/j.rser.2018.06.058`.

[79] K. Terün. *Assessing Alternative Fuel Types for ULCVs in Face of Uncertainty*. Tech. rep. 2020. URL: `http://repository.tudelft.nl/.`.

[80] Transport & Environment. *Methane escaping from ’green’ gas-powered ships fuelling climate crisis - Investigation*. Apr. 2022.

[81] Ulstein and Clarckson & Platau. *Ulstein presentation Heavy Transport Vessels*. 2022.

[82] Ulstein Design & Solutions B.V. *HX120*. 2022.

[83] United Nations. *The 17 Sustainable Development Goals*. 2022. URL: `https://sdgs.un.org/goals`.

[84] J. S. Van Duijn. *Modelling diesel-ammonia two-stroke engines*. Tech. rep. 2021. URL: `http://repository.tudelft.nl/.`.

[85] Y. H. Venus Lun, K. h. Lai, C. W. Wong, and T. C. Cheng. “Environmental governance mechanisms in shipping firms and their environmental performance”. In: *Transportation Research Part E: Logistics and Transportation Review* 78 (May 2015), pp. 82–92. ISSN: 13665545. DOI: `10.1016/j.tre.2015.01.011`.

[86] Voort. *Systems Engineering Voort*. 2022. URL: `https://www.voort.com/vakgebied/wat-is-systems-engineering/`.

[87] X. Wang, U. Shipurkar, A. Haseltalab, H. Polinder, F. Claeys, and R. R. Negenborn. “Sizing and Control of a Hybrid Ship Propulsion System Using Multi-Objective Double-Layer Optimization”. In: *IEEE Access* 9 (2021), pp. 72587–72601. ISSN: 21693536. DOI: `10.1109/ACCESS.2021.3080195`.

[88] C. Wolfram, O. Shelef, and P. Gertler. “How will energy demand develop in the developing world?” In: *Journal of Economic Perspectives*. Vol. 26. 1. Dec. 2012, pp. 119–138. DOI: `10.1257/jep.26.1.119`.

[89] S. Zhang, Y. Li, H. Yuan, and D. Sun. “An alternative benchmarking tool for operational energy efficiency of ships and its policy implications”. In: *Journal of Cleaner Production* 240 (Dec. 2019). ISSN: 09596526. DOI: `10.1016/j.jclepro.2019.118223`.

[90] Y. Zhou, N. Pavlenko, D. Rutherford, L. Osipova, B. Comer, J. Bates, S. Bleuanus, J. Bradshaw, M. Kaas, P. Lauer, and T. Tirovola. *The potential of liquid biofuels in reducing ship emissions*. Tech. rep. 2020. URL: `www.theicct.org`.

[91] J. Zwaginga, K. Stroo, and A. Kana. “Exploring market uncertainty in early ship design”. In: *International Journal of Naval Architecture and Ocean Engineering* 13 (Apr. 2021), pp. 352–366. ISSN: 20926790. DOI: `10.1016/j.ijnaoe.2021.04.003`.

A

Blended Design 1.0

In chapter 2.2 the high-level methodology of *Blended Design* is explained. The various functions of one iteration are elaborated on in this appendix to get a better technical understanding of the method. To get a full understanding of the *Blended Design 1.0* method, the thesis of Zwaginga et al. [91] can be best consulted.

Holtrop & Mennen resistance calculation
First the resistance of the design needs to be estimated. This is done with the Holtrop & Mennen method [31]. The addition of several types of resistance which are estimated in this method result in the total resistance.

Hull-propeller interaction
With the resistance calculation done, this function calculates the power needed for the propulsion system of the ship design according to the open water performance of a marine propeller [66]. It can calculate the hull-propeller interaction and determine the brake power which should be sufficient to propel the ship design.

Weight scaling: W_{estfun}
Based on the installed power, an estimation of the engine weight can be made. This is done by scaling the weight of multiple important systems and installations onboard.
The weight of other influential components on board, like the hull weight, systems weight and fuel weight is calculated by multiplying basic parameters with values of a reference ship or outcomes of a sensitivity analysis.
The weights of these installations and systems are important for determining the stability and the center of gravity of the ship design.

Righting arm: GZ_{fun} **&** KG_{calc}
To ensure a stable design, the maximum righting arm needed for each ship design is calculated for a range of heel angles ϕ – from 0.01 to 60 degree, as can be seen in equation A.1. This is important since the *Blended Design* tool is intended to be used for heavy lifting cargo vessels. Constructing a poly fit through these points, the maximum values at selected heel angles is calculated by solving a moment balance.

$$KN = \frac{KG - KB}{\tan(\phi) + KB} * \sin(\phi) \tag{A.1}$$

Mission module
This module calculates the amount of cargo objects that can be transported for all diameters that might occur considering the market projections for increase in size of the monopiles and jackets in the selected period.

