Technical and economical feasibility of zero-emission walk to work vessels

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TU Delft Acta Marine

Technical and economical feasibility of zero-emission walk to work vessels

by

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Cover photo: Acta Centaurus performing a motion compensated gangway transfer at Deutsche Bucht (Acta Marine, 2020)

Preface

To combat climate change, urgent action is needed now to reduce emissions. Technical and economical feasibility will determine what zero-emission Walk To Work (W2W) vessels will look like in the future. With this research, I will contribute to reducing emissions on several levels: reducing W2W vessel emissions while also reducing indirect emissions of wind energy and thereby bringing actual zero-emission electricity one step closer. I strongly believe that it is possible to achieve a nearly zero-emission world, and therefore I am proud that I am and will be contributing to the energy transformation that the (maritime) world will most definitely undergo in the coming years.

I would like to thank Austin Kana. You supported me from the beginning of this path with your time and knowledge. During our biweekly digital meetings for this master thesis, but also during the Bachelor End Project in 2019, I learned a lot from you.

Secondly, I would like to thank my colleagues Benny Banen, Simon Anink, Bouwen Legemate, and the rest of Acta Marine. Acta Marine is the company and problem owner that led to this graduation topic. Benny, Simon, and Bouwen, thank you for your daily guidance and knowledge about W2W vessels, the offshore wind industry, and alternative energies. I learned a lot from you, and I am happy that I could spend my graduation, working at this interesting company in an interesting sector. Moreover, I am grateful that during Covid-19 and all related restrictions, Acta Marine still made it possible for me to visit two of their W2W vessels. I went to see the Acta Auriga in Hull, England, and I went to see the Acta Centaurus in Peterhead, Scotland. These visits gave me the full experience of what W2W vessels are.

Finally, I would like to thank everyone who helped me with this research on a personal level. My friends and especially my roommate for all the good laughs and cold beers, which helped me keep up the good work, my girlfriend for always being there and supporting me, and my father and mother for making me who I am.

Xander Suy
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Abstract

Urgent action is needed to decrease maritime emissions. The renewable wind energy sector must also decrease its life cycle greenhouse gas (GHG) emissions. Total GHG emissions from offshore wind turbines are approximately 120% more compared to onshore wind turbines. Moreover, it is estimated that Walk to Work (W2W) vessels are responsible for 3.3% of the total life cycle emissions of offshore wind turbines. Especially during operation and maintenance (O&M), there are no substantial emissions other than those caused by marine support. This research investigates the technical and economical feasibility of a zero-emission W2W vessel during its operational life. W2W vessels use dynamic positioning (DP), a motion compensated gangway, and a motion compensated crane to transfer technicians and cargo to offshore structures to enable them to perform installation, commissioning, and O&M.

This research has used literature research to collect data, insights on W2W vessels, insights on the offshore wind market, and information on alternative energy carriers. Furthermore, a parametric model is written to test the technical feasibility and the Robust Decision Making (RDM) method is used to test the economical feasibility.

The building rate of new offshore wind farms (OWF) is expected to quadruple by 2030, wind turbines are increasing in size and height, and OWFs are expected to move further offshore. These three expected trends imply a higher demand for W2W vessels and require adaption of the specifications of the vessel and mission equipment. The operational profile of the W2W vessel is unique due to its high operational mode in DP, which is usually 90% to 98%. Additionally, the fuel tanks of the W2W vessels are excessively large for the required autonomy of 2 to 4 weeks.

Characteristics including life cycle emissions, (future) price development, energy density, and social perspective are used to select hydrotreated vegetable oil as a blend-in fuel, compressed or liquid cryogenic hydrogen, methanol, ammonia, and batteries as potential alternative energy carriers. All of them have a lower contained energy density compared to fossil fuels, leading to increased space requirements. Alternative energy carriers are also more expensive today, but energy prices are expected to decrease, while fossil fuel prices are expected to increase.

A parametric model has been developed and applied to 18 configurations between energy converters, energy carriers, and autonomy duration. The model takes a base case and estimates required energy, volume for storage, length, width, weight, draught, and power for DP operations. It has been concluded that all 18 configurations are technically feasible.

An RDM is performed to test the economical feasibility of the 18 configurations among 13122 different futures based on the formulated uncertainties (energy carrier price, energy carrier availability, annual utilisation of a W2W vessel, day rate, CAPEX, and OWF to port sailing distance) and a potential carbon tax (CT). Results are evaluated for profit (NPV), operational uptime, and emissions per wind turbine connection. First, it has been concluded that batteries and compressed hydrogen are highly unlikely to be feasible options because of their low operational uptime. Secondly, a fuel cell running on either liquefied hydrogen or methanol, is unlikely to make profit. Third, it is highly likely that a single fuel green ammonia ICE configuration will be the most profitable among green alternative energy carriers. Fourth, single fuel green methanol ICE configurations could be profitable but are less likely to be profitable than ammonia under the assumptions made. Lastly, for an average LSMGO price (Nov 2018 - Nov 2021), a high CT is unlikely to make alternative energy carriers more profitable than LSMGO.

The ammonia ICE configuration seems the most robust option for zero-emission W2W vessels, but it requires a nuance. To safely operate W2W vessels running on ammonia, safety needs to be addressed more. Because of its toxicity, the on board systems need to be carefully designed for this, regulations are lacking, and passengers and crew need to be comforted with the safety of ammonia. If a vessel owner wants to invest today, in a single-fuel converter, an ICE with LSMGO leads to most profit, HVO gives a mix between profit and less emissions, or methanol gives no emissions but a risk on the profit side.

The end product of this research is the developed model, which allows for changed input for the variables. In due course, when more accurate information becomes available, the assessment and evaluation can be redone quickly. Hence, decision making can be done easier and faster.

Contents

Abbreviations and chemical formulas

Abbreviations

BEP	Break-even point
CAPEX	Capital Expenses
CCS	Carbon Capture and Storage
CSOV	Commissioning Service Operation Vessel
CT	Carbon Tax
CTV	Crew Transfer Vessel
DAC	Direct Air Capture
DC	Daughter Craft
DMDU	Decision Making under Deep Uncertainty
DP	Dynamic Positioning
DR	Day Rate
DUT	Delft University of Technology
EBIT	Earnings Before Interest and Tax
EBITDA	Earnings Before Interest, Tax, Depreciation, and Amortization
EBT	Earnings Before Tax
EC	European Commission
EEA	European Economic Area
EEA	Epoch-Era Analysis
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Index
ETS	European Trading System
EU	European Union
EWTC	Emissions per Wind Turbine Connection
FC	Fuel Cell
GHG	Greenhouse Gas
GT	Gross Tonnage
H&M	Hull and Machinery
H2C	Compressed Hydrogen
H2L	Liquefied Hydrogen
HFO	Heavy Fuel Oil
Hs	Significant wave height
HT	High Temperature
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
IEA	International Energy Agency
IGF	International code of safety for ships using gases or other low-flashpoint fuels
IMO	International Maritime Organisation
IRR	Internal Rate of Return
KPI	Key Performance Indicator
LNG	Liquefied Natural Gas
LOA	Length Overall
LOHC	Liquid Organic Hydrogen Carrier
LPG	Liquefied Propane Gas
LSMGO	Low Sulphur Marine Gas Oil
LT	Low Temperature
MCG	Motion Compensated Gangway
MDO	Marine Diesel Oil
MGO	Marine Gas Oil

Abbreviations

MRV	Monitoring, Reporting, and Verification
NIMBY	Not In My Backyard
NPV	Net Present Value
O&G	Oil and Gas
O&M	Operation and Maintenance
OPEX	Operational Expenses
OSV	Offshore Service Vessel
OWF	Offshore Wind Farm
P&I	Protection and Indemnity
PEMFC	Polymer Electrolyte Membrane Fuel Cell
POB	Persons on Board
PW	Pay Willingness
RDM	Robust Decision Making
ROI	Return On Investment
SEEMP	Ship Energy Efficiency Management Plan
SMR	Steam Methane Reforming
SOFC	Solid Oxide Fuel Cell
SOV	Service Operation Vessel
TP	Transition Piece
TRL	Technology Readiness Level
TTW	Tank-to-wake
ULSFO	Ultra Low Sulphur Fuel Oil
VC	Vast CAPEX
VLSFO	Very Low Sulphur Fuel Oil
W2W	Walk to Work
WACC	Weighted Average Cost of Capital
WTT	Well-to-tank
WTW	Well-to-wake

Chemical formulas

CO_2	Carbon dioxide
CH_3OH	Methanol
CH_4	Methane
H_2	Hydrogen
H_2O	Water
NH_3	Ammonia
NO_x	Nitrous Oxides
O_2	Oxygen
SO_x	Sulphur Oxides

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1 Introduction

This research investigates the technical and economical feasibility of a zero-emission Walk to Work (W2W) vessel during its operational life.

Definition 1 *In this research, zero-emission is defined as zero CO_2 emissions.*

W2W vessels have a unique operational profile compared to, for example, transport vessels whose main goal is to transport goods from port to port. W2W vessels can be classified as Offshore Service Vessels (OSV). The primary function of OSVs is to sail somewhere to perform a job (Banen, 2021). W2W vessels sail in Dynamic Positioning (DP) mode from one wind turbine to another, while both the DP system and the Motion Compensated Gangway (MCG) require power when the W2W vessel is stationary at a wind turbine. Investigating the relationship between this unique operational profile and zero-emission feasibility makes this research challenging and unique.

1.1. Regulations on maritime emissions

Climate change is a major topic right now. The long-term weather pattern changes and influences average temperature but also causes extreme weather events, which, among other things, changes wildlife populations and habitats and causes higher sea levels (Nunez, 2019). The average increase of temperature is caused by the Greenhouse Gas (GHG) effect; trapped gasses let in light but keep heat from escaping.

The international maritime sector contributes, respectively, 1.8%, 2.8%, 2.76% and 2.89% of the total CO_2 emissions of the world in 1996, 2007, 2012, and 2018 (IMO, 2009b) (IMO, 2014) (IMO, 2020a). Maritime emissions represent approximately 13% of the overall European Union (EU) GHG emissions from the transport sector in 2015 (European Commission, n.d.-c). These findings underline the need to change something now. The maritime sector must reduce its emissions to limit climate change. Urgent action is needed to change the amount of (maritime) GHG emissions, which can be addressed to the energy transformation.

In 2015, 195 nations signed the Paris Agreement and set the goal of substantially decreasing GHG emissions to limit the temperature increase in this century to preferably 1.5°C. All nations committed to reduce their levels of pollution and strengthen their commitments over time (Natural Resources Defense Council, 2021) (European Commission, n.d.-b).

1.2. Offshore wind turbines: a source for renewable energy

Offshore wind turbines are part of the solution to reduce worldwide emissions because wind turbines produce renewable energy. The new building growth rate of offshore wind farms (OWF) is expected to quadruple between 2020 and 2030 (O'Sullivan, 2021a) but there is a problem. Offshore wind turbines have life cycle GHG emissions that are more than twice as high as onshore wind turbines due to all vessels that are required to build and maintain wind turbines (S. Wang et al., 2019).

1.3. Walk to Work vessels

One of the vessels required for the construction, installation, maintenance, and operation of offshore wind turbines is a W2W vessel. W2W vessels are vessels equipped with an MCG, which enables the transfer of personnel and light cargo to an offshore structure (e.g., an offshore wind turbine). An example of a W2W vessel using its MCG can be seen on the cover page.

A W2W vessel has a high energy consumption for all its operations, which nowadays often comes from fossil sources. When a W2W vessel uses fossil sources, it has emissions. Part of the solution to reduce indirect emissions from an offshore wind turbine is a zero-emission W2W vessel. To enable a zero-emission W2W vessel, it is presumed that an alternative energy carrier is necessary with limited additional alterations to the design.

1.4. Acta Marine: company introduction

The growth in the offshore wind sector, the increasing demand for W2W vessels and the belief that the OWF supply chain must become sustainable itself add to the reason that this research is supported by Acta Marine. Acta Marine, as the problem owner, provided data of their W2W vessels, shared their insights in both the OWF market and the maritime offshore market, and provided day-to-day guidance in developing this research.

1.5. Problem definition

The main adverse effect of OWFs moving farther offshore is that the transit distance and duration increase while also the weather conditions are harsh. This requires the W2W vessel to increase its operational sailing distance while maintaining the same effectiveness. To enable this, the required power and required energy may need to increase.

Simultaneously, there is a desire to reduce worldwide GHG emissions. OWFs are part of this solution because they produce renewable energy. However, lifecycle GHG emissions of OWFs still need to decrease.

Therefore, the focus lays on decreasing the emissions of all vessels used during the life cycle of an OWF, including W2W vessels. An option is to reduce energy consumption by changing the design of the vessel or changing operations. However, these solutions will only be part of the solution as it will not bring the emissions to zero. Another promising option is the use of alternative energy carriers to minimise emissions. However, the main shared characteristic of alternative energy carriers is that their contained energy density is lower than that of conventional energy carriers, such as marine diesel oil (MDO) or marine gas oil (MGO).

So, the main problem is that to maintain the same effectiveness, to keep the same operability, while also being able to sail to OWFs further offshore and being able to reduce emissions, extra space and volume is required to store alternative energy carriers on a W2W vessel.

1.5.1. Research question

This research aims to minimise the emissions of W2W vessels. Hence, this research aims to verify which alternative energy carriers, are a technically and economically viable option to reach zero-emission W2W vessels. The main research question of this research is:

“***What is the technical and economical feasibility of a zero-emission walk to work vessel, while maintaining current and future effectiveness requirements?***”

The main research question of this research is solved by answering the following seven subquestions:

1. “*What are the trends in the offshore wind industry, who are the influential stakeholders, and how do they influence the future proof design of W2W vessels?*”

2. “*What is the state-of-the-art in W2W vessels and what are their current and future effectiveness requirements?*”

3. “*What is the state-of-the-art in potential alternative energy carriers, what are their important properties and what is their relevance for W2W vessels?*”

4. “*Which are the requirements for an assessment methodology that covers future trends, energy carrier choice, and W2W vessel design implications and what methodologies are best suited for this?*”

5. "*How can the technical and economical feasibility of multiple strategies be found and what are possible scenarios which may be used in deciding which strategy needs to be chosen for zero-emission W2W vessels?*"

6. "*How will the implementation of alternative energy carriers influence the operational effectiveness, CAPEX, OPEX, revenue and profit of zero-emission W2W vessels, over time?*"

7. "*How can the feasibility of zero-emission W2W vessels be validated and verified?*"

1.6. Social and scientific relevance

Research can be scientifically relevant without being socially relevant (Shaw and Elger, 2013). This research makes sure that it is relevant both scientifically and socially because doing research is both expensive as time consuming. The scientific relevance is shown by the goal to increase the understanding of alternative energy carriers in combination with vessels. Moreover, there is little public scientific knowledge about W2W vessels since the first purpose built W2W vessel launched only in 2014 and to date, there are only 21 active in Europe (section 2.5). There is sufficient industry knowledge about offshore vessels, however, knowledge on W2W vessels is very limited and an increase in knowledge is therefore relevant.

This research is also socially relevant. If both the technical and economical feasibility of zero-emission W2W vessels would be proven, it is highly likely that zero-emission W2W vessels are actually going to be designed. This would mean less life cycle emissions by wind turbines, and this research could thus bring society one step closer to a zero-emission society.

If the feasibility is not proven, this research is still relevant because it shows that the direction which will be taken in this research is not the direction to get to zero-emission. It could well be that the results of this research are that low-emission (instead of zero-emission) W2W vessels are technically and economically feasible. This would bring society at least a step closer to the goal of a zero-emission society.

1.7. Report outline

Chapter 2 covers the first two subquestions on stakeholders, trends in the offshore wind industry, and state-of-the-art W2W vessels. First, it explains which stakeholders are relevant, what their interest and power related to a zero-emission W2W vessel is, and whether there are potential conflicts between stakeholders. Secondly, the offshore wind industry is investigated to understand the market W2W vessels operate in and to discover trends which may influence the design of W2W vessels. Thirdly, an analysis on the operation and requirements of W2W vessels is performed.

Chapter 3 finds the answer to the third subquestion on alternative energy carriers. First, it investigates whether there are relevant regulations to which W2W vessels must comply. Then energy converters are investigated, and the alternative energy carriers are pre-selected. Lastly, an analysis based on the characteristics of the alternative energy carriers is performed on the potential energy carriers for zero-emission W2W vessels.

Chapter 4 defines the research gap and the scope of the research. Chapter 5 determines the properties that a methodology must fulfill and thus finds the answer to subquestion four. These properties are used to select 2 methodologies which can be used to find the feasibility both technically and economically. This chapter also gives the strategy on how these 2 methods can be combined.

Chapter 6 investigates whether zero-emission W2W vessel may be technically feasible. A self-made parametric model is proposed, explained, and implemented. Chapter 7 checks the economical feasibility using a Robust Decision Making (RDM) method. A set of uncertainties and potential policies is used to create a very large number of potential futures. The technically feasible solutions are tested among these futures to find economical possibilities.

In chapter 8, the validation is performed. Validation is done by reassessing all assumptions that have been made for this research and by performing a sensitivity analysis. Chapter 9 gives conclusions, recommendations and describes the industry, scientific, and societal contributions. Lastly, chapter 10 gives a personal reflection on the performed research.

2
Walk to Work vessels

This chapter will cover an analysis on W2W vessels. The chapter discusses the stakeholders involved with (zero-emission) W2W vessels, discusses the offshore wind industry to find relations with the W2W vessel design, and investigates the (future) requirements of a W2W vessel. This chapter investigates the first two subquestions:

1. "*What are the trends in the offshore wind industry, who are the influential stakeholders, and how do they influence the future proof design of W2W vessels?*"

2. "*What is the state-of-the-art in W2W vessels and what are their current and future effectiveness requirements?*"

To investigate these subquestions, section 2.1, contains a stakeholder analysis. The definition of a W2W is found in section 2.2 after which an intensive look is taken at the offshore wind market in which the W2W vessel will operate in section 2.3. Then, two different W2W vessel categorisations are made in section 2.4 after which an overview of all current purpose built W2W vessel is presented in section 2.5. Lastly, the operational profile is investigated in section 2.6 and an investigation of technical, economical, and environmental requirements is carried out in section 2.7, section 2.8, and section 2.9.

2.1. Stakeholder analysis

Stakeholders play an important role in establishing the need for this research. The identified stakeholders include OWF owners, wind turbine suppliers, W2W vessel owners, but also other vessel owners (in the offshore wind industry), port authorities, research organisations including Delft University of Technology (DUT), and regulatory bodies.

A strategy to map OWF stakeholders has been proposed and adapted to the Operation and Maintenance (O&M) phase of OWFs by Ahsan and Pedersen (2018). Each stakeholder is placed in one of four categories (Figure 2.1) to determine the level of interest and power that the stakeholder has on the research. This section applies the same strategy to the stakeholders of this research and also identifies potential conflicts.

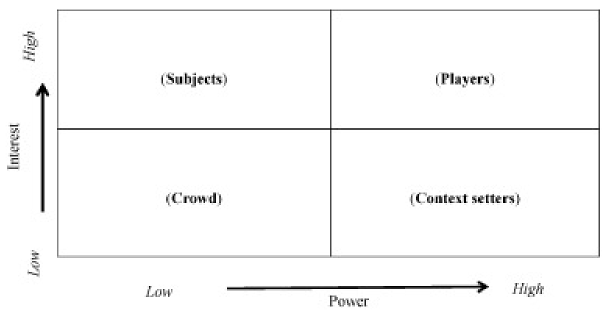


Figure 2.1: Stakeholder's power/interest matrix (Ahsan and Pedersen, 2018)

2.1.1. Offshore wind farm owners

OWF owners are the driving force for offshore wind technology (Brans, 2021). The OWF owner decides which company supplies the turbines and which company is in charge during O&M. The OWF owner wants a high return for its investment, while, on a lower level, it also requires having a green image. A growing market creates a shortage in wind turbine suppliers, builders, and vessels which are necessary to operate an OWF. Therefore, it is likely that the margins of OWF owners will decrease and that more focus will go to the profit margin than to their green image. It is therefore seen that OWF owners have average to high interest and very high power in this research. This places them in the player category.

2.1.2. Wind turbine suppliers

The three main wind turbine suppliers in Europe are Siemens Gamesa Renewable Energy (SGRE), Vestas, and General Electric Renewable Energy (GE) (Legemate, 2021). Suppliers design the wind turbines, oversee the building and commissioning of the OWF, and often arrange all vessels required for the project, including W2W vessels. Their goal is the same as OWF owners; making as much profit as possible while also keeping a green image. Because the wind turbine supplier hires the W2W vessel, their power is deemed very high.

All three suppliers are disclosing that they require vessel owners to decrease their emissions (Legemate, 2021). Consequently, the interest and power of wind turbine suppliers in this research is deemed relatively high, which also places them in the player category.

2.1.3. Walk to Work vessel owners

Along with making profit while keeping a green image, W2W vessel owners must also provide good working circumstances because there is a shortage of good crew (Boersma, 2021). This makes it rewarding to invest in the newest technologies and the highest comfort standards. The interest in investing in the newest technology and reaching for zero-emission W2W vessels is thus high. The expected shortage of W2W vessels, places the W2W vessel owners, at least temporary in the player category. Later, they may shift to the subject category.

Acta Marine has an above average interest in zero-emission W2W vessels, which is supported by this research. Acta Marines strategy deviates from competitors as their goals is not only to provide service but also to be green. Although Acta Marine is only one of multiple W2W vessel owners, by supporting this research their power in in this subject enlarges. Power is deemed lower and interest higher, than all W2W vessel owners together.

2.1.4. Regulatory bodies

Governments and the International Maritime Organisation (IMO) have a high interest in obtaining lower emissions in the maritime sector. This is underlined by new proposals to set limits on the number of emissions that a vessel may have (European Commission, 2021). These bodies do not have to make profit and their power is very high because they may set regulations. Regulatory bodies are therefore placed in the player category. Regulatory bodies may conflict with (W2W) vessel owners if they set regulations which cannot be met or lead to a loss-making company.

2.1.5. Influential maritime companies

Other maritime companies may heavily influence the alternative energy carrier that will have the lowest threshold for W2W vessels. Investments by major companies may lead to a lower threshold because obstructions may either be removed or decreased. When an influential shipping company makes a large investment, the market may follow with the ease of mind that obstructions will be resolved by the investor. Since the obstructions will be resolved faster, the threshold for a new technology will be lower and therefore more attractive.

A potential conflict is identified between the major shipping companies and W2W vessel owners. Because the operational profile is very different between them, it is possible that a different strategy is the best solution for the different vessel types. If the major shipping companies are investing in a different alternative energy carrier, it is possible that the energy carrier required by W2W vessel owners has a set-back. Because power is high and interest is low, the major shipping companies are categorised as context setters.

In the same way as very large shipping companies may influence the market, smaller companies working in the same offshore wind industry as W2W vessels may influence the decisions in the strategy for zero-emission W2W vessels. When, for example, another vessel owner decides to use a vessel running on batteries and requires a recharging buoy in the field, this enables the W2W vessel owner to easily share in the benefits of this recharging facility and does not need to make all investments. It is expected that (bunker) resources may more easily be shared. The same potential conflict as for large shipping companies is identified between offshore wind industry vessel owners and W2W vessel owners. However, since the operational profile is more alike between these two owners, the chance of conflict is smaller.

2.1.6. Research organisations and institutions

Research organisations are actively doing research in the field of alternative energy carriers. Their power in zero-emission W2W vessels is not high but also not zero because an energy carrier first needs to be researched to find its potential. After that, a new technology can be researched further by companies that see commercial possibilities. The DUT has an above average interest in using the newest alternative energy carrier technologies and encourages the use of renewable energy to decrease adverse fossil fuel effects. Therefore, the DUT is supporting this research but also collaborates in projects such as the Green Maritime Methanol project (Green Maritime Methanol, n.d.), SH2IPDRIVE (WEBREDACTIE 3ME, 2021), and the MENENS Project (aqualink, 2021). By supporting this research, DUT shows interest and tries to increase its power in zero-emission W2W vessels. Research organisations and institutions are placed in the subject category due to their low power and high interest in zero-emission W2W vessels.

2.1.7. Port authorities

Port authorities influence the infrastructure around storing and bunkering new alternative energy carriers. If a port is the first (in the region) to provide bunker facilities for a specific energy carrier, the investment costs will be relatively high. On the other hand, when a port is first, it will attract all vessels in the region to bunker at this specific port. Therefore, the expected demand and thus profit is high. However, if there are no vessels which need a specific alternative energy carrier, few ports would provide bunker facilities and if no port provides facilities to bunker an energy carrier, only few companies will build vessels running on this energy carrier. This means there is a conflict between the two stakeholders on who goes first: the vessel owner or the port authority. Port authority power is deemed large because the port is the supplier. On the other hand, if a port decides not to provide a specific alternative energy carrier, the vessel owner may decide to choose a different port. The latter is easier for shipping companies than for vessels working in the offshore wind industry because their port is set to be the port where the wind turbine parts are stored (Banen, 2021).

2.1.8. Offshore personnel

Offshore personnel, either technicians or crew, on a W2W vessel are the ones that will experience a new technology firsthand. If the new technology influences the operational effectiveness or the safety level of a W2W vessel, they will directly be influenced. Although offshore personnel have little power alone, united, they have an increased influence in the technology used to make W2W vessels zero-emission. Due to low power and high interest, offshore personnel are placed in the subject category.

A potential conflict is identified between offshore personnel and W2W vessel owners. Offshore personnel want to have the safest energy carrier possible while the same effectiveness is remained. W2W vessel owners may take higher risks to maximise profit. If this means an alternative energy carrier with more safety issues is selected, a potential conflict occurs.

2.1.9. Stakeholder power interest matrix

The main stakeholders consist of four players, two context setters, and two subjects (Figure 2.2). The matrix shows that W2W vessel owners and the three other players are both powerful and have a high interest in zero-emission W2W vessels. However, what must not be forgotten is that although their interest in zero-emission W2W vessels may be high, they may still have other interests. This is the case for all four players who still need to make profit. Therefore, zero-emission W2W vessels will not be economically feasible without other incentives from other stakeholders and other stakeholders influence the feasibility of zero-emission W2W vessels.

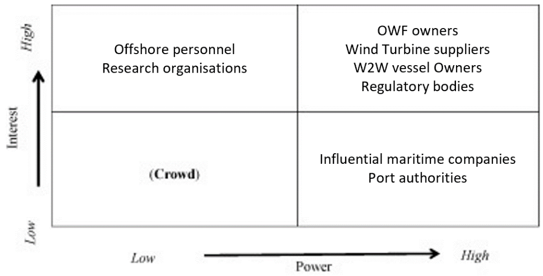


Figure 2.2: Power/interest matrix for zero-emission W2W vessel stakeholders

2.2. Walk to Work vessel definition

According to DNV GL (2015), *"The W2W vessel is a floating structure (i.e., a vessel) ranging in size from a small workboat to a large semi-submersible offshore facility on which a gangway system is installed by which W2W personnel transfers are undertaken."*. DNV GL (2015) shows what is meant by ranging in size with Figure 2.3. This research will focus on monohull service vessels which will be called W2W vessels throughout this research.

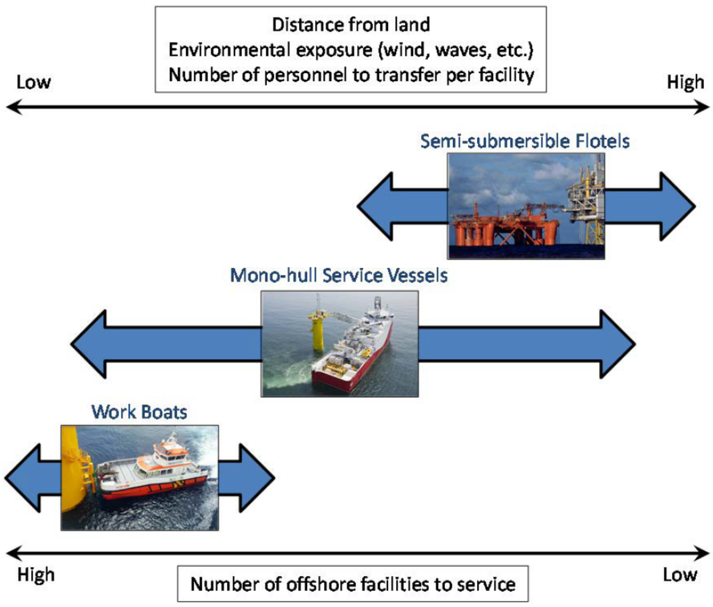


Figure 2.3: Illustration of possible W2W vessel suitability (DNV GL, 2015)

Out of the three vessel types, monohull vessels have the biggest working area. W2W vessels main goal is to give safe access to offshore structures. Safe access is achieved because the vessel is equipped with a DP system and a MCG. The DP system ensures that a floating structure remains in a fixed position with respect to the sea bottom and therefore does not crash into an offshore structure (Sørensen, 2011). The MCG dampens motion of the vessel due to waves and therefore creates a safe passage from the vessel to the offshore structure (Roelofs, n.d.). These two requirements (DP and MCG) make it possible for a W2W vessel to perform its basic job; safely transporting personnel and cargo to an offshore structure. W2W vessels can be deployed on offshore facilities, either for use in an OWF or in an oil and gas (O&G) field.

2.3. Offshore wind energy

To understand what the (future) requirements of a W2W vessel are, the offshore wind industry must be investigated. Wind energy is a renewable energy which means that zero emissions are produced during operation. However, during production, dismantling, and maintaining with the help of (W2W) vessels, emissions are produced. Still, production with wind turbines is currently one of the greenest energies around when looking at the total life cycle emissions (Guezuraga et al., 2012). Governments all over the world, specifically in the European countries, are focusing on the development of new OWFs (European Commission, n.d.-d).

2.3.1. Onshore or offshore wind

As of 2000, the size and market growth of OWFs has been increasing (Kaldellis and Kapsali, 2013). OWFs are necessary for three main reasons. The first one is that space is limited in densely populated countries in Europe and that there is more space available at sea. A second reason is that the wind is unobstructed (and thus stronger and more continuous) offshore, which creates the possibility to generate more energy. The third reason is to keep the group with a negative perspective on wind turbines satisfied. Although in the EU, 71% of its citizens are in favor of wind energy, a small group of citizens remains with a negative social perspective on wind turbines (wind-energy-the-facts.org, n.d.) (European Commission, 2007). The main part of this group is against building wind turbines close to their homes and would be in favor if the wind turbines were built further away from them (NIMBY or Not In My Backyard principle) (uit het Broek et al., 2019).

2.3.2. Offshore wind farm life cycle greenhouse gas emissions

While both onshore and offshore wind turbines have an average lifetime of 20 years, the total life cycle GHG emissions are approximately 120% more for offshore wind turbines (S. Wang et al., 2019). This is mainly due to transport and installation but also due to manufacturing (more materials needed for foundation), dismantling, disposal, and operation and maintenance (S. Wang et al., 2019). If W2W vessels would have lower emissions, the life cycle GHG emissions of OWFs would decrease.

According to Thomson and Harrison (2015), manufacturing and installation (commissioning) account for 78.4% of total life cycle GHG emissions, O&M for 20.4% and dismantling and disposal (decommissioning) for 1.2%. A breakdown of O&M shows that 14.3% of these emissions are caused by supporting vessels (W2W vessels and Crew Transfer Vessels (CTV)) (Thomson and Harrison, 2015). According to Łebkowski (2020), average CTV emissions are 0.2 tCO_2/hr. A W2W vessel has an average fuel consumption of 7.2 m^3/day (Figure 2.13), energy density of Low Sulphur Marine Gas Oil (LSMGO) is 36.7 GJ/m^3, and life-cycle emissions are 87.1 kg CO_2/GJ ((Pavlenko et al., 2020)). For 24/7 operations a W2W thus averages 0.96 tCO_2/hr. Therefore, the estimate is made that W2W vessels emit 5 times as much as CTVs.

According to Kock (2021), on average, during (de-) commissioning 2 W2W vessels are required and during O&M 1 W2W vessel is required. On average the O&M phase has a duration of 20 years, and the (de-) commissioning have a combined average duration of 3.5 years (Dinh and Mckeogh, 2019).

According to these assumptions, W2W vessels account for 2.43% of total life cycle GHG emissions of wind turbines during O&M and 0.85% in (de-) commissioning (Figure 2.4). Although this number is most probably not accurate, it gives a rough estimate on the influence W2W vessel have on the life cycle GHG emissions of OWFs.

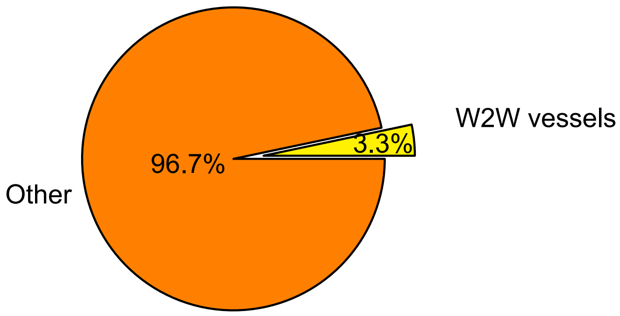


Figure 2.4: Life cycle GHG emissions of offshore wind turbines (Based on estimates from subsection 2.3.2)

2.3.3. Offshore wind farm locations

When looking at the prospected worldwide locations of OWFs, it is estimated that by 2030, European waters will remain the area with the most new wind turbines (Lee and Zhao, 2020). European waters with OWFs include the North Sea, the Norwegian Sea, the English Channel, the Celtic Sea, the coastal waters of Ireland and the United Kingdom, the Bay of Biscay, Skagerrak and the Kattegat, the Baltic Sea, the Gulf of Bothnia, and the Gulf of Riga. Although other OWF areas including Asia, China and North America are also growing, it is estimated that the European market share will still be 45.5% in 2030 (Lee and Zhao, 2020). For this reason, the scope of this research will be the European waters.

It is estimated that the North Sea will remain the dominant location with 80% of all OWFs in Europe until 2026 (O'Sullivan, 2021a). By 2030, it is estimated that over 12.5% of OWFs will be in the Baltic Sea while still 75% will be in the North Sea (O'Sullivan, 2021a). The operational area (Europe) will thus remain the same for W2W vessels in the coming years. The prospected locations of new OWFs in Europe are mapped in Figure 2.5.

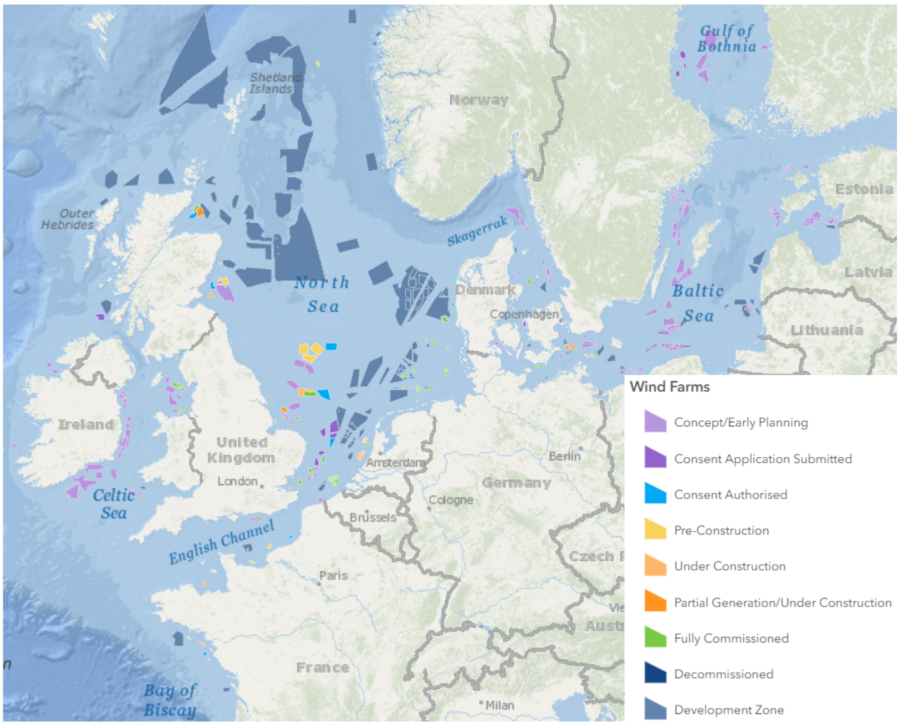


Figure 2.5: Current and future OWFs and their project status in European waters (4coffshore.com, n.d.)

2.3.4. Floating wind turbines

In direct relation to the location is the water depth and thus the type of foundation. Most wind turbines until 2030 will be in shallow water. Therefore, the foundations will mostly be bottom fixed. However, floating farms will eventually get a market share when shallow waters will not provide enough space anymore. It is expected that 3% to 4% of annual installations will be floating wind turbines between 2026 and 2030 (O'Sullivan, 2021a). Since floating wind turbines will only add minor additional requirements to W2W vessels (Ampelmann, n.d.) and the market share is expected to remain very small in foreseeable future, floating wind turbines are not considered in this research.

2.3.5. Offshore wind farm building procedures

For this research, it is important to have some basic knowledge on the designing, commissioning, servicing, and maintaining of OWFs.

Design

A wind turbine consists of six main different parts (Figure 2.6). The bottom part (the part on the ground) is the foundation. On top of the foundation comes the transition piece (TP) on which the turbine tower is built. This turbine tower consists, depending on its height, of two or three pieces (Davis, 2021). On top of the tower is the nacelle. The nacelle supports the hub and houses the gearbox and the generator.

The nacelle can turn relative to the turbine tower to be able to always face the wind. The hub, which is attached to the front of the nacelle, connects the three blades of the turbine.

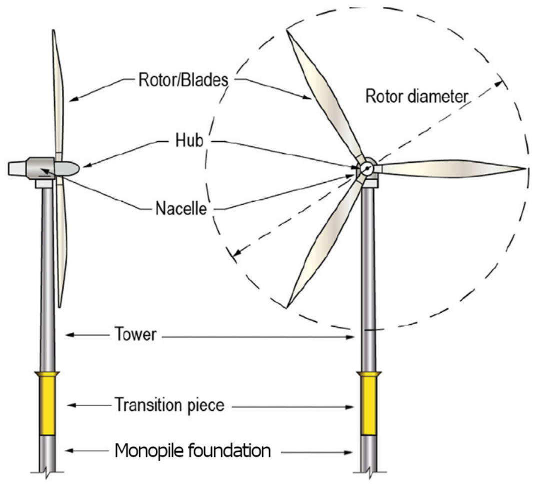


Figure 2.6: Wind turbine components (Kaynia, 2018)

Foundation
The first step in the building process is the construction of the foundation. Until 2020, the main choice of foundations were monopiles (81.2%), followed by jackets (9.9%). The monopile is the most popular because it is relatively inexpensive, series work is easier, and the installation speed is higher than rival bottom structures. A W2W vessel sails after a construction vessel and a higher turbine installation speed thus means that more crew on the W2W vessel is required for the building phase. More crew influences the size of a W2W vessel, mainly in the accommodation part.

