Master's thesis

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Zero-emission ready

Master's thesis in Marine Technology
Supervisor: Stein Ove Erikstad
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MASTER THESIS

Zero Emission Ready

Thomas Furnes Søgaard

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Master Thesis in Marine Systems Design

Stud. techn. Thomas Søgaard

"Zero emission ready"

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Background

The goal is to reduce CO_2 emissions from shipping by 50% by 2050. With the expected increase in seaborne transport, this implies that the average reduction needs to be 70%, with a significant part of the fleet being zero emission.

For a ship designed and built during the next few years, 2050 is within the range of the lifetime of the vessel. Low and zero emission technology is developing fast, but for most vessel types it is not a viable option today. An alternative path is to prepare new vessels for retrofitting parts of their powering system, along with new and stricter regulations, new technology opportunities and the availability of new infrastructure.

Overall aim and focus

The overall aim of the master thesis is to review the different options related to alternative fuels in order to reach the emission goals of 2050, using Epoch-era analysis early in the design phase with a goal of minimizing risk in terms of early choices.

Scope and main activities

The candidate should presumably cover the following main points:

1. *Provide an overview of the current status and important development trends related to modularity and alternative fuels.*
2. *Provide a state-of-the-art, state-of-technology, literature review on modularization and feasibility of alternative fuels on ships today.*
3. *Perform a case study for short-sea shipping*
4. *Discuss and conclude*

Modus operandi

At NTNU, Professor Stein Ove Erikstad will be the responsible advisor.

The work shall follow the guidelines given by NTNU for the MSc Project work

Stein Ove Erikstad
Professor/Responsible Advisor

ABSTRACT

A ships lifetime spans from 20 to 30 years. The last 20 to 30 years technology have become more sophisticated, new laws and regulations have been introduced and we have been through a financial crisis as well as we are currently struggling with a pandemic. When designing a ship today, this is something that needs to be taken into account. Knowing what the future holds is not possible, but it is still important to make an effort to create a ship that manages to perform through a wide variety of future scenarios. The uncertainty of the future is something that needs to be addressed in the decision-making progress of a ship. Is business as usual still good enough, is an improvement of today's standard needed, or does one need to think outside the box?

The overall aim of the master thesis is to review the different options related to alternative fuels in order to reach the emission goals of 2050. To do so, a literature review is done related to design under uncertainty as well as on alternative fuels to understand today's status quo. A total of 5 energy carriers where assessed; battery, hydrogen, ammonia, methanol and LNG. After an introduction to both decision support tools and potential alternative fuels, a case study was conducted checking the performance of MDO up against LNG. The question that was to be answered in this illustrative case was:

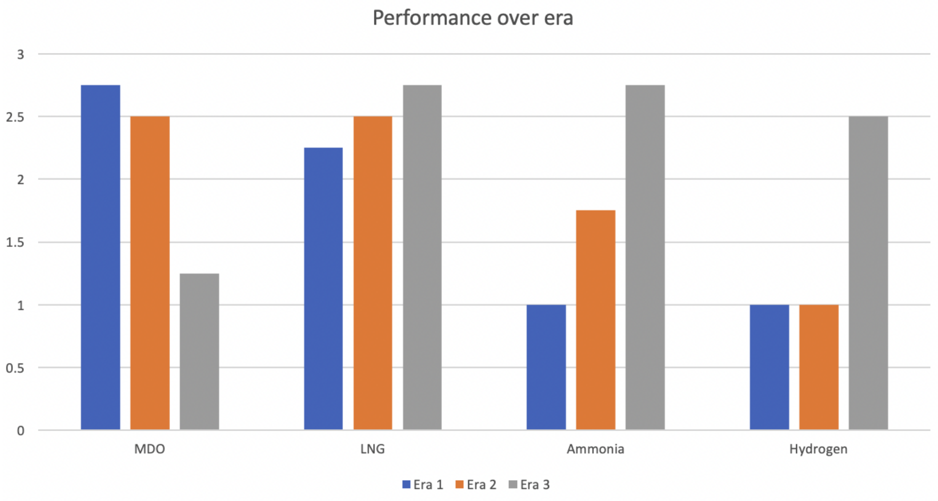
> *Should one design a flexible ship in a way that allows cheap and quick retrofitting in the future or should one design a ship the conventional way if minimizing costs is the goal?*

This illustrative case was approached by making predictions about the future and see how the two options performed. The results where given in terms of risk involved with choosing the one or the other where LNG proved to be a lower risk option.