First several arrangements of both monopiles and jackets are calculated which physically fit on the available deck area of the ship, according to their length, width, depth and weight constraints, which is illustrated in figure A.1. With these numbers, the weight criterion is reviewed by checking if the total weight is beneath the maximum cargo weight determined in the previous function. A separate function, a stacking algorithm, determines if and to what height the monopiles could be optimally stacked in order to still meet the stability criteria of the ship design.
All these constraints are then combined results in the total number of cargo pieces the ship is able to transport.

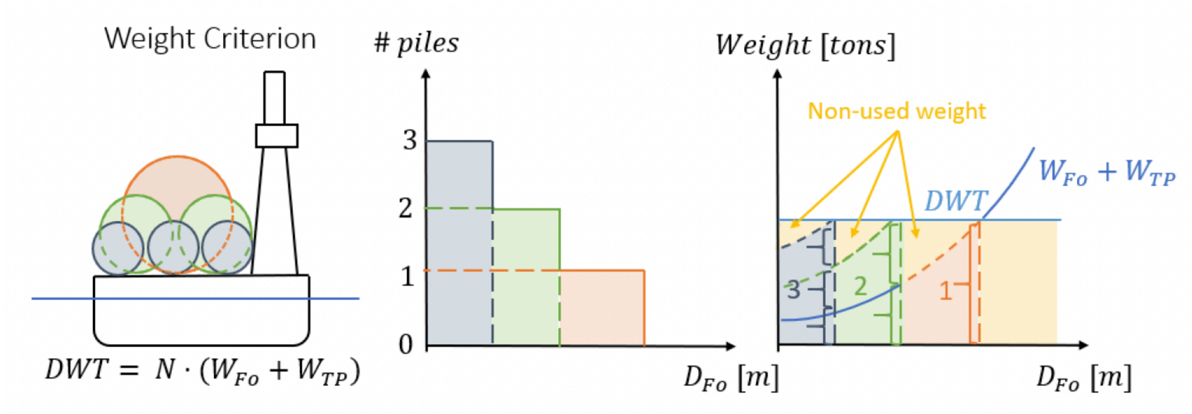


Figure A.1: The number of piles physically fit on the deck as dictated by the weight criterion, from [91]

Costs and income
This module calculates the cost and income for each ship design based on the transported cargo and market demand obtained in previous functions. This is done in several steps. First the total amount of trips the issued ship design is able to complete in one year is calculated based on the total sail time of the mission, harbor time and cargo (un)loading time of the ship. The big, bulky cargo will take longer to load and unload, resulting in less trips per year. Than the financial performance is calculated. The costs for several installations and systems are determined beforehand since they yield from input from the user. A rough estimate of the new build costs of the design is made. This is important since it will influence the OPEX and CAPEX costs of the ship design, since these are based on percentages of the new build cost.

The CAPEX is depended on the new build costs since this is a percentage of the depreciation and the interest of the ship (tax, repay, loan interest, RoE).
The OPEX is a function of the maintenance, storage costs, installation costs and management costs and the number of people working on board of the ship, since they have to be paid when the ship is operational.
Lastly the VOYEX captures the expenses per voyage; per trip of the design. In this metric things as fuel costs and the revenue of the cargo are used.

With these numbers the profit per year can be calculated, making it possible to calculate the expected cash flow for each scenario as part of the uncertainty modelling. Now everything is in place in order to run a market performance calculation, which can be reviewed to make decisions on basic dimensions and operational speed.