Transition piece
The TP is placed on top of the monopile foundation and has multiple functions. The part must be strong enough to carry the weight of the turbine, provides access, ensures that cable connections can be made, and protects the entire foundation from corrosion.

The TP provides access for maintenance with multiple entrance points. Ladders are accessible at water level and are therefore ideal to transfer technicians with a CTV or daughter craft (DC) when the sea is calm. When the sea is not calm, CTVs or DCs cannot provide access through the ladders and a W2W vessel is necessary.

On the TP platform, there are multiple gates to ensure that a safe transfer can be made in many conditions. A W2W vessel can connect its MCG to the gate on the TP platform to transfer technicians to the wind turbine. A MCG transfer can be seen on the cover of this research. With this connection, also stepless cargo transport up to a certain weight is possible. If heavier cargo needs to be transported to the wind turbine, a motion compensated crane (offshore crane) is used to put the cargo on the TP platform.

The air gap between water level and the TP platform is influenced by factors such as tide difference, 1 in 100 years maximum wave height, water depth, and building standardisation (Anink, 2021). Building standardisation influences the air gap because it may be less expensive to use the same wind turbine in the whole OWF although the depth is varying. It is seen that the average air gap is increasing and thus the height at which a safe transfer must be performed increases. However, it is also seen that the increase in airgap is not so large that it leads to increased MCG and offshore crane requirements.

The turbine installation speed is important because more crew is needed on W2W vessels if more wind turbines need to be commissioned. However, it is not expected that this speed will be significantly increased. Even if this happens, it is more likely that 2 W2W vessels will be used at the same time.

Operation and maintenance
To maximise the operation time of wind turbines, maintenance is carried out. The wind turbines are maintained by technicians which need to be given access to the wind turbine by the W2W vessel. A

distinction is made between corrective and preventive maintenance. Corrective maintenance is responsive to failure, which means that the maintenance is being carried out whenever something is failing, and preventive maintenance is maintenance to prevent something to fail and is done according to schedule. Most of the time, a W2W vessel under O&M contract, is doing both types of maintenance at an OWF (Anink, 2021).

When a W2W vessel provides corrective maintenance on one side of the OWF and a wind turbine breaks down on the other side, the W2W vessel needs to sail there to provide corrective maintenance. During sailing to the other side of the OWF, no technicians can be transferred and thus the W2W vessel has operational downtime. However, this downtime is included in the calculations for the crew, which may be reduced compared to a vessel which only provides preventive maintenance.

2.3.6. Trend: Offshore wind industry is growing

OWFs become bigger in size and stronger in capacity. Since 2015, the power capacity of wind turbines has grown with 16% achieving an average capacity of 8.2 MW per wind turbine in 2020 (O'Sullivan, 2021b). Most projects after 2022 have wind turbines ordered ranging from 10 to 13 MW (O'Sullivan, 2021b). Technical and political developments cause growth in the offshore wind market. To build all planned OWFs, the building speed almost needs to quadruple by 2030 (O'Sullivan, 2021a).

Up to 2026, approximately nine OWFs per year are commissioned in Europe. From 2026 to 2030, it is estimated that this number goes up to approximately 12 OWFs per year. This means that there will be around 200 OWFs with an equivalent of 12.000 wind turbines at the end of 2030. A growth of the total OWFs directly influences the demand for all required vessels related to building OWFs. OWFs that require servicing reach a cumulative capacity of over 100 GW by 2030 (O'Sullivan, 2021a).

Simultaneously, OWFs also move further offshore and more OWFs are built every year. Although the majority of OWFs are still built within 60 km from the shore, the average distance to OWFs is continuously increasing (Banen, 2021) (O'Sullivan, 2021b). To date, three OWFs are built at a distance greater than 100 km from the shore and permits are already given out for OWFs with a distance of almost 200 km to shore (O'Sullivan, 2021b). OWFs at a greater distance require more energy storage on the W2W vessel.

2.4. Walk to Work vessel types

W2W vessels can be classified in the OSV category. However, also between W2W vessels, a categorisation can be made. Two types of categorisation can be made; an OWF building phase categorisation and a building purpose categorisation.

2.4.1. Building phase categorisation

The building of an OWF can be split up in four phases as can be seen in figure Figure 2.7. The first category of W2W vessels is named the Commissioning Service Operation Vessel (CSOV). A CSOV supports (de-)commissioning of an OWF. Specific requirements depend on the specific OWF, but a CSOV typically has a contract of 3 to 12 months, and requires capacity for 60 to 120 Persons On Board (POB) (Legemate, 2021).

Figure 2.7: The four main phases in the lifetime of an OWF

Secondly, there is the operation and maintenance (O&M) category. O&M projects are serviced by a Service Operation Vessel (SOV). Its requirements depend on its specific job, but its goal is to safely transfer personnel to perform maintenance on the wind turbine. The main difference between CSOVs and SOVs is that the latter category is often purpose built for one specific OWF (Anink, 2021). This is possible because SOVs are typically on 5-to-10-year contracts (Legemate, 2021). By designing specifically for one project, costs can be minimised. Since, SOVs typically require less POB (approx. 60), it is seen that SOVs have less accommodation. The rest of the vessel is often much alike and therefore, sometimes CSOVs are used for O&M projects with a short duration.

Lastly, W2W vessels can also be used to give safe access to O&G platforms but this is left out of scope. An overview of the building phase categorisation can be seen in Figure 2.8a.

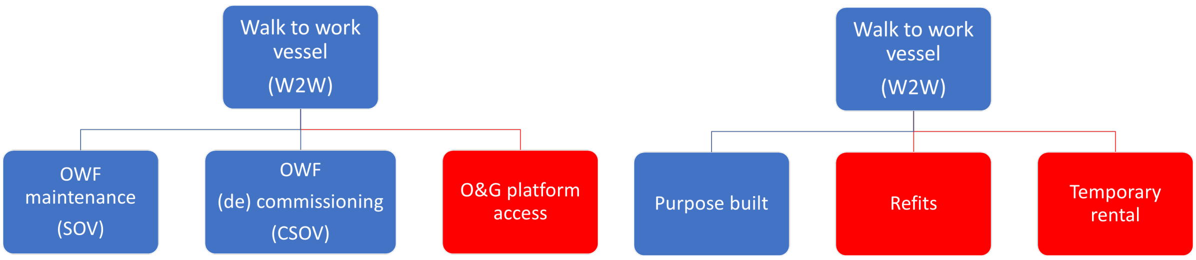
2.4.2. Building purpose categorisation

Demand for W2W vessels, either built for the short or long term, is directly linked to the amount of OWFs and therefore increasing. Three categories of build purpose in W2W vessels can be identified and can be seen in Figure 2.8b.

Temporary rentals are vessels working permanently in the O&G sector which are used whenever there is shortage. These vessels will be equipped with a rental MCG to perform W2W jobs but are not available whenever the oil price is high (Offshore Technology, 2012). Moreover, their fuel consumption is higher because they are not specifically designed to do the W2W job. Due to high fuel costs and extra costs for renting a MCG, this leads to the highest costs of the three categories.

The second category are refits of vessels which were often used in the O&G industry or used as general multi-purpose vessels. Therefore, they are equipped with a permanent MCG and other investments might be made to make it as efficient as possible. Fuel costs are, however, still higher and the operability lower than the last category because it was never specifically designed for a W2W job.

The third category are purpose built W2W vessels. Purpose built W2W vessels are specifically designed to transfer people (and cargo) to an offshore platform safely and as efficient as possible. Because of this, a purpose built W2W vessel is more efficient than a refit or a temporary rental. These vessels are thus not over-engineered (unnecessary costs) or under-engineered (lack of performance). Purpose built vessels can be built with the newest techniques and are therefore more suitable for a zero-emission strategy than refits or rentals who will need massive refitting. This research will therefore only focus on purpose built vessels.



(a) Building phase categorisation (b) Build purpose categorisation

Figure 2.8: Two categorisations of W2W vessels (red is out of scope)

2.5. Overview of Walk to Work vessels

Up to 2021, in Europe, there are 20 purpose built W2W vessels from 7 owners active and 13 on order. An overview of these vessels can be seen in the appendix (Table A.1). The state-of-the-art in zero-emission W2W vessels are two vessels on order by Awind. These vessels can operate zero-emission up to six hours on battery and solar power (Integrated Wind Solutions, 2021). Figure 2.9 shows the variety of vessels with box plots of POB, Length Overall (LOA), Gross Tonnage (GT) and max speed.

The expected growth in the number of OWFs directly demands a growth in the number of W2W vessels. The use of non-purpose built vessels today, knowing they have downsides, shows that there is already a shortage of purpose built W2W vessels today. Fearnley Offshore Supply market analyst Jesper Skjong states that 50 SOVs are required by 2030, of which 32 in Europe (Foxwell, 2021). Maritime Strategies International (MSI) associate director Ferenc Pasztor asserts that 600 SOVs are required by 2050 and that purpose-designed and built vessels are preferred (Foxwell, 2021). These two assertions implicate an exponential growth in demand for SOVs in the next years.

2.6. Operational profile of Walk to Work vessels

When investigating the operational profile, two kinds of cycles are defined. The long cycle describes the time between leaving the port and returning. The short cycle describes the sequence of operation from one wind turbine to another.

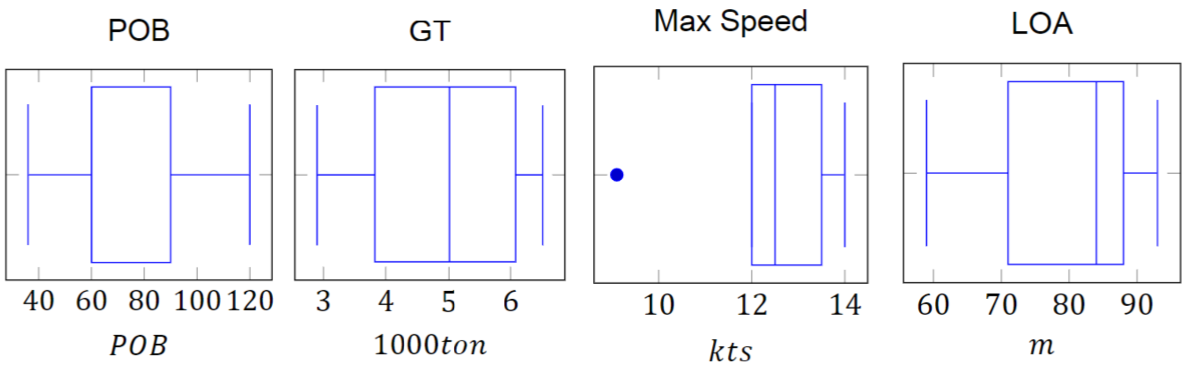


Figure 2.9: Boxplots of POB, GT, max speed, and LOA of current purpose built W2W vessels

2.6.1. Long cycle

The long cycle starts in the base port and ends when it returns from the OWF. In port, the crew is changed, cargo to restock the warehouse with spare parts comes aboard, the vessel is bunkered, the vessel is restocked with fresh water and food, the grey water tank is emptied, and there is time for some repairs which cannot be done offshore. A typical port call is around eight hours, from which bunkering usually does not take up more than 1 hour. After the port call, the vessel goes seawards. Depending on the distance to the OWF and the speed of the W2W vessel, this transit can take a while. This transit is identified as the first main task of the W2W vessel:

1. *Transporting personnel (and cargo) from port to an OWF and back.*

For task 1, the W2W vessel needs a propulsion system with enough power capacity and energy storage to sail at a certain speed for a certain distance. When the W2W vessel arrives at the OWF, the first group of technicians will be transferred to a wind turbine. Furthermore, some cargo may be transferred as well. This process is called the short cycle and will be discussed in more detail in subsection 2.6.2. Transferring persons and cargo are identified as main tasks 2 and 3.

2. *Transfer personnel safely from the W2W vessel to the offshore structure and back.*
3. *Transfer cargo items safely from the W2W vessel to the offshore structure (and back).*

For tasks 2 and 3, the W2W vessel needs to be able to hold it position with a DP system while it also needs a MCG for task 2 and an offshore crane for task 3.

After a technician's shift, which normally takes 12 hours, their 12 hours of free time on the W2W vessel start. During this time, the technicians need to eat, relax, and sleep. This all comes back in the fourth task of the W2W vessel:

4. *Provide accommodation and facilities.*

When not in port, the W2W vessel needs to survive on its own, which means that it needs to have enough energy, fresh water, provisions, and medicine on the W2W vessel. Typically, the long cycle has a duration of 14 or 28 days. The autonomy of the W2W vessel is the fifth main task:

5. *Be autonomous for the duration of the long cycle.*

2.6.2. Short cycle

The short cycle describes the intermediate steps to transfer cargo or a technician to a wind turbine. The short cycle starts when the vessel is located at the OWF and starts navigating in DP to the designated wind turbine. When the W2W vessel reaches the 100 m zone around the wind turbine, the vessel stops and the captain gives the "standby - operational" call. If the wind turbine is already in operation, the wind turbine is stopped and rotated in the idling position. The vessel will remain standby operational at the 100 m zone until the client is ready to transfer. When the sign is given, the W2W vessel will start 'moving in' to the wind turbine. When arriving at the wind turbine, either a crew transfer with the MCG, a cargo transfer with the MCG or the offshore crane, or both operations will occur. When finished, the vessel starts 'moving out' of the 100m zone and continues underway in DP to the next wind turbine.

When the W2W vessel arrives here, the short cycle is over. Typically, the contract determines that the time in the 100 m zone may not take longer than 30 to 40 minutes with a maximum of 3 or 4 persons and 3 pieces of cargo. The total short cycle currently is accepted to be approximately 70 minutes in the wind industry (Legemate, 2021). If moving in and moving out (DP manoeuvring in the 100m zone) could be optimised, the short cycle time could decrease. However, larger turbines will lead to more cargo and technician transfers to perform the same amount of work. This would increase the short cycle time. Therefore, it is expected that the short cycle time will approximately remain the same. The long and short cycles and their interaction are schematically displayed in Figure 2.10.

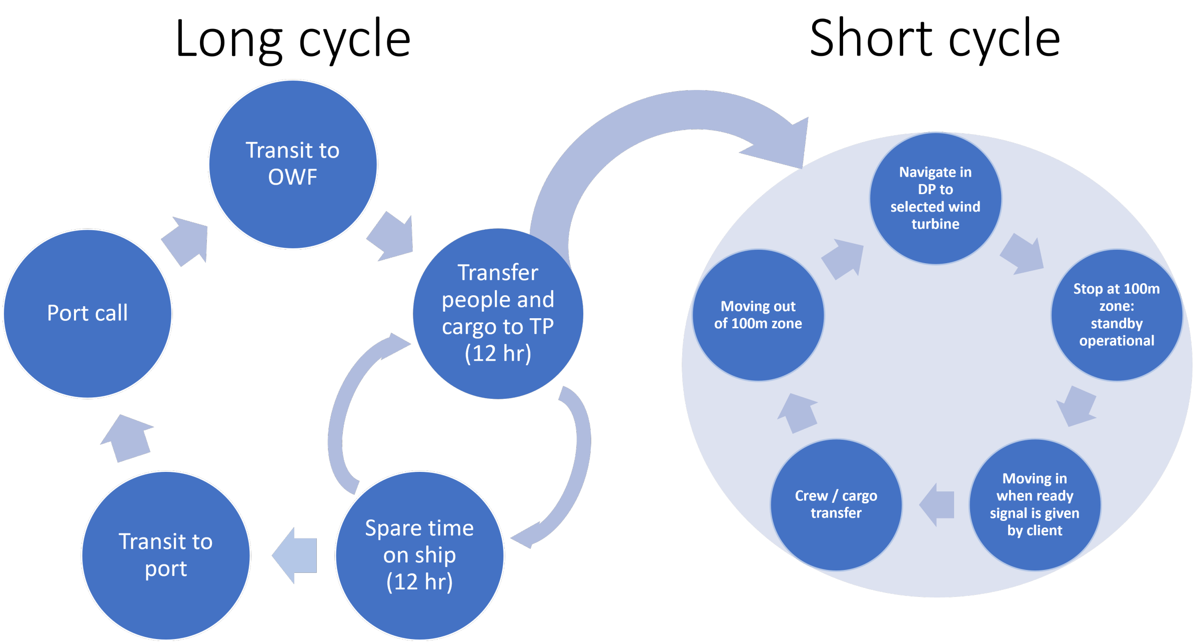


Figure 2.10: Schematic overview of the long and short cycle of a W2W vessel

2.6.3. Fuel consumption

To investigate how much fuel is necessary on a vessel, the fuel consumption must be known. Fuel consumption depends partly on the operation mode of the vessel. In the long cycle, three different stages can be identified; in transit, operating in OWF, and in port. In each of these stages, the vessel is operating in a different mode. Assuming a transit speed of 10 to 12.5 kts, an OWF distance of 60 to 200 km, a long cycle duration of 14 or 28 days, and a port call of 8 to 24 hours, the vessel is in transit for 0.4% to 3.2% and in port for 1.2% to 7.1% of the long cycle. The W2W vessel is in the OWF for the remaining time and thus the operational uptime (W2W vessel able to operate in OWF) varies between 89.6% and 98.4%. The percentage of long cycle stages is visualised in Figure 2.11.

During the short cycle, the vessel also operates in different modes; underway in DP to the next wind turbine, standby operational, moving in or out, and MCG or offshore crane transfer. To determine the fuel consumption, it is essential information how long the vessel operates in each mode. In this research, it is assumed that the operations are on average according to Figure 2.12, which is based on actual operation data from the Acta Marine W2W fleet.

Fuel consumption depends on the mode that the vessel is operating in, but also depends on the weather conditions, the hull form, mission equipment of the W2W vessel, and other factors. Figure 2.13a, depicts the average fuel consumption of purpose built W2W vessels Acta Auriga and Acta Centaurus. The short cycle average fuel consumption of these vessels is given in Figure 2.13b.

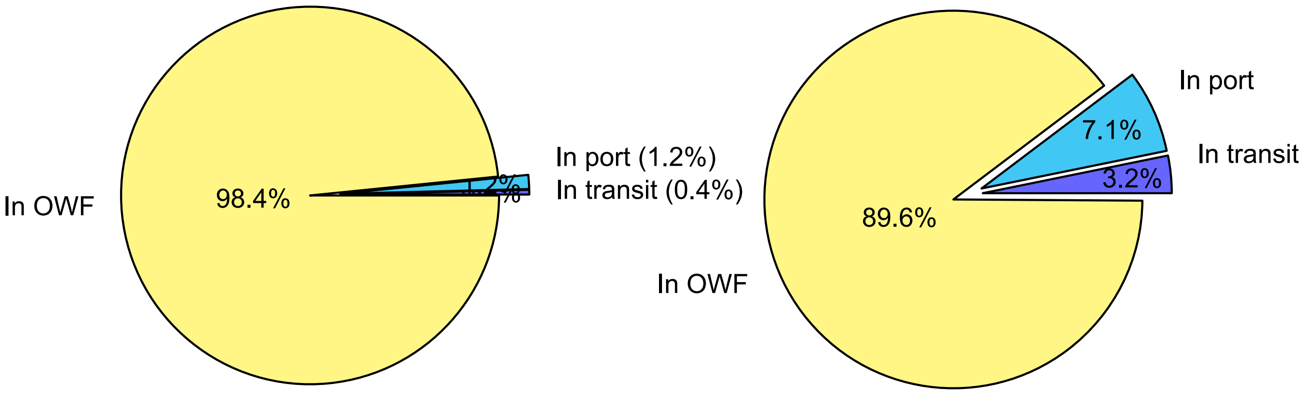


Figure 2.11: Percentage of each operational mode for highest (left) and lowest (right) operational uptime. (Based on assumptions in subsection 2.6.3

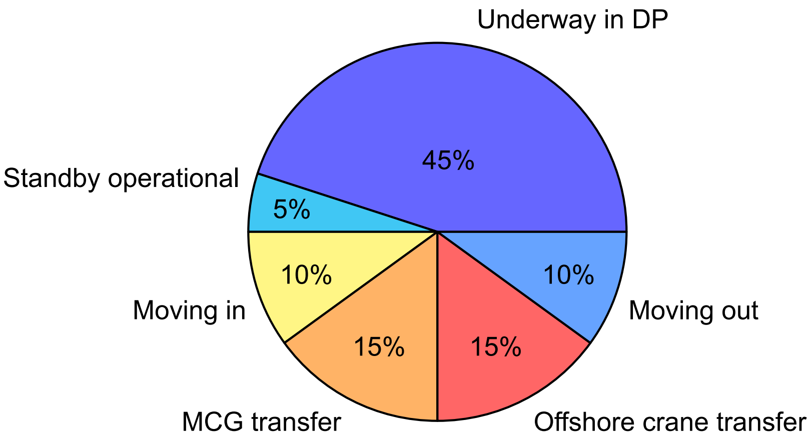
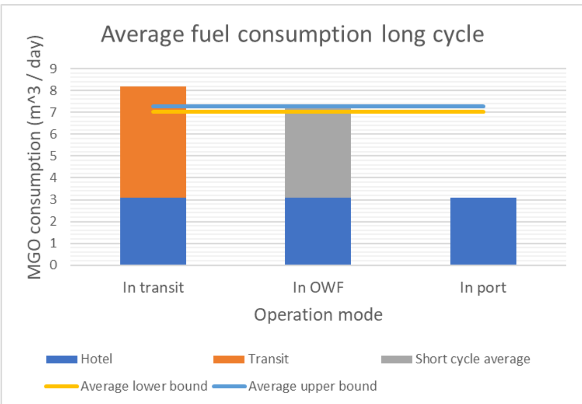
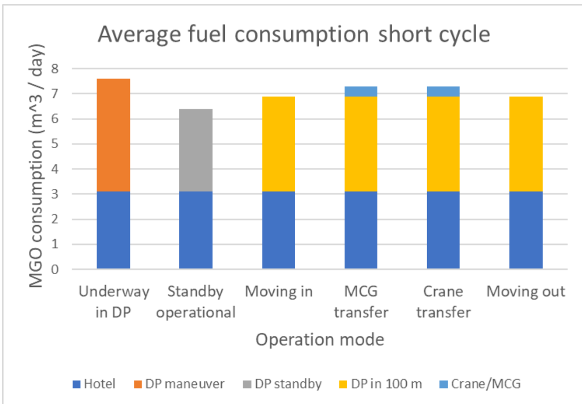


Figure 2.12: Average percentage of each operational mode in short cycle



(a) Average fuel consumption long cycle



(b) Average fuel consumption short cycle

Figure 2.13: Average fuel consumption of purpose built W2W vessels Acta Auriga and Acta Centaurus.

2.7. Technical requirements

The five tasks of the W2W vessel, determined in subsection 2.6.1, relate to the technical requirements for the vessel. In this section, these are discussed.

2.7.1. Propulsion system

The main factors which influence the propulsion system of a W2W vessel according to Staal (2021) and Banen (2021) are (not in order):

1. The maximum speed and acceleration that the vessel needs to achieve during transit.
2. The maximum speed and acceleration the vessel needs to achieve in DP mode.
3. How much power and energy the DP system, the MCG and the offshore crane require and how often the system is in action.
4. In what (weather) conditions the vessel needs to operate.
5. How much cargo needs to be transported for spare wind turbine parts and repair materials.
6. How long the vessel needs to be autonomous.
7. What distance the vessel needs to sail at transit speed.
8. How many persons are on the W2W vessel and what kind of facilities are installed.

These requirements should lead to a propulsion system including energy storage, energy converters, and propellers. Often in offshore vessels with DP, a diesel-electric combination is installed. According to Wärtsilä (n.d.) for offshore vessels, diesel-electric may be selected for flexibility because the vessel has to be efficient under numerous operating conditions. Depending on the energy converter and the chosen energy carrier, the propulsion system may be significantly changing in size and price.

2.7.2. Dynamic Positioning

For W2W vessels, normally the DP system determines the required power. There are three classifications for DP. DP1 has no redundancy. This means that when a single fault occurs, the DP system may fail. For safe transfers, this is not acceptable and therefore DP1 is not used on W2W vessels. DP2 has redundancy for active components. When a system such as the generator, thruster, or switchboard fails, the vessel will remain in its position. This is often done by adding a redundant back-up of this component or system to the vessel. DP3 is even more redundant; the vessel must remain in DP when a compartment is in fire or in flood (Kongsberg, n.d.). In practice, this means that there should be two fully operational engine rooms. In the offshore wind industry, nearly all vessels are required to have DP2 and thus all active components must have a back-up (Legemate, 2021).

2.7.3. Speed

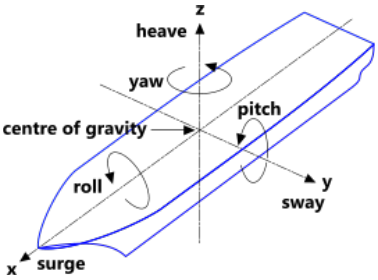
For regular vessels in the transport sector, the transit speed determines the required installed power. For offshore vessels, the propulsion system mainly depends on the DP system. However, transit speed becomes increasingly important since OWFs are located further away and therefore it is required that it is checked whether the maximum speed can be reached with the installed power for the DP system. The required power depends on the resistance which has a square relationship with the vessel speed as can be seen in Equation 2.1 (Klein Woud and Stapersma, 2002). Average transit speed is approximately 10 kts (18.52 km/h), but most W2W vessels have a maximum speed of 12.5 kts (Figure 2.9).

$$R = C_1 * V_s^2 \tag{2.1}$$

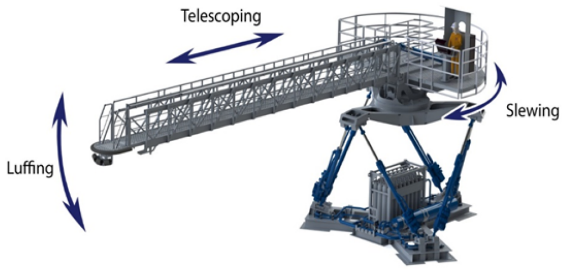
2.7.4. Motion compensated gangway

For transporting personnel and lightweight cargo to the wind turbine, an MCG is used. The MCG compensates the motion of the vessel to create a safe and steady passage to the wind turbine. The motions of a W2W vessel (Figure 2.14a) due to waves, wind, and current, all need to be compensated.

Surge, sway, and yaw are, to a certain precision compensated by the DP system but DP has a margin which is too large to safely transfer technicians to the wind turbine. Therefore, all six motions need to be compensated by the MCG. A 3D MCG uses a system to compensate all six motions by allowing luffing, telescoping, and slewing (Figure 2.14b). Sometimes a 6D MCG is used which uses a hexapod, but this is costlier than a 3D variant and is only necessary in critical operations (de Greef, 2021).



(a) Vessel motions (CalQlata, 2021)



(b) MCG degrees of freedom (Chung, 2016)

Figure 2.14: Vessel and MCG motions.

Allowable significant wave height (Hs) for safe operation of the MCG is an important Key Performance Indicator (KPI) for a client. A high allowable Hs creates longer operational uptime but also needs a more expensive system. A typical required Hs in tender documents is between 2.5m and 3.5m.

'Normal' MCGs which are placed on the deck have limited capacity of changing heights. Luffing capacity is the only way to increase or decrease the landing height. Tender documents show that most clients set a limit of 10 degrees static luffing angle. To allow for smaller luffing angles and easier stepless access, an MCG with a tower elevator (front page for example) creates a height difference by rising the MCG platform. This is now seen as the new standard in the W2W market (Banen, 2021).

2.7.5. Offshore crane

For some tenders, it is required to lift heavy weight cargo on the TP platform or to replace cargo on the vessel. The MCG is often not strong enough for heavy weight cargo and often has limited access to the deck and warehouse due to its length. Therefore, a W2W vessel is often equipped with a motion compensated crane (offshore crane). This offshore crane has two different load capacities: one where the motion control is on (at sea) and one where it is off (in port). Typical values for tender offers are 3-5 tons in MC mode and 20 tons for in-port lifting.

2.7.6. Deck and warehouse

To store all materials used for commissioning or maintaining the wind turbines, free deck space and a warehouse are required. Typically the deck area and warehouse are 500 to 1000 square meters. The deck and warehouse storage are often fully occupied, which means that there is no space in the warehouse or on deck available to store extra energy (Boersma, 2021).

2.7.7. Tanks and storage

The vessels autonomy is important for clients because the longer the vessel can stay at sea, the longer it can operate. For this reason, there needs to be enough of the energy carrier, fresh water, provisions, and medicine on the W2W vessel to ensure that the autonomy is long enough. The size of these storage and tanks influences the W2W vessel design. An autonomy of four weeks is common for W2W vessels. Longer is not necessary because after 28 days, the crew needs to be changed due to regulations. Additionally, longer than 28 days away from the port is not favorable because some repairs can only be done in port and provisions are only fresh for a certain amount of time (Boersma, 2021).

German law requires that crew changes every two weeks and therefore W2W vessels with German crews often return to port every two weeks and this may become a trend (Boersma, 2021). On the other hand, OWFs are moving to locations further from shore (subsection 2.3.6). Therefore, transit time increases and therefore Banen (2021) assumes autonomy will remain at four weeks. Currently, most W2W vessels have enough fuel for approximately 100 days of sailing which is considered way to much. Therefore, the storage tank volume may be optimised.

2.7.8. Accommodation

The amount of POB influences the accommodation size of the vessel. Therefore, it is important to investigate the amount of POB. The vessel crew to operate the vessel is a fixed number, the hotel crew who cleans and cooks is varying depending on the amount of POB, and the amount of project personnel (technicians) depends on the project.

The amount of project personnel depends on the number of technicians that are required per wind turbine and how many wind turbines are visited per day. The maximum amount of wind turbines that can be visited depends on the short cycle time. An average short cycle time of 70 minutes would mean a maximum of 20.6 transfers per day can be done.

W2W vessels typically have between 60 and 120 POB. This means that there is often over capacity on CSOVs. SOVs are often designed for a specific project and therefore the number of cabins is known.

All POB need a bed which can either be in single or double cabins. Additionally, a lot of space is accumulated in other spaces like the galley, mess, gym, changing room, dry room, cinema, offices, and meeting rooms. Depending on the requirements of the clients, the spaces can be according to the Maritime Labour Convention (Organisation, 2020) or need to be bigger and supply more comfort. In recent tenders and according to Banen (2021), it is noticed that clients increasingly require a higher level of comfort. Furthermore, specifically in the offshore wind industry, some clients are asking single cabins for all their technicians (Anink, 2021). This is the norm, but since it requires a lot more space, sometimes persons must share a cabin with bunk beds.

2.7.9. Operational requirements

Among the technical requirements are the operational requirements. As can be seen in Figure 2.11, the operational uptime can differ quite substantially when port time is increased, or transit duration becomes longer due to lower velocities or OWFs farther away. Currently, it is determined that operational uptime must remain above 90% to remain competitive.

Another operational requirement is depending on the ports the W2W vessel may need to visit in its lifetime. Acta Marine research has concluded that a W2W vessel must remain with a 20m width dimension and may not have a larger draught than 5.8m.

2.8. Economical requirements

To be economically feasible, the total costs must be lower than revenue. When the total costs are lower, the competitiveness of competitors increases, which may lead to increasing profits. For this reason, the vessel needs to be built as efficient as possible. The total cost of ownership is split up in Capital Expenses (CAPEX) and Operational Expenses (OPEX).

2.8.1. Capital expenses

According to Martin (2009), CAPEX depends on materials, labour, and overhead. The materials category mainly exists of steel, engine(s) and other major purchases like offshore cranes or MCGs. The big challenge in ship building lays in minimizing the materials while still fulfilling the requirements of the vessel. After the design is optimised, the design will be sent out to shipyards to get an offer. Price competitiveness of a shipyard depends on “material supply, facilities, availability of skilled labour, wage rates, labour productivity, exchange rates, and subsidy” (Martin, 2009). Because material prices are approximately equal for all shipyards, the differences between shipyards are wage rates and labour productivity and quality. However, subsidy, taxes, and exchange rates, which differ per country, can influence the cost heavily and therefore, this is considered essential criteria in the selecting process of a shipyard. The CAPEX of a vessel is thus a big uncertainty and influenced by a lot of factors. At the same time, CAPEX has a great influence on the total costs.

2.8.2. Operational expenses

OPEX are all costs which are incurred by the operation of the vessel. The main cost categories will be discussed below.

Fuel & lubricants

These costs depend on the fuel price and consumption. If the fuel consumption can be decreased, OPEX will decrease. The fuel price mainly depends on the selected fuel and on supply and demand.

Moreover, (excise) taxes are an important factor in the pricing of fuels. The fuel consumption depends on the selected fuel and engine and thus depends on the power demand of the propulsion system, DP2, MCG, offshore crane, and hotel.

Marine crew salaries
The salary of the marine crew depends on the hourly rate of a crew member, on the number of hours worked, and the number of crew members. The hourly rate depends on the country of origin of the crew and the function of a crew member. Clearly, a captain earns more than a deckhand. The number of crew members necessary and how many hours they may work mainly depends on regulations. To decrease marine crew salaries, the hourly rate must decrease and thus it must be looked at which country of origin has beneficial hourly rates.

Lodging food, fresh water, and travel expenses
The height of this cost category depends on the quality of lodging, food, and travel. A better crew requires higher quality than cheaper crew. To decrease these expenses, the quality level must decrease.

Insurances
Hull & Machinery (H&M) and Protection & Indemnity (P&I) insurances depend on the type of vessel, flag, and operational area. The operational area is set by the client, and therefore, a different flag could decrease insurance costs.

Maintenance & repairs (incl. docking)
The costs related to maintenance & repairs depend on the quality of the vessel and how the vessel is handled. When the quality of materials and crew is high, lower maintenance costs are expected, but high-quality materials mean increased CAPEX and high quality crew mean increased salaries.

Depreciation
Depreciation is the ratio between the vessel value when bought compared to the residual value for a certain depreciation period. If the depreciation period is selected too long, it is possible that the vessel is not fully depreciated before it is no longer used. When this period is selected too short, the depreciation cost will become too high.

Internet
Internet speed on the W2W vessel is an increasingly important KPI when a vessel is chosen. This is so important for the client because all logistics are arranged through the internet and the technicians request communication possibilities. Internet is costly at sea and therefore it is often paid for directly by the client.

Other operational expenses
Other costs include port, agent, pilot, customs, channel expenses, communication, and weather report costs, discharging waste oil, bilge and garbage, work permits, and visas. These costs are relatively small and depend on the project. Therefore, it is often paid for by the client but handled by the vessel owner.

2.8.3. Revenue and profit

When the vessel will operate, typically the client will have to pay a vessel day rate (DR) which covers, but is not limited to, the marine crew, insurance, maintenance and repairs and depreciation. On top of the DR, the client pays directly for the other mentioned costs. Therefore, the profit is the DR revenue minus the expenses covered by the DR.

The DR and utilisation rate are great uncertainties in determining the profitability of a W2W vessel. If the DR is very high, but utilisation is very low, not enough income is generated. This also works the other way around (Low DR, high utilisation). The DR and utilisation are depending on the type of vessel, experiences with the vessel and above all supply and demand. It is unknown how a future W2W vessel with zero-emission capabilities would influence the DR an utilisation, but it is expected that these will slightly increase. However, this is a great uncertainty.

2.9. Environmental requirements

As mentioned in the introduction, the climate is changing which is partly caused by vessel emissions. For this reason, regulations are made to limit vessel emissions, but as introduced, these regulations are not applicable to the offshore industry.

However, there are still environmental requirements for the vessel. In Figure 2.15, it is illustrated how the environmental requirements of a vessel are set. First, there are regulations (for offshore vessels). Secondly, there are requirements from the client. For some clients, Acta Marines emissions tie in directly with the sustainability goals of these clients. Third, there is an intrinsic motivation of the vessel owner. Lastly, clients might be bound to emission reductions by regulations, hence there is an indirect effect.

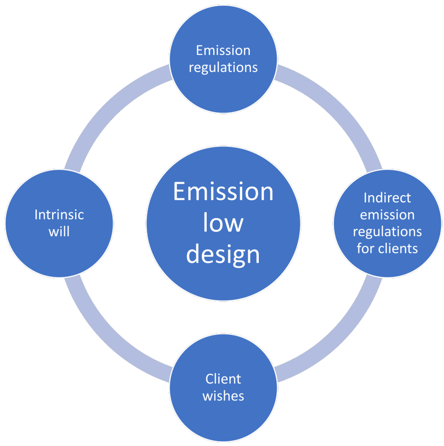


Figure 2.15: Design circle; the four factors which determine an emission low design.

2.9.1. Client environmental key performance indicators

To select the best tender, a client often uses KPIs. These KPIs always depend on technical and economical requirements. The winner of the tender is the cheapest offer who can deliver all technical requirements. Sometimes, experience is also a factor which weighs in when the winner is selected because the client can be more confident that the tender will be executed with good quality in the set time.

According to Banen (2021), environmental requirements are starting to play a role when a tender offer is selected. Recent tenders contain a section on sustainability to create the possibility to select on this. According to Legemate (2021), the tender winner does not always need to meet the environmental requirements because the economical requirements are still key. However, the fact that there is a sustainable section in tender offers means that clients are thinking on this and when a vessel is designed to create work in a more sustainable way, this could mean a step ahead of competitors. According to Sidze and Miksx (2021), Vestas selects tender offers based on these environmental requirements.

Until now, most companies have publicly stated goals to decrease their carbon footprint. However, most companies will only decrease their direct or scope 1 emissions. Scope 1 contains the emissions that are directly emitted by the company, such as the emission of company vehicles and factories. Scope 2 contains all emissions released by the emission of purchased electricity, steam, heat, and cooling (Bernoville, 2020). Scope 3 contains all indirect emissions not contained in scope 2. There are 15 categories of scope 3 emissions, but the most important scope 3 for this research is 'Transportation and distribution' (Bernoville, 2020). All W2W emissions are scope 2 and/or scope 3 emissions for the tender owner. Therefore, if a tender owner wants to decrease its full carbon footprint, W2W vessels must decrease its emissions.

Vestas, which represented 23.9% of all OWF capacity in Europe in 2020, has called on the supply chain of OWFs to start actively working on a carbon neutral supply chain (Legemate, 2021). This is a clear sign that the company starts acknowledging the fact that it needs to do something in fighting climate change and might be willing to pay more to achieve low carbon footprint through scope 2 and 3. Siemens (68%) is less spoken out than Vestas to date, but did state that they are looking at suppliers to ensure sustainability in the supply chain (Siemens Gamesa Renewable Energy, S.A., 2020). This means that the companies which represent 92% of the market set their course to achieve sustainability in the supply chain. This is considered a strong signal to change the design of future W2W vessels to be more sustainable.