Alternative 1: MDO	**Risk**
0-10 years	Medium
10-20 years	High

Alternative 2: LNG	**Risk**
0-10 years	Low
10-20 years	Low

In addition to the illustrative case, MDO, LNG, ammonia and hydrogen were all assessed in a epoch-era analysis. Here, the performance of the alternative fuels are being evaluated in multiple different scenarios ranging from a conservative setting similar to today's standard and to a more abrupt future where technologies have come a far way and rules and regulations are very strict. The analysis takes factors like e.g. emission taxes, regulation related to operation areas, fuel price and more into account. Their performance through every scenario are evaluated to see which performs best overall.



The combination of these two approaches gives valuable insight to what needs to be accounted for early on in a decision-making process when the goal is a value-robust design. It can also contribute to find the answer to the question regarding whether flexibility is worth the extra investment or not.

SAMMENDRAG

Levetiden til et skip strekker seg fra 20 til 30 år. De siste 20 til 30 årene har teknologi blitt mer sofistikert, nye lover og regler er introdusert, vi har vært igjennom en finanskrise og akkurat nå er vi midt i en pandemi. Når man designer et skip i dag, er dette noe man må ta hensyn til. Å vite hva fremtiden bringer er ikke mulig, men det er likevel viktig å gjøre enn innsats for å lage et skip som kan operere og prestere gjennom flere ulike og uforutsette scenarioer. Usikkerheten knyttet til fremtiden er noe man må diskutere når valg skal tas i en designprosess. Er *"business as usual"* bra nok? Trenger man å forbedre dagens standard, eller må man tenke helt utenfor boksen?

Det overordnede målet til denne masteroppgaven er å gjennomgå de ulike valgene man har med tanke på alternative drivstoff eller energibærere, slik at man kan gjøre gode valg og nå utslippsmålene innen 2050. For å gjøre dette, er det blitt gjort en litteraturstudiet på design under usikkerhet i tillegg til på fem ulike alternative brensler / energibærere; batteri, hydrogen, ammoniakk, methanol og flytende naturgass(LNG). Etter en introduksjon til både noen beslutningsstøtteverktøy og relevante alternative brensler, en case-studie er blitt gjennomført for å sjekke prestasjonen til ordinær dieselmotor mot LNG-motor. Spørsmålet som skulle svares på i den illustrative casen var:

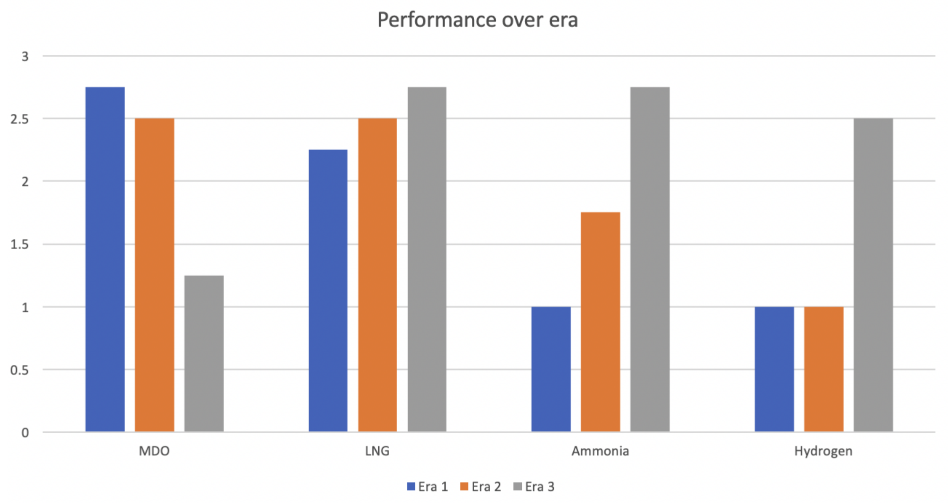
> *Burde man designe et fleksibelt ship på en slik måte at det tillater en rask og billig ombygging i fremtiden, eller bør man designe et skip på den konvensjonelle måten hvis målet er å minimere kostnad?*

Den illustrative casen ble gjennomført ved å gjøre visse forutigelser om fremtiden og se hvordan de to ulike valgene presterte. Resultatene ble presentert i form av hvilke risiko de to valgene ville innbært, hvor det viste seg at LNG innebar lavest risiko.