B
EEXI variables explained

Table B.1: All variables and parameters of the EEXI equation

Variable	Unit	Parameter	Description
P_ME	kW	Power main engine	Python_functions P_b, break power (83% MCR_lim or 75% MCR)
C_FME	gCO2/gfuel	Conversion factor between fuel consumption and CO2 emission	No. NOx technical file –> use 3.114 tCO2/tfuel for Diesel ships or EEDI 2.2.1
SFC_ME	g/kWh	Specific fuel consumption main engine	Test report on NOx technical file, otherwise 190 g/kWh
P_AE	kW	Power auxiliary engines	Onboard monitoring, discuss this with Ulstein
C_FAE	gCO2/gfuel		No NOx technical file? –> use 3.114 tCO2/tfuel for Dieselships or EEDI 2.2.1
SFC_AE	g/kWh		Test report on NOx Technical File, otherwise assume 215 g/kWh
fj	-	Ship specific design elements	See calculation with Froude Number & exponents in EEXI 2.2.6
P_PTI	kW	Power of shaft motor	Only if shaft motor is installed. If > 0, weighted average of (SFC_ME*C_FME) & (SFC_AE*C_FAE) is used
feff	-	Corr. factor	Correction factor for innovative energy efficiency technologies
P_AEeff	kW	Innovative mechanical energy efficient technology for auxiliary engine	Innovative mechanical energy efficiency technologies
C_FAE	gCO2/gfuel		No NOx technical file? –> use 3.114 tCO2/tfuel for Dieselships or EEDI 2.2.1
SFC_AE	g/kWh		Test report on NOx Technical File, otherwise assume 215 g/kWh
f_eff	-	Corr. factor	Availability factor each innovative energy technology, waste energy recovery system is 1.06
P_eff	kW	Innovative mechanical energy efficient technology for main engine	EEDI 2.2.5.4: output of innovative mechanical energy efficiency
C_FME	gCO2/gfuel		No. NOx technical file –> use 3.114 tCO2/tfuel for Diesel ships or EEDI 2.2.1
SFC_ME	g/kWh	Specific fuel consumption main engine	Test report on NOx technical file, otherwise 190 g/kWh
fi	-	Capacity correction factor for ice-class ships	Capacity correction factor ice-classed ships, take 1 for no ice class
fc	-	Cubic capacity correction factor	Cubic capacity correction factor if DWT/GTratio < 0.35
fl	-	Factor for general cargo ships equipped with cranes and other cargo-related gear	Factors for general cargo ships with cranes, fl = f_cranes*f_sideloader*f_roro
capacity		Capacity	Concider taking 50%*DWT_total, since cargo load. EEDI: 70%*DWT
fw	-	Factor for speed reduction at sea	Correction factor speed reduction at sea
V_ref	kn	Ship speed	Variable speed at every iteration
fm			1 (or 1.05 for ice-classed ships)

C
Extra results profit

To demonstrate the fact that the carbon tax has influence on the profits and ROI, a graph showing the profit and total CO_2 tax price per voyage was set up as can be seen in figure C.1. Because the method calculates the total amount of CO_2-equivalent GHG per used fuel, the longer ships tend to have better profits due to the fact they can bring more cargo, generating more income. The bumps in the plot are a result of the steps of cargo the ship design is able to load, again increasing the amount of profit the design is able to make.

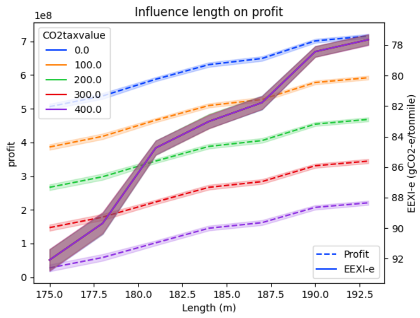


Figure C.1: The total profit and carbon tax price per trip

A comparison for each alternative fuel under different set values of carbon tax. What becomes clear in figures C.2 and C.3 is that green fuels are much less susceptible under carbon tax compared to the gray fuels, since they emit less harmful GHGs. Therefore the profit of these fuels remain roughly the same no matter what carbon tax is enforced.

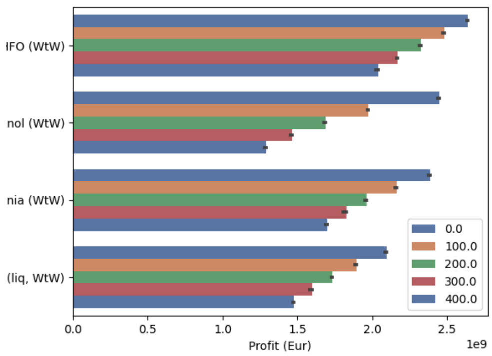


Figure C.2: The profits for several CO_2 tax values for each gray WtW fuels

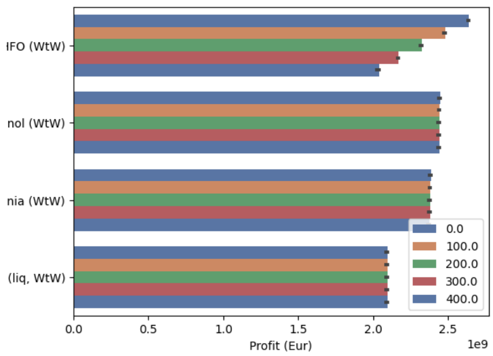


Figure C.3: The profits for several CO_2 tax values for each green WtW fuels

D

Confidential: Verification HX120

This appendix is removed for obvious reasons.