2.10. Chapter conclusion

In this chapter, the following subquestions were investigated:

1. "*What are the trends in the offshore wind industry, who are the influential stakeholders, and how do they influence the future proof design of W2W vessels?*"
2. "*What is the state-of-the-art in W2W vessels and what are their current and future effectiveness requirements?*"

Multiple stakeholders were identified with different levels of interest and power (Figure 2.2). A few conflicts were found with one main conflict involving W2W vessel owners: High power, low interest maritime shipping companies may influence the maritime energy market to direct to an energy carrier which is not suitable for W2W vessels due to a different operational profile. Furthermore, a conflict between low emissions, high profit, and lacking regulations is identified for the OWF owner, the wind turbine supplier, and the W2W vessel owners.

Multiple trends and their influence on the future proof design of W2W vessels have been identified:

- The offshore wind sector will continue to grow for at least a decade while the number of new installations per year will almost quadruple. Therefore, more W2W vessels are required.
- Offshore wind turbines have life cycle GHG emissions which are approximately 120% more compared to onshore wind turbines due to all vessels that are required for building the wind turbines. Therefore, decreasing emissions on all vessels makes OWFs even greener.
- Typically, no more than 60 technicians are based on SOVs, where between 60 and 120 technicians are expected at an average CSOV. This number is not expected to grow and therefore no design changes are required here.
- OWFs will move further offshore, which makes the transit time longer and requires more energy.
- The size of OWFs will increase, which increases the short cycle time. Therefore, 24/7 operations are expected to remain necessary.
- In European waters, the North Sea will remain the dominant building place with still 75% of all new building projects in 2030. Therefore, the W2W vessel will be designed for this operational area. This means the W2W vessel will operate in an area with a lot of development and investments in alternative energy carriers, which is a large advantage.

The state-of-the-art in W2W vessels is identified as two vessels on order which can run for six hours on battery and solar power. It is also identified that there is thus a long way to go to zero-emission W2W vessels. Currently, their effectiveness is ranked based on the identified technical, economical, and environmental requirements. Technically, the W2W vessel must remain effective in transferring technicians and cargo safely to a wind turbine and back. Therefore, the mission and vessel equipment must adapt accordingly to the trends seen in the OWF industry. Economically, it is expected that the margins will increase slightly due to a shortage of W2W vessels and thus now is the moment to invest in (more expensive) alternative energy carrier systems. Environmentally, it is presented that clients are openly stating their personal emission reducing targets including their scope 3 emissions (W2W vessels). However, no KPIs are set in tenders yet. This is expected soon.

3
Alternative energy carriers

In this chapter, the third sub-question is investigated:

3. "*What is the state-of-the-art in potential alternative energy carriers, what are their important properties and what is their relevance for W2W vessels?*"

In this chapter, in section 3.1, the regulations on emissions are investigated which are applicable to W2W vessels. In section 3.2, energy converters are discussed, which are used to transmit the energy carrier to electrical or mechanical energy. Lastly, sections 3.3, 3.4, and 3.5 discuss alternative energy carriers and their technical, economical, environmental, and social characteristics.

3.1. Regulations

The IMO has set their ambition to reduce CO_2 with 40% by 2030 and 70% by 2050 with 2008 as reference year. Furthermore, it has the ambition to reduce total GHG emissions by 50% in 2050. IMO has adapted three measures to decrease CO_2 emissions: The Energy Efficiency Design Index (EEDI), the Ship Energy Efficiency Management Plan (SEEMP), and the Energy Efficiency Operational Indicator (EEOI) (IMO, n.d.-b) (IMO, 2009a). There are also regulations in place to decrease NO_x and SO_x. However, since these are not GHG, these are left out of scope in this research. It could be, that the solution to decrease CO_2 also decreases NO_x and SO_x, but this is not investigated.

EEDI limits the number of emissions per amount of transport work. It is mandatory for most new vessels and accounts for 72% of emissions from the new-build fleet (ICCT, 2011) and therefore accounts for a large part of the emissions of the maritime sector. However, the EEDI does not apply to offshore vessels.

The goal of the SEEMP is to improve the energy efficiency of a vessel cost-effectively. This management plan is different for each vessel and may contain whatever the vessel owner wants. By making SEEMP a requirement for all merchant vessels, the IMO wants to ensure that every vessel owner considers new technologies and practises to improve efficiency (IMO, n.d.-a). Although the SEEMP is required for offshore vessels, it does not impose direct emission caps.

The voluntary EEOI provides an example of a calculation method for the efficiency of a vessel's operation. This efficiency is expressed in CO_2 emissions per unit of transport work and indicates a performance-based approach to monitor efficiency. This efficiency depends on the distance travelled and transport work and is only applicable to the same category of vessels as EEDI (not offshore) (IMO, 2009a).

The relatively slow progress of IMO has prompted the EU to develop their own regulations, although it has the opinion that a global approach would be more beneficial. The regulations include monitoring, reporting, and verification (MRV) (European Commission, 2013). However, if a vessel does not transport cargo or passengers for commercial purposes, it is not subject to MRV and therefore all offshore vessels are excluded (Dufour, 2017).

Secondly, the European Commission (EC) has introduced the European Trading System (ETS). Companies receive or buy CO_2 allowances and because the total amount of CO_2 allowances is capped, companies either emit less or pay more. Since the cap is decreasing every year, companies are forced to reduce their emissions (European Commission, n.d.-a). The maritime sector has been excluded from the ETS until now to prevent interference with the IMO regulations (The Maritime Executive, 2017).

The proposed new set of regulations in the ’fit for 55’ package includes the maritime sector in ETS, but leaves offshore exempt (Lurkin et al., 2021).

The ’fit for 55’ package, proposed in July 2021, is in review and can take up to 2 years to be implemented (European Commission, 2021) (Evans and Gabbattis, 2021). With this package, the EC targets a 55% net reduction of all GHG emissions in 2030. Along with gradually including the maritime and aviation sector in ETS, it brings fuel EU Maritime, a revision of the taxation directive, and a lot more initiatives which do not influence the maritime sector directly. The ’fuel EU Maritime’ initiative aims to increase the use of sustainable alternative energy carriers with fuel standard reduction targets (Lurkin et al., 2021).

A revision of the taxation directive must end the tax exemption on fossil bunkering and will impose taxation based on energy amounts instead of volume. Furthermore, it should lower taxes for greener energy carriers (Lurkin et al., 2021). Although these regulations show the incentive of the EU to reduce emissions, offshore vessels are still left exempt (Saul and Abnett, 2021). In contrast, although offshore is and will remain exempt in the near future, there are already rumours that the next package of regulations might impose regulations on the maritime offshore industry as well (Anink, 2021). Because of this great uncertainty when a policy will be introduced, a vessel owner must make predictions on when to act.

Even with the IMO measures in place, CO_2 emissions are expected to rise without innovative measures, alternative energy carriers, and new technologies. Although there are regulations in place for the maritime sector, the offshore sector is not imposed with useful CO_2 emission regulations and therefore CO_2 emission reductions need to be stimulated by a different source.

3.2. Energy converters

The Internal Combustion Engine (ICE) is the most dominant technology to transmit chemical energy to mechanical energy in the maritime market today (DNV, 2020). The ICE is known to run on diesel and must therefore be changed to run on alternative carbon low energy carriers to remain the dominant technology. Besides the proven ICE technology, a second technology is worth investigating: the Fuel Cell (FC), which uses chemical reactions to convert an energy carrier into electrical energy.

3.2.1. Internal combustion engine

Currently, most ICEs run on diesel. Diesel engines are highly developed, power output ranges from 500 to 80.000 kW, shaft speeds run from 80 to 3.500 rpm, and efficiencies are between 35% and 60% (Streng, 2021). The diesel engine is characterised by its high reliability and it in-sensitiveness for energy carrier quality. Disadvantages include low power density, high specific emissions, and low acceleration (Klein Woud and Stapersma, 2002). Power densities for modern diesel engines are in the range from 45 to 71 W/kg and 32 to 55 W/L (van Biert et al., 2016).

Although the ICE needs to be developed to be able to burn alternative energy carriers, the big engine makers believe this is possible soon. Therefore, it could be possible that the ICE remains the dominant technology for the next 20 to 30 years (DNV, 2020).

Liquefied Natural Gas (LNG) and Liquefied Propane Gas (LPG) engines are available and already used today, methanol engines are on order but not yet fully developed (MAN Energy Solutions, 2021a), and ammonia engines are expected to be ready for installation in 2024 (MAN Energy Solutions, 2021b). Lastly, MAN is planning on having a hydrogen-powered engine ready in 2030 (MAN Energy Solutions, n.d.). There are also smaller players who claim to bring hydrogen-powered combustion engines to the market by 2025 but this is considered not reliable enough (Prevljak, 2021) (ABC, 2020).

3.2.2. Fuel cell

An FC converts the energy from an energy carrier into electrical energy through an electrochemical reaction. FCs have high efficiencies, low noise, and low vibrations (DNV GL, 2019a). There are two types of promising FCs for maritime use (DNV GL, 2017). A Solid Oxide Fuel Cell (SOFC) and a Polymer Electrolyte Membrane Fuel Cell (PEMFC). The basic working of a hydrogen FC can be seen in a schematic diagram in Figure 3.1. FCs need hydrogen-rich energy carriers and therefore fuel reformers are often needed.

SOFCs are relatively expensive and have high temperatures ranging between 500°C and 1000°C (Xing et al., 2021). Because of this high temperature, no fuel reforming needs to be done externally

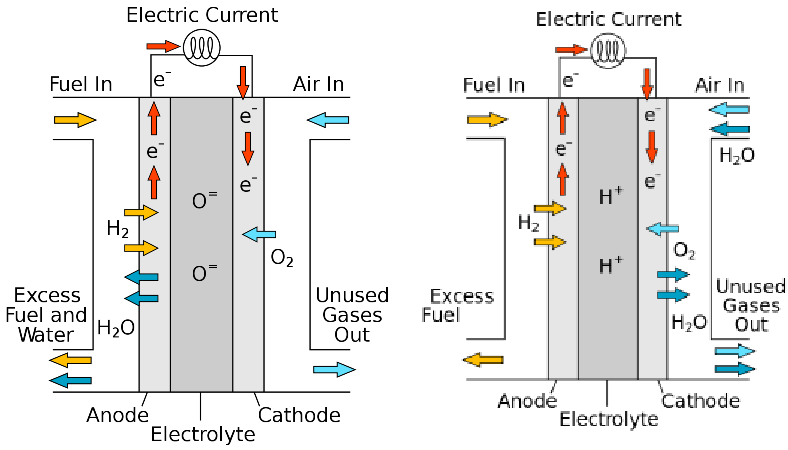


Figure 3.1: Basic schematic diagram of a hydrogen fuel cell (Sakurambo, 2007).

because the temperature reforms the energy carriers already. Due to heat recovery, the theoretical efficiency can be up to 85% (DNV GL, 2017) but due to the same heat the SOFC has a long start-up time and safety hazards need to be addressed.

A High Temperature (HT) PEMFC uses a mineral acid electrolyte and can reach temperatures up to 200°C (Xing et al., 2021). Because of the high temperature, there is little platinum poisoning, which means no fuel reformer is needed.

A Low Temperature (LT) PEMFC uses a water-based polymer membrane and can therefore not operate at high temperatures (60°C to 85°C (Xing et al., 2021)). A LT PEMFC needs a platinum catalyst which adds cost. However, the low operating temperature allows for flexible and safe operation and quick start-up time (Xing et al., 2021). LT PEMFCs have the most maturity because the automotive industry has investigated this technology for years and is therefore expected to be the only feasible technology for vessels on the short term (Bethoux, 2020). If pure hydrogen is not chosen as an energy carrier, a fuel reformer is necessary to purify a different energy carrier to attain pure hydrogen. The efficiency is moderate, around 60%. Fuel reformer efficiency for both methanol and ammonia is approximately 70% (Y. Wang et al., 2020)(Alagharu et al., 2010), which leads to a system efficiency of 42%.

The maximum output of a LT PEMFC is only a few MW, which would be enough for W2W vessels. A single FC stack is available in 200 kW (Ballard, n.d.) to 400 kW (TECO 2030, 2020) which can be combined to attain bigger FCs. An FC has no primary mechanical moving parts, which makes it relatively reliable (Xing et al., 2021). However, the electrolyte, electrode and bipolar plate are degrading (de Bruijn et al., 2008) (Hawkes et al., 2009) causing the expected lifetime not to exceed 40.000 hours (Office of Energy Efficiency & Renewable Energy, n.d.). Start-up times of PEMFCs are only seconds, which is a good property to offset sudden changes in the required load due to external events.

Costs for an FC system are expected to cost €2000/kW (TNO, 2020) but are expected to decrease due to increasing development and scale-up. Additional cost comes from the short, expected lifetime. 40.000 running hours does not come close to the 20-30 years that a conventional diesel engine runs (Xing et al., 2021). Replacement will add high additional investment costs.

3.3. Pre-selection of alternative energy carriers

A pre-selection is performed based on a Technology Readiness Level (TRL) and on investigations on the energy carriers that fulfill the TRL. The TRL is used to ensure that no underdeveloped technologies are investigated which have no potential to reduce emissions soon. The TRL used in this research is the TRL scale used by the International Energy Agency (IEA) and can be seen in Figure 3.2. Often, a TRL scale of 1 to 9 (instead of 1 to 11) is applied by NASA and EU (NASA, n.d.) (European Commission, 2014) but the TRL of the IEA is specially designed for energy and therefore used in this research. In this research, a presumed TRL of 5 of higher is required to be considered. For example, metal hydrogen or hydrogen peroxide powders are therefore not considered as alternative energy carriers.

The fuels considered in this research, with a TRL of 5 or higher, are *LNG*, *LPG*, *Biofuels (Hydrotreated Vegetable Oil (HVO))*, *compressed hydrogen (H2c)*, *cryogenic liquid hydrogen (H2l)*, *Liquid Organic Hydrogen Carriers (LOHC)*, *methanol*, *ammonia*, *batteries* and *nuclear*. Preliminary investigation to these fuels have been performed to make a smaller selection of alternative energy carriers that are actually suitable for zero-emission W2W vessels.

It is decided that LNG and LPG will both not be selected as alternative energy carrier in this research because their emission reduction of 20.3% and 16.5% are deemed too small (CE Delft, 2011) (Brinks and Hektor, 2020).

Currently, there is little infrastructure (expected) for producing LOHC. Therefore, using LOHC is not possible right now and probably not in the near future either. Right now, LOHC is investigated to transport hydrogen using existing crude oil tankers instead of it being used as a maritime energy carrier (Hydrogenious Technologies, 2018). Therefore, LOHC is not further considered in this research.

Nuclear energy is also not selected as alternative energy carrier because the social perspective is deemed to be too bad due due to a few very big disasters at nuclear power plants, including the Fukushima Daiichi nuclear disaster (2011) and the Chernobyl disaster (1986) (TIME.com, 2009). Next to the low social acceptance of nuclear energy, there are more problems. Nuclear power has radioactive waste disposal which is very harmful for the environment if not stored well. Moreover, accidental release of radioactivity could be very harmful for the ones who are subjected to this and being too close to a reactor is dangerous.

More elaboration on LNG, LPG, LOHC and nuclear energy including their positive characteristics can be found in Appendix B.

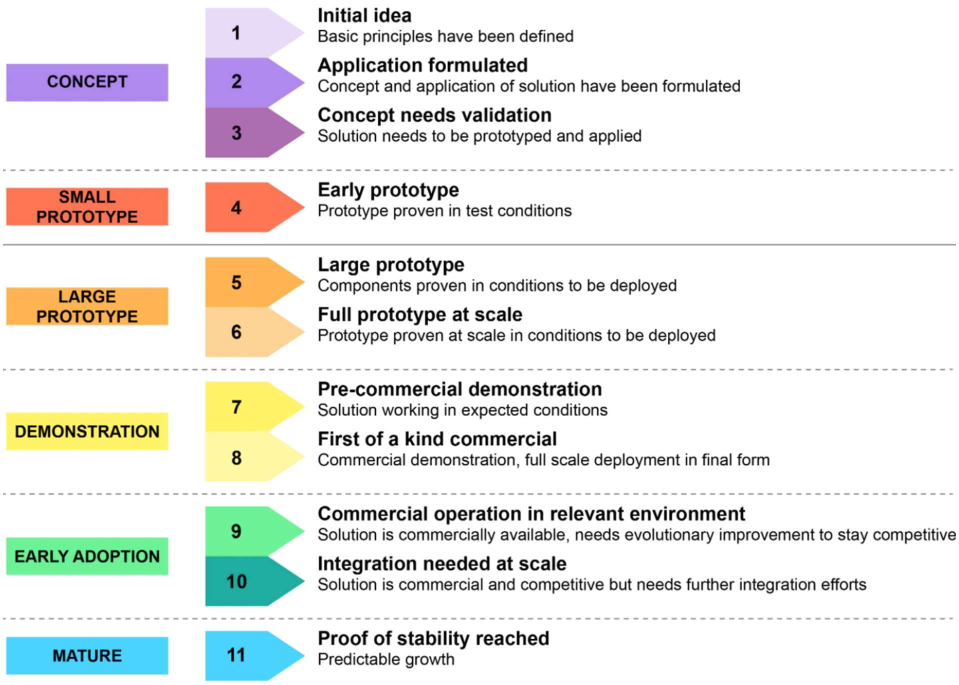


Figure 3.2: Technology readiness level scale applied by IEA (2020)

3.4. Energy carrier characteristics

In this section, the important characteristics will be discussed. Both technical, economical, environmental, and social characteristics are examined.

3.4.1. Well-to-wake emissions

When aiming for low emission vessel operations, it is important to understand that there are upstream or well-to-tank (WTT) and downstream or tank-to-wake (TTW) emissions (Comer and Osipova, 2021). WTT emissions are all emissions which occur during the production, processing, and delivery of an energy carrier. TTW emissions are all emissions that occur when the energy from the energy carrier is used. Together, WTT and TTW emissions form the total emissions or well-to-wake (WTW) emissions. The life cycle of a marine energy carrier from well-to-wake is depicted in Figure 3.3. For a fair comparison between different energy carriers, it is important to compare WTW emissions. Data on WTW emissions are not widely available for all alternative energy carriers. This is due to the various techniques used to determine the WTT emissions and the influence of the energy converter and its efficiency on the TTW emissions. Moreover, it depends on the location where it is produced because different techniques to produce and process are used and most importantly the transport emissions differ. For this reason, the values named in this research are the best average estimates currently available in literature. Real emissions will vary from this.

When alternative energy carriers are discussed, some energy carriers are determined to have the potential to be zero-emission. The potential to be zero-emission means that an alternative energy carrier with zero-emission in the TTW phase is zero-emission only if emissions in the WTT phase are also decreased to zero. This means that also zero-emission energy carriers must be used to extract, produce, process, and transport.

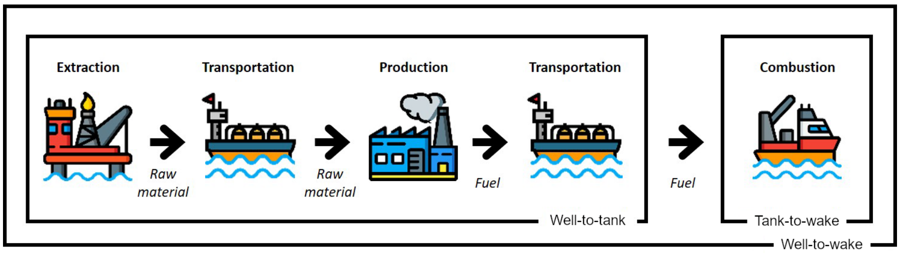


Figure 3.3: Lifecycle of a marine energy carrier from well to wake (Rozendaal, 2021)

3.4.2. Costs

Although economics are not the only thing to worry about, eventually choosing a different energy carrier will come down to financial possibilities. Therefore, the energy carrier price is essential information. Although this price is often not yet known, third parties have estimates which can be used during the selection process. The price uncertainty will impose uncertainty to the hole financial part of this project. Although price can be estimated, it not known. The methodology should incorporate this.

When prices are found in dollars, the average exchange rate from January 2018 until November 2021 of 1 EUR = 1.16 USD is used to determine the price in euros (marcotrends.net, 2021).

Moreover, it is important to look at the full price. A lot of (international) governments are looking into, or already have introduced, a carbon tax (CT) system. This will increase the price of every energy carrier which still emits carbon.

3.4.3. Energy density

From a more technical aspect, it is essential to look at the energy density or how much energy is stored in how much weight or volume. Some of the alternative energy carriers require pressurised storage, which makes it required to have a tank with a substantial size on the vessel. For this reason, energy density including storage is more interesting than energy density alone. In Figure 3.4, a comparison in energy density for multiple alternative energy carriers can be seen. In this figure, the arrows indicate the energy density including storage. It can be seen that most alternative energy carriers have a higher contained energy density than conventional diesel fuels.

3.4.4. Availability (in ports)

It is important that enough of the selected energy carrier is available in the ports that the vessel will use. If there is not enough available in port, the vessel cannot be used. According to Egbertsen (2021), in Europe, the availability of different energy carriers is usually bigger than in the rest of the world, which makes it easier to switch. For a SOV with a O&M contract, the availability choice might be easier because during the contract, the SOV will have the same base port. In case a port does not have the infrastructure in place, it could be arranged that the necessary energy carrier comes to the port every time the vessel makes a port call. For CSOVs, the port may be changing every few months, meaning

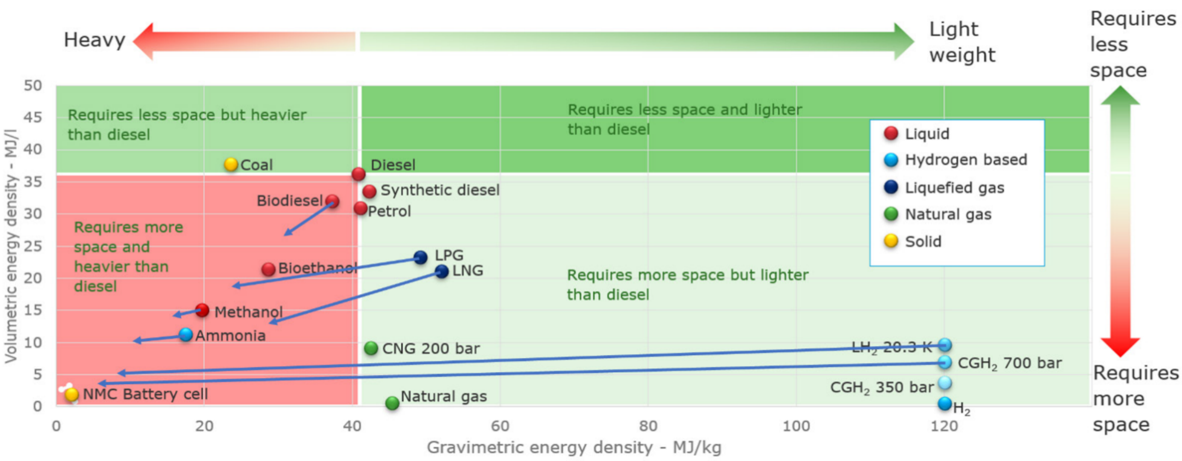


Figure 3.4: Volumetric and gravimetric energy density. Arrows indicate contained density (DNV GL, 2019b)

that the availability scale of a specific energy carrier in ports in European waters must be bigger. If there is not enough availability of an energy carrier, trucks must come to the port to bunker the W2W vessel. The high uncertainty on future availability of alternative energy carriers again adds uncertainty to this research.

3.4.5. Bunkering efficiency

Along with the availability of the energy carrier in the port, the efficiency of bunkering (flow rate) is essential information. Lower energy density might mean that more of the energy carrier needs to be bunkered which takes longer. Moreover, some energy carriers might be less easy to handle because they are not in fluid form or because there are big safety risks concerned with bunkering. This all could take extra time which means downtime in performing the actual job of the vessel.

3.4.6. Safety (spillage)

To select a different energy carrier, it is essential to understand the safety risks. Alternative energy carriers could be flammable, toxic when in contact, toxic when breathing damps, explosive, or else. Some of these safety hazards can be handled easier than others and therefore the effects of these safety hazards need to be examined. Some safety issues may be solved with extra crew training, or with extra safe tanks or with double walled pipes through the hole vessel. Safety issues are often addressed in regulations.

3.4.7. Regulations

For some alternative energy carriers, there is no regulation yet. This makes it a risk to invest in this energy carrier because it could be possible that the vessel will not fulfil to regulations when these will act into force. In contrast, the vessel could become too expensive because too strong demands have been met when designing for the new energy carrier. This problem is partially solved because classification bureaus already have classification in place for most new energy carriers (Eknes, 2021). When a classification bureau already has the classification in place, they think this classification will meet the regulations and therefore this decreases the risk.

3.4.8. Crew qualifications

As already introduced in subsection 3.4.6 and subsection 3.4.7, some alternative energy carriers might need additional training for crew. However, it could well be that this energy carrier also influences the crew size and qualifications because the energy carrier requires maintenance. More or higher qualified crew leads to higher crew expenses and optional extra space required on the vessel (living space).

3.4.9. Social perspective

If the social perspective on an alternative energy carrier is bad, it could be that the image of the company is affected by switching to this energy carrier. Furthermore, this could lead to clients not selecting the company anymore or at least not selecting the specific vessel anymore. Another result of a bad social perspective is that ports or even governments could say that the vessel is not welcome.

3.5. Alternative energy carriers

The pre-selected alternative energy carriers are discussed one by one in this section.

3.5.1. Diesel fuels (Benchmark)

Marine vessels use a variety of diesel fuels to create the required energy on the W2W vessel. Fuels include Heavy Fuel Oil (HFO), MDO, and MGO. Moreover, low sulphur variants exist including LSMGO (max 0.1%), Very Low Sulphur Fuel Oil (VLSFO) (max 0.5%) and Ultra Low Sulphur Fuel Oil (ULSFO) (max 0.1%).

HFO is currently most used in the maritime industry (Fritt-Rasmussen et al., 2018). HFO consists of a wide range of marine residual fuels and some distillate fuels (DNV, 2011). Distillates are components of crude oil which are evaporated and then condensed back into a liquid. HFO is characterised by its high viscosity and high sulphur content. Due to this high viscosity, HFO must be preheated before burning and due to its high sulphur content, HFO can only be used in combination with scrubbers since there is a sulphur cap.

MDO is a blend of distillates and HFO, but with very low HFO content so that it does not have to be heated during storage (Marquard & Bahls, 2015a). MGO consists only of distillates and therefore has an even lower viscosity. Therefore, MGO does not need to be heated during storage or to be preheated before pumped into the engine (Marquard & Bahls, 2015b). In 2021, the most used fuel by the W2W vessels of Acta Marine was LSMGO (Legemate, 2021) and therefore this fuel is chosen as a benchmark fuel. The density of LSMGO is 0.86 kg/l (Legemate, 2021) and the volumetric energy density is estimated to be 36.7 GJ/m^3 or 42.7 GJ/t.

WTW emissions

Since there is no life cycle assessment available for LSMGO, the WTW CO_2 emissions of MGO are considered. The WTW CO_2 emissions of MGO are 87.1 kg CO_2/GJ (Pavlenko et al., 2020). Furthermore, it is known that LSMGO has max 0.1% sulphur per regulation.

Cost

The cost of diesel fuels is varying over time depending mostly on the oil price. For reference, Appendix C shows the price developments of HFO (IFO-380), MGO, LSMGO, VLSFO, and ULSFO from November 2018 to November 2021. The average price and variability for LSMGO (498$ / ton or 10.05 €/GJ [1]) is very similar to MGO and to ULSFO and will be used as today price in this research. An ICE running on LSMGO costs approximately 636 €/kW according to TNO (2020) and according to TNO (2020), the tank storage system costs approximately 27 €/GJ.

Bunkering, regulations, and social perspective

The availability in ports and the bunkering efficiency of LSMGO is very high because of the years of experience with using diesel oil. The flash point is 66°C and LSMGO is therefore not considered a low-flash point fuel. Regular crew is trained for the use of diesel fuel in combination with an ICE and regulations are around for years. Emission regulations are expected to become stricter in the future. A risk of continuing to use LSMGO is that the regulations might become too strict to continue sailing with the vessel. Additionally, the social perspective of diesel fuels is bad. Because it is difficult to understand the differences between marine diesel fuels, the general perspective is that all marine diesel fuels are bad for the environment. Therefore, using a fuel with a different name would be more accepted in comparison with any marine diesel fuel.

[1] On March 29, 2022, the LSMGO price has risen to 1362 $ / ton or 27.50 €/GJ (Ship & Bunker, 2021). This is more than 2.5 times higher and is caused by the Ukraine war (Islam, 2022). Because it is uncertain whether this price will drop back to original levels or remains at the higher reached levels, the average price of 10.05 €/GJ is used in this research.

3.5.2. Hydrotreated Vegetable Oil

A biofuel is an energy carrier produced from biomass. According to DNV GL (2019a), HVO is one of the most promising biofuels and is therefore investigated. HVO is suitable as drop-in fuel and in principle compatible with existing infrastructure and engine systems. This makes it very promising as alternative. The energy density of HVO is 43.7 GJ/m^3 or 47.2 GJ/t and is therefore more energy dense than LSMGO. There are no known safety issues, extra regulations, or extra crew qualifications for biofuels.

Emissions of HVO

Emission reductions vary enormously depending on the feedstock and production process. HVO has a WTW CO_2 emission reduction of approximately 60% and NO_x reduction of 10% compared to LSMGO (DNV GL, 2019a). Furthermore, HVO has very low levels of SO_x emissions compared to LSMGO (DNV GL, 2019a).

Costs of HVO

Average HVO prices are currently higher than LSMGO, while the market knows very big price and availability differences between regions. European prices averaged 1388.5 $/t or 25.36 €/GJ between August and November 2020 (S&P Global Platts, 2020). When production grows, the price is expected to decrease, as is the same with other alternative energy carriers. CAPEX and OPEX costs are expected to remain approximately the same as for LSMGO. CAPEX for the ICE and energy storage are estimated to remain equal to LSMGO. OPEX is expected to increase slightly due to monitoring of the propulsion system. A risk associated with HVO is that the energy carrier is subsidised to promote its use. When HVO will no longer be subsidised, the price will increase. This makes HVO an uncertain choice for a long-term strategy.

Bunkering of HVO

There is practically no infrastructure for HVO bunkering to date. However, with small modifications, regular HFO bunker systems can be used as HVO bunker suppliers. HVO is available in very few ports, but truck bunkering is already possible. Global HVO production capacity is expected to keep growing rapidly, but European production capacity in Europe is expected to remain approximately constant due to feedstock limitations. Global HVO production capacity can be seen in Figure 3.5.

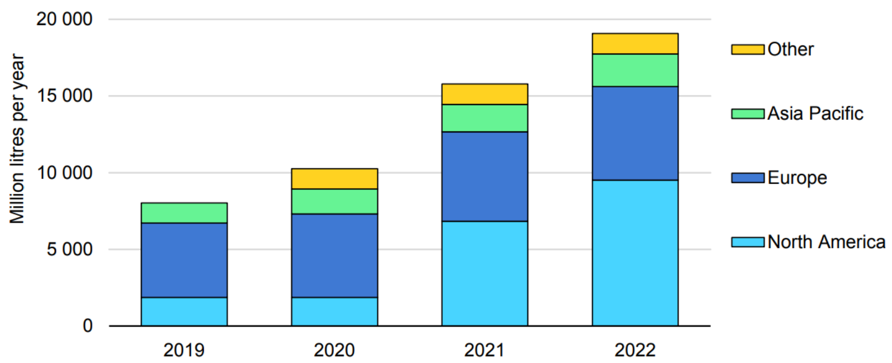


Figure 3.5: Global HVO production capacity based on planned capacity expansions, conversions, and new builds (IEA, 2021)

Social perspective of HVO

The social perspective of biofuels and thus HVO is considered neutral. This is because a lot of articles have been written on the alleged negative impacts of biofuels, including increasing food prices or land-grab by plantation developers (van der Horst and Vermeylen, 2011). On the other hand, academics promote biofuels as a green and great alternative to marine diesel (TU Delft, n.d.).

HVO conclusion

HVO has the potential to bring a CO_2 reduction of 60% or even higher compared to LSMGO. It is not a zero-emission energy carrier and can therefore be used as an intermediate energy carrier before the design of W2W vessels can become zero-emission. In addition, the production capacity will never be enough to serve the complete maritime sector. Although it is more expensive, it is a great blend-in fuel to reduce emissions without expensive modifications to the current fleet. Lastly, because HVO is subsidised, the energy carrier will most likely only be applicable for a short period.

3.5.3. Hydrogen

Hydrogen, or H_2, is one of the energy carriers that is considered to achieve zero carbon emissions. As can be seen in the chemical formula, hydrogen does not contain carbon. Hydrogen can be stored both as a compressed gas (H2c) or as a cryogenic liquid (H2l). According to DNV (2021b), hydrogen is the smallest of all molecules, has a wide flammability range, ignites easily, and may self-ignite. These characteristics make sure that a safe design is required and multiple storage methods are considered with their own advantages and disadvantages.

Production of hydrogen

TTW emissions of hydrogen are zero, but WTT emissions are not per definition zero. This depends on how pure hydrogen is produced. One way of producing hydrogen is through Steam Methane Reforming (SMR). When SMR is applied, high pressure steam (H_2O) reacts with natural gas (CH_4) which results in pure grey hydrogen and CO_2. Currently, almost all produced hydrogen in the world is grey hydrogen (TNO, n.d.).

Blue hydrogen is produced in the same way as grey hydrogen with one difference. After SMR is applied, CO_2 is largely captured and stored, called Carbon Capture and Storage (CCS). Storage places could, for example, be empty gas fields.

Electrolysis splits water (H_2O) into pure green hydrogen and oxygen. If electrolysis is powered by renewable energy (wind or solar), no CO_2 is emitted during this process. However, the generation of wind or solar energy has indirect emissions, which are partly caused by the emissions of W2W vessels. Therefore, green hydrogen is almost zero-emission [2]. CO_2 WTT emissions and thus (WTW) are approximately 9-12 kg CO_2 per kg grey hydrogen, 1-4 kg CO_2 per kg blue hydrogen, and 0-0.6 kg CO_2 per kg green hydrogen (Mérida, n.d.).

Cryogenic liquid or compressed hydrogen

To store hydrogen as a liquid, it needs to be cooled down to -253°C and be compressed to a slight overpressure of between 1 and 10 bar (DNV, 2021b). At -252.87°C and 1.013 bar, H2l has a density of close to 71 kg/m^3 (Air Liquide, n.d.). To store hydrogen as a gas, it needs to be compressed to 250 to 700 bar (DNV, 2021b). At 700 bar, H2c has a density of 42 kg/m^3 (Air Liquide, n.d.).

Energy density of hydrogen

Hydrogen has an energy density of approximately 120 MJ/kg (Molloy, 2019). This means 5.04 GJ/m^3 for H2c at 700 bar or 8.52 GJ/m^3 for H2l. When stored in the required tanks, it can be seen in Figure 3.4 that H2c has an energy density including storage of approximately 5.5 MJ/kg and 4 MJ/l and H2l approximately 8.5 MJ/kg and 5 MJ/l.

Cost of hydrogen

Estimated costs for grey hydrogen are 1.5€/kg (12.50 €/GJ), depending on the price of natural gas and disregarding the cost of CO_2 (European Commission, 2020). Blue hydrogen is estimated to cost 2€/kg (16.67 €/GJ) and green hydrogen is estimated to cost between 2.5€/kg and 5.5 €/kg, averaging 33.33 €/GJ (European Commission, 2020). Costs for green hydrogen are decreasing rapidly because electrolyser costs have been reduced by 60% in the last 10 years and are estimated to reduce by 50% again by 2030. In regions with cheap renewable energy, green hydrogen is therefore expected to be compatible with grey methanol by 2030 (European Commission, 2020). According to IRENA (2020a), the price of green hydrogen can be reduced to 1 $/kg (7.18 €/GJ) by 2050 if mainly electrolysers and renewable electricity cost decrease (Figure 3.6).

An FC running on hydrogen costs approximately 2000 €/kW and the tank storage system costs approximately 1180 €/GJ according to TNO (2020).

[2] Note that hydrogen in itself is an indirect GHG with 6 to 12 times the effect of CO_2 due to its contribution to the greenhouse effect by increasing the amounts of other gases such as methane, ozone, and water vapor (Warwick et al., 2022). Hydrogen slip will become an important topic in the future (Anink, 2021)

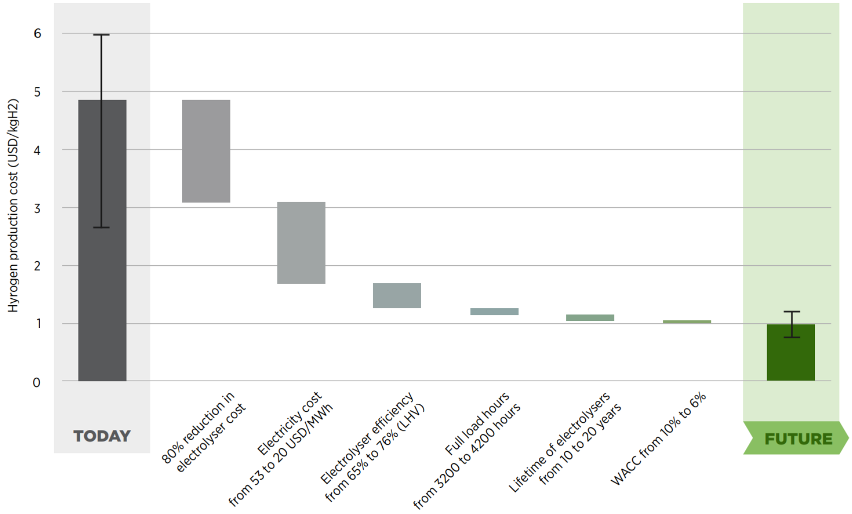


Figure 3.6: A combination of cost reductions can deliver 80% reduction in hydrogen cost (IRENA, 2020a)

Bunkering of hydrogen

Grey hydrogen is currently available all over the world, but no infrastructure and bunkering facilities are in place in port (DNV GL, 2019b). Production of green hydrogen is still very limited but is increasing with Europe being the area with the highest density of hydrogen projects. For reference, a map with all current green hydrogen projects can be seen in Appendix D.

Since hydrogen can be produced directly from electrolysis, green hydrogen could be produced in a port if enough renewable electricity is available. When produced in a port, no long-distance transport of hydrogen would be needed, decreasing the cost and footprint.