Alternative 1: MDO	Risk
0-10 years	Medium
10-20 years	High

Alternative 2: LNG	Risk
0-10 years	Low
10-20 years	Low

I tillegg til den illustrative casen er MDO, LNG, ammoniakk og hydrogen blitt analyst i en epoch-era analyse. Denne analysen evaluere prestasjonene til de ulike brenslene i en rekke ulike scenarioer. Scenarioene starter veldig konvensjonelt og blir mer og mer abrupte hvor ny teknologi er kommet og strenge regler er innført. Analysen tar hensyn til faktorer som utslippskatt, lover og regler relatert til operasjonsområder, brenselpris med mer. Prestasjonene til de ulike brenslene er evaluert for å se hvilke som gjør det best alt i alt.



Kombinasjonen av disse to måtene å angripe problemet på kan gi verdifull innsikt i hva som er viktig å ta hensyn til tidlig i en beslutningsprosess hvor målet er å lage et robust design. Det kan også hjelpe til med å finne svaret på om det er verdt å investere i fleksibilitet eller ikke.

PREFACE

This paper is the result of a master thesis at the Department of Marine Technology at the Norwegian University of Science and Technology (NTNU) in Trondheim. The work is a continuation of my project thesis written fall 2019. This thesis marks the end of my Master of Science (MSc) degree, with specialization within Marine Systems Design and Logistics.

The thesis is motivated by the continued demand for lowering emissions in the shipping industry. The marine industry, although conservative, has lately picked up the pace in terms of thinking alternative fuels, motivated by IMO's goal of reducing emissions by 50% by 2050. The main goal of this thesis has been to explore the viability of some alternative fuels to see if they are worth the extra investment as of now.

AKNOWLEDGEMENT

I would like to express my gratitude to my supervisor Professor Stein Ove Erikstad for guidance and counseling during the work on the master thesis. Your great insight and knowledge about the maritime industry has helped me tremendously.

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ABBRIVIATIONS

CAPEX = Capital expenditures
OPEX = Operational expenditures
TRL = Technology readiness level
GHG = Greenhouse gases
LNG = Liquefied natural gas
CNG = Compressed natural gas
MDO = Marine diesel oil
HFO = Heavy fuel oil
LBG = Bio-LNG
CCS = Carbon capture and storage
ICE = Internal combustion engine
NO_x = Nitrogen oxides
SO_x = Sulfur oxides
KPI = Key performance indicator
C_F = Cost of fuel

1 PROBLEM DESCRIPTION

Climate awareness is steadily increasing and the shipping industry is experiencing increasing pressure to act upon the Paris Agreement and lower greenhouse gas emissions. To ensure sustainability in future shipping, ships build today and in the future need to run on alternative fuel or the possibility to do so. The life expectancy of a ship today is around 20 to 30 years. In 25 years from now, new technologies have emerged, and possibly, this technology will help ships becoming greener. As the title of this thesis refers to, the vision is zero-emission. Today, ships are almost exclusively fueled on heavy fuel oil (HFO) or marine diesel oil (MDO) which in the future may potentially be very expensive due to pollution taxes. Ships running entirely on HFO will also not have access to ports in emission controlled areas (ECA), making their operational area smaller and thus less competitive in the market. To be able to compete in the market, alternative fuels that lower the emissions - preferably as far as to zero emissions, are needed. Today, the technology is not fully ready to implement these alternative fuels. There are multiple reasons for this, like energy efficiency, capacity problems and rules, and regulations. However, a solution to this can be to plan for this when building new ships by implementing flexibility to the ship, Choi (2018). This is what is going to be further explored in this thesis. Are higher flexibility and a lower risk worth the investment, or should one go for the cheap alternative but with higher potential risk? An answer to this question is not the goal, moreover how one should go about finding it.