Bunkering efficiency of hydrogen depends on its form. When compressed, the flow rate must be carefully controlled to prevent explosions. Two options are available to bunker H2c. Pressure balancing and compressing the gas into the vessel (Hyde and Ellis, 2019). The latter allows for careful flow control but requires expensive equipment. This makes bunkering more expensive but safer and is therefore the preferred option. H2l can be bunkered using cryogenic pumps. This technology is well understood from the experience with LNG (Hyde and Ellis, 2019).

Safety and regulation of hydrogen

Hydrogen has a low flash point, a wide flammability range and is potentially explosive. In addition, because of its low density and small particle size, it can leak easy through joints and cracks in piping or storage. When leaked, hydrogen easily disperses and dissipates (Saffers and Molkov, 2014) but it also forms quickly to a flammable gas mixture causing serious fire hazards. Moreover, although it is odourless, invisible, and not toxic, it does cause asphyxiation because it replaces the oxygen in the air at high concentrations (Xiao et al., 2018).

Storage of H2c in tanks is safe, but the release must be controlled to avoid explosions (Paczkowski, 2004). H2l storage is more challenging because most materials become brittle at cryogenic temperatures. When H2l would be leaked, the hull could be damaged because it is not made from the same material. After a leakage, vapour clouds are formed which remain very cold. Serious dangers are posed by these vapour clouds to people working on the W2W vessel.

Currently, there are no international regulations specifically for hydrogen. However, due to its low flashpoint, it must comply with the International code of safety for ships using gases or other low-flashpoint fuels (IGF) code. For H2l, there are recommendations to carry it for transport. However, these regulations were developed for a pilot project and are therefore not directly applicable to any other project (ABS, 2021). In addition, they are not applicable to using the energy carrier but only for storage. There are land-based implementations for hydrogen which give some understanding. Therefore, classification bureaus write a lot about their perspective on using hydrogen on vessels (ABS, 2021) (DNV, 2021b).

3.5.4. Methanol

Methanol, or CH_3OH, is the simplest alcohol and has the lowest CO_2 and highest hydrogen properties of any liquid energy carrier (COWI and CE Delft, 2021). Methanol is a colourless liquid and has a slight alcoholic odour when pure (NIOSH, 2010)(O'Neil, 2013). It is liquid between -97.6°C and 64.7°C (EPA DSSTox, n.d.), has a density of 791 kg/m^3 at 20°C (COWI and CE Delft, 2021) and the volumetric energy density is 15.8 GJ/m^3 (IRENA and Methanol Institute, 2021). A vessel running on methanol will require energy carrier tanks approximately 2.5 times larger than LSMGO fuel tanks (DNV GL, 2019a).

Green methanol

Green methanol is not carbon free but carbon neutral, which means that no extra carbon is emitted during the process. According to IRENA and Methanol Institute (2021), there are two routes to create renewable or green methanol. Bio-methanol is produced from biomass and green e-methanol is made with captured CO_2 from renewable sources and green hydrogen. CO_2 can either be captured through Bio Energy Carbon Capture and Storage or Direct Air Capture (DAC). The different production methods for methanol can be seen in Figure 3.7.

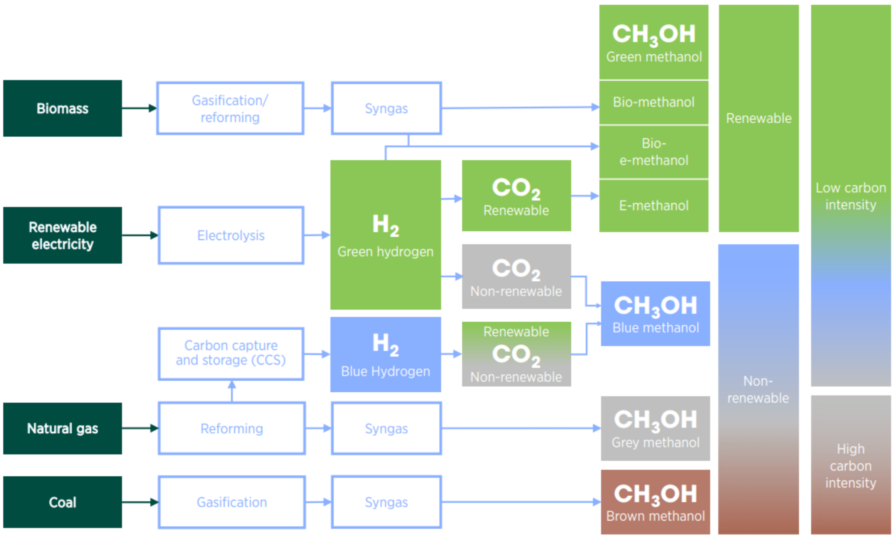


Figure 3.7: Principal methanol production routes (IRENA and Methanol Institute, 2021)

To date, only 0.2 Mt of green methanol is produced per year, while 100 Mt of blue, grey, and brown methanol is produced per year (IRENA and Methanol Institute, 2021). Because methanol is already produced on a big scale, the industry is already established and there is a lot of experience in handling and storing methanol both on land and on vessels. Therefore, a rapid increase in green methanol is expected when required (IRENA and Methanol Institute, 2021). One of the benefits of Methanol is that in the next couple of years the transition between grey and green methanol can be made through bio-methanol. Bio-methanol plants are currently already under construction.

Emissions of methanol

Methanol is sulphur-free and in an ICE, the reduction of NO_x emissions can be up to 60% but since this is not enough to comply to tier III regulations, an additional scrubber system must be installed. Methanol CO_2 emissions are 67 kg/GJ in the TTW phase. For grey methanol, the WTT CO_2 emissions are 20 kg/GJ, where this is -67 kg/GJ to achieve carbon neutrality for green methanol (Brynolf, 2014).

Cost of methanol

Current and future methanol costs for both bio-methanol and e-methanol are estimated to remain higher than brown, grey, or blue methanol. Bio methanol is expected to decrease from €39/GJ in 2019 to €24/GJ in 2050 whereas green methanol from DAC is expected to decrease from €57/GJ in 2019 to €29/GJ (ABS, 2022). CAPEX for the methanol energy carrier system is expected to increase compared to LSMGO because extra piping and double walls need to be installed (DNV GL, 2019a). OPEX is expected to decrease slightly because less maintenance is expected (Boersma, 2021).

An ICE running on methanol would cost approximately €655/kW according to TNO (2020), an FC running on methanol would cost approximately €2022/kW according to Ogden et al. (1999) and according to TNO (2020), the tank storage system costs approximately €45/GJ.

Bunkering of methanol
Grey methanol is available in over 100 major ports today (Methanol Institute, 2020b). In Appendix D, a map showing all ports with methanol is depicted. This map shows that methanol is widely available in Europe but also in other major ports around the world. Although methanol is available, there is almost no bunkering infrastructure. Currently there is only one port, Gothenburg, with bunkering facilities for methanol. In other ports, bunkering can be done by truck or by bunker barge (DNV GL, 2019a).

Creating bunkering facilities should not be a big challenge. Since methanol is liquid at atmospheric pressure, it can be stored and bunkered much like normal diesel fuels. Costs for infrastructure to store and bunker methanol will therefore be low, compared to most other alternative energy carriers (Methanol Institute, 2020b). Since the volumetric density of methanol is more than two times lower, bunkering might take longer.

Safety, regulations, and crew qualifications of methanol
According to Bureau Veritas (n.d.), methanol is both toxic and flammable when stored as a liquid. The high toxicity of its vapours must be resolved with specific ventilation systems. This is necessary to ensure safe working conditions for the crew. Furthermore, methanol is completely soluble in water, which mitigates the risk of leakage in an incident. The crew should also follow a safety management training on how to handle methanol properly to mitigate the risk.

IMO (2020b) has published interim guidelines for the safety of vessels using methyl/ethyl alcohol as fuel. Along with these regulations, methanol also must comply to the IGF code because its flashpoint, 9°C is below 60°C (ILO, n.d.). All high-pressure fuel components need to be designed with double walls which impacts the design the most (DNV GL, 2016b)(IMO, 2018).

3.5.5. Ammonia
Ammonia or NH_3 is a colourless substance and becomes liquid under -33°C which means that a small pressure or temperature decrease is necessary to handle ammonia as a liquid (NIST, n.d.). The volumetric energy density of ammonia is 11.4 GJ/M^3 or approximately 7 GJ/M^3 including storage (Brinks and Hektor, 2020). The gravimetric energy density is 18.6 GJ/t.

Ammonia does not contain carbon, which means that TTW CO_2 emissions are zero. If renewable energy is used to produce ammonia, WTT CO_2 emissions can also be zero which makes ammonia a potential zero-emission energy carrier. However, currently most ammonia is produced from natural gas through the Haber-Bosch process, which combines grey hydrogen with nitrogen gas at high pressures (300 bar) and high temperatures (400-500°C).

As with hydrogen and methanol, there are different ammonia colours. Green ammonia is produced from green hydrogen and nitrogen. Grey ammonia is produced from grey hydrogen from natural gas. Lastly, blue ammonia is produced in the same way as grey ammonia, but CCS is applied (Brinks and Hektor, 2020).

Emissions of ammonia
CO_2 emissions of ammonia depend on the WTT phase. Approximately 85 kg CO_2 per GJ is emitted during the WTT phase for grey ammonia (Brinks and Hektor, 2020). According to, IEAGHG (2017), up to 89% of CO_2 can be captured, but this will increase the costs significantly. Blue ammonia therefore has average emissions of 9.4 kg CO_2 per GJ. When renewable energy is used for the electrolysis of hydrogen and the ammonia forming process, green ammonia has zero WTW CO_2 emissions.

Ammonia virtually eliminates SO_x. The amount of NO_x emissions depends on the engine technology that is used but is expected to be approximately equal to the NO_x emissions of LSMGO. Therefore, the use of a scrubber is necessary to comply with NO_x regulations.

Cost of ammonia
Current ammonia prices depend on day and region. Since 2016, the price has been below 400$/t and was approximately 200 to 300 $/t (or 11.59 €/GJ) (DNV GL, n.d.-b). Blue ammonia costs are on average 65% higher than brown ammonia (Irlam, 2017). According to IRENA (2019), green ammonia costs

between 650 and 850 $/t (averaging 25.47 €/GJ) and slightly decreases to an average of $25.14/GJ (21.67 €/GJ) by 2050 (Lloyds Register, 2020).

An ICE running on ammonia would cost approximately 731 €/kW according to TNO (2020), an FC running on ammonia would cost approximately 797 €/kW according to Lövdahl and Magnusson (2019) and according to TNO (2020), the tank storage system costs approximately 75 €/GJ.

Bunkering of ammonia

Grey ammonia is available all over the world because it is used a lot as fertilizer. Global production is still increasing and reached 176 million ton in 2020 (IEA, 2017). The existing availability of ammonia in ports in European waters (map in Appendix D) is considered spread enough to start using ammonia today.

For ammonia to become attractive as a marine energy carrier, it needs to be green ammonia. Therefore, especially the increase in green ammonia is interesting. Since green ammonia is based on green hydrogen, this is the bottleneck in producing green ammonia. However, just as with green hydrogen or green methanol, it is possible to use the existing availability of the blue or grey version to energise the vessel.

Ammonia is often stored compressed when stored in smaller volumes than 5000 tons because this costs less energy than storing it liquefied (Brinks and Hektor, 2020). Therefore, bunkering will most likely also be in compressed form. If the pressurised ammonia is bunkered, the pressure in the vessel tank increases. This pressure build-up and condensing of ammonia costs time but must happen with caution to mitigate explosion danger. A safety valve must be installed which opens when too much pressure is built up. Currently, there is no bunkering infrastructure for ammonia, so ammonia needs to be bunkered by bunker barge or truck. The volumetric energy density of ammonia is about 3.2 times lower compared to LSMGO. Therefore, bunker time is increased.

Safety, regulations, and crew qualifications of ammonia

Ammonia has more safety concerns than other alternative energy carriers and this is considered one of the major downsides of ammonia. Ammonia is toxic, soluble, corrosive, and flammable.

The concentration of ammonia which is considered dangerous is so low that humans do not detect it. Therefore, detectors should be installed around the ammonia system. Because ammonia is very soluble, it is absorbed by body fluid which can lead to severe chemical skin burns. To reduce this risk, water sprays need to be installed which are turned on in case of leakage because water sprays can absorb the ammonia from the air. Moreover, emergency showers and eye wash stations need to be installed to prevent injury after contact. Lastly, the ventilation systems need to be designed to shut off after ammonia detection so that the ammonia is not spread through the vessel.

According to Brinks and Hektor (2020), the preferred choice for storing ammonia in a vessel is pressurised because for cold storage additional back-up systems are required. Pressurised tanks need a minimum distance from the side and bottom of the vessel (to limit the risk of tank damage in a collision or grounding). The tanks must be away from the engine room, they must be protected against areas with risk of mechanical damage, such as offshore cranes and MCGs, and double-walled pipelines are necessary. In case of a serious breach of the system, the breach automatically leads to an abandon ship situation. There is no recovery from such an event.

Ammonia is considered a low-flash-point fuel and therefore needs to apply to the IGF regulations. There are no specific regulations for ammonia yet, but Brinks and Hektor (2020) thinks that the overall safety management will be comparable to the safety management of LNG.

Social perspective of ammonia

The social perspective of ammonia is negative because ammonia is toxic. This means that people and crew are afraid of the energy carrier. However, the fact that green ammonia is carbon free could influence the overall perspective. According to Haskell (2021), the perception of the wider community on ammonia needs to change before it will be accepted as an energy carrier. The community readiness will be accelerated when shown (to the wider community) that green ammonia is one of the best WTW CO_2 emission performers (Haskell, 2021).

3.5.6. Batteries

Batteries have the potential to be zero-emission because they can electrically power a vessel using only renewable energy. In 2015, the first commercial operations with a fully electric powered car ferry started (Ship Technology, 2015). Batteries are expected to increase in cycle life and energy density (DNV GL, 2016a). These two characteristics combined with the expected lower costs (DNV GL, 2016a) show the potential for bigger fully electric vessels. The social perspective of batteries is very good due to campaigns in the automotive industry.

Traditionally, batteries have not been used for energy storage on vessels because the energy density was too low for lead-acid and nickel cadmium batteries (DNV GL, 2016a). However, with the introduction of lithium-ion batteries, the energy density has increased up to eight times (DNV GL, 2016a). Still, the energy density is very low with 0.4 GJ/t or 0.28 GJ/m^3 which is 106 times lower (gravimetric) or 132 times lower (volumetric) compared to LSMGO.

Emission of batteries

The emissions of a battery powered vessel are solely depending on the WTT emissions of the chosen energy. If 100% renewable energy is stored in the battery, there are no emissions, however, when a combination of renewable and fossil energy is loaded into the batteries, this is not the case. Therefore, batteries have the potential to be zero-emission whenever only renewable energy is used.

Cost of batteries

The cost of the battery system on a vessel is estimated to cost 500$/kWh (119732 €/GJ) (MAN Energy Solutions, 2019). This covers the hole battery system. On top of this CAPEX, the OPEX depends on renewable energy prices which may fluctuate between different ports in different countries. European electricity prices are on average 31.94 $/GJ (27.54 €/GJ) in 2021 and expected to drop to 5.56 $/GJ (4.79 €/GJ) in 2050 (IRENA, 2020a)(IRENA, 2020b).

Recharging batteries

To recharge batteries, the vessel must be plugged in to the energy network in port. However, only a few ports in the world can supply enough shore energy to make sure that vessels have no emissions in port. Therefore, the EU makes shore energy mandatory in all ports in the European Economic Area (EEA) by 2030 for all container and passenger vessels (Lurkin et al., 2021). Therefore, it is assumed that enough energy will be available for W2W vessels in the EEA ports. In 2019, the charging power available for cruise ships is 8.8 MW, which was deemed to be the maximum according to MAN Energy Solutions (2019).

Another possibility to recharge renewable energy would be to recharge in an OWF using a special recharging buoy. Due to the high energy density of batteries, this is the only feasible possibility for W2W vessels. An optimum should be found in how often and long should be recharged at sea. This optimum should be compared with other vessels who have no downtime in the OWF due to recharging. This option would only be viable for SOVs operating in already operating OWFs because in (de-)commissioning there is no energy available.

Safety and regulation of batteries

Batteries have very high safety standards. However, it is still possible that a thermal runaway scenario is initiated. In this case, a special foam needs to be automatically injected into the module. If a thermal runaway scenario is detected early enough, the foam will most likely work well enough to limit the damage to the specific module. In this case, the rest of the modules will still work (DNV GL, 2019c).

After a thermal runaway scenario, a lot of toxic gasses potentially came free from the battery. Therefore, batteries should be stored in a closed space and the space needs to be ventilated with a dedicated ventilation system.

In a closed space, with a dedicated ventilation system installed and an automatic foam injection, if a thermal runaway scenario is detected, batteries are perfectly safe on a W2W vessel.

3.6. Chapter conclusion

In this chapter, the third subquestion was investigated:

3. "*What is the state-of-the-art in potential alternative energy carriers, what are their important properties and what is their relevance for W2W vessels?*"

Suitable alternative energy carriers with a TRL of 5 or higher have been discussed. The important properties of the selected alternative energy carriers have been shown, and a selection based on possible applicability to W2W vessels follows.

Green energy carriers are more expensive than fossil variants. However, it is expected that electrolysis becomes cheaper, renewable energy becomes less expensive, and increasing (carbon) taxes for fossil fuels will be implied, which will lead to a break-even point (BEP) in the future where green energy will be cheaper. The higher the CT, the earlier this BEP will be achieved.

There are no CO_2 regulations that a W2W vessel must comply with. Therefore, all CO_2 reductions must come from intrinsic motivation, from client requests, or from indirect emission regulations to which the client must comply with, as could be seen in the design circle (Figure 2.15).

Furthermore, the advantages and disadvantages of energy converters have been reviewed. The main advantage of an ICE is that it is highly developed. The main advantage of an FC is that it has a higher efficiency and that there are no moving parts which will lead to less maintenance.

HVO has CO_2 emission reductions of approximately 60% compared to LSMGO. This is not enough for zero-emission but could be used to decrease emissions if concluded that no zero-emission energy carrier is already feasible for W2W vessels.

Methanol has the potential to be carbon-neutral and both hydrogen, ammonia, and batteries have the potential to be zero-emission. Methanol, hydrogen, and ammonia will be investigated further to determine if they should be used as a replacement of LSMGO on the W2W vessels. Batteries will also be further investigated in combination with a recharging possibility at sea. This would only work for SOVs operating in an active OWF. Table 3.1 gives an overview of the main characteristics of the considered alternative energy carriers for this research; LSMGO (as benchmark), HVO (as possible transition fuel), hydrogen, methanol, ammonia, and batteries (for SOVs only).

Table 3.1: Main characteristics of the selected alternative energy carriers for this research. Values are the best approach in literature, can thus be used for describing the order of magnitude, and not be used as the truth. Colours indicate good (green) to bad (red).

	CO_2 emissions			Fuel costs		Energy density				Social perspective	Remarks
	WTT	TTW	WTW	2021	2050	Energy only		Incl. storage		(1-5)	
	kg CO_2/GJ			€/GJ	€/GJ	GJ/t	GJ/m^3	GJ/t	GJ/m^3		
LSMGO	13.5	73.6	87.1	€ 10.05 [1]	≈	≈	≈	42.7	36.7	4	*Benchmark*
HVO	-38.3	70.8	32.6	€ 25.36	≈	≈	≈	47.2	43.7	2	
Hydrogen											
Natural gas / grey	115.2	0	115.2	€ 12.50	+						
Renewable / green	0	0	0	€ 33.33	€ 7.18					1	*Carbon free*
Compressed (700 bar)	+			+	+	120	5.0	5.5	4		
Cryogenic liquid (-253 □)	+			+	+	120	8.5	8.5	5		
Methanol						≈	≈	12.5	15.8	No opinion is known	
Natural gas / grey	20.0	67.0	87.0	€ 14.49	€ 20.69						
Renewable / green	-67.0	67.0	0	€ 57.00	€ 29.00						*Carbon neutral*
Ammonia						18.6	11.4	11.4	7		
Natural gas / grey	85.0	0	85.0	€ 11.59	+					3.5	
Renewable / green	0	0	0	€ 25.47	€ 21.67						*Carbon free*
Batteries (renewable)						0.43	0.31	0.40	0.28	1	
Renewable / green	0	0	0	€ 27.54	€ 4.79						*Carbon free*

4

Scope and research gap

This chapter formulates the discovered research gap and thus defines the problem which is not answered by any other existing studies (Wolf, 2021). A research gap is shown for the technical and economical feasibility of zero-emission W2W vessels. This chapter also gives the scope of this research.

4.1. Scope

in the first 3 chapters, multiple demarcations are made to keep the feasibility of this research doable. These demarcations are defined in the scope as followed:

- Only W2W vessels defined as mono-hull service vessels by DNV GL are considered in this research (Figure 2.3).
- The operational area for the zero-emission W2W vessels is defined as the European waters which includes the North Sea, the Norwegian Sea, the English Channel, the Celtic Sea, the coastal waters of Ireland and the United Kingdom, the Bay of Biscay, Skagerrak and the Kattegat, the Baltic Sea, the Gulf of Bothnia, and the Gulf of Riga.
- The zero-emission W2W vessels will support only offshore wind turbines and thus not any other kind of offshore structures.
- Only the design of new purpose built zero-emission W2W vessels is investigated and thus not the possibility of refitting old vessels.
- The only two considered energy converters are an ICE and an FC.
- The considered energy carriers are: LSMGO (as benchmark), HVO (as blend-in or transition fuel), H2c or H2l, methanol, ammonia, and batteries (for SOVs only).
- Only CO_2 and no other types of GHG emissions are investigated because CO_2 emissions are by far the largest.

4.2. Research gap

The offshore wind industry is growing and new installations per year will almost quadruple by 2030. This creates a growing demand for W2W vessels with an estimated 600 SOVs required in 2050. At the same time, locations of OWFs are expected to move further away from shore. Therefore, the duration of transit or speed during transit increases, so more energy must be stored on the W2W vessel.

Additionally. it is discovered that the life cycle GHG emissions of offshore wind turbines are approximately 120% more than onshore wind turbines. It is also estimated that W2W vessels account for 3.3% of the life cycle emissions of offshore wind turbines. This makes it clear that reducing the emissions of W2W vessels directly influences the life cycle GHG emissions of offshore wind turbines. Reducing emissions can be done using alternative energy carriers. The social relevance of decreasing emissions is visible when looking at climate change predictions.

The current and predicted shortage of W2W vessels might increase the DR if the shortage lasts. Moreover, the requirements for more complex vessel and mission equipment for the W2W vessel will lead to higher CAPEX (and indirectly OPEX). Additional systems required for the W2W vessel to use alternative energy carriers are also expected to increase CAPEX and OPEX.

It is also shown that there is a lot of uncertainty in the development of future W2W vessel designs. This is driven by uncertainty in the offshore wind industry and by characteristics on alternative energy carriers. However, there are predictions on how the market and certain parameters will change or remain the same. Therefore, scenario modelling could be a solution to provide insight on how to change the design both technically as economically feasible to cope with certain scenarios.

A research gap is shown in a technical and economical feasibility of zero-emission W2W vessels. Currently W2W vessels are both technically and economically feasible but this is not yet investigated for zero-emission W2W vessels.

5 Methodology

This chapter describes the methodology selection based on the previously discovered certainties, uncertainties and model requirements. After the methodology is chosen, a strategy is given to find the required results of this research.

5.1. Certainty and uncertainty

In the first chapters, information has been collected on (future) W2W vessels and on alternative energy carriers. It has been concluded that there are both a lot of certainties as uncertainties on the future W2W vessels and the alternative energy carriers.

The certainties that have been discovered are mostly technical aspects. We know for example that the design of W2W vessels is much aligned between different vessel owners, the consumption is known, but also on the energy carrier side of the story, the contained energy densities are known.

An example for uncertainty is given in section 2.8. In this section it has been seen that the CAPEX of a W2W vessel is very much depending on market conditions and therefore can vary quite a lot. Additionally, it has been seen that the current average DR and average utilisation is known but that it is unknown how these will change for future zero-emission W2W vessels.

On top of this, section 3.1 has shown that it is unknown when a CO_2 regulation package will be applicable for the offshore sector and if so in which form. Lastly, section 3.4, showed that there are large uncertainties on future alternative energy carrier characteristics. It is known what the price is today, but what will the price do by 2050? The same is true for the availability of the energy carrier.

The number of certainties concerning the technical design and the number of uncertainties on economical future predictions let the author decide that a solution must be found in 2 steps. First, a parametric model will be proposed to determine the technical feasibility of zero-emission W2W vessels, and second all technical configurations must be tested on their economical feasibility. The economical feasibility must be tested with a methodology that handles a certain amount of uncertainty.

Definition 2 *A technical configuration is a configuration of different energy converters, energy carriers, and autonomies.*

5.2. Methodology selection

As introduced, the methodology to find the economical feasibility must be able to handle a certain amount of uncertainty. However, if multiple technical configurations are found to be also economically feasible, a recommendation needs to be made. Therefore, it is decided to select a decision-making methodology. To do this, the level of uncertainty must be identified. Marchau et al. (2019) has identified levels of uncertainty which can be seen in Figure 5.1.

Uncertainty levels have been divided in levels 1, 2, 3, 4a, and 4b. Level 1 uncertainty is uncertainty where the future is almost certain with an error range. Level 2 are a range of futures with a probability level. Level 3 is described as a situation with (few) multiple plausible futures. Uncertainty level 4a is described as a situation with many plausible futures and uncertainty level 4b as an unknown future.

To determine the correct level of uncertainty, it is looked if all uncertainties could be modelled under a certain level. Level 1 is not the correct level because than we would know the 2050 price already. However, level 1 would be sufficient for the distance of OWFs since there is a good estimate.

Level 2 is true for the DR and utilisation. It is assumed that the largest likelihood is that they remain equal to today and that likelihood decreases for higher or lower numbers.

Level 3 would be correct for the port availability. It is yet unknown who will act first, the vessel owner or the port authority. The one who invests first is the pioneer but also has the highest risk and without demand, there is no need for supply. Therefore it is unkown how port availability will develop. However, there are multiple plausible futures to be thought of and therefore port availability falls into level 3 uncertainty.

The 2050 price of the energy carriers needs at least level 4 uncertainty because multiple instance have different estimates on the 2050 price. Additionally, it is unknown if these estimates are correct and therefore many plausible futures without probability weights need to be modelled. Level 4b would mean that the future is completely unknown but this research is based on predictions and therefore is not completely unknown. For this reason, the uncertainty level of the method must be 4a.

The selected methodology must be able to compare multiple technical configuration, because, assuming that multiple technical configurations are feasible, an advice should be given in which technical configuration must be invested. The methodology must also be able to evaluate outcomes based on multiple criteria. This is because in this research not only profit, but also emissions and perhaps more criteria are used to evaluate a technical configuration under a certain future. This comparison between multiple scenario outcomes must highlight both differences and influences of certain scenarios on the criteria.

Lastly, finding an optimised solution is possible but not thrust worthy when under deep uncertainty. Therefore, the methodology must be able to aim for a robust solution. A solution is robust if it performs well under multiple futures. Although, it could also be that the solution is over designed, at this stage the author finds it more favourable to find a solution that works fine under multiple futures than perfect under only 1 future.

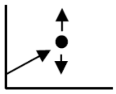
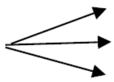
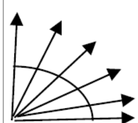
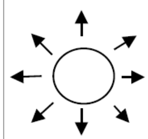
	Complete determinism	Level 1	Level 2	Level 3	Level 4 (deep uncertainty)		Total ignorance
					Level 4a	Level 4b	
Context (X)		A clear enough future 	Alternate futures (with probabilities) 	A few plausible futures 	Many plausible futures 	Unknown future 	
System model (R)		A single (deterministic) system model	A single (stochastic) system model	A few alternative system models	Many alternative system models	Unknown system model; know we don't know	
System outcomes (O)		A point estimate for each outcome	A confidence interval for each outcome	A limited range of outcomes	A wide range of outcomes	Unknown outcomes; know we don't know	
Weights (W)		A single set of weights	Several sets of weights, with a probability attached to each set	A limited range weights	A wide range of weights	Unknown weights; know we don't know	

Figure 5.1: Uncertainty levels (Marchau et al., 2019)

Multiple decision-making methods are described in the researched literature. According to Moallemi et al. (2020) there are 9 methodologies appropriate for decision making under deep uncertainty (DMDU). Marchau et al. (2019) adds Dynamic Adaptive Planning to the list of DMDU methodologies and Terün (2020) adds the Markov decision process. The 11 DMDU methodologies, their description, their uncertainty level, and their aim are listed in Table 5.1

According to Terün (2020), the Real Options Analysis and the Markov Decision Process have uncertainty level 2 and are therefore not suitable. Moreover, at uncertainty level 2, the probabilities for different scenarios would need to be modelled, which is believed to be very difficult for the topic of alternative energies (Terün, 2020). However, probability could be modelled as equal for all scenarios. Terün (2020) determines that the uncertainty level for the Info Gap decision theory is 4b. This is deemed to be too uncertain since there is more information available and, therefore, it is expected to present less accurate outcomes than necessary.

When looking at the other proposed DMDU methodologies, it is seen that only Robust Decision Making (RDM) and Epoch-Era Analysis (EEA) aim for robustness. Therefore, these methods are the

Table 5.1: Overview of the considered methods, based on Terün (2020) and Moallemi et al. (2020)

Methodology	Description	Uncertainty level	Aim	Cite
Info-gap (IG) decision theory	It uses a non-probabilistic model to evaluate pre-specified decisions under severe uncertainty and prioritises and decides based on robustness and opportuneness.	4b	Robustness & opportuneness	(Marchau et al., 2019) (Ben-Haim, 2019)
Robust Decision Making (RDM)	RDM combines Decision Analysis, Assumption-Based Planning, scenarios, and Exploratory Modelling to stress test strategies over myriad plausible paths into the future and identify policy-relevant scenarios and robust adaptive strategies, not to make better predictions but to yield better decisions under conditions of deep uncertainty.	4a	Robustness	(Lempert, 2019)
Many Objective Robust Decision Making (MORDM)	Identifies trade-offs between strategies, re-evaluates their performance under deep uncertainty, and uses interactive visual analytics to support the selection of robust management strategies.	4a	Optimality	(Singh et al., 2015)
Adaptive Policy Making (APM)	APM accepts that it is impossible to predict the long-term future and, in response, designs a flexible policy that can be adapted over time, depending on how the future unfolds.	4a	Flexibility	(van der Pas et al., 2013)
Dynamic Adaptive Policy Pathways (DAPP)	DAPP sequences the implementation of actions over time such that the system can be adapted to changing conditions, with alternative sequences specified to deal with a range of plausible future conditions.	4a	Flexibility	(Haasnoot et al., 2019)
Decision Scaling (DS)	DS supports decision making under climate uncertainty while it is general enough to address other uncertainties. DS makes the best and most efficient use of uncertain but potentially useful climate change projections.	4a	Optimality	(Brown et al., 2019)
Real Options Analysis (ROA)	ROA prioritises adaptation interventions while it considers the possibility to adjust them in the future. ROA determines whether interventions should be immediate or delayed and tests their value.	2	Flexibility	(Econadapt, n.d.)
Engineering Options Analysis (EOA)	EOA assesses the value of including flexibility in the design and management of technical systems. Also, it calculates the value of options in terms of the distribution of additional benefits.	3	Flexibility	(de Neufville and Smet, 2019)
Epoch-Era Analysis (EEA)	EEA clarifies the effects of changing contexts over time on the perceived value of a system in a structured way.	3	Robustness	(Moallemi et al., 2020) (Rader et al., 2014)
Dynamic Adaptive Planning (DAP)	DAP specifies objectives and constraints, to determine short-term actions, and establishes a framework to guide future (contingent) actions. The plan is explicitly designed to be adapted over time to meet changing circumstances.	4a	Flexibility	(Walker et al., 2019)
Markov Decision Process (MDP)	MDP solves dynamic decision making problems with partly random conditions and partly under control by decision makers. It evaluates the performance of designs, by lifetime performance and how they adapt to changing environments, policies, etc.	2	Flexibility	(Kana et al., 2015)

only two that are applicable for this research. When comparing the 2 methods, it is seen that RDM has uncertainty level 4a, while EEA has level 3. Since this research is placed at uncertainty level 4a, the method that is selected for this research is RDM.

5.3. Robust Decision Making

RDM is a decision-making method aimed at robust decisions. It is specifically used for climate change topics because the uncertainty is so high that it is hard to define the probability (Groves and Lempert, 2007). RDM approaches a problem by running a model a myriad of times to test one possible solution against many plausible futures. Visualisation and statistical analysis are used to identify key variables that distinguish futures that meet or miss the goals (Lempert, 2019). The method is better understood when looking at the visualisation in Figure 5.2.

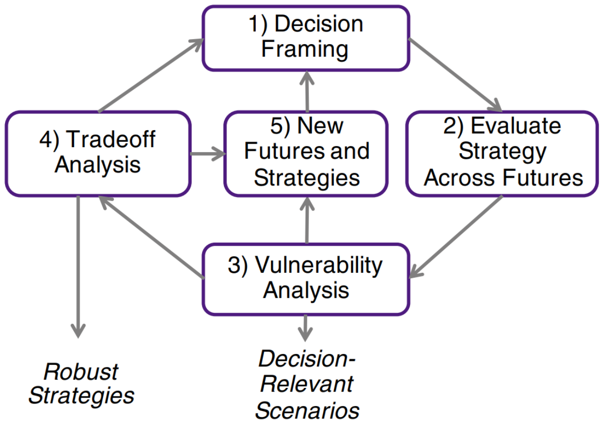


Figure 5.2: Steps in an RDM analysis (Lempert, 2019)

In *step 1*, the decision framing occurs where the key variables, such as objectives, criteria, uncertainties, connections, and relationships, are defined. This information is often stored in an 'XLRM' framework which contains exogenous uncertainties (X), policy levers (L), relationships (R), and performance measures (M) (Lempert et al., 2003). In *step 2*, the strategy is evaluated across many different futures. Simulation models are used to generate a large database of results. *Step 3* uses visualisation and data analytics to find and characterise vulnerabilities. The key variables that distinguish futures that meet or miss the goals are identified in this step. Both absolute and relative performance measures are used to compare strategies. In *step 4* trade-off analyses are performed. Performance is compared with objectives such as reliability and cost in (multi-) objectives trade-off curves. *Step 5* uses the vulnerabilities from step 3 and the trade-off analyses from step 4 to find potential new futures and strategies which can be re-evaluated in an iterative process by starting at step 1 again.

The use of RDM in combination with alternative fuels for ultra large container vessels has been explored by Terün (2020).

5.4. Strategy overview

The strategy to find a solution contains 2 main parts. First, the technical configurations (different combinations of energy converter, energy carrier, and autonomy duration) will be tested. The first test is whether the required energy will fit in current W2W vessel. If it does not fit, adaptions need to be made to the hull length. Then the new design is calculated, and the new required power and energy are calculated. Apart from the technical aspect, the economical aspect in terms of CAPEX will also be calculated in this stage. All feasible technical configurations will be inserted as input in the RDM model and will be tested according to many futures. This strategy is displayed in Figure 5.3.

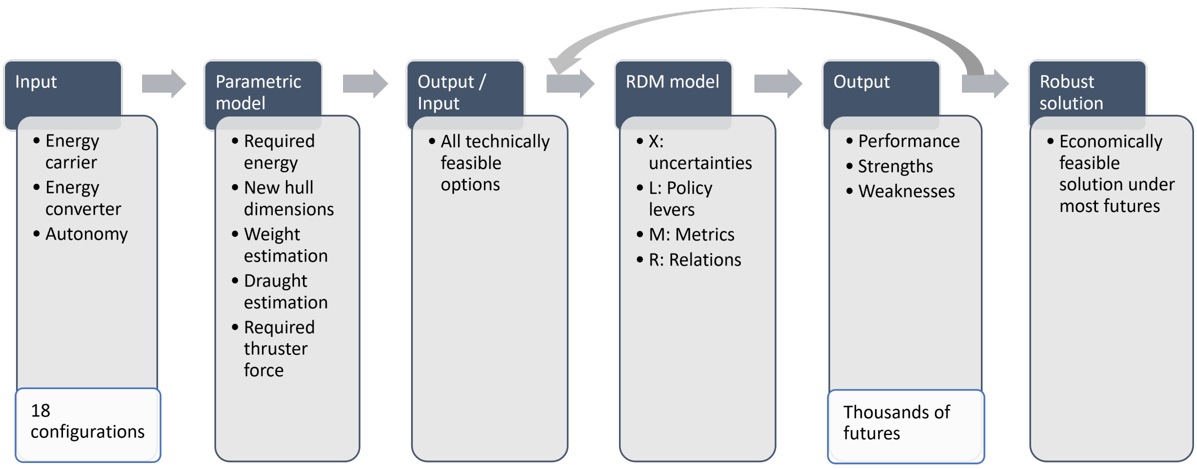


Figure 5.3: Research strategy

5.5. Chapter conclusion

This chapter has answered subquestion 4:

4. "*Which are the requirements for an assessment methodology that covers future trends, energy carrier choice, and W2W vessel design implications and what methodologies are best suited for this?*"

The methodology must be able to handle a certain level of uncertainty, to make a comparison between the results of multiple scenarios, to evaluate with multiple input criteria, and to find a conceptual basic design. The decision has been made to use two methodologies. A parametric model will be used for the technical feasibility, and an RRM method is used for the economical evaluation.

6
Parametric model

This chapter discusses the parametric model and its application. The model overview is introduced in Figure 6.1 and explained in detail in section 6.2 to section 6.7. Section 6.8, performs a verification on the parametric model. Section 6.9, presents the application of the parametric model to 18 technical configurations on base case the Acta Centaurus. Lastly, section 6.10, gives the conclusions and thus gives the answer to the technical feasibility for the different technical configurations.

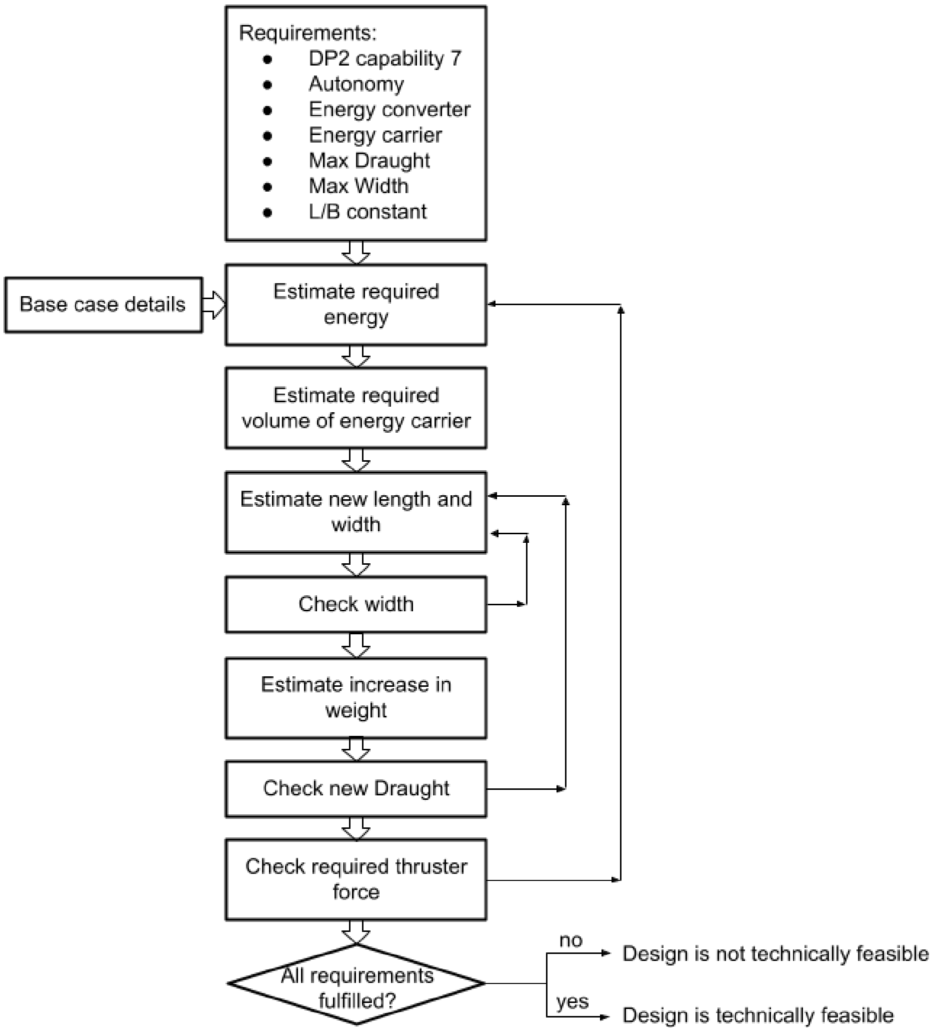


Figure 6.1: Parametric model overview

6.1. Base case: Acta Centaurus

To find the technical feasibility of the different combinations of energy carriers, energy converters, and autonomy, a state-of-the-art vessel will be used as a base case and modified. Using a base case and then modifying it instead of designing from scratch might influence the results of this research. However, it also makes the research easier, and it is expected that this way the feasibility will not be affected much. This assumption is revisited later in this research.

The chosen vessel is the Acta Centaurus because this is the newest vessel from Acta Marine which can provide all required data. As identified previously, the main concern to store alternative energy carriers on the W2W is whether it fits or not. The Acta Centaurus is equipped with 800 m^3 of fuel tanks and this is concluded to be too much (section 2.7). When investigating the general arrangement, it is also discovered that by using voids as fuel tanks, up to 80 m^3 (10%) of additional fuel may be stored.

Another concern is whether the vessel has enough installed power available to counteract all environmental force on the vessel. Table 6.1 shows the main dimensions of the Acta Centaurus. Figure 6.2 shows the wind and water contour and the corresponding centroid of the Acta Centaurus, which is necessary to find the environmental forces on the vessel.

Table 6.1: Main dimensions of Acta Centaurus

Parameter	Value	Unit	Name
Length overall	93.4	m	L_{oa}
Length between perpendiculars	83.8	m	L_{pp}
Draught	5.6	m	D
Maximum breadth at water line	18.0	m	B

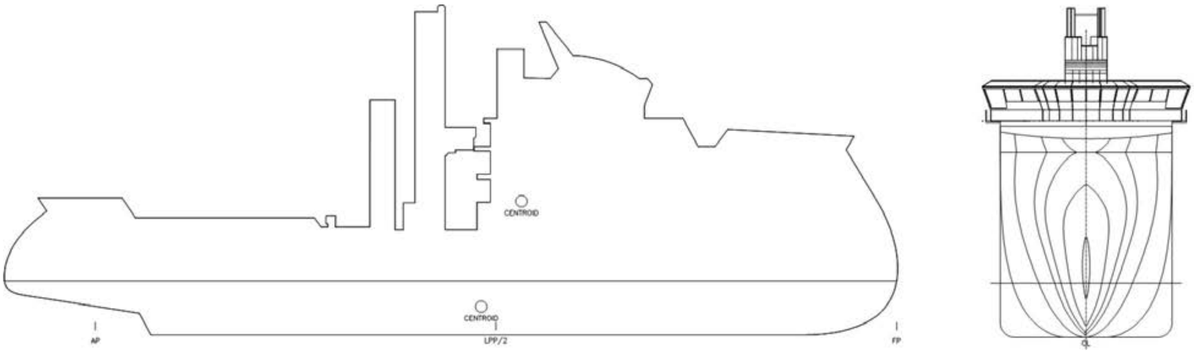


Figure 6.2: Wind and water contour and corresponding centroid of the Acta Centaurus

6.2. Required Energy

The theoretical fuel autonomy of 100 days of the Acta Centaurus is derived from the average fuel consumption of 7.2 m^3/day, the capacity of 800 m^3, and a 10% margin. The relatively low margin of 10% is set at this level for two main reasons. The margin could be higher because it might be unsure whether a port has the energy carrier available. However, the vessel will return to the same port for the duration of the project and therefore this is not the case. The second reason to keep the margin low is that the OWFs are relatively close to shore and therefore, in a worst-case scenario, the vessel could always return to port early when the energy level becomes critical. In this research, the margin is kept low at 10% because it has been concluded that energy storage of alternative energy carriers is critical in terms of volume and therefore it is not reasonable to have a high margin.

Because the W2W vessel is never longer at sea than 4 weeks and it has also been determined in section 2.7 that the required autonomy might decrease to 14 days in the future, the required energy is calculated for 14 or 28 days. However, since it is already discovered that the energy density of batteries is so extremely low, an autonomy of 1 or 2 days is investigated in combination with recharging at sea. An autonomy of 1 or 2 days requires recharging at sea and leads to less short cycles.

The required energy is based on the average consumption of the current LSMGO ICE W2W vessels. When an FC is used, the efficiency of energy carrier to energy is expected to be higher. It is decided to model the efficiency as a set percentage in order not to complicate the technical solutions. ICE efficiency is set at 40% while FC efficiency is set at 60%. The fuel reformer efficiency for methanol and ammonia is set at 70% (Y. Wang et al., 2020)(Alagharu et al., 2010). According to DNV (2021a), a battery may be used between an 80% and 20% state of charge and therefore a theoretical battery efficiency of 60% will be used. The required energy can be calculated with Equation 6.1.

$$E_{req} = C_{avg} * EDV_{LSMGO} * Aut * \frac{\eta_{ICE}}{\eta_{conv} * \eta_{reformer}} * (1 + margin) \quad (6.1)$$

Where:

- E_{req}, Required energy ($GJ/trip$)
- C_{avg}, Average LSMGO consumption (m^3/day)
- EDV_{LSMGO}, Volumetric energy density LSMGO (GJ/m^3)
- Aut, Autonomy ($days$)
- η_{ICE}, Converter efficiency of ICE ($-$)
- η_{conv}, Converter efficiency of either ICE. FC or theoretical battery ($-$)
- $\eta_{reformer}$, Reformer efficiency for ammonia and methanol ($-$)
- $margin$, Margin ($-$)

6.3. Required volume of energy carrier

Using the required energy per situation combined with the contained volumetric energy density of the other energy carriers, an estimate of the required energy in terms of volume can be found. These estimates according to Equation 6.2, are assumed to be good enough for this feasibility research.

$$V_{req} = \frac{E_{req}}{cEDV} \quad (6.2)$$

Where:

- V_{req}, Required volume to store energy (m^3)
- $cEDV$, Contained volumetric energy density (GJ/m^3)

6.4. Required length and beam

The Acta Centaurus will be elongated and widened at the centre of buoyancy so that this does not change. This decision to elongate and widen the vessel at exactly this location might influence the results of this research and therefore need to be revisited later. The cross-sectional area at this location is 180 m^2. 85% of this area is used for new storage tanks so that the rest may be used for additional piping, hallways, etc. The author was unable to find an accurate percentage in the literature and therefore it is recognised by the author that this percentage needs to be varied later to test its influence on the findings. 85% is the best guess of the professional knowledge of the author. To accommodate the required energy, the hull is modified in terms of length and width. A constraint is introduced for a constant L_{pp}/B ratio (from now on L/B ratio), to keep the vessel form as constant as possible. This constraint will most likely influence the findings of this research and is revisited later. Due to the constant L/B ratio, an elongation causes an automatic widening as well. The added volume by widening the vessel depends on the hull form and can be estimated by multiplying the added width, L_{pp}, and height of the cross section. Equation 6.3, which is created by the author, shows how to estimate the added volume due to a increase in length and beam. The next step is to match the added volume with the required volume to find the corresponding increased length and beam.

$$V_{add} = \left(A_{cs} * L_{add} + h_{cs} * (L_{pp} + L_{add}) * \frac{L_{add}}{LB_{ratio}} \right) * \eta_{use} \quad (6.3)$$

Where:

- V_{add}, Added volume (m^3)
- L_{add}, Added length (m)
- A_{cs}, Cross sectional area at cut through (m^2)
- h_{cs}, Distance between keel and deck at cut through (m)
- L_{pp}, Length between perpendiculars (m)
- $LB_{ratio} = Lpp/B$, Ratio Lpp and B (-)
- η_{use}, Percentage of cross sectional area used for new tank volume

6.5. Added weight

The added weight is important to determine the new draught. The added weight consists mainly of the additional energy carrier weight including its storage tank weight and the additional material used for the lightweight of the vessel. The change in lightweight is calculated by using the method of Watson et al. (1976). They divide the empty weight of a vessel into 4 categories; weight of steel, weight of all machines, weight of outfitting (stairs, cabling, piping etc.) and weight of a margin. The added weight for the contained energy carrier and the other 4 categories will be discussed separately in the following subsections.

6.5.1. Contained energy carrier weight

The weight of the energy carrier can be calculated using the gravimetric energy density including storage (Equation 6.4).

$$W_{req} = \frac{E_{req}}{cEDG} \tag{6.4}$$

Where:

- W_{req}, Required energy weight (ton)
- $cEDG$, Contained gravimetric energy density (GJ/ton)

6.5.2. Steel weight

The steel weight (W_{steel}) in tons is calculated with Equation 6.5.

$$W_{steel} = K * E^{1.36} * (1 + 0.5 * (C_B^{'} - 0.7)) \tag{6.5}$$

Where:

- K, A constant depending on vessel type (0.041-0.051 for offshore supply vessels)
- E, The E parameter that describes the vessel geometry according to Equation 6.6 (m^2)
- $C_B^{'}$, A corrected block coefficient

The E parameter is calculated according to Equation 6.6.

$$E = L_{pp} * (B + T) + 0.85 * L_{pp} * (D - T) + 0.85 * E_{ss} + 0.75 * E_{dh} \tag{6.6}$$

Where:

- E_{ss}, The E parameter for super structures.
- E_{dh}, The E parameter for the deck house.

Since the goal is to calculate the *added* steel weight only, Equation 6.5 and Equation 6.6 can be adapted. Since the block coefficient hardly changes for elongation and widening in the centre of the vessel, Equation 6.5 is simplified to not be corrected for the block coefficient. Equation 6.6 can also be cleared of the E parameter for the super structure and the deck house since they are not adapted. The added steel weight can thus be calculated with Equation 6.7.

$$W_{steel_{add}} = K * E_{add}^{1.36} \tag{6.7}$$

Where:

$$E_{add} = L_{add} * (B + 0.15T + 0.85D) \tag{6.8}$$

6.5.3. Outfit weight

To determine the weight of the outfitting, Watson et al. (1976) has analysed multiple vessels to find relations between the length, width, and the outfitting weight. These estimates are from the 70s and have probably changed over time but are currently the best literature found by the author. Additionally, only 2 (offshore) supply vessels have been analysed. Given the assumed similarity between the outfitting of W2W vessels and passenger vessels with accommodation, it is chosen to combine data points from both vessel types to find a relation that can be used in this research. Figure 6.3 shows the data point and relations that Watson et al. (1976) have found supplemented with the relationship when combining the data points. The relation that has been found is $C_0 = 0.006374 * L_{pp} - 0.06248$ and is used to calculate the outfitting weight according to Equation 6.9.

$$W_{outfit} = C_0 * L_{pp} * B \tag{6.9}$$

Where:

- W_{outfit}, All other weights including stairs, cabling, piping, etc. (ton)

The added outfit weight is thus depending on the elongation of the vessel, as expected, and can be seen in Equation 6.10.

$$W_{outfit_{add}} = (0.006374 * L_{add} - 0.06248) * \left(L_{add} * \left(B + \frac{L_{add}}{LB_{ratio}}\right) + L_{pp} * \frac{L_{add}}{LB_{ratio}}\right) \tag{6.10}$$

6.5.4. Machinery weight

The weight of the machinery depends on the type of converter. An FC is expected to be less heavy than an ICE with approximately 2.19 kg/ekW (Ballard, n.d.). Currently, the installed generators of the Acta Centaurus deliver a total of 5480 ekW with a total weight of 46800 kg (Acta Marine, 2018). This means the current ICE weight is approximately 8.54 kg/ekW. These relations will be used to make an estimate of the increase or decrease in machinery weight according to Equation 6.11.

$$W_{machinery_{add}} = -W_{machinery_{des}} + r_{conv} * P_{req} \tag{6.11}$$

Where:

- $W_{machinery_{add}}$, Added weight due to machinery (ton)
- $W_{machinery_{des}}$, Design weight for machinery (ton)
- r_{conv}, Weight power relation per converter (kg/ekW)
- P_{req}, Required power (ekW)

6.5.5. Margin and total added weight

The weight margin (η_W) is considered good enough at $\eta_W = 0.03$ or 3% according to Watson et al. (1976) and will therefore not be altered. The total added weight will be according to Equation 6.12.

$$W_{ship_{add}} = (W_{steel_{add}} + W_{machinery_{add}} + W_{outfit_{add}}) * (1 + \eta_W) + W_{E_{req}} - W_{E_{des}} \tag{6.12}$$

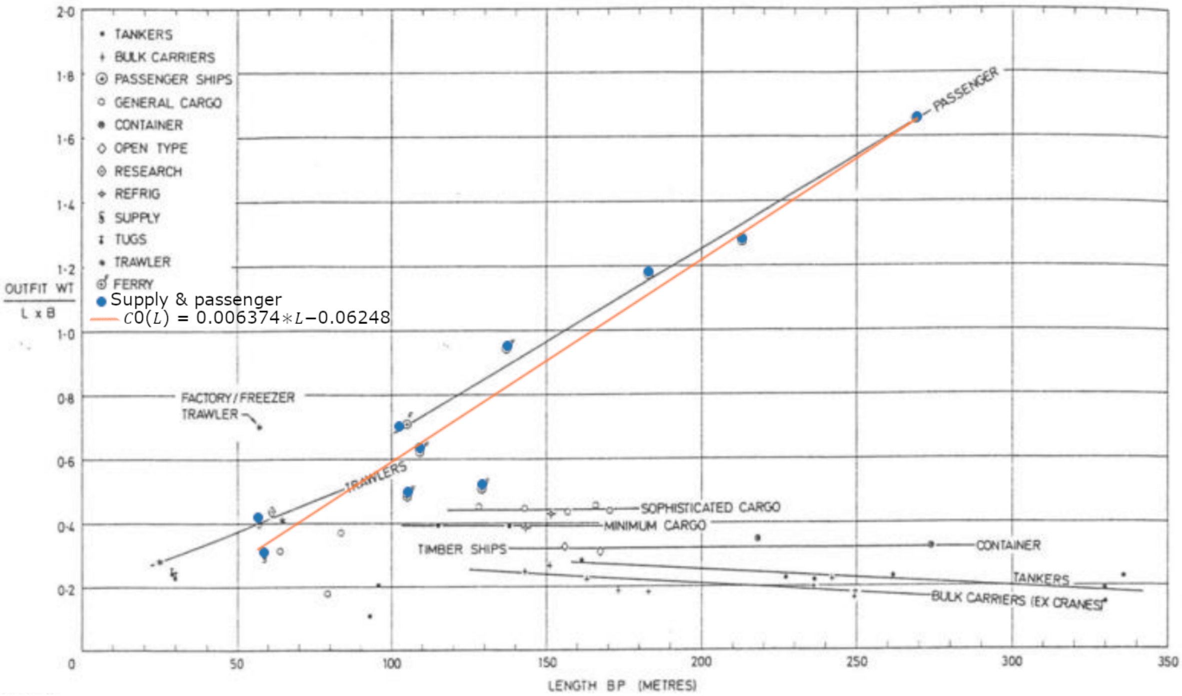


Figure 6.3: The ratio between outfit weight and square numbers (L x B) per vessel type and size (Watson et al., 1976), supplemented with trendline for combination of offshore supply vessels and passenger vessels.

6.6. Draught

The added draught can be estimated using the underwater volume of the new hull, the new waterline area, and the total added weight. If no hull modifications need to be performed, there is no added underwater volume. However, in some cases, the total added weight is higher than zero, but no hull modifications were necessary. This is, for example, the case for the methanol ICE 28-day configuration. In this case, the waterline is used in combination with the added weight to find the new draught. Whenever hull modifications are necessary, both the underwater volume and the waterline change. This results in Equation 6.13 for the draught.

$$D_{new} = D_{des} - \frac{(L_{pp} + L_{add}) * D * \frac{L_{add}}{LB_{ratio}} + A_{cs} * L_{add} - \frac{W_{ship_{add}}}{\rho_{sea}}}{A_{wl_{des}} + (L_{os_{des}} + L_{add}) * \frac{L_{add}}{LB_{ratio}} + L_{add} * B} \tag{6.13}$$

Where:

- D_{new}, New draught (m)
- D_{des}, Design draught (m)
- ρ_{sea}, Sea water density (t/m^3)
- $A_{wl_{des}}$, Designed water line area (m^2)
- $L_{os_{des}}$, Designed longitudinal distance between the fore most and aft most point under water(m)

6.7. Required thruster force

The objective of the DP system is to maintain the location of the W2W vessel. To do this, it should counteract all forces that act on the vessel. According to DNV's yearly updated assessment of station keeping capability of dynamic positioning vessels (DNV, 2021a), to check the DP capability, a static balance between the environmental forces and the actuator forces is sufficient to check a ship design. The environmental forces exist from wind, current, and wave drift forces as can be seen in Equation 6.14.

The environmental forces depend on the direction of the individual forces, but for this analysis it is set that the direction will be the same for all three environmental forces. The vessel coordinate system and the direction of the environmental forces are shown in Figure 6.4. The environmental forces depend on wind speed, current speed, Hs, and the peak wave period. These conditions are all related and are given a DP capability number. If a vessel can maintain its position under all corresponding conditions, it is given this DP capability number. The DP capability number from DNV (2021a), can be seen in Appendix E.

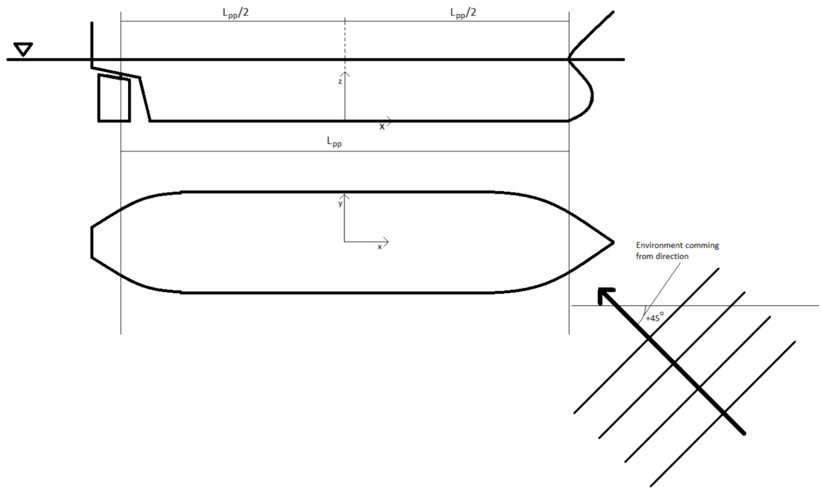


Figure 6.4: Vessel coordinate system and environmental directions (DNV, 2021a)

$$\vec{F}_{environment} = (\vec{F}_{wind} + \vec{F}_{current} + \vec{F}_{wavedrift}) * DF \tag{6.14}$$

Where:

- $\vec{F}_{wind}$, Wind force
- $\vec{F}_{current}$, Current force
- $\vec{F}_{wavedrift}$, Wave drift force
- DF, Dynamic factor of 1.25 to allow for dynamic forces.

6.7.1. Wind force

Above water, the wind varies considerably. Willemse et al. (2008) states that the velocity variation is commonly modelled with a power-law profile with a surface velocity of zero. The commonly used power law is given in Equation 6.15.

$$V(z) = V(z = 10m) * \left(\frac{z}{10}\right)^{0.125} \tag{6.15}$$

Where:

- $V(z)$, Velocity at height z
- $V(z = 10m)$, Velocity at 10m (typical measurement height)
- z, Desired height in metres

The wind forces and moment are calculated using equations 6.16, 6.17, 6.18, and 6.19 from DNV (2021a).

$$F_{x_{wind}} = 0.5 * \rho_{air} * (V_{wind}[DP])^2 * AF_{wind} * (-0.7 * cos(\alpha)) \tag{6.16}$$

$$F_{y_{wind}} = 0.5 * \rho_{air} * (V_{wind}[DP])^2 * AL_{wind} * (0.9 * sin(\alpha)) \tag{6.17}$$

$$\alpha_2 = \begin{cases} \alpha, & 0 \leq \alpha \leq \pi \\ 2\pi - \alpha, & \pi \leq \alpha \leq 2\pi. \end{cases} \tag{6.18}$$

$$M_{z_{wind}} = F_{y_{wind}} * (XL_{air} + 0.3 * (1 - 2 * \alpha_2/\pi) * L_{pp}) \tag{6.19}$$

Where:

- $F_{x_{wind}}$, Force due to wind in x-direction (N)
- $F_{y_{wind}}$, Force due to wind in y-direction (N)
- $M_{z_{wind}}$, Moment due to wind around z-axis (Nm)
- $\rho_{air} = 1.226$, Air density (kg/m^3)
- AF_{wind}, Frontal projected wind area as from a picture in front view (m^2)
- AL_{wind}, Longitudinal projected wind area as from a picture in side view (m^2)
- α, Direction of environment
- XL_{air}, Longitudinal position of the area centre of AL_{wind} (m)

6.7.2. Current force

The current force is calculated similarly to the wind force with some differences. The current is generally constant over most of the depth and decreases near the seabed. Since the W2W vessel operates in relatively deep water, the latter can be neglected. Willemse et al. (2008) states that the longitudinal force, due to the underwater shape of the vessel, is mainly skin friction. The transverse force on the other hand, is pressure drag. According to DNV (2021a), the current forces and moment can be approached using equations 6.20, 6.21, and 6.22.

$$F_{x_{current}} = 0.5 * \rho_{sea} * (V_{current}[DP])^2 * B * D * (-0.07 * cos(\alpha)) \tag{6.20}$$

$$F_{y_{current}} = 0.5 * \rho_{sea} * (V_{current}[DP])^2 * AL_{current} * (0.6 * sin(\alpha)) \tag{6.21}$$

$$M_{z_{current}} = F_{y_{current}} * (XL_{current} + max(min(0.3 * (1 - 2 * \alpha_2/\pi), 0.25), -0.2) * L_{pp}) \tag{6.22}$$

Where:

- $F_{x_{current}}$, Force due to current in x-direction (N)
- $F_{y_{current}}$, Force due to current in y-direction (N)
- $M_{z_{current}}$, Moment due to current around z-axis (Nm)
- $\rho_{sea} = 1026$, Sea density (kg/m^3)
- $AL_{current}$, Longitudinal projected submerged current area as from a picture in side view (m^2)
- $XL_{current}$, Longitudinal position of the area centre of $AL_{current}$ (m)

6.7.3. Wave drift force

A formulation for the wave drift force is developed by Pinkster (1979). It exists of 5 components but the first one is dominant according to Willemse et al. (2008). According to DNV (2021a), the wave drift forces and moment can be approached using equations 6.23, 6.24, 6.25, 6.26, and 6.27.

$$F_{x_{wavedrift}} = 0.5 * \rho_{sea} * g * (H_s[DP])^2 * B * h(\alpha, bow_{angle}, C_{WL_{aft}}) * f(T'_{surge}) \tag{6.23}$$

$$F_{y_{wavedrift}} = 0.5 * \rho_{sea} * g * (H_s[DP])^2 * L_{os} * (0.09 * sin(\alpha)) * f(T'_{sway}) \tag{6.24}$$

$$T'_{surge} = T_z/(0.9 * L_{pp}^{.33}) \tag{6.25}$$

$$T'_{sway} = T_z/(0.75 * B^{.5}) \tag{6.26}$$

$$M_{z_{wavedrift}} = F_{y_{wavedrift}} * (x_{L_{os}} + (0.05 - 0.14 * \alpha_2/\pi) * L_{os}) \tag{6.27}$$

Where:

- $X_{L_{os}}$, Longitudinal position of Los/2 (m)
- bow_{angle}, Bow angle (rad)
- $C_{WL_{aft}} = A_{WL_{aft}}/(L_{pp}/2 * B)$, Water plane area coefficient behind midship (-)
- $A_{WL_{aft}}$ Water plane area behind midship (m^2)

6.7.4. Thruster forces

The Acta Centaurus is equipped with 5 thrusters, but in the worst-case scenario (a switchboard failure), only 2 of these thrusters remain active to create thrust. The available thrust can be calculated with equations 6.28, 6.29, and 6.30.

$$T_{eff} = T_{nom} * \beta_T \quad (6.28)$$

$$T_{nom} = \eta_1 * \eta_2 * (D_{prop} * P)^{2/3} \quad (6.29)$$

$$P = \eta_m * P_B \quad (6.30)$$

Where:

- T_{eff}, Effective thrust (N)
- T_{nom}, Nominal thrust with no wind, waves or current present (N)
- D_{prop}, Propeller diameter in meter (m)
- P, Power applied to the propeller (kW)
- P_B, Brake power in bollard pull (kW)
- η_1 and η_2, Efficiency factors (-)
- β_T, Thrust loss factor (-)
- η_m, Mechanical efficiency (-)

6.8. Verification of parametric model

Verification is the process of checking whether the built model was built correctly. To verify whether the parametric model is built correctly, the model can be tested with real data. The predictions of Acta Marine for the LSMGO ICE configurations are in agreement with the average RDM conclusions. When inserting an unusual number, the parametric model also behaves as expected. Table 6.2 shows the tested cases and results.

Table 6.2: Verification cases to test the parametric model

Test case	Result	Expected?
Autonomy of LSMGO at 100 days	No changes in vessel design	Yes
Gravimetric density of batteries at 0.1 GJ/t (25% of actual)	Length and width remain equal. Energy carrier weight*4. D increases to 7.58m (was 5.70) for 2-day autonomy.	Yes
Increase DP capability number with 1	Environmental forces increase and thus required thruster force increases	Yes
Required energy *2	required volume *2, more cases require design modifications	Yes
Added length + 20 m	Added width + 4.3 m, required thruster force increases	Yes
Added weight + 1000 ton	All draughts increase	Yes

6.9. Parametric model applied

With the parametric model build and verified, it can be applied to the 18 technical configurations that could be feasible options. These exist from combinations between energy carriers, energy converters and different autonomies.

The required energy, calculated with Equation 6.1, is shown per situation in Table 6.3. The required volume, according to Equation 6.2, is displayed in Table 6.4. From this table, it can be concluded that 13 out of 18 investigated options fit in the current hull in terms of volume and 5 need design modifications. The added length and width, are found by solving for $V_{add} = V_{req}$ and are shown in Table 6.5 and Table 6.6. The contained energy weight can be seen in Table 6.7 and the total weight can be seen in Table 6.8. With the new vessel dimensions and vessel weight known, the draught can be calculated and is shown in Table 6.9. The design load of the Acta Centaurus is a fuel tank filled for 50% which means 400 m^3 or 344 ton. Since this weight is larger than some technical configurations require, it is possible that the draught decreases. However, a constraint is set to avoid this and thus the minimum added draught is always zero. It can be noted that the added draught is relatively small for all technical configurations which can be led back to the fact that the length and width have also been increased in this technical configurations which led to an increased buoyancy.

For every situation, the environmental forces and thruster forces need to be calculated. If the maximum environmental force is lower than the thruster force, the propulsion system does not have to be changed. The summation of all environmental forces in DP capability 7 for the Acta Centaurus can be seen in Figure 6.5a. Because the thrusters are located far from the centre of rotation of the vessel, the moment around z that they can provide is significantly higher than the environmental moment and therefore the moment is not of interest. From the plot, it can be seen that the environmental forces in x-direction are smaller than in y-direction, which is expected as the longitudinal wind, wave, and current area is larger than the frontal area. In y-direction, the thrusters have no barriers and provide 8% more thrust than required for a static equilibrium. This is as expected because the Acta Centaurus is already in operation. When checking the environmental forces for different energy carriers, energy converters, autonomy, and thus sometimes design modifications, it can be noted from Figure 6.5b, which contains all polar plots, that there is not a lot of difference between the technical configurations.

6.10. Chapter conclusion

This chapter has answered the technical part of subquestion 5:

5. “*How can the technical and economical feasibility of multiple strategies be found and what are possible scenarios which may be used in deciding which strategy needs to be chosen for zero-emission W2W vessels?*”

In this chapter, a parametric model has been proposed, verified, and applied to 18 different technical configurations of energy carriers, energy converters, and autonomy. It can be concluded that, based on this parametric model, all investigated technical configurations are technically feasible options to use for zero-emission W2W vessels.

Table 6.3: Required energy depending on energy converter and autonomy.

Converter	**ICE**		**FC**		**FC+reformer**		**Battery**	
Autonomy (days)	14	28	14	28	14	28	1	2
Required Energy (GJ)	4069	8139	2713	5426	3875	7751	194	388

Table 6.4: Required contained volume depending on type of converter, autonomy, and type of energy carrier. Colour index: green doesn't require design impact, orange does require design impact, grey is not investigated because either not logical or impossible.

	Converter	ICE		FC		Battery	
	Autonomy (days)	14	28	14	28	1	2
Required volume (m^3)	LSMGO	111	222				
	HVO	93	186				
	H2c			678	1356		
	H2l			542	1085		
	MeOH	258	515	245	490		
	NH3	581	1163	554	1107		
	Battery					692	1384

Table 6.5: Added length depending on type of converter, autonomy, and type of energy carrier. Colour index: green no added length, orange needs longer hull, grey is not investigated because either not logical or impossible.

	Converter	ICE		FC		Battery	
	Autonomy (days)	14	28	14	28	1	2
Added Length (m)	LSMGO	0	0				
	HVO	0	0				
	H2c			0	1.39		
	H2l			0	0.6		
	MeOH	0	0	0	0		
	NH3	0	0.83	0	0.67		
	Battery					0	1.47

Table 6.6: Added width depending on type of converter, autonomy, and type of energy carrier. Colour index: Green no added width, orange needs wider hull, grey is not investigated because either not logical or impossible.

	Converter	ICE		FC		Battery	
	Autonomy (days)	14	28	14	28	1	2
Added width (m)	LSMGO	0	0				
	HVO	0	0				
	H2c			0	0.30		
	H2l			0	0.13		
	MeOH	0	0	0	0		
	NH3	0	0.18	0	0.14		
	Battery					0	0.32

Table 6.7: Required energy weight depending on type of converter, autonomy, and type of energy carrier. Colour index: Green is lower than design load (344 ton), orange is higher than design load, grey is not investigated because either not logical or impossible.

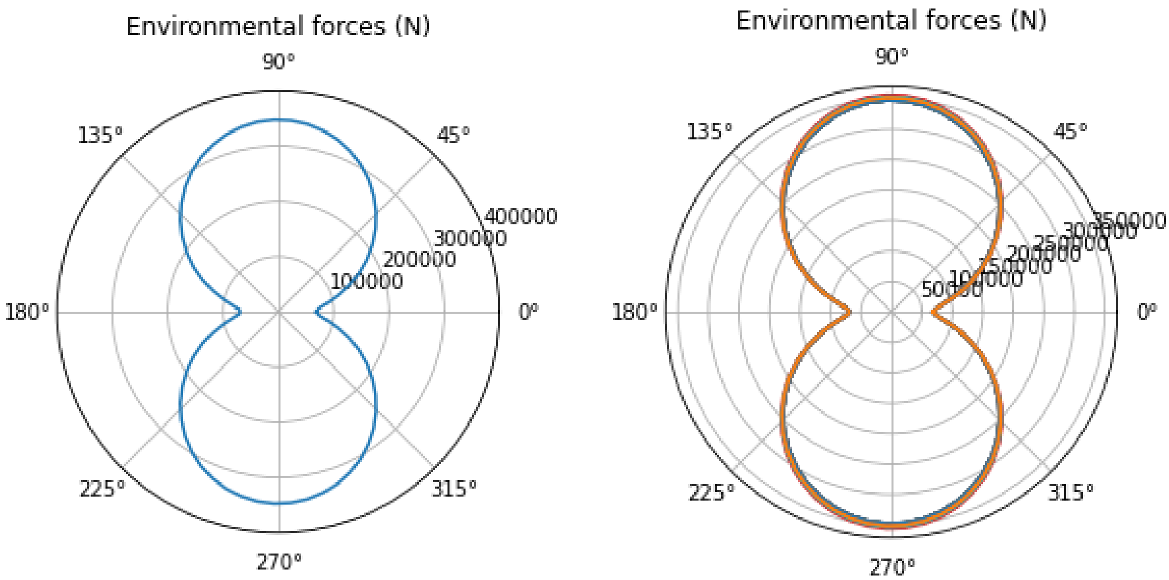
	Converter	ICE		FC		Battery	
	Autonomy (days)	14	28	14	28	1	2
Required contained energy carrier weight (ton)	LSMGO	95	191				
	HVO	86	172				
	H2c			493	986		
	H2l			319	638		
	MeOH	326	651	310	620		
	NH3	356	713	339	679		
	Battery					484	969

Table 6.8: Total added weight depending on type of converter, autonomy, and type of energy carrier. Colour index: Green is negligible added weight (up to 12 ton) orange is more added weight, grey is not investigated because either not logical or impossible.

	Converter	**ICE**		**FC**		**Battery**	
	Autonomy (days)	14	28	14	28	1	2
Added weight (ton)	LSMGO	0	0				
	HVO	0	0				
	H2c			113	608		
	H2l			0	259		
	MeOH	0	307	0	240		
	NH3	12	369	0	299		
	Battery					92	578

Table 6.9: Added draught depending on type of converter, autonomy, and type of energy carrier. Colour index: green is no added draught, yellow is increased draught, and grey is not investigated because either not logical or impossible.

	Converter	**ICE**		**FC**		**Battery**	
	Autonomy (days)	14	28	14	28	1	2
Added draught (m)	LSMGO	0	0				
	HVO	0	0				
	H2c			0.08	0.13		
	H2l			0	0.05		
	MeOH	0	0.21	0	0.16		
	NH3	0.01	0.09	0	0.07		
	Battery					0.06	0.10



(a) Environmental forces on Acta Centaurus for DP capability 7

(b) Environmental forces for all investigated situation for DP capability 7

Figure 6.5: Environmental forces

7

Robust Decision Making model

Sections 7.1 to 7.4 will first discuss the XLRM framework in which all uncertainties, policies, metrics, and relationships will be set. After a model is built around this XLRM framework, section 7.5 will perform verification to exclude potential errors from the model.

Section 7.6 discusses step 2 and 3 of the RDM which evaluates the technical configuration across multiple futures and performs a vulnerability analysis on this evaluation. In this section the first results are presented on the economical feasibility of zero-emission W2W vessels. In section 7.7, a trade-off analysis on the results is performed and new futures are proposed for a second RDM. Section 7.8 discusses the second RDM iteration. Normally, an RDM is performed a myriad of times to optimise the results, but in this research this is deemed unnecessary. Section 7.9, gives the final conclusions on the economical feasibility of the 18 technical configurations under all proposed economical situations.

7.1. Exogenous uncertainties (X)

Exogenous uncertainties are uncertainties that cannot be controlled by a company (Farlex Financial Dictionary, 2009). The exogenous uncertainties used in this RDM are the energy carrier price, energy carrier availability, annual utilisation of a W2W vessel, DR or pay willingness (PW), vessel costs, and OWF to port sailing distance.

7.1.1. Energy carrier price

The price of the energy carrier has a large impact on the daily costs of the vessel. The average price of LSMGO over the last 3 years (€10.05/GJ [1]) and the average consumption per day (7.2 m^3/day) give a good estimate of the daily energy carrier costs over the years; €3000/day. The energy costs impact the total costs for the client and thus negatively impact the DR.

Energy carrier prices fluctuate over long periods of time. Furthermore, the prices of renewable energy carriers are expected to decrease, whereas the price developments of LSMGO and HVO are unknown. In chapter 3, long-term price projections have been found for all different energy carriers. A summary of the important prices can be found in Table 7.1. These prices represent the starting and end prices in this research. However, the price development over the years is still unknown, and the 2050 projection is based on a lot of uncertainty itself.

Table 7.1: Summary of the important energy carrier prices

	Fuel costs 2022	Fuel costs 2050	Source
LSMGO	€ 10.05 [1]	€ 10.05	Ship & Bunker, 2021
HVO	€ 25.36	€ 25.36	S&P Global Platts, 2020
Hydrogen	€ 33.33	€ 7.18	European Commission, 2020; IRENA, 2020a
Methanol	€ 57.00	€ 29.00	ABS, 2022
Ammonia	€ 25.47	€ 21.67	IRENA, 2019; Lloyds Register, 2020
Batteries	€ 27.54	€ 4.79	IRENA, 2020a; IRENA, 2020b

Since short-term price fluctuations depend on supply and demand for all energy carriers, it is decided to ignore fluctuations. However, long-term price changes will be incorporated. Since there is no knowledge of the future, a simple linear price decrease is assumed from the 2022 price to the 2050 projection. It is decided that complicated projections on energy price per year or exponential decrease is not beneficial because this only adds uncertainty to the model and does not per definition give a better result.