2 INTRODUCTION

2.1 BACKGROUND AND MOTIVATION

Emissions of greenhouse gases, hereby referred to as GHG, from human activities is, according to *IPCC, 2013. Climate Change: The Physical Science Basis.* (2013), the top contributor to the earth's temperature rise. Now, as we see the imminent consequences of climate change, environmental conservation and protection get increasingly more attention all around the world. Shipping has for a long time been in the shadows of the automotive industry, however, more focus is being directed towards the maritime industry. The shipping industry is seen as the most environmentally friendly transport industry, but being responsible for approximately 90% of the world trade *ICS | Shipping and World Trade* (2018), the contribution to GHGs is still huge and not to be neglected. The goal is to reduce CO_2 emissions from shipping by 50% by 2050. With the expected increase in seaborne transport, this implies that the average reduction needs to be 70%, with a significant part of the fleet being zero-emission.

For a ship designed and built during the next few years, 2050 is within the range of the lifetime of the vessel. Low and zero-emission technology is developing fast, but for most vessel types it is not a viable option today. An alternative path is to prepare new vessels for retrofitting parts of their powering system, along with new and stricter regulations, new technology opportunities and the availability of new infrastructure. The term "Zero-emission ready" is a rewrite of a similar service DNV-GL has for future LNG retrofitting, "LNG-ready", *LNG Ready* (2019)

The overall aim of the master thesis is to investigate how flexibility in ship design and decision making under uncertainty, mainly energy-related energy converters, can enable cost and time-efficient retrofitting of key power system components during the lifetime of the vessel towards low or zero-emission, alongside tightening regulations, new technology opportunities, and fuel infrastructure. This will be done by creating an illustrative case the makes the problem more tangible and easier to grasp.

3 SCOPE & LIMITATIONS

This masters thesis researches a couple of chosen alternative fuels, their energy converters and environmental performance. It is a result of a purely theoretical study and is consequently limited by the already existing literature. The alternative fuels that have been reviewed are batteries, hydrogen, ammonia, methanol, and LNG as bridging fuel. Due to technological maturity, LNG has been more deeply assessed.

4 LITERATURE REVIEW

4.1 DESIGN TO HANDLE CONTEXTUAL UNCERTAINTY AND RISK MITIGATION

Design processes have been much studied throughout the years. Pahl & Beitz (2013) divided the process into four phases, namely *Planning and task clarification*, *Conceptual design*, *Embodiment design*, and *Detailed design* illustrated in Figure 4.1.

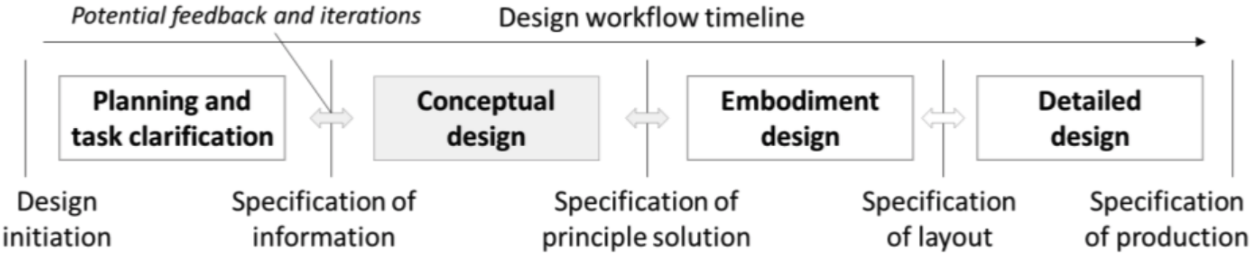


Figure 4.1: The design process as described by Pahl & Beitz.

This thesis will focus on a part of the conceptual design process, where the main features of a ship are determined. This includes the ship's capabilities, dimensions and outline specification. As this is a thesis on zero-emission possibilities, the process of choosing machinery and fuel type is of interest. As seen in Figure 4.1, design can be divided into phases where each phase is expected to deliver further information into the next phase. However, a problem related to this can be illustrated in Figure. Early on in a design process, decisions are made based on little information, and as time pass, the freedom to change gets smaller, or at least much more expensive.