The projection for 2050 is increased and decreased with 30% to find the influence of the price of the energy carrier on the economic feasibility of the W2W vessel. A 30% uncertainty is chosen after considering the enormous volatility that energy prices have shown due to Covid-19 (Olubusoye et al., 2021) and the Ukraine war (Islam, 2022). These events show that predictions are often wrong, and a (large) uncertainty must be taken into account for the projected price in 2050. As explained in section 5.3, the first iteration of the RDM needs to provide information on which variables additional information is required by varying more.

The price developments used in the RDM can be seen in Figure 7.1. Only renewable electricity falls below the LSMGO price before 2050. However, the graph does not show converter efficiencies, which influence the amount of energy that is required, and does not show a potential CT. The latter is a separate uncertainty and is discussed in another section.

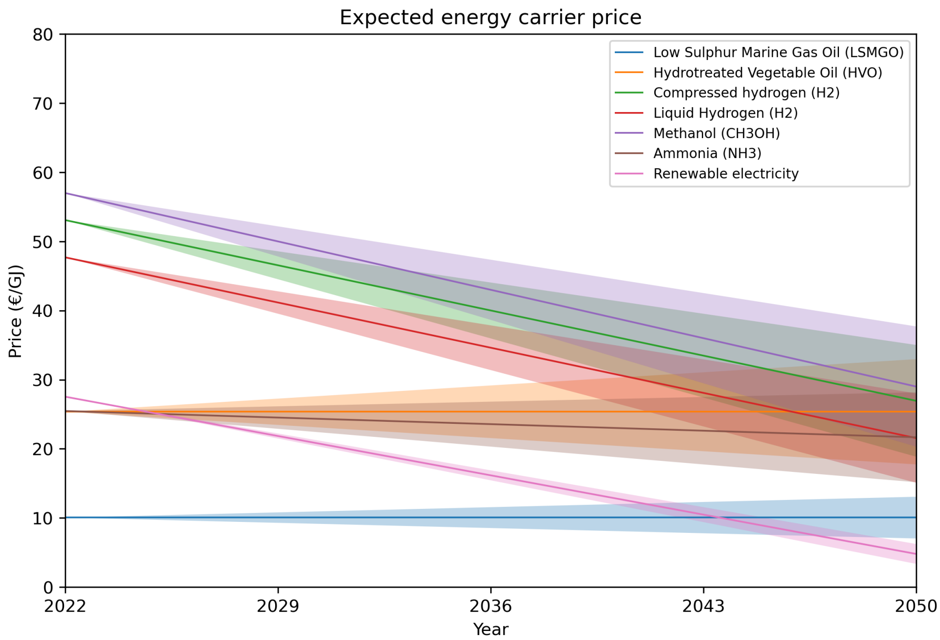


Figure 7.1: Energy carrier price projections (Based on Table 3.1)

7.1.2. Energy carrier availability

The availability of energy carriers is the second exogenous uncertainty. W2W vessels work from one base port for the entire duration of the project, and this base port needs to have bunker facilities for the specific energy carrier in place. If this is not the case, the W2W vessel must be bunkered through trucks, which is more time-consuming and more expensive.

The average availability is based on the authors' professional opinion. This could influence the results of this work and therefore its impact must be investigated [3]. The average availability of LSMGO in the ports used by Acta Marine was 80% and is expected to remain at 80%. However, it is possible that this increases or decreases slightly. Therefore, higher and lower projections for 2050, with a linear increase or decrease of 70% and 90% are also investigated.

The current availability of HVO for Acta Marine is 30% and is expected to increase. This is because in section 3.5 it was found that with relatively small modifications regular HFO bunkering systems can be used. However, it is not expected that HVO will overtake LSMGO before 2050, because the author

[3]The (average) availability is something the author cannot find in the public literature. It has been attempted to contact the 15 ports most used by Acta Marine. However, most of these ports either did not have their own projections (publicly available) or did not respond, which led to too little information to draw a conclusion.

expects that other energy carriers will become more dominant before 2050. Today, an average availability of 30% is estimated to increase to 50% by 2050. However, due to uncertainty in development, higher and lower projections with a linear development to 30% (constant) and 70% (increase) are also investigated.

The third energy carrier, of which there is already availability, is renewable electricity. This is estimated to be available in 10% of ports and is expected to increase to 40%. This increase is mainly powered by the proposed 'fit for 55' package (European Commission, 2021) from the EC, which requires ports to deliver shore power. However, the package is not yet approved, and grey power may also be delivered as shore power. On the other hand, the author thinks that it is feasible that an even higher increase in availability will occur due to the increase in OWFs and other green energy options. As illustrated, it is not yet known how the availability of green electricity will develop. For this reason, a higher and lower projection of 2050 with linear development to 10% (constant) and 70% (steep increase) are also investigated.

The average availability of alternative energy carriers is also expected to increase. Currently, there is no public bunkering infrastructure available for green methanol, green ammonia, or green hydrogen, and it is also difficult to predict when this infrastructure will become available. Acta Marine hears rumours that in 2030 public port availability will arise (Banen, 2021). However, it could also start earlier if a port decides that it is time or it could start later because the demand is not yet high enough. Therefore, the availability is modelled to start in 2025, 2030, or 2035. In addition to this, it is expected that the availability will increase to 50% with a lower limit of 20% and a higher limit of 80%.

The availability of bunker infrastructure in ports is shown in Figure 7.2 and shows the expectations of the author.

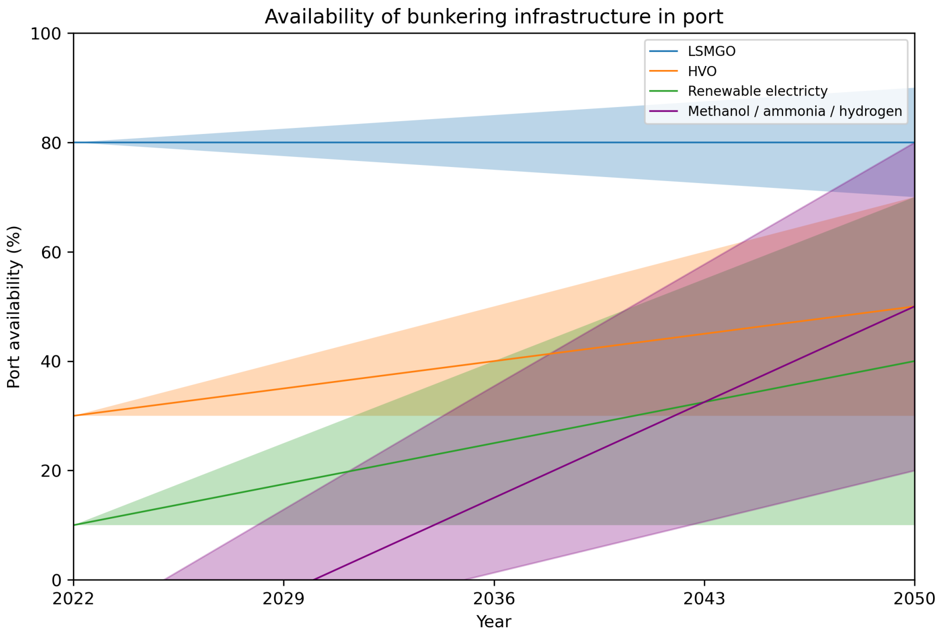


Figure 7.2: Availability of energy carriers in port.

7.1.3. Utilisation of a W2W vessel

Also, the utilisation of the W2W vessel will have an impact on its profitability, because when the vessel is not on contract, it costs money because there are many fixed and constant costs. However, it is never expected that the W2W vessel has a utilisation of 100%. This is simply not possible due to the need for maintenance and idle time between different projects. According to Legemate (2021), a rough number on the average utilisation rate of Acta Marine W2W vessels is 80% (292 days per year). Therefore, it is assumed that the maximum utilisation of the W2W vessel is 90% (329 days) per year. It is also assumed that in the worst-case scenario, the W2W vessel can only be used for 70% of the year. This is not very unlikely because there are always fewer jobs in winter because maintenance is easier in summer. Utilisation will be modelled to remain constant for the W2W vessel throughout its lifetime. This is accurate because in some years it can go better than in other years, but the average utilisation rate is expected to remain between 70% and 90%. The considered rates are shown in Table 7.2.

Table 7.2: Utilization rate of the future W2W vessel

Scenario	Low bound	Expected	High bound
Utilization	70%	80%	90%

7.1.4. Day rate

Just like the utilisation, the DR may vary between summer and winter, per project, per vessel, per economic phase, and is influenced by many more parameters. Therefore, the DR is also modelled to be continuous. The expected DR is modelled as the historic average with a low and high bound of 20% lower or higher. 20% is chosen as it is slightly higher than the deviation that has been seen.

The client has always paid for the LSMGO in addition to the DR. Therefore, the PW of the client is estimated to be the DR plus the average LSMGO fuel costs per day, which are €3000. In addition, the assumption is made that clients are expected to pay more (€1000) for a zero-emission vessel because it is good for their image. The PW minus the daily energy carrier costs can be used as the DR for the vessel owner. For confidentiality reasons, the actual numbers are excluded for this report.

7.1.5. OWF to port distance

The distance between an OWF and a port is important because it influences the operational uptime of the W2W vessel. In other words, it decreases the amount of time that the W2W vessel can use for short cycles. In chapter 2, it has been concluded that most OWFs are still built within a 60 km distance from shore, but future OWFs (permits already granted) will be at greater distances of up to 200 km. To determine the influence of the distance, the OWF to port distance is set at 50, 125, or 200 km, which can be seen in Table 7.3.

Table 7.3: Distance between the OWF and the port

Scenario	Low bound	Expected	High bound
Distance (km)	50	125	200
NM	27	67.5	108

7.1.6. Vessel costs

In this research CAPEX is modelled as the summation of a variable 'Vast CAPEX' (VC) and a constant 'energy system CAPEX'. Total CAPEX can be calculated with Equation 7.1.

$$CAPEX = Vast\,CAPEX + Energy\,system\,CAPEX \tag{7.1}$$

Where:

- $Vast\,CAPEX$, All CAPEX without energy carrier system CAPEX. Is modelled as exogenous uncertainty according to **??**.
- $Energy\,system\,CAPEX$, CAPEX for the energy converter and the (tank) storage. This is depending on the technical configuration according to Table 7.4.

The costs for the vessel without its energy system and design modifications are considered constant and are defined as VC. As discussed in section 2.8, CAPEX depends on materials, labour, and overhead. VC already includes mission equipment, vessel equipment, financing costs, and contingencies The low bound, average, and high bound VC are based on historical values from market investigation by Acta Marine. For this reason they are excluded for confidentiality reasons.

In addition to the VC, the energy system costs, and hull adaption costs are part of the total CAPEX. According to Guegan et al. (2020), 90% of CAPEX of OSVs depends on vessel lightweight. This gives a tool to calculate the added costs for hull adaptions based on the old and new lightweight. However, most added lightweight is 0.07% for the 28 days H2c FC case. Since this lightweight addition is so extremely low, the author has decided that this addition in CAPEX falls below the precision of this research outcome and is therefore neglected.

Energy system costs are divided into converter costs and storage tank costs. The cost relations per kW for the converter and per GJ for the storage system of chapter 3 are used to calculate the additional CAPEX. The results are shown in Table 7.4. The table shows the great differences between converters and energy carriers. For different autonomy periods, relatively large differences can also be seen for hydrogen and batteries. This is as expected because the storage systems for hydrogen are complicated and thus expensive, whereas for batteries, the costs exist solely of the storage system because there is no converter.

Table 7.4: CAPEX energy carrier system. Colour index: Green is the low end (up to 30% higher than the base case), orange is average, red is the high end (factor 5 higher than the base case), and grey is not investigated because it is either not logical or impossible.

	Converter	**ICE**		**FC**		**No converter (battery)**	
	Autonomy (days)	14	28	14	28	1	2
Energy carrier CAPEX (10^6 €)	LSMGO	3.60	3.71	nan	nan	nan	nan
	HVO	3.60	3.71	nan	nan	nan	nan
	H2c	nan	nan	14.80	18.64	nan	nan
	H2l	nan	nan	14.80	18.64	nan	nan
	MeOH	3.77	3.96	11.22	11.37	nan	nan
	NH3	4.10	4.40	4.61	4.86	nan	nan
	Battery	nan	nan	nan	nan	23.20	46.40

7.2. Policy Levers (L)

Policy levers are tools, such as laws and regulations, that a government uses to direct, manage, and shape changes in public services (BCCDC, 2016). The policy lever considered in this research is a CT which changes in size and start year. Other policy levers including subsidies and external forces which accelerate price decreases or availability have also been considered. However, it is decided that these will complicate the model to much while they are very hard to model due to their randomness.

The CT policy lever implements a fine for all emitted WTW CO_2. As concluded in section 3.1, the maritime industry is currently excluded from the EU ETS system but is likely to be included before May 2024. However, offshore will be left exempt. A new EC starts in 2025 and ends in 2030 and rumours are that this commission will imply a CT by the end of its term (Anink, 2021). However, it can always be earlier or later, and therefore it is modelled that the CT will start at 2025, 2030, or 2035.

In January 2022, the EU ETS price for 1 ton CO_2 is $80 (€69) (European Energy Exchange AG, n.d.). It is expected that the CT increases further but will start at a lower price for shipping (Banen, 2021). Therefore, the assumption is made that the CT will start at 50 €/ton CO_2. Furthermore, ABS (2022) states that a CT of 300 €/ton CO_2 is required to make alternative energy carriers competitive. This CT is therefore set as maximum because when this is reached, there is no incentive anymore to increase the CT since it is cheaper to switch to alternative energy energies. €100 is chosen as the low limit 2050 price because the price of an ETS was €69 on January 2022, is expected to be €79 in 2030 and thus if linearly extrapolated will be approximately €100 in 2050. The CT is modelled as a linear increase from 50 to 100, 200, or 300 €/ton CO_2. This can be seen in Figure 7.3.

7.3. Metrics (M)

There are three metrics that describe the performance of the W2W vessel. Operational uptime, profit, and emissions.

7.3.1. Operational uptime

The number of wind turbine connections illustrates the effectiveness of the W2W vessel and thus influences the PW of the client. As explained in chapter 2, the number of transfers depends on the weather conditions, the vessel capabilities, and the client pace. The average short cycle time was concluded to be 70 minutes and thus 20.6 transfers per day when in field. In order not to complicate the model, the

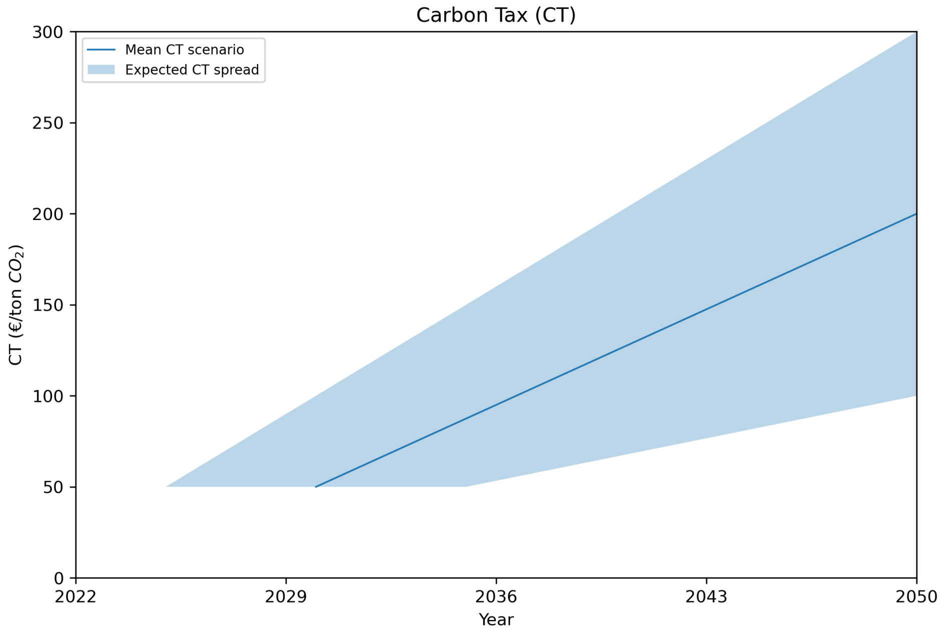


Figure 7.3: Carbon Tax projections

weather conditions and client pace are set to be constant and as concluded in chapter 6, the vessel capabilities hardly change.

However, a port call costs time and recharging at sea would also cost time. Thus, this would negatively influence the average number of transfers per day and thus the effectiveness, project duration, and PW of the client. The highest and lowest operational uptime were displayed in Figure 2.11 and show that port time and transit influence operational uptime quite significantly (98.4% to 89.6%). The operational uptime is calculated according to Equation 7.2.

$$uptime = ((V_{trans} * D_{OWFtoPort} * 2 + T_{port} + 6 * x * IfBatt) * PC)/(x * hpd) * 100 \quad (7.2)$$

Where:

- uptime, Operational uptime per x days (%)
- V_{trans}, Transit speed (km/h)
- $D_{OWFtoPort}$, Distance between a OWF and port (km)
- T_{port}, Time in port (h)
- x, Period used in calculation (days)
- PC, Port Calls per x days (either 1 or 2)
- IfBatt, A constant of either 1 (for batteries) or 0 (for other energy systems)
- hpd, Hours per day (24)

The distance between an OWF and a port is an exogenous uncertainty, and the time in port depends on the bunker time which is different per energy carrier. The transit speed is held constant at 10 kts or 18.52 km/h and the number of port calls is either 1 or 2 per 28 days, corresponding to the amount of energy that the vessel can take. In addition to port calls every 14 or 28 days, the battery needs to be recharged every day or every other day depending on the technical configuration.

7.3.2. Profit

As identified previously, the objective is not only to investigate the technical feasibility of the zero-emission W2W vessel, but also the economical feasibility. The profit of the vessel is an important metric. The W2W vessel may not lose money and targets for return on investment (ROI) and payback time must be met.

According to OECD (2014), the long-term interest rate for the last 10 years (December 2011, December 2021) in the euro area has been a maximum of 4.1%, a minimum of -0.1%, and had an average of 1.6%.

When ROI is equal to the long-term interest rate, the BEP is found for investing or not. Therefore, the investor requires a higher ROI than the long-term interest rate.

To compare multiple proposals, the Net Present Value (NPV) or Internal Rate of Return (IRR) can be used. The highest NPV indicates the best investment, and if the NPV is positive, the company is making profit under the assumptions that are made. However, the NPV depends so much on these assumptions that an investor will most likely not invest in a low NPV. Therefore, in practise, a certain NPV threshold is expected.

Another possibility is to use the IRR. If the IRR is higher than the weighted average cost of capital (WACC), the investment makes a margin above capital costs including debt and equity returns. The problem with IRR is that it cannot consider the rate at which the earnings are reinvested. However, the practical importance of the IRR method is great because it allows the comparability of investment forms with flexible cash flows.

Although both options are suitable, the NPV method is selected for this research so that multiple proposals can be easily compared. The NPV formula is shown in Equation 7.3.

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} \tag{7.3}$$

Where:

- R_t, Net cash inflow-outflows during a single period t
- i, Discount rate or return that could be earned in alternative investments
- t, Number of timer periods

7.3.3. Emission reduction per wind turbine

Since the goal of this research is to reduce emissions to zero, the emissions per wind turbine must also be zero. As discussed above, this is theoretically possible for green methanol, green ammonia, and green hydrogen. However, this is not possible for HVO and LSMGO (benchmark). Therefore, the emissions for these energy carriers are calculated to compare the reductions.

To describe the emissions of a maritime vessel, there is the EEDI, which is discussed in section 3.1. EEDI describes the emissions per amount of transported work. However, W2W vessels carry relatively low volumes of cargo and do not cover a lot of distance, and therefore emissions must be described differently.

As identified in section 2.6, the operational time of the W2W vessel can be split into three categories; port, transit, and OWF. During transit, emissions can be described per unit of distance and in port per unit of time. However, the goal is to express the emissions in a unit of W2W vessel work. The work of the W2W vessel is to transfer personnel and cargo to a wind turbine. It is not fair to measure the number of persons or cargo weight because this is different every time and hardly affects the short cycle time. For this reason, the number of connections is measured, and emissions are measured per wind turbine connection. The equation to measure the emissions per wind turbine is shown in Equation 7.4.

$$EWTC = \frac{m_{CO_2}}{n_{WTC}} \tag{7.4}$$

Where:

- EWTC, Emissions per Wind Turbine Connection (kg)
- m_{CO_2}, Total emitted CO_2 per x days (kg)
- n_{WTC}, Number of Wind Turbine Connections per x days

7.4. Relationships (R)

The relationships explain how all uncertainties, policies, and metrics are influenced by each other. A relationship matrix has been set up to visualise all direct relations. Only direct relations are given because including indirect relations will greatly complicate the model while also introducing many what-ifs.

An example of an indirect relationship is the relation between the energy carrier price and the emissions per wind turbine connection. At first sight, there is no direct relation. However, one could say that a lower alternative energy carrier price leads to a higher attractiveness to invest in alternative energy carriers which leads to lower emissions per wind turbine connection. One could also say that a high utilisation number is more likely to represent a SOV and, therefore, vessel costs are likely to be lower. These indirect relations are not considered in the model. However, it is important to note that they (might) exist and therefore the model will not be a perfect representation of reality.

An example of a direct relationship is the relationship between the energy carrier price and the CT. If the CT increases, the price of carbon-emitting energy carriers also increases. Another example is the relationship between operational uptime and profit. If the operational uptime is higher, the client is more likely to have a higher PW, and thus a higher profit. Additionally, a higher operational uptime decreases the emissions per wind turbine connection because the vessel is operating longer in the OWF in the same amount of time. An overview of all direct relations is shown in Table 7.5.

Not all relations are directly modelled to find the required results. The relation between utilisation and DR or PW is a relation which can be seen in the market because vessel owners are willing to decrease their DR if a longer contract can be acquired. Although this relation is not directly modelled, one can see its influence by comparing results for high utilisation with low PW and the other way around.

The relation between operational uptime and availability is assumed to have a minimum impact on the results and is therefore not modelled. The relation between operational uptime and PW is assumed to be existing, but this relationship will be considered, if necessary, in a second iteration after provisional conclusions are drawn.

Table 7.5: Relationship matrix between exogenous uncertainties (X), policy levers (L) and metrics (M). ↑ is a positive relationship. (If one increases, the other increases as well.) ↓ is a negative relationship. (If one increases, the other decreases.) - is no direct relationship. Green arrows (↑↓) are relations that are modelled. Black arrows are relationships which are not (directly) modelled.

	Price (X)	Availab. (X)	Utili. (X)	DR & PW (X)	Dist. (X)	VC (X)	CT (L)	Uptime (M)	Profit (M)	EWTC (M)
Price		↓	-	-	-	-	↑	-	↓	-
Availability	↓		-	-	-	-	-	↑	↑	-
Utilisation	-	-		↓	-	-	-	-	↑	-
DR & PW	-	-	↓		-	-	-	↑	↑	-
Distance	-	-	-	-		-	-	↓	-	↑
Vessel costs (VC)	-	-	-	-	-		-	-	↓	-
Carbon Tax (CT)	↑	-	-	-	-	-		-	↓	-
Uptime	-	↑	-	↑	↓	-	-		↑	↓
Profit	↓	↑	↑	↑	-	↓	↓	↑		-
EWTC	-	-	-	-	↑	-	-	↓	-	

Upon investigating the relationship matrix (Table 7.5), most relationships are between metrics and exogenous uncertainties or policy levers. There are not many direct relationships between exogenous uncertainties and policy levers or among each other.

Total CO_2 emissions are affected by the choice of alternative energy carrier and energy consumption per day. The number of wind turbine connections is influenced by operational uptime, which itself is affected by multiple others, including the choice of the energy carrier and the distance between the OWF and the port.

Operational uptime, or time in the OWF, is mainly influenced by the time in port and the duration of transit. Because these three phases make up the long cycle period, the operational uptime is the remaining time after subtraction of the port and transit time. The port time is mainly affected by bunker time, which is affected by the bunker duration of the alternative energy carrier but also by the availability of this energy carrier. Because if the energy carrier is not available, bunker trucks must provide bunkering which increases the bunker time. The time in transit depends on the velocity of the W2W vessel (constant in this research) and on the distance between the OWF and the port. Operational uptime influences the total emissions per wind turbine and influences PW.

The profit, which is compared in the form of a 20-year NPV is influenced by the cash inflow, cash outflow, and the interest rate. The interest rate is set constant with the long-term interest rate for the last 10 years (1.6% according to OECD (2014)). However, it is common to bring equity to the table, which is either from the company itself (savings) or from shareholders. This is not a loan. Equity from shareholders requires a higher equity return than the interest rate on the loan. According to Hartholt (2022), the required equity rate has, on average, been 10% in the last years. A made-up debt share of 30% high interest and 70% low interest is used in this research. The required interest rate can be calculated as the WACC and is equal to 4.12% (Equation 7.5).

$$WACC = i_1 * DS_1 + i_2 * DS_2 = 1.6\% * 0.7 + 10\% * 0.3 = 4.12\% \tag{7.5}$$

Cash inflow and outflow are influenced by a list of things. The calculation of cash flows as performed in this research is summarised in Equation 7.6 up to Equation 7.14.

$$revenue = PW + Hotel\,catering\,fees \tag{7.6}$$

$$OPEX = Fixed\,OPEX + Energy\,Carrier\,costs + CT\,costs + Truck\,costs\,(Port\,availability) \tag{7.7}$$

$$Gross\,Margin = revenue - OPEX \tag{7.8}$$

$$EBITDA = Gross\,Margin - overhead \tag{7.9}$$

$$EBIT = EBITDA - Amortization - Depreciation\,W2W - Depreciation\,intermediate\,and\,special\,surveys - Depreciation\,FC\,or\,battery\,replacement \tag{7.10}$$

$$EBT = EBIT - interest \tag{7.11}$$

$$interest = (Debt\,start\,year + Debt\,end\,year)/2 * Interest\,Rate \tag{7.12}$$

$$Netresult = EBIT - Tax \tag{7.13}$$

$$Cash\,flow = EBIT + Depreciation + Amortization - Tax - investment - CAPEX\,surveys - CAPEX\,FC\,or\,battery\,replacement + Termination\,value \tag{7.14}$$

7.5. Verification of XLRM model

All exogenous uncertainties (X), policy levers (L), relationships (R), and metrics (M) have been modelled in a python script. Before, the second step of the RDM, evaluating the strategy across the multiple futures, can be started, the model working must be verified first. This is done by inserting multiple unusual numbers to see how the model reacts. When inserting unusual numbers, according to the test cases in Table 7.6, the model behaves as expected.

7.6. RDM step 2 and 3: Evaluating and vulnerability analysis

In this section, the operational uptime, the CO_2 emissions per wind turbine connection, and the NPV will be evaluated and analysed under all possible futures. The goal of this analysis is to find strengths and weaknesses of the different futures which enable a second iteration of the RDM to perform better.

7.6.1. Operational uptime analysis

The operational uptime is analysed for all 18 technical configurations, and all the uncertainties. However, the only uncertainty that influences the operational uptime is the distance between the OWF and the port. The results are shown in (Figure 7.4).

Table 7.6: Verification cases to test the models.

Test case	Result	Expected?
Vast CAPEX 2*expected	90% of scenarios have negative NPV	Yes
Vast CAPEX to €0	95% of scenarios have positive NPV	Yes
Day rate 2*expected	All scenarios have NPV higher than €70 million	Yes
Day rate to €0	All scenarios have NPV lower than €80 million	Yes
All energy carrier prices equal to LSMGO price	Ammonia and methanol ICE have the highest average NPV due to CT on HVO and LSMGO. Ammonia FC is less profitable due to the FC costs	Yes
Speed to 0	Operational uptime to 0	Yes
Distance to 10.000 km	Max operational uptime to -225% because sailing time is larger than 28 days	Yes
CT at constant €1000	It heavily decreases NPV of LSMGO and HVO scenarios. LSMGO high CT becomes loss making in 100% of the scenarios. Average case of all LSMGO and HVO becomes loss making	Yes
Utilisation to 0	All scenarios have NPV lower than €80 million	Yes

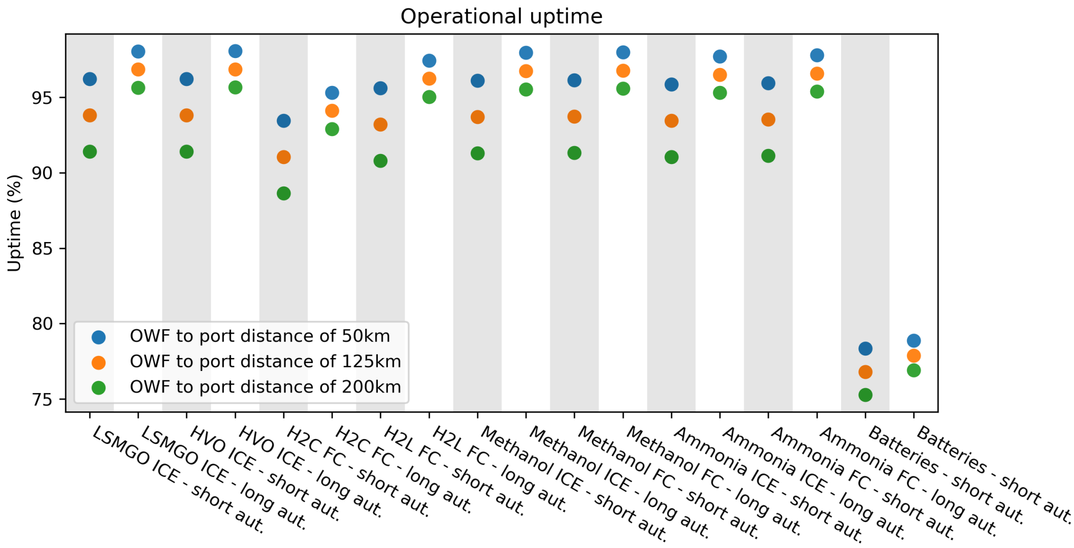


Figure 7.4: Operational uptime

From the graph, it can be seen that the operational uptime of batteries is very low compared to the others. This can be led back to the fact that the there is a significant downtime in field to recharge the batteries. It may also be noted from the graph that the OWF to port distance has a reduced impact on the long autonomy cases compared to the short autonomy.

One of the effectiveness requirements for a new W2W vessel is that operational uptime is greater than 90%. Therefore, it is determined from Figure 7.4 that batteries are not a feasible option at this time. In addition, for 200 km between the port and the OWF, the operational uptime of H2c drops below 90%. This is mainly due to the longer bunker duration of gas. Since future OWFs are expected to be located farther from shore and because the aim is to achieve a robust solution, H2c is deemed not feasible.

To calculate the emissions per wind turbine connection, an absolute number is required. In section 2.6, it has been concluded that the average short cycle time is 70 minutes. The number of wind turbine connections per 28 days can be calculated with this short cycle time. For an OWF to port distance of 200 km and only for long autonomy's, the number of wind turbine connections can be seen in Table 7.7.

Table 7.7: Number of wind turbine connections for 28 days (long autonomy) for different technical configurations

LSMGO	HVO	H2C	H2CL	Methanol		Ammonia		Batteries
ICE	ICE	FC	FC	ICE	FC	ICE	FC	
564	564	549	561	564	564	562	563	454

7.6.2. CO_2 emission analysis

In this research, the assumption is made that methanol, ammonia, hydrogen, and batteries have no WTW emissions. This assumption is based on the theory that if all WTT emissions are also zero, the alternative energy carriers have zero WTW emissions. In reality, this is not true, but the WTT emissions are relatively low compared to the WTW emissions, and it is assumed that the supply chain supporting alternative energy carriers is also reducing its emissions.

The LSMGO and HVO emissions are calculated with Equation 7.15. The WTW CO_2 emissions for both energy carriers are shown in Table 7.8 for 28 days. Emissions per wind turbine connection, calculated with Equation 7.4, can be seen in Table 7.9.

No energy carriers are excluded based on these results because it was already known that these energy carriers would emit CO_2. However, the results are necessary to map the amount of CO_2 emissions that are reduced by switching to alternative energy carriers. In addition, the amount of carbon is required to calculate the CT. As an example, the CT per year is shown in Table 7.10 for an 80% utilisation, an autonomy of 28 days, and the average CT policy.

$$m_{CO_2} = \dot{CO}_2 * E_{req_{day}} * x \tag{7.15}$$

Where:

- m_{CO_2}, Total emitted CO_2 per x days (kg)
- $\dot{CO}_2$, CO_2 emissions (kg/GJ)
- $E_{req_{day}}$, Required energy per day (GJ)

Table 7.8: WTW CO_2 emissions for 28 days for LSMGO and HVO

	WTW emissions (kg/GJ)	**WTW emissions (t/28 days)**
LSMGO	32.6	708.9
HVO	87.1	264.9

Table 7.9: WTW CO_2 emissions per wind turbine connection in tons for a 28 day autonomy (tons). Colour index: Green to red for zero-emission to 1.4 tons of emissions.

	LSMGO ICE		HVO ICE	
	14-day Aut.	28-day Aut.	14-day Aut.	28-day Aut.
OWF to port distance of 50 km	1.35	1.29	0.50	0.48
OWF to port distance of 125 km	1.31	1.27	0.49	0.47
OWF to port distance of 200 km	1.28	1.25	0.48	0.47

Table 7.10: Carbon tax in k€ / year based on scenario with 28-day autonomy, utilisation of 80% and the average carbon tax scenario (linear increase between €50 in 2030 to €200 in 2050)

	t/year	2022	2023	2024	2025	2026	2027	2028	2029	2030
LSMGO	7392.8	0	0	0	0	0	0	0	0	370
HVO	2762.5	0	0	0	0	0	0	0	0	138

	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040
LSMGO	425	481	536	591	647	702	758	813	869	924
HVO	159	180	200	221	242	262	283	304	325	345

	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
LSMGO	980	1035	1090	1146	1201	1257	1312	1368	1423	1479
HVO	366	387	407	428	449	470	490	511	532	553

7.6.3. First NPV analysis

Combining the 18 technical configurations from chapter 6 with the average, lower, and higher limits of the exogenous uncertainties and policy levers, 13122 situations are calculated and thus 13122 NPVs are found. This is shown with Equation 7.16.

$$Number\,Of\,Situations = Energy\,Carrier\,Converter\,Combinations\,(18) * Energy\,Carrier\,Price\,Levels\,(3) * Availability\,Levels\,(3) * Utilisation\,Levels\,(3) * Pay\,Willingness\,Levels\,(3) * Carbon\,Tax\,Policies\,(3) * Vast\,CAPEX\,Levels\,(3) = 18 * 3^6 = 13122 \quad (7.16)$$

Figure 7.5 shows violin plots of the NPV distribution for the different energy carriers. The plots visualise the range and likeliness of profit levels for the different technical configurations. A dashed line is visualised at 0 to visualise when investments may become profitable. Ammonia, in combination with both an ICE and an FC, performs relatively well. Additionally, it is noted that the CT does not show much variation in the LSMGO and HVO NPV distributions. However, a deeper analysis is required to see how the uncertainties and policy levels influence the NPV's of the individual energy carriers.

All 13122 NPVs are plotted in a cloud plot to show a distinction between NPV for the different technical configurations, different levels of PW, and different VC (Figure 7.6). The influence of PW on the NPV can be seen better when plotting the different NPV violin plots per energy carrier and PW in Figure 7.7. Another distinction can be seen when zooming in on the average PW. Figure 7.8 shows a clear relation between the different levels of VC and the profit of the technical configuration. Also, in this case it is possible to zoom in further on the average VC. In Figure 7.9, this case can be seen and it can be noted that for the technical configuration of batteries the utilisation is less determining than for the other technical configurations. When zooming in one level further, Figure 7.10 shows the 2050 price influence. Another zoom in (in Figure 7.11), shows the profit per autonomy duration and shows why batteries had such tall violin plot compared to other technical configurations. It shows that hydrogen and batteries with a long autonomy perform relatively bad compared to their short autonomy in terms of NPV. The last zoom in shows NPV per port availability (Figure 7.12) and shows that this hardly influences the profit. Although, the relations are only showed for particular situations, they are true for other economical situations as well.

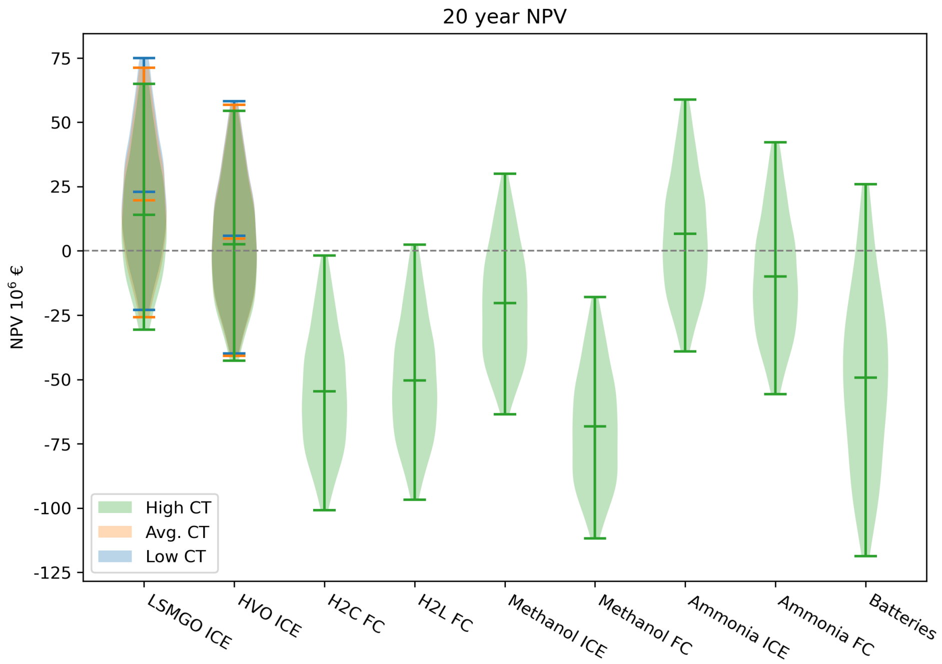


Figure 7.5: Violin plots of the NPV distribution for the different energy carriers under all different situations.