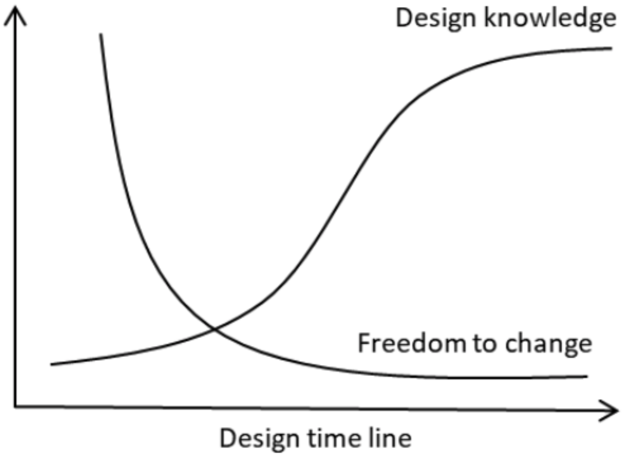


Figure 4.2: Illustration of the relation between design knowledge and freedom to change (Mistree et al. (1990)).

Throughout the literature, the conceptual phase is also referred to as preliminary and early-stage. After the conceptual design phase comes the choice of design concept. Making such a decision requires that many decisions already have been made. According to Rehn (2018), 60 – 80% of the total lifecycle costs are already determined at this stage, yet only a minimal of the total costs are expended at this stage. A high degree of design freedom is something that characterizes the conceptual design phase. Having an understanding of this makes it easier to see that it is important to make value-robust conceptual design decisions.

There are multiple ways of handling contextual uncertainty in engineering design. Ross et al. (2008) defines two possibles approaches: 'passive' or 'active. A versatile design is what one would call a passive approach. These are designs where extra capabilities that might be used in the future are considered. According to Choi (2018), a *Swiss Army Knife* is an example of this. The buyer usually doesn't know if they will use every tool on the pocketknife, however, they believe that the tools might create value in the future. Choi (2018) also uses an offshore supply vessel (OSV) as an example of a versatile design, albeit an inflexible one. An OSV is often designed with multiple capabilities in order to operate a wide specter of different operations.

Figure 4.3: Swiss army knife.

Figure 4.4: Inflexible multi-purpose ship.

An active approach, on the other hand, are designs where changeability has been implemented in the design to handle contextual uncertainty. Examples of active approaches are a flexible design, adaptable design, changeable design, and scalable design. Standardization and modularization is a way of implementing this ability to the design. This gives the designers the possibility to delay costly investment decisions for extra functions and capabilities until the operation phase where more information will become available.

The question is then; What is the best approach to handle contextual uncertainty? There is no answer to this, as this will vary from case to case. Both passive and active approaches have their advantages as well as disadvantages. One can argue that an active approach is a way of mitigating risks in the initial design decisions, however, with an active approach, downtime must be taken into account when adding new functions or capabilities to the ship. This downtime can be crucial because this lowers the response time of the vessel, creating a time gap between the supply and demand. A versatile ship, on the other hand, would always be ready to perform all its services. However, a versatile ship may risk to never use some of its functions or capabilities throughout its lifetime, meaning the extra investments have gone to waste. This can be a significant threat to stakeholders in the maritime sector as the cost of acquisition of marine systems is high. These extra expenditures will significantly increase the CAPEX and possibly also increase the OPEX as a result of increased fuel consumption and reduced deck area.

5 ZERO EMISSIONS FUELS AND ALTERNATIVES

The alternative fuels that are most commonly talked about today are LNG (liquefied natural gas), LPG (liquefied petroleum gas), methanol, bio-fuels, hydrogen as well as batteries. How far the technologies have come within these fields are somewhat different. A common way of expressing the maturity of a technology is by using the concept technology readiness level (TRL). TRL is a system developed by NASA and it is a systematic measurement system to support the assessment of a particular technology's maturity Mankins (1995) and a way of comparing the maturity of technologies ,Mankins (1995). The 9 levels of TRL are explained in Figure 5.1 below.