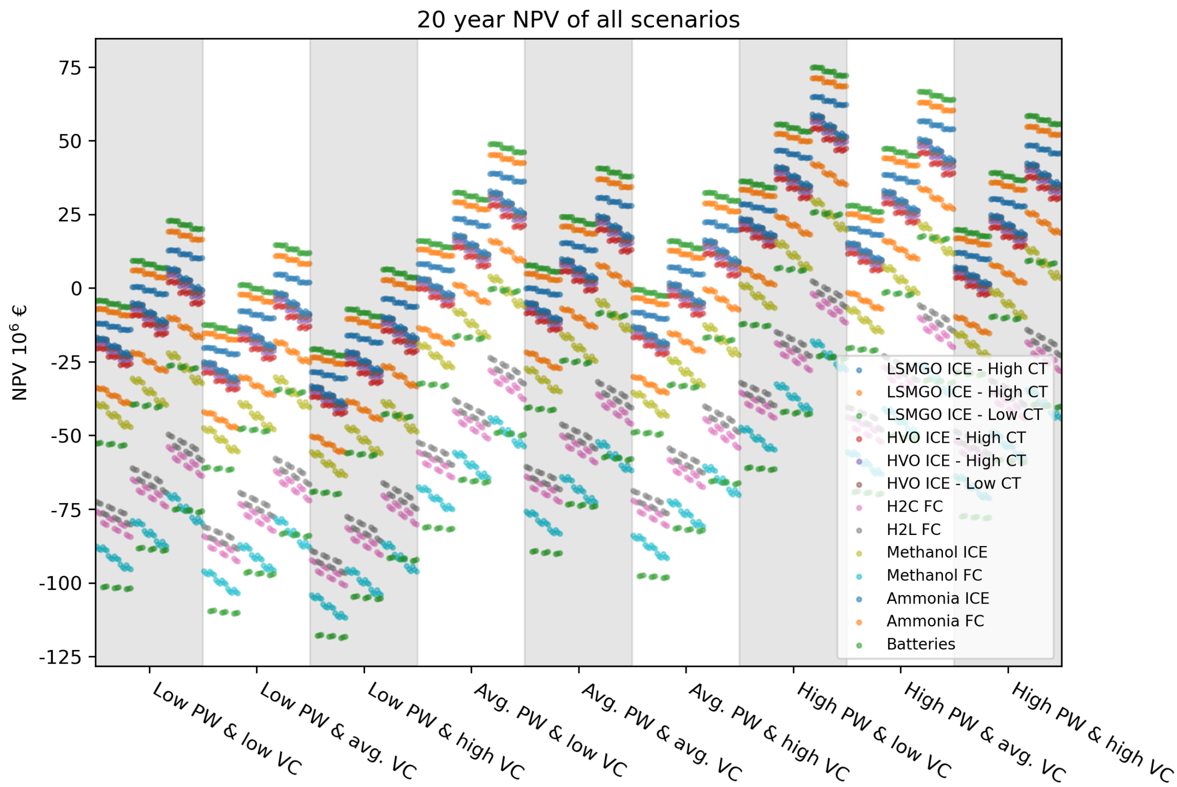


Figure 7.6: All 20-year NPVs for all technical configurations under all economical situations. A distinction between pay willingness (PW) and vast CAPEX (VC) levels can be seen.

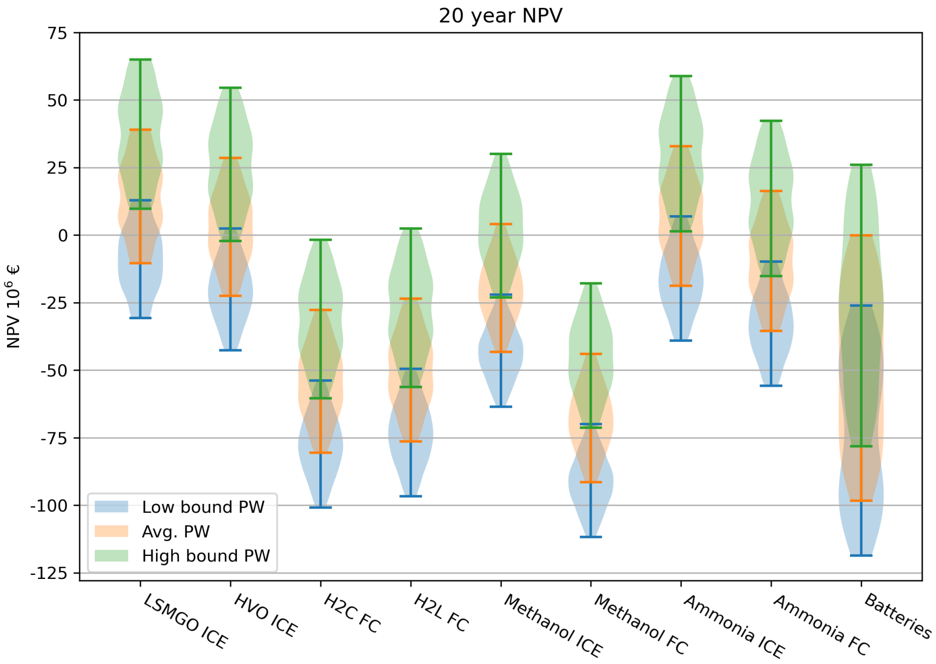


Figure 7.7: 20-year NPVs for all technical configurations. A distinction is shown for pay willingness (PW).

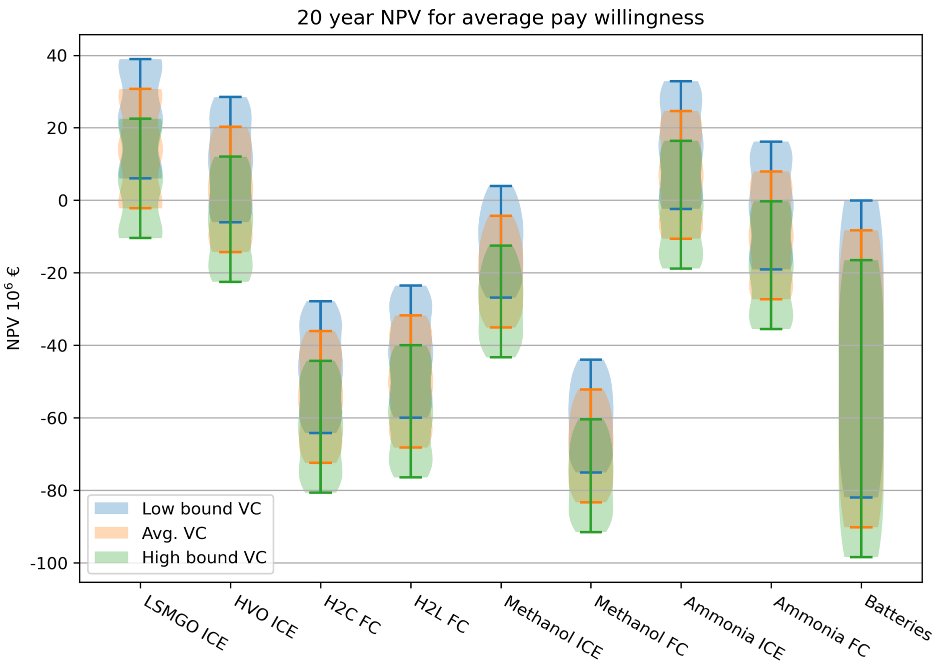


Figure 7.8: 20-year NPVs for all technical configurations. A distinction is shown for vast CAPEX (VC).

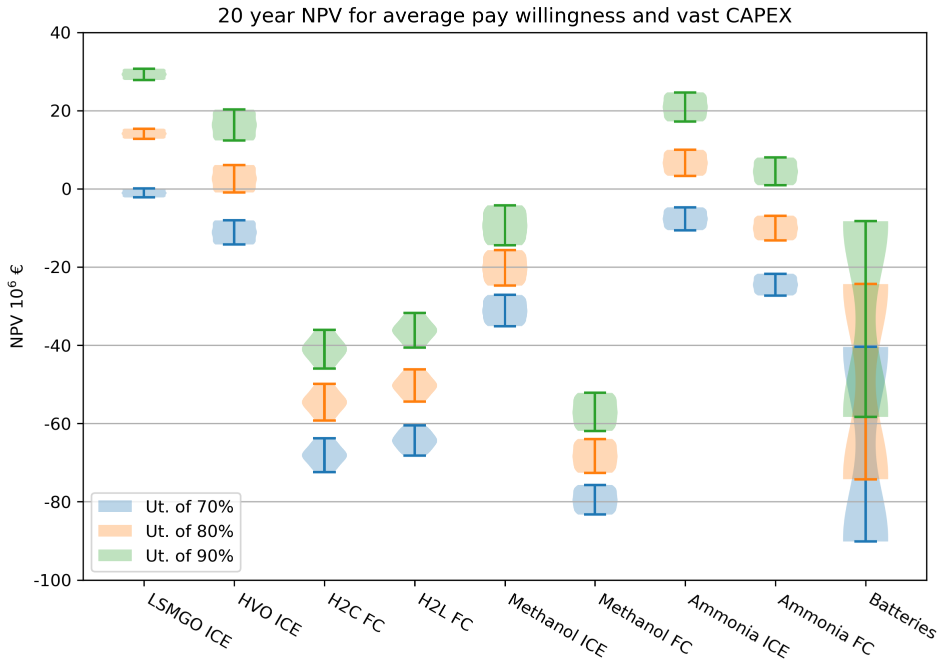


Figure 7.9: 20-year NPVs for all technical configurations. A distinction is shown for utilisation.

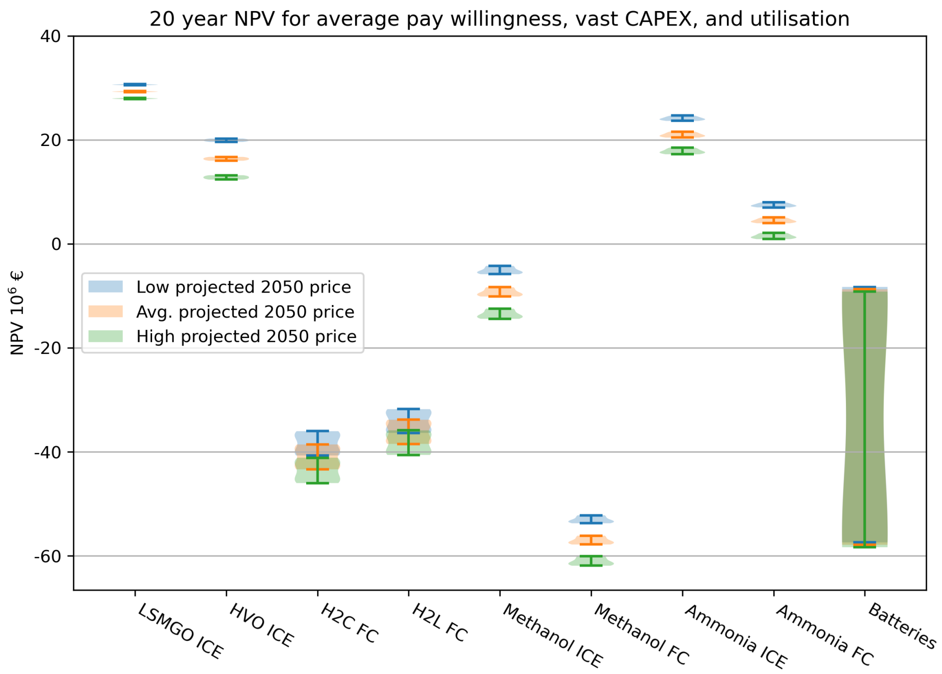


Figure 7.10: 20-year NPVs for all technical configurations. A distinction is shown for different 2050 price levels.

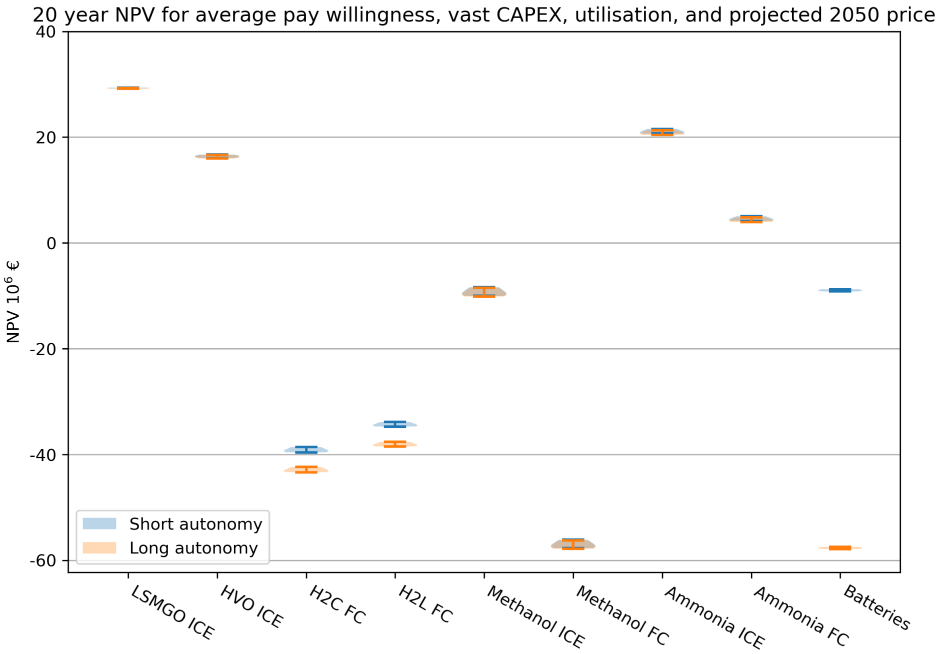


Figure 7.11: 20-year NPVs for all technical configurations. A distinction is shown for a short and long autonomy.

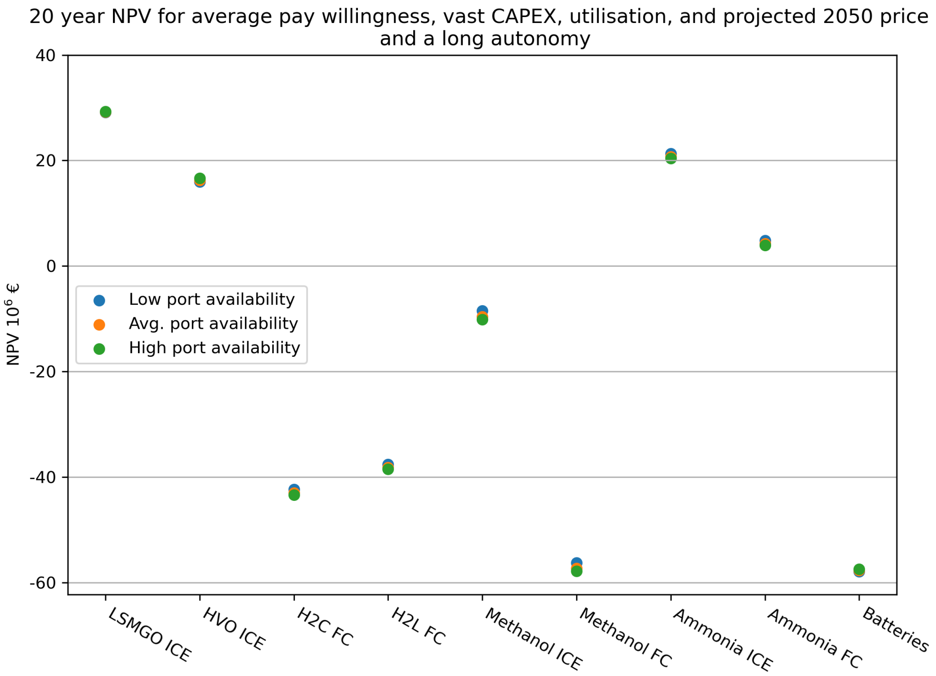


Figure 7.12: 20-year NPVs for all technical configurations. A distinction is shown for different port availability levels.

7.7. RDM step 4 & 5: Trade-off analysis and new futures

In the previous section, during the analysis of the results, some conclusions could already be drawn. Due to the low operational uptime of batteries and H2c, it is decided that these 2 energy carriers are no longer investigated as feasible options.

In the NPV analysis it can also be seen that in all tested scenarios, a positive NPV for H2l, H2c, and methanol FC is hardly possible under the assumptions from this research. Therefore, these 3 combinations are also excluded for further investigation.

Third, it has been seen that the NPV of W2W vessels designed for a short autonomy is not always considerably higher, except for batteries. However, because batteries are already excluded because of their low operational uptime, there are no combinations of energy carriers and converters that significantly improve their NPV for a short autonomy. Additionally, the emissions are higher for short autonomies than for long autonomies. For this reason, short autonomies are no longer investigated separately. Of course, it is still possible for the vessel owner to perform long cycles with a 14-day autonomy, but the vessel design will be made for an autonomy of 28 days.

Lastly, NPV is not sensitive to port availability. The difference in NPV between low and high port availability is minimal and therefore no longer investigated. On the other hand, it is seen that PW, VC, and utilisation have a large impact on the NPV results. Because their impact is so great, an intermediate step is introduced between the high and low case.

Another conclusion is that the variation in the price of the 2050 energy carrier influences the results only a little. For this reason, in a new simulation, the high and low case of the 2050 energy carrier price will increase and decrease with 50% instead of 30%.

For new futures, the relationship between operational uptime and PW was supposed to be incorporated. However, since the operational uptime of the remaining energy carriers and converters is almost equal, this is deemed unnecessary.

7.8. Second round of RDM

If all the results are plotted, it is seen that there are situations where LSMGO with a low CT has negative NPVs as a result. However, this is not expected, as the W2W vessel industry is currently profitable. Therefore, it is investigated for which situations this occurs.

An interesting observation is that a high utilisation (90%) always leads to positive NPVs in the low CT LSMGO case. However, a high VC in combination with a low PW (strongest driver) and an average to low utilisation leads to loss-making scenarios. Since these scenarios are unrealistic, it is decided that these scenarios must no longer be investigated. By deleting these scenarios for all combinations, the NPV distribution of the combinations changes and is therefore plotted in Figure 7.13.

One could argue that if the lowest scenarios are unlikely, then the highest scenarios are also unlikely. However, it is decided that these scenarios (low CAPEX, high PW) are more likely to occur because it is assumed that the PW is more likely to increase than to decrease.

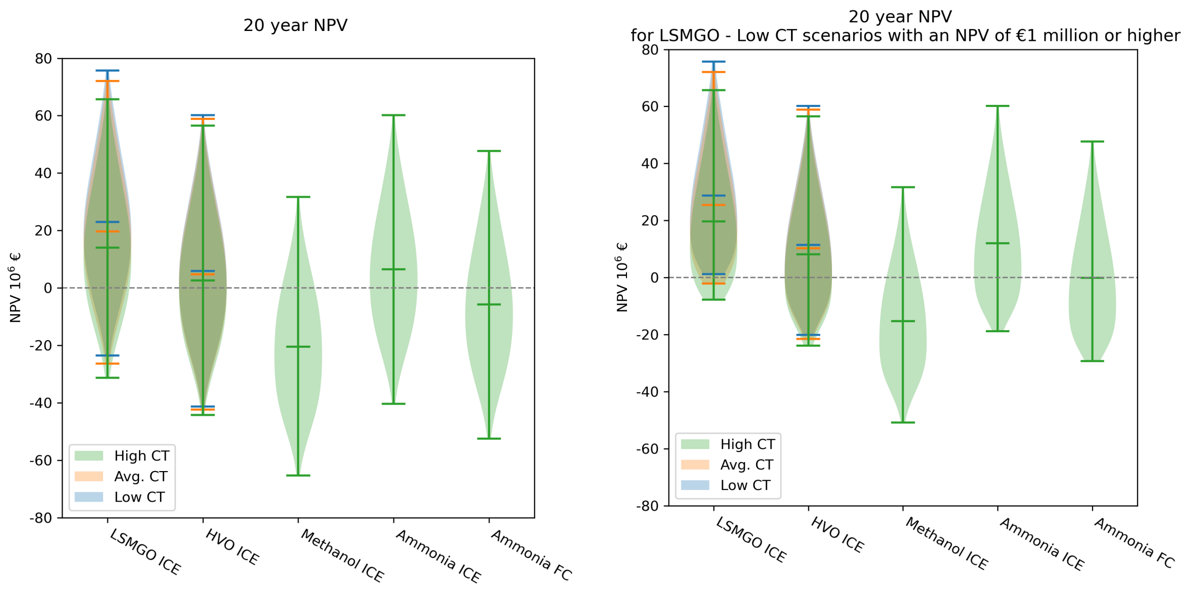
Although Figure 7.13, says a lot about the spread of NPV, it does not say a lot about individual scenarios. Therefore, these are investigated more closely.

When the two energy converters for ammonia are compared for all different scenarios, an ammonia ICE combination has a higher NPV than the ammonia FC combination. Therefore, it may be concluded that at this time an FC is not the winner for the W2W vessel under the current assumptions. However, there are situations where an ammonia FC is both technically and economically feasible.

When comparing the ammonia ICE combination with HVO, we see that ammonia performs better in terms of NPV in 74% of the scenarios for a low CT policy. For an average and high CT policy, ammonia outperforms HVO in 100% of the cases. Therefore, we may also carefully conclude that, under the assumptions made, it is better to invest in an ammonia ICE than in an HVO ICE.

Under all CT policies, in 0% of the scenarios, one of the other four combinations performs better than an LSMGO ICE combination. Even when comparing the possibility of a low bound 2050 price for the alternative energy carriers and a high bound 2050 price for LSMGO, the same is observed.

When the low-bound 2050 price of ammonia is compared with the high-bound 2050 price of methanol, ammonia still performs better because the the low bound methanol price is still higher than the high bound ammonia price. If all variables are left constant except for the energy carrier price, it is seen that the PW of methanol needs to increase by approximately €7000 to achieve the same NPV as an ammonia ICE configuration.



(a) Under all new futures

(b) Under all new futures where LSMGO with a low CT policy has a NPV of more than €1 million

Figure 7.13: Violin plots of the NPV distribution for the different energy carriers

7.9. Chapter conclusion

This chapter has answered the second part of subquestion 5 and subquestion 6.

5. "*How can the technical and economical feasibility of multiple strategies be found and what are possible scenarios which may be used in deciding which strategy needs to be chosen for zero-emission W2W vessels?*"

An RDM has been performed with a combination of variables and subvariables. These are energy carrier price, energy carrier availability, annual utilisation of a W2W vessel, DR or PW, vessel costs, OWF to port sailing distance, and CT policies. The strategy or combination of energy carrier and converter can be chosen using three metrics: NPV to measure profit, emissions per wind turbine connection to compare the reduced emissions, and operational uptime to measure the efficiency of the vessels time.

6. "*How will the implementation of alternative energy carriers influence the operational effectiveness, CAPEX, OPEX, and profit of zero-emission W2W vessels, over time?*"

The implementation influence depends on the technical configuration. The operational effectiveness measured in operational uptime for H2c is below 90% for 28-day autonomies and a OWF to port distance of 200 km. For batteries, this operational uptime even decreases to below 80%. For this reason, these combinations are not deemed feasible for the implementation on W2W vessels.

Energy carrier CAPEX, the CAPEX for the energy converter and the storage tank, is largely depending on the technical configurations. FCs and batteries are a lot more expensive than ICEs. Additionally, storage tanks must be a lot larger which make them more expensive while the storage tanks are also more expensive due to their characteristics to contain compressed, cold, explosive, or toxic energy carriers.

The lifetime of an FC is not to exceed 40.000 hours (Office of Energy Efficiency & Renewable Energy, n.d.) and therefore must be replaced every 5 years. This heavily impacts the CAPEX that must be invested in the vessel over the lifetime of the W2W vessel. The batteries have an expected lifetime of 10 years and must thus also be replaced at least once, which increases CAPEX (Banen, 2021). A conventional ICE has an expected lifetime of 20 to 30 years and thus does not lead to large amounts of added CAPEX at later years. However, OPEX for the ICE is a lot higher due to the amount of maintenace required for the ICE. Because maintenance schemes are very different for the ICE, FC, and battery, the division between OPEX and CAPEX is great. However, the total costs for the battery are considerably lower.

OPEX is also influenced by the implementation of alternative energy carriers. The largest influence in OPEX comes from the alternative energy carriers themselves. Their price is considerably higher than the price of LSMGO and therefore increases OPEX. However, prices are expected to decrease, which decreases OPEX over the years. The reverse is seen for OPEX of CO_2 emitting energy carriers since it is expected that a CT will be introduced and gradually increased.

OPEX is also increased due to the expected increase in truck bunkering. Because alternative energy carriers are not widely available, trucks with the correct energy carrier must provide this energy carrier in port to the W2W vessel. These costs are also projected to decrease as the port availability is expected to increase.

Profit of W2W vessels over time is also heavily impacted by the implementation of alternative energies. Due to the higher OPEX and higher CAPEX total costs increase. However, it is also expected that customers are willing to pay slightly more. It is concluded that no alternative energy carrier will earn the same amount of profit as LSMGO. An ICE running on ammonia comes closest with an average NPV of 12 million and has a positive NPV in 71% of the tested situations. Mainly due to the higher energy carrier price, the methanol ICE combination has an average NPV of -16 million, but still has a positive NPV in 20% of the tested situations.

8 Validation

According to Aumann (2007), model validation is the process in which it is checked if a model represents the correct behaviour of a system. Validation can be performed both operationally and conceptually (Sargent, 1984). A sensitivity analysis is another important step in the validation process (Kerr and Goethel, 2014)

8.1. Operational and conceptual validation

Operational validation is checking if the system works just as in reality by observing reality. This is, however, not fully possible because we cannot fast forward into the future. However, it can be seen that the NPV of LSMGO under average conditions is positive but can become negative under less favourable conditions (CT). This is in line with current profitability prospects.

Also, it is not possible to validate the operational technical solutions because then there should be already operating W2W vessels on alternative energy carriers. What can be operationally validated is that it is possible to create vessels running on alternative energy carriers since they are either already on order or conceptual design is in the late stages. Additionally, W2W vessels with a battery power system with 6 hours of running time are technically feasible since these are currently being built.

Conceptual validity is checking whether the theory and assumptions which are made can be justified and is therefore always possible. In every scientific research, some assumptions must be made. However, the author is of the opinion that these assumptions do not greatly influence the results of this research as is discussed below. The main assumptions can be divided in technical and economical assumptions.

8.1.1. Technical assumptions

The parametric model is based on some assumptions which might influence the findings. It is important that these assumptions are discussed about their potential influence on the findings. The assumptions are summarised and justified here:

- The results are based on a base case instead of designing each situation from scratch.
  - This means that all characteristics of the calculated technical configurations are based on this base case. It is assumed that this is okay because the Acta Centaurus is a relatively new and modern vessel.
- The hull is elongated and widened in the centre of buoyancy.
  - When necessary, the base case is elongated and widened in the centre of buoyancy to prevent a change in buoyancy. In a detailed design, it may not be possible to evenly distribute the new weight in order not to influence the trim of the vessel. However, it is presumed that this influence will not be a major issue. For a final design, this must be evaluated.
- The vessel is both enlarged in terms of length and width, but C_b and T are not scaled. The L/B ratio is set to remain constant.
  - The vessel is not enlarged in all dimensions for simplification reasons. The L/B ratio is set to be constant, and the block coefficient is assumed to remain constant for small elongations.

If the result would have been that a technical configuration was not feasible, this should have been checked but for now its influence is presumed to be minor.

- The added outfit weight is based on very old estimates.
  - The added outfit weight is calculated to be of only minor influence to the total weight and thus added draught. Therefore, it is presumed that the assumption does not largely influence the results.
- 85% of the cross sectional area is used for new storage tanks.
  - For 75%, the added length, added width and added weight slightly increase but the draught remains approximately equal. The maximum difference is seen for the H2c FC configuration with a 26 cm length increase and 5 cm width increase. For 95%, the results are approximately equal but shorter. This assumption is therefore not largely influencing the model results.
- The energy converter efficiency is set to be constant as 40% for the ICE, and 60% for the FC and the battery. The fuel reformer required for methanol and ammonia when using an FC is set to be constant at 70% efficiency. In reality efficiencies are depending on multiple factors but these are neglected in this research.
  - Efficiencies have been tested for lower and higher values (30% and 50 % for ICE, 50% and 70% for the FC an battery, and 60% and 80% for the fuel reformer). These test cases show no significant changes and therefore the assumption to keep the efficiencies constant at their original values is assumed to be okay to make.

Starting from blank would probably give slightly different results. However, this research attempts to prove the feasibility and does not attempt to provide a full vessel design.

8.1.2. Economical assumptions

Assumptions of the economic model include exogenous uncertainties and policy levers. However, also other variables are sometimes assumed but not varied. These must be tested for their influence.

The price of the alternative energy carrier for 2050 cannot be validated, but best currents and estimates have been used, and therefore it is expected that this is valid.

Port availability is hard to validate because most ports are unresponsive, but it seems likely that alternative energy carrier availability will grow as demand grows, and demand is likely to grow as governmental bodies find it an increasingly important topic.

Annual utilisation is based on current utilisation and is not expected to change much. Some changes are expected as the demand for green solutions grows, but demand may decrease due to increasing DRs.

The DR or PW is also based on current DRs and, therefore, assumed validated. However, it is possible that DRs change rapidly as a result of an increase in OWFs, but it is also possible that DRs drop for other reasons. Multiple DRs have been investigated to determine their influence with 20% increase or decrease. In the freight market, the increase and decrease have easily been 100%, but in this market, there is a multitude of supply and demand. The 20% is considered a good limit for W2W vessels according to de Vries (2022), because the volatility is already 10%, but it could increase.

OWF to port distance is based on OWFs with permits already in place. Therefore, it is expected that these OWFs will become operational in 20 years, and it is likely that a W2W vessel will operate here.

VC is varied quite substantially. It could be possible that higher CAPEX is demanded than the high bound by a shipbuilder, but one could argue that a regular vessel would also not be bought for this price. The other way around, it is possible that in different times, the VC is lower than the low bound, but this is less likely in current times.

A CT is not yet announced, but it is very likely that a CT of some sort will be implied in the following years because for several companies financial drive will be the only incentive to switch to sustainable alternatives. The start date is modelled no earlier than 2025 because governmental and regulatory bodies have always been known for long lasting trajectories before decisions are made. 2035 is modelled as the late limit, because it is assumed that by than the CT must be introduced. €100 as low 2050 price is linearly extrapolated from the EU ETS system and €300 is assumed to be necessary according to ABS (2022) to make zero-emission alternatives more profitable for multiple shipping sectors.

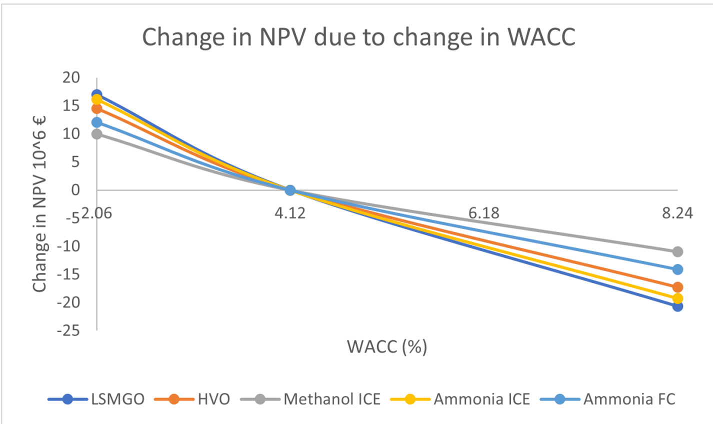
8.1.3. Sensitivity analysis

A sensitivity analysis makes sure that the model is not too sensitive for certain assumptions. In the RDM, a sensitivity analysis on exogenous uncertainties and policies has already been performed. It has been concluded that NPV is not sensitive to port availability and that PW, VC, and utilisation have a large impact on NPV results. Since these influences are as expected, the model shows the correct behaviour.

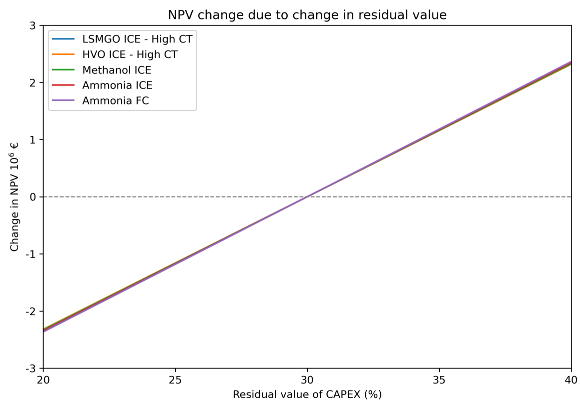
The model also needs to be checked for assumed constants. A WACC of 4.12% is used. To test the sensitivity of the model to this WACC, a 100% increase and 50% decrease are performed. The results are shown in Figure 8.1a. The figure shows that WACC largely influences NPV. This is as expected because all future cash flow is discounted with the exponentially growing discount rate based on WACC. It can also be seen that the influence of WACC is greater for the most profitable energy carrier (LSMGO) and decreases for less profitable technical configurations (methanol ICE). This is expected because for a less profitable option, there is less money to be discounted. The results of this analysis are not unexpected but emphasise the dependence of the results on WACC.

Another assumption is that the residual value of the W2W vessel is 30% of the building CAPEX after 20 years. The sensitivity of this residual value is tested and shown in Figure 8.1b. It is seen that a change in residual value is linearly connected with a change in NPV. 10% change in residual value leads to a change in NPV of approximately €2.4 million and is slightly different for the different alternative energy carriers, which is expected because the energy carrier CAPEX is different for each.

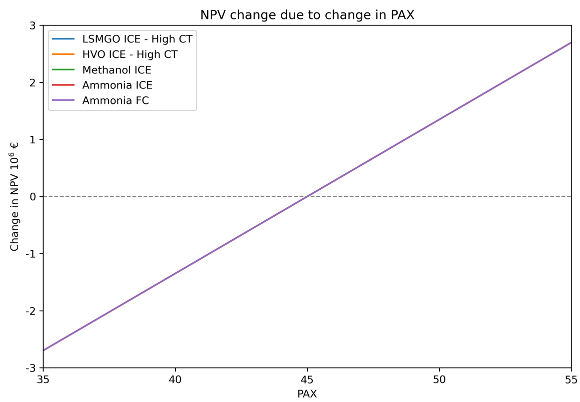
The last assumed constant is that the number of POB remained constant. Its influence is shown in Figure 8.1c and shows a linear relationship with NPV which is the same for all energy carriers. This is expected as the number of POB was kept constant for all energy carriers in this research.



(a) Sensitivity analysis of NPV for a changing WACC



(b) Sensitivity analysis of NPV for a change in residual value of CAPEX



(c) Sensitivity analysis of NPV for a change in persons on board

Figure 8.1: Sensitivity analysis of NPV

8.2. Chapter conclusion

This chapter has answered the validation part of subquestion 8.

7. "*How can the feasibility of zero-emission W2W vessels be validated and verified?*"

The feasibility of zero-emission W2W vessels cannot be directly validated and verified. However, models that determine the technical and economical feasibility can be validated and verified. The exogenous uncertainties and policy levers have been conceptually validated. Additionally, a sensitivity analysis is performed. These two validation techniques ensure that the model is validated.

Verification is done in earlier sections (section 6.8 and section 7.5) per model by checking the average results of the LSMGO ICE configuration. These results are in alignment with the expectations of Acta Marine under the assumed conditions. Also, the conditions are presumed to be correct. Second, unusual values have been inserted to check how the model reacts. In this way, the model is verified for mistakes. No errors have been found, so the model is assumed to be verified.

9 Conclusions, contributions, and recommendations

In this chapter, a conclusion of this research is given by answering the main research question and all of its subquestions. Furthermore, the contributions to industry, science, and society are described. Lastly, recommendations are given for future research.

9.1. Conclusions

To combat climate change and achieve the goals set in the Paris Agreement, the maritime industry must change. To achieve these goals, the maritime industry must act now, and zero-emission alternative energy carriers, as a fuel replacement, will play a significant role. However, the many variables, unknowns, dependencies, and criteria will lead to different ideal solutions for different types of vessels and markets. Limited research has yet been conducted in the direction of walk to work (W2W) vessels, while it is a rapidly growing young sector that provides service to offshore wind farms. Therefore, the following research question was formulated for this research:

"***What is the technical and economical feasibility of a zero-emission walk to work vessel, while maintaining current and future effectiveness requirements?***"

The main research question of this research is solved by answering the seven subquestions that will be answered subsequently.

1. "*What are the trends in the offshore wind industry, who are the influential stakeholders, and how do they influence the future proof design of W2W vessels?*"

The answers to the first subquestion are found in chapter 2. Influential stakeholders are offshore wind farm owners, wind turbine suppliers, W2W vessel owners, but also other vessel owners (in the offshore wind industry), port authorities, research organisations including Delft University of Technology, and regulatory bodies. A potential conflict is identified between the major shipping companies and W2W vessel owners. If the proposed solution is different for the major shipping companies, it is likely that their large influence will lead to a setback for the alternative energy carrier most suitable for W2W vessels. Another potential conflict is identified between offshore personnel and W2W vessel owners. Offshore personnel want at least the same safety as for current installations while maintaining the same effectiveness. W2W vessel owners may take small risks in optimising profit and improving public image. The level of interest and power of the stakeholders are mapped using the method of Ahsan and Pedersen (2018). The power and interest of offshore wind farm owners, wind turbine suppliers, W2W vessel owners, and regulatory bodies are the highest.

Several trends have been identified for the offshore wind industry. However, only a few influence the future-proof design of W2W vessels. The offshore wind industry is growing and new installations per year will almost quadruple by 2030. This creates a growing demand for W2W vessels, which can lead to higher revenues. Offshore wind farm locations are expected to move farther away from shore. Therefore, the duration of transit or the speed during transit increases, so more energy must be stored in the W2W vessel. Wind turbines are expected to become larger in terms of size and power capacity, and therefore, more or larger spare items are necessary, requiring more additional deck and warehouse space on the W2W vessel. Finally, it is seen that offshore wind farm owners accelerate their focus on emissions and actively ask suppliers to look into their own emissions. Therefore, it is important that W2W vessel suppliers also investigate these emissions.

2. "*What is the state-of-the-art in W2W vessels and what are their current and future effectiveness requirements?*"

In chapter 2, the state-of-the-art in W2W vessels is identified as two W2W vessels currently under construction that can run for six hours on battery and solar power. Effectiveness is measured with technical, economical, and environmental requirements. Technically, the W2W vessel must remain effective in transferring technicians and cargo safely to a wind turbine and back. Therefore, mission and vessel equipment must adapt accordingly to the trends seen in the offshore wind farm industry. Also, operational uptime must remain above 90%. Economically, it is expected that margins will increase slightly due to a shortage of W2W vessels, and thus now is the time to invest in (more expensive) alternative energy carrier systems. Environmentally, the selected alternative energy carrier must emit fewer CO_2 emissions than Low Sulphur Marine Gas Oil (the current fuel) does.

3. "*What is the state-of-the-art in potential alternative energy carriers and converters, what are their important properties and what is their relevance for W2W vessels?*"

Chapter 3 has investigated alternative energy carriers with a technology readiness level of 5 or higher. The state-of-the-art in zero-emission alternative energy carriers are compressed hydrogen, liquefied hydrogen, methanol, ammonia, and batteries. The state-of-the-art in energy converters is the fuel cell. Important properties for energy carriers are well-to-wake emissions, price, volumetric and gravimetric energy density, availability in port, bunkering efficiency, safety, regulations, and social perspective.

The important characteristics of the energy converter are the cost per power output, efficiency, maintenance or replacement interval, start-up time, and potential additional safety systems.

There are no CO_2 regulations that a W2W vessel must comply with, and therefore all CO_2 reductions must come from intrinsic motivation or client requests, as can be seen in the design circle (Figure 2.15).

The selection of alternative energy carriers is based on their possible applicability to W2W vessels and their specific characteristics. Hydrotreated vegetable oil has CO_2 emission reductions of approximately 60%. This is therefore not enough for zero-emission but could be used as a blend-in fuel or used in a dual fuel engine until the availability of green alternatives increases. Methanol has the potential to be carbon neutral while both hydrogen, ammonia, and batteries have the potential to be zero-emission. Methanol, hydrogen, and ammonia are further investigated to determine if they should be used as a replacement energy carrier on W2W vessels. Batteries will also be further investigated in combination with a recharging facility at sea. In Table 3.1, an overview of the main characteristics was given.

4. "*Which are the requirements for an assessment methodology that covers future trends, energy carrier choice, and W2W vessel design implications and what methodologies are best suited for this?*"

Chapter 5 has set criteria for a methodology and has selected the most suitable methodologies for this research. The methodology must be suitable for handling a certain level of uncertainty, be able to make a comparison between the results of multiple scenarios, be able to evaluate with multiple input criteria, and find a conceptual basic design. The decision has been made to use two methodologies. A Robust Decision Making method is used for the economical evaluation and covers future trends and energy carrier choice. A parametric model is used to determine the technical feasibility and covers the implications of the design of W2W vessels.

5. "*How can the technical and economical feasibility of multiple strategies be found and what are possible scenarios which may be used in deciding which strategy needs to be chosen for zero-emission W2W vessels?*"

Chapter 6 has used a self-developed parametric model to investigate the technical feasibility of 18 technical configurations of energy carrier, energy converter, and autonomy duration. It was discovered that with some adjustments in the dimensions of the vessel, all 18 technical configurations are technically feasible. The added length and width are largest for a compressed hydrogen fuel cell 28-day configuration with 2.17 m longer and 0.47 m wider. The 28-day battery-powered autonomy configuration leads to an increase of 180% in energy carrier weight. The maximum increase in draught is 14 cm on an original draught of 5.6 m for the compressed hydrogen fuel cell 14-day configuration. The required thruster force is recalculated for all technical configurations with new dimensions using the DNV station keeping capability assessment (DNV, 2021a). No more power is required to maintain the same DP station keeping capabilities.

Chapter 7 describes possible scenarios for an economical analysis with a combination of variables and subvariables. These are the energy carrier price, energy carrier availability, annual utilisation of a W2W vessel, day rate or pay willingness, CAPEX, the sailing distance between an offshore wind farm and the port, and the carbon tax policies. Net present value, emissions per wind turbine connection, and operational uptime are used as metrics to select the most robust technical configuration.

6. “*How will the implementation of alternative energy carriers influence the operational effectiveness, CAPEX, OPEX, and profit of zero-emission W2W vessels, over time?*”

Chapter 7 discovers that the operational uptime for batteries and compressed hydrogen may be less than 80% and 90%. The operational uptime of other alternative energy carriers and converters remains above 90%. An internal combustion engine (ICE) is much less expensive than fuel cells and batteries and storage tanks are more voluminous and more complex, making them more expensive. Also, a fuel cell or battery needs to be replaced, respectively, every 5 or 10 years, which greatly increases CAPEX investments at later times.

The high price of alternative energy carriers and the unavailability of energy carriers in port lead to larger OPEX. On the other hand, OPEX is also expected to increase for diesel fuels since a carbon tax is expected. Although clients are expected to pay slightly more, it is concluded that no alternative energy carrier will earn the same amount of profit as with current fuels. The ammonia ICE configuration comes closest with an average net present value of 12 million and a positive net present value in 71% of the situations tested. The methanol ICE configuration has an average net present value of -16 million and has a positive net present value in 20% of the situations tested.

7. “*How can the feasibility of zero-emission W2W vessels be validated and verified?*”

Chapter 7 addresses the validation and verification of this research. Verification is done by inserting unusual values and checking how the model reacts. The model has reacted correctly in all tested cases. Furthermore, verification is done by checking the average results of the LSMGO ICE configuration. These results align with the expectations of Acta Marine. No errors were found, so the model is verified.

Conceptual validation is applied to the exogenous uncertainties and policy levers of the RDM model. Additionally, a sensitivity analysis is performed which has not yielded unexpected results. Therefore, the model is also validated.

Finally, a conclusion is provided to the main research question.

“***What is the technical and economical feasibility of a zero-emission walk to work vessel, while maintaining current and future effectiveness requirements?***”

Technically, it is feasible to have zero-emission W2W vessels operating on:

- Compressed and liquefied hydrogen in combination with a fuel cell.
- Methanol in combination with a fuel cell or an internal combustion engine.
- Ammonia in combination with a fuel cell or an internal combustion engine.
- Batteries running on zero-emission electricity.

Economically, it is feasible to have zero-emission W2W vessels operating on:

- Ammonia in combination with a fuel cell or an internal combustion engine.
- Methanol in combination with an internal combustion engine.

- Batteries running on zero-emission electricity.

It is feasible to have zero-emission W2W vessels that maintain **current and future effectiveness** requirements for:

- Liquefied hydrogen in combination with a fuel cell.
- Ammonia in combination with a fuel cell or an internal combustion engine.
- Methanol in combination with a fuel cell or an internal combustion engine.

It is both **technically** and **economically** feasible to have zero-emission W2W vessels while maintaining their **current and future effectiveness** requirements for:

- Ammonia in combination with a fuel cell or an internal combustion engine.
- Methanol in combination with an internal combustion engine.

9.1.1. Nuances

Under the assumption that only zero-emission single-fuel energies are investigated, this research implies that an ammonia ICE configuration is the most robust option. However, ammonia as the most robust winner, requires some nuances.

- Safety needs to be more addressed before investing. Ammonia is toxic and can be lethal above a certain threshold. Fuel storage, bunkering, and an appropriate ventilation system are considered feasible but need to be investigated more closely to prevent leaks. This could induce additional costs but is not expected to be so substantial that the net present value ranking changes.
- Although ammonia is a potentially zero-emission energy carrier, due to it toxicity, crew and passengers are not yet 100% comfortable with ammonia. Therefore, comforting of crew and passengers, before sailing on ammonia is possible, is considered necessary.
- There is no regulation on ammonia yet. Therefore, a ship designer must prove to regulatory bodies that the ammonia W2W vessel is safe. This is more difficult and therefore costlier than designing a vessel according to regulations.

The methanol ICE configuration also requires some nuance. The net present value of the single fuel zero-emission methanol ICE configuration is low compared to the ammonia configurations. This might imply that methanol is not a very good solution to invest in. However, it is currently seen that the market is betting on the methanol ICE dual fuel configuration (A.P. Moller - Maersk, 2021)(Van Oord, 2021)(Anink, 2021). Therefore, the question is raised why this model gives low net present value results for a methanol ICE configuration. The dual-fuel blue methanol configuration is more flexible than a single-fuel zero-emission configuration. This results in a low investment with potential high rewards on the short term because the blue versions of methanol can already be used today for emission reductions. Also, dual-fuel engines give the flexibility to use fossil fuels whenever there is no blue or green version available. However, this research focused only on zero-emission W2W vessels, therefore only on single-fuel converters running on green energy carriers, and therefore ammonia which has a lower expected energy carrier price seems to be more robust.

Because green methanol is currently still very expensive and green ammonia is assumed to be relatively cheap, green methanol needs a pay willingness of almost €7000 higher than that of green ammonia to become profitable in single fuel converters. However, the main drivers of the models is the price of the energy carrier, so if projections are wrong, the results can be completely different. Furthermore, there could be more uncertainties and (indirect) relationships that might lead to different outcomes that have not been taken into account. In conclusion, under the single fuel zero-emission assumptions, ammonia seems to be the most robust option, but is not yet suitable in the opinion of the author because of the nuances stated above, which first need to be overcome in the next years. It is recommended to investigate blue energy carriers and dual fuel engines for even more robust options on the short term.

Lastly, it is seen that even the proposed carbon tax of 300 € / ton CO_2 (ABS, 2022 in 2050 is not high enough to make any of the proposed zero-emission energy carriers more profitable[4]. To ensure that the maritime sector starts using zero-emission energy carriers, something needs to happen now. This can be either an even higher carbon tax or subsidies for the zero-emission alternatives. Lastly, because zero-emission energy carriers give some commercial opportunities that fossil fuels do not have, and because there is a high intrinsic motivation in both Acta Marine and the offshore wind sector, the author is very positive on the chance that zero-emission W2W vessels will be around sooner than later.

9.2. Contributions to industry, science, and society

Where section 1.6 has discussed how this research is socially and scientifically relevant, this section discusses the actual contributions of this research to industry, science, and society.

9.2.1. Industry contribution

The W2W vessel industry is a relatively new sector which faces a large challenge in the beginning of its existence. This is both an opportunity because the vessels still need to be optimised and a challenge because of the relative immaturity compared to other segments.

Clients and governmental bodies are increasingly focusing on emissions and, therefore, it is important to start investigating the possibilities of zero-emissions W2W vessels in an early stage. This research has shown that technically it is possible to use all tested technical configurations on W2W vessels. However, it has also shown that under current assumptions, not all technical configurations are economically viable.

The industry is helped by this knowledge because not only the W2W vessel segment is reconsidering its propulsion systems, but most of the industry is. By determining that it is feasible for zero-emission W2W vessels to make almost the same amount of profit as when running on LSMGO, it has been shown that there are possibilities. The industry benefits from this research because it can adapt the given tool to their own specifications and find its own solutions. The tool is not designed for other vessel types, but could be used with slight adaptions for other offshore support vessels.

This research has shown that if developments in ammonia safety systems are continued, in a few years ammonia can be a robust option with the knowledge of today. However, even more important is the developed model, which allows for changed input for the variables. In due course, when more accurate information becomes available, the assessment and evaluation can be done quickly. Hence, decision making can be done easier and the time intensive decision analysis does not have to be performed again.

9.2.2. Scientific contribution

This research has shown a lot of information on W2W vessels which was still lacking in literature. Stakeholders have been identified, the offshore wind industry is analysed, and the total greenhouse gas emissions of W2W vessels have been estimated. An overview of all currently sailing W2W vessels has been given and two categorisations are proposed. Lastly, the long and short cycle are identified, which describes the operational profile in the W2W vessel segment. However, these cycles may also exist in an adapted form for other vessel types.

Furthermore, this research has increased scientific knowledge on alternative energy carriers in combination with a specific vessel type. Multiple large organisations have predicted that the future energy mix will be a variety of existing alternative energy carriers because each operational profile leads to different solutions. Therefore, it has been relevant to investigate the W2W vessel approach. It has shown that methanol, ammonia, and batteries can all play a role in the transition to zero-emissions in the W2W vessel segment.

9.2.3. Societal contribution

This research has proven that it is both technically and economically feasible to have zero-emission W2W vessels. This is relevant for society because this outcome is likely to lead to the construction of zero-emission W2W vessels. If emissions can be reduced in the life-cycle of offshore wind farms, the

[4] If the LSMGO prices remain at their spiked levels (more than 2.5 times higher than currently assumed), the carbon tax is likely to be high enough, but this is not investigated.

green energy from wind turbines gets one step closer to actual zero-emission electricity, benefiting the planet.

This research has also shown that zero-emission energy carriers cannot be used with the same profitability. Therefore, it is important that governments and regulators incite new regulations to promote zero-emission alternatives. Although this is already known, this research is another confirmation.

9.3. Future recommendations

The following points are recommendations based on this research:

- Improve model with influence of port availability on operational uptime. Currently, it is assumed that this will not change the relative results, but modelling this is necessary for assurance.
- Currently, the model assumes that alternative energy carriers have zero well-to-wake emissions. However, this is not true at this moment, and therefore, well-to-tank emissions must be better investigated to be introduced into the model.
- The model only considers CO_2 emissions, but other emissions, such as SO_x, NO_x, and particulate matter are also important to consider in the decision.
- The pay willingness is currently considered a varying number based on historical data on the day rate and the assumption that clients are willing to pay slightly more. However, the pay willingness is highly depending on supply and demand for the offshore wind market and also depends on demand from the oil & gas market. Therefore, it is recommended to create a supply and demand model to better predict pay willingness.
- Currently, the client (charterer) does not always operate 24/7, but the model assumes that it does. If this is not necessary, batteries could be an option. However, this needs to be investigated.
- Because fuel cells are still state-of-the-art, there are no predictions on their price in a few years. Because the fuel cell needs to be replaced every 5 years, the costs may be very high. It is recommended to investigate how the price of the fuel cell will develop and if its useful life may increase. If this happens, the fuel cell might become a suitable option for W2W vessels.
- It is seen that the market is betting on methanol dual fuel configurations. This could decrease the price of methanol and could increase the prices of other alternative energy carriers. It is recommended to investigate the power and influence of this trend on the results of this research.
- Price of the energy carriers is seen as the main driver of the results. Therefore, it is interesting to create a model that determines the price of energy carriers based on the price of green electricity, atoms (natrium, hydrogen, carbon), processing, transport, and demand and supply. Incorporating this model into the current model will most likely make more fair comparisons than the model does now. Because if, for example, the green electricity price goes up, all prices should go up.

10
Personal reflection

My 7 years in Delft were a great period of my life. I have learned a lot of new things, made new best friends, and eventually became an engineer.

In 2015, I attempted to start a bachelor in Aerospace engineering. However, after 6 months I had to conclude that university life in combination with joining a student association was not a match for me. Therefore, when I started my bachelor's degree in Marine Technology in 2016, I was determined to succeed and managed to obtain all my ECTS in the first year. Finally, I managed to finish my bachelor degree without any major hurdles in 3.5 years. The last year of the bachelor consisted of a major highlight with an exchange to Hong Kong and my bachelor thesis. In Hong Kong I became independent and enjoyed the Asian culture. The finishing work, the Bachelor End Project, was the design of the lead vessel of the Novimar Vessel Train. A pretty cool project in which my enthusiasm for ship design grew.

I did not doubt to follow up my bachelor Marine Technology with a master Marine Technology. During my masters, I became the company leader at Watersport Academy de Kaag and therefore, I decided to put my studies on a lower level for the duration of 1 year. At the Kaag I developed planning skills, leadership skills, organisational skills, and I became even more stress resistant. After this year, I went back to fully focus on my masters and with this research complete, I have finished my masters in 2.5 years. I am really proud of myself for achieving the engineer title in a field that I am very enthusiastic about.

The road to becoming an engineer was not always a smooth one. With Covid-19 around, lots of distractions which were around when doing the bachelor were not around with the masters. However, everyone from Voorstraat 42, JC Khan, Watersport Academy de Kaag, Acta Marine, my family, other friends, and my girlfriend still made it a great time.

During exams periods, I never really struggled with studying at home because the goals were short-term. However, when switching to the thesis with a duration of 9 months, it was way more difficult. Therefore, it was very nice to be able to work at the Acta Marine office, even when there was no one else. This made my life a lot easier. At Acta Marine, I learned how to cooperate with multiple stakeholders and sometimes conflicting interests.

During these 7 years, I learned a lot of things related to marine technology, but also my enthusiasm for coding in Python grew. I learned that data is key to good results and therefore I was struggling a lot in the economical part of this research. The economical feasibility of this research depends a lot on 2050 projections, and this was hard for me to use because it makes my results less trustworthy. However, I have also learned that these projections are the best available data that can be used for these kind of projects, and therefore they are usable.

To conclude, during my period at university, I have learned a lot and I look forward to the future and the new things I will learn.

A

Purpose built W2W vessels overview

Table on next page.

Table A.1: Purpose built W2W vessels overview

Vessel name	Owner	Year built	POB	LOA (m)	B (m)	D (m)	GT	V_{max} (kts)	Source
Acta Auriga	Acta Marine	2018	120	93,4	18	5,6	6078	12	Acta Marine, n.d.-a; VesselFinder, n.d.-a
Acta Centaurus	Acta Marine	2019	120	93,4	18	5,6	6078	12	Acta Marine, n.d.-b; VesselFinder, n.d.-b
Bibby Wavemaster 1	Bibby Marine	2017	90	89,65	20	6,3	6241	13	Bibby Marine Limited, n.d.; VesselFinder, n.d.-c
Bibby Wavemaster Horizon	Bibby Marine	2019	60	89,65	20	6,3	6100	13	Bibby Marine Services, n.d.
Edda Mistral	Østensjø	2018	62	81	17	5,4	4881	13,5	Østensjø Rederi, n.d.-a; Gondan, n.d.
Edda Passat	Østensjø	2017	62	82	17	5,4	4873	13,5	Østensjø Rederi, n.d.-b; Gondan, n.d.
Esvagt Alba	Esvagt	2021	60	70,5	16,6	5,4	3830	12	Esvagt, n.d.; VesselFinder, n.d.-d
Esvagt Albert Betz	Esvagt	2019	42	70,5	16,6	5,5	2998	12	Esvagt, n.d.; VesselFinder, n.d.-e
Esvagt Faraday	Esvagt	2015	60	83,7	17,6	6,5	5006	14	Esvagt, n.d.
Esvagt Froude	Esvagt	2015	90	83,7	17,6	6,5	5006	14	Esvagt, n.d.
Esvagt Havelok	Esvagt	2021	60	70,5	16,6	5,5	3830	12	Esvagt, n.d.; VesselFinder, n.d.-f
Esvagt Mercator	Esvagt	2017	36	58,5	16,6	5,5	2901	12	Esvagt, n.d.
Esvagt Njord	Esvagt	2016	60	83,7	17,6	6,5	5007	14	Esvagt, n.d.;
Esvagt Schelde	Esvagt	2020	60	70,5	16,6	5,5	3830	12	Esvagt, n.d.; VesselFinder, n.d.-g
Seaway Moxie	Siem Offshore	2014	60	74	17	6,4	4367	9,1	Ulstein, n.d.-a; VesselFinder, n.d.-h
Wind of Change	Louis Dreyfus	2019	90	83	19,4	5	6485	12,5	Cemre Shipyard, n.d.-a; VesselFinder, n.d.-i
Wind of Hope	Louis Dreyfus	2021	90	84	19,4	5	6499	12,5	Cemre Shipyard, n.d.-b; VesselFinder, n.d.-j
Windea Jules Verne	Windea/B. Schulte	2020	120	93,4	18	6,4	6081	13	Ulstein, n.d.-b; VesselFinder, n.d.-k
Windea La Cour	Windea/B. Schulte	2016	60	88	18	6,4	5897	13,9	Ulstein, n.d.-c; VesselFinder, n.d.-l
Windea Leibniz	Windea/B. Schulte	2017	60	88	18	6,4	5897	13,5	Ulstein, n.d.-d; VesselFinder, n.d.-m

B

Not selected alternative energy carriers.

More elaboration on LNG, LPG, LOHC and nuclear energy, which are not considered as alternative energy carrier for zero-emission W2W vessels, including their positive characteristics can be found in this appendix.

B.1. Liquefied Natural Gas

Natural gas becomes liquid at -163°C and 1 bar and therefore needs to be stored in insulated tanks (DNV GL, 2019a). The volumetric energy density of LNG is 22.4 GJ/m^3 or 50 GJ/t (Mogensen, 2021). To store LNG, special tanks are required which can handle the cold and pressure. Therefore, storing the same amount of energy requires approximately two times more volume for LNG than LSMGO. Its lower weight compared to LSMGO, makes it easier to store the LNG at higher levels due to less reduction of stability

B.1.1. Well to wake emissions of LNG

LNG reduces 20% of CO_2 emissions compared to LSMGO (Pavlenko et al., 2020) (CE Delft, 2011) and is practically sulphur and thus SO_x free (DNV GL, 2019a). According to CE Delft (2011), LNG has 55.6 kg/GJ of WTT CO_2 emissions, 13.8 kg/GJ of TTW CO_2 emissions, adding up to 69.3 kg/GJ of WTW CO_2 emissions. In addition, NO_x emissions are lower than for LSMGO. When LNG is used in an ICE, methane slip occurs. Over a 20-year period, methane is 80 times more potent at warming than carbon dioxide (Anink, 2021).

B.1.2. Cost of LNG

According to Ship & Bunker (2021), prices for LNG were approximately 14.73 $/GJ (12.70 €/GJ) on average from January to November 2021. CAPEX for an LNG propulsion system is decreasing because LNG is moving towards a fully developed technology. OPEX for LNG is approximately equal to LSMGO but is expected to decrease. This is because ports will offer discounts for lower emission vessels and because less maintenance is necessary because gas is cleaner than LSMGO (DNV GL, 2019a).

B.1.3. Bunkering of LNG

Bunkering infrastructure for LNG is moving quite rapidly because the number of vessels running on LNG is still growing. Essentially, LNG is available everywhere, but it is not yet available everywhere for vessels (DNV GL, 2019a). A map with ports supplying LNG in Figure B.1, shows that LNG bunkering for vessels is not a problem in Europe, but is harder in the rest of the world.

Since 1.6 times the amount of LNG must be stored to store the same amount of energy as with HFO, the flow rate must be 1.6 times higher to bunker in the same time. According to ABS (2020), this is possible.

B.1.4. Safety and regulations of LNG

Because LNG boils at -163°C, it must be stored at cryogenic temperatures. This introduces safety hazards for explosions and leakage. The International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code) entered into force in January 2017 and brought the full regulatory

Figure B.1: LNG bunkering infrastructure (DNV GL, n.d.-a)

framework for using LNG as an energy carrier on your vessel. However, there are no international standards for bunkering the vessel. Some governments and some ports do have regulations for this.

B.1.5. Social perspective of LNG

According to research on the social perception on LNG (Folia Consultores, 2017), the overall general acceptance of LNG is positive because of the improvement of air quality. Although there is also a negative perception of LNG which comes from the knowledge that LNG is still a fossil fuel, the general social perspective is positive (Folia Consultores, 2017).

B.1.6. LNG conclusion

LNG will not be considered in this research. LNG can be used today and reduces WTW CO_2 emissions with 20% but this is not deemed enough. Moreover, methane slip, which is considered 10 times worse than CO_2, makes it debatable whether using LNG improves the environment.

B.2. Liquefied Petroleum Gas

LPG is a mixture of propane and butane in liquid form. Specific mixtures are used to achieve the desired saturation, pressure, and temperature characteristics (DNV GL, 2019a). LPG occurs as a by-product from oil and gas refinery or production (DNV GL, 2019a). Average LPG energy density is 23.5 GJ/m^3 or 46 GJ/t (Mogensen, 2021).

B.2.1. Emissions of LPG

According to Xydas (2021), LPG has 99% less SO_x and it meets IMO 2050 GHG Strategy. DNV GL (2019a), adds that LPG slip must be minimized because the global warming potential of LPG slip is very high. Moreover, it estimates a NO_x emission reduction of between 10% and 20% depending on the engine. Brinks and Hektor (2020) estimates CO_2 emissions to be 72.7 kg CO_2 per GJ.

B.2.2. Costs of LPG

LPG is currently not freely available for bunkering and therefore relatively expensive with 40 $/GJ (34.48 €/GJ) (prices, n.d.). It is expected that LPG would be cheaper on a larger scale, but a larger scale is not expected because LNG has similar characteristics as LPG and is already available. CAPEX of LPG is roughly half of CAPEX for LNG because the tanks to store LPG do not have to withstand cryogenic temperatures. OPEX is expected to be similar to LNG (DNV GL, 2019a).

B.2.3. Bunkering of LPG

Currently, LPG infrastructure is extensive but there is no LPG bunkering infrastructure. Figure B.2 presents an overview of LPG infrastructure in Europe. Distribution can either be done using trucks, pipelines, or special bunkering vessels. LPG carriers could use the LPG they carry as their energy carrier. Bunkering LPG can be done at the same velocity as HFO which is comparable with LSMGO bunkering velocity. LPG bunkering is not expected to give any problems since there is already a lot of experience with LPG tankers.

Figure B.2: Overview of European import and export LPG terminals (DNV GL, 2019a)

B.2.4. Safety, regulations, and crew training of LPG

Since LPG has a higher density than air, it will be difficult to detect whenever there is a leakage. Therefore, leak detectors and ventilation need to be installed to mitigate this risk. Crew needs training to understand the leak detectors. LPG carriers are allowed to use LPG as an energy carrier under the IMO IGF code, but for other vessels that want to use LPG as an energy carrier, there is no regulation in place (DNV GL, 2019a). LPG regulation is not on the political agenda and therefore not expected in the future (DNV GL, 2019a).

B.2.5. LPG conclusion

LPG will not be considered further in this research because the emission reduction is only 16.5% compared to LSMGO, the infrastructure is lacking and not expected to become extensive, and no regulations are expected. LPG will most likely be used as an energy carrier for LPG tankers but is not deemed a viable option for W2W vessels.

B.3. Liquid Organic Hydrogen Carrier

Both compressed and cryogenic liquid hydrogen are characterized by high safety requirements due to high pressure and low temperature, respectively (Niermann et al., 2019). LOHC stores hydrogen in a storage molecule based on hydrogenation forming and has the potential to be cheap, safe, and easily manageable. Moreover, compared to the compressed or cryogenic liquid versions, LOHC has a higher energy density (6.9 GJ/m^3 or 6.5 GJ/m^3 including storage) and transportation is less complicated (Niermann et al., 2019). The relative low price of dibenzyltoluene (4 €/kg), which is the only storage molecule currently used, supports large-scale applications (Hydrogenious Technologies, 2018) (Arlt, 2014). This cost is lower than pressurising or cooling down hydrogen gas. Methanol or ammonia could also be seen as a hydrogen carrier but will be discussed separately. LOHC can be bunkered through normal bunkering systems since it is not cold or pressurised and is also not toxic or flammable. However, the energy density of LOHC only is lower, which means that a higher flow rate is required, requiring bigger pipes and valves. Removing the hydrogen empty dibenzyltoluene can occur simultaneously while bunkering hydrogen rich LOHC and therefore does not cost extra time. It does, however, require extra pipes and valves and therefore complicates the operation.

Hydrogen is stored with a storage molecule based on hydrogenation forming a LOHC. De-hydrogenation frees the hydrogen atom. This can be seen in Figure B.3

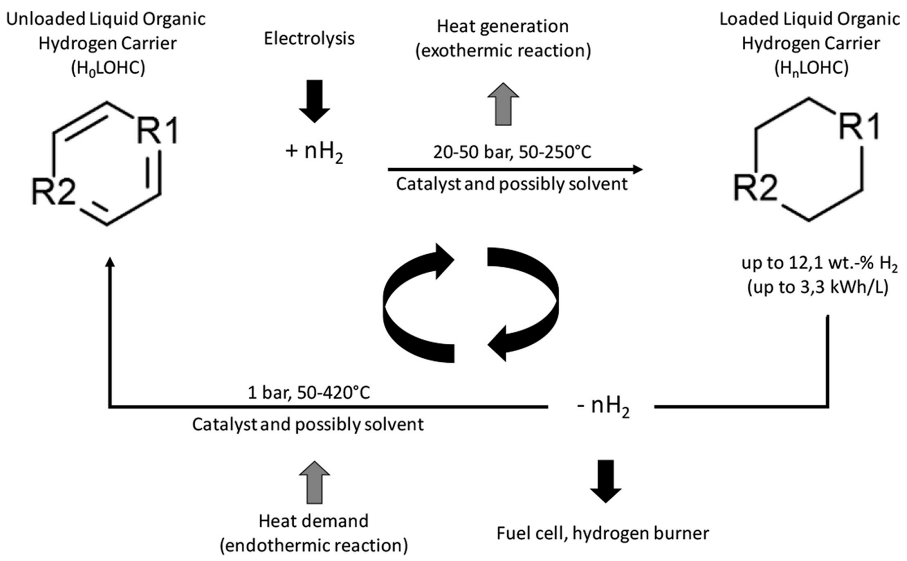


Figure B.3: Concept of the LOHC storage (Niermann et al., 2019)

Currently, there is little infrastructure (expected) for producing LOHC. Therefore, using LOHC is not possible right now and probably not in the near future either. Right now, LOHC is investigated to transport hydrogen using existing crude oil tankers instead of it being used as a maritime energy carrier (Hydrogenious Technologies, 2018). Therefore, LOHC is not further considered in this research.

B.4. Nuclear

Nuclear energy could be used as zero-emission energy carrier. Small Modular Reactors are technically feasible to install as vessel propulsion machinery (Jacobs, 2007). Nuclear energy has very low WTT and no TTW emissions. If extraction and transportation would be done with 100% renewable energy, nuclear energy could also be 100% renewable.

To date, there is one reactor technology that fulfils all requirements to be used commercially in vessels: the marine Molten Salt Reactor (m-MSR) (Gennaro, 2021). Firstly, a m-MSR is running on liquid fuel which solidifies when the temperature is below 450°C, which makes it walk-away safe. Secondly, m-MSR runs at ambient pressure and therefore cannot explode. Because the vessel will be fuelled for life, there are no safety concerns in bunkering and no accidental radiation releases can occur. Furthermore, a benefit of m-MSR is that the fuel can be drained or poisoned to solidify the fuel (Gennaro, 2021). When solidified, the fuel will not work anymore and does not expel any radiation to the environment. This means that there is no radioactive waste at the end of a vessel lifetime. Draining or poisoning is activated whenever the vessel sinks, capsizes, is grounded, is in a collision, whenever there is a fire or explosion on a vessel, whenever there is an attack from pirates, or during other serious maritime accidents. Lastly, according to Safety4Sea (2021), if passenger accommodation would be away from the reactor, it would be impossible to be exposed to maximum permissible radiation doses. If the crew would wear protective clothing when near the reactor, the exposure would also never be above 5 rems and thus not be critical (ICRP, n.d.).

However, nuclear energy has one major problem. The public opinion on nuclear energy is very bad.

This is mainly caused due to a few very big disasters at nuclear power plants, including the Fukushima Daiichi nuclear disaster (2011) and the Chernobyl disaster (1986) (TIME.com, 2009). Next to the low social acceptance of nuclear energy, there are more problems. Nuclear power has radioactive waste disposal which is very harmful for the environment if not stored well. Moreover, accidental release of radioactivity could be very harmful for the ones who are subjected to this and being too close to a reactor is dangerous.

Furthermore, nuclear propulsion systems must be applied on a larger scale to become competitive with other zero-emission energy carriers (Nelissen, 2021) (Gennaro, 2021). The total life cycle cost of propulsion with m-MSR between 2020 and 2050 would be the lowest of all energy carriers in this chapter. This total life-cycle cost is however calculated with the assumption that creating large-scale operations are started in 2020. The problem of large-scale operations is that there must be legislation and policy incentives. However, as stated, the public opinion on nuclear energy is very bad which leads to very little incentives.

To conclude, there are no technical barriers that cannot be solved and economically speaking, nuclear energy is also a good competitor on the long term. However, to achieve large-scale application, public acceptance must significantly increase, which is not expected to happen soon and therefore nuclear energy is not investigated further during this research.

C

Bunker prices Rotterdam

Nov 5, '18 - Nov 3, '21	High	Low	Average	Spread
Rotterdam - LSMGO	$719.50	$191.75	$498.00	$527.75
Rotterdam - IFO380	$491.75	$125.25	$330.50	$366.50
Rotterdam - VLSFO	$611.50	$157.75	$431.00	$453.75
Rotterdam - MGO	$718.75	$190.00	$500.50	$528.75
Rotterdam - ULSFO	$710.00	$485.00	$581.50	$225.00

Figure C.1: Bunker prices of different fuels in Port of Rotterdam (Ship & Bunker, 2021)

D

Energy carrier (future) availability maps

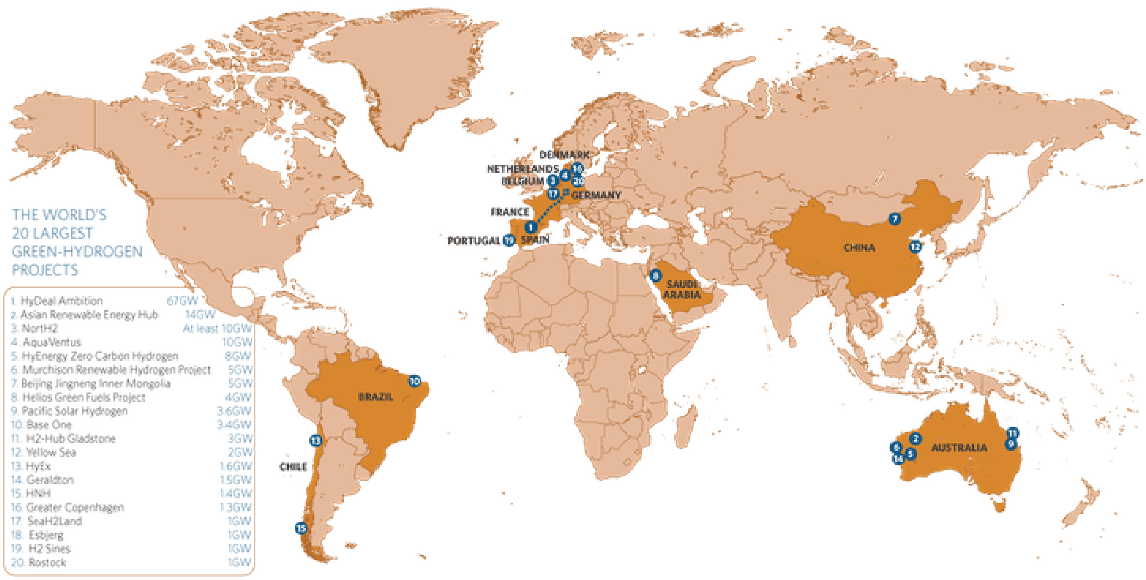


Figure D.1: Green hydrogen projects on the world map (IRENA, 2020a)

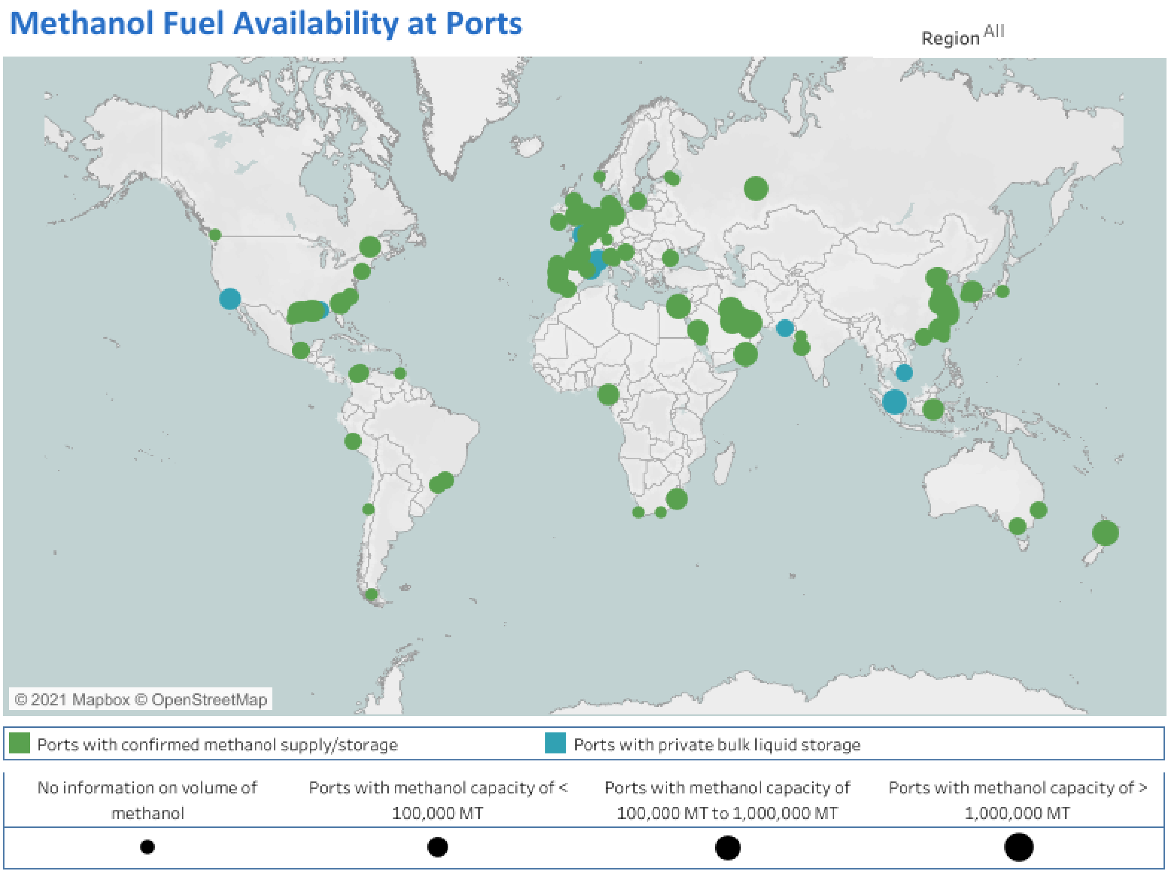


Figure D.2: Methanol Fuel Availability at Ports (Methanol Institute, 2020a)

Figure D.3: Availability of ammonia in ports in European waters (DNV GL, n.d.-a)

E

DP capability

Beaufort (BF) number	*DP capability number*	*Beaufort description*	*Wind speed*) [m/s]*	*Significant wave height [m]*	*Peak wave period [s]*	*Current speed [m/s]*
0	0	Calm	0	0	NA	0
1	1	Light air	1.5	0.1	3.5	0.25
2	2	Light breeze	3.4	0.4	4.5	0.50
3	3	Gentle breeze	5.4	0.8	5.5	0.75
4	4	Moderate breeze	7.9	1.3	6.5	0.75
5	5	Fresh breeze	10.7	2.1	7.5	0.75
6	6	Strong breeze	13.8	3.1	8.5	0.75
7	7	Moderate gale	17.1	4.2	9.0	0.75
8	8	Gale	20.7	5.7	10.0	0.75
9	9	Strong gale	24.4	7.4	10.5	0.75
10	10	Storm	28.4	9.5	11.5	0.75
11	11	Violent storm	32.6	12.1	12.0	0.75
12	NA	Hurricane force	NA	NA	NA	NA

*) The wind speed is the upper limit of the mean wind speed 10 m above sea level for the given DP capability number. The given peak wave periods represent the 95% confidence interval found from the world wide scatter diagram.

Figure E.1: DP capability numbers and Beaufort scale wind, wave height, wave period and current speed (DNV, 2021a)

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