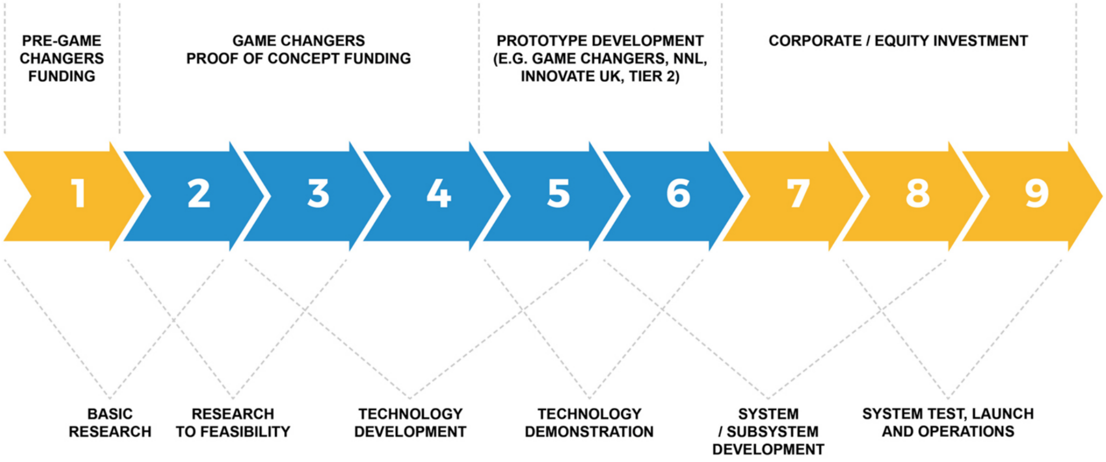


Figure 5.1: TRL as defined by *Technology Readiness Levels* (2018)

With the goal of reducing emissions by as much as 50% within 2050, the need for change is urgent. However, technological breakthroughs are needed in the different fields, but until that happens, a plan of how one can best facilitate the new technology to come would be of help. In the following sections, some relevant alternative fuels are introduced showcasing both advantages and challenges related to implementing them as well as how realistic it is at this point in time.

In *Comparison of Alternative Marine Fuels*, DNV GL has done an assessment on multiple alternative fuels and have rated their respective maturity with a grading system from 1 to 4 where;

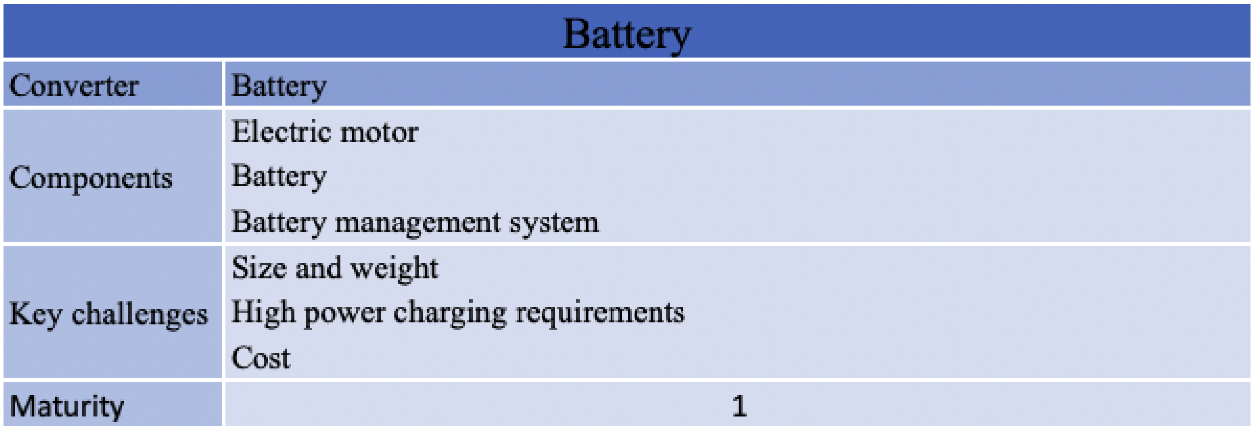
- 1. Measures that are off the shelf and commonly used on new ships.
- 2. Measures that are commercially available, but not fully mature.
- 3. Measures that are under piloting, and/or with only a few commercial applications.
- 4. Measures that have not been tested in full scale and no piloting or full-scale testing underway.

Although TRL is commonly used to describe the maturity of the technology, the maturity is steadily changing as technology develops, DNV GL's interpretation was in this case preferred as that report was newest.

5.1 BATTERY

The idea of combining electrical power with an internal combustion engine came for a long time ago. In 1901, J. Lohner and F. Porsche, presented a hybrid vehicle, Budde-Meiwes et al. (2013). However, the technology did not further advance, so the concept failed. Despite multiple attempts and concepts, it took many years to successfully create a hybrid vehicle. Electric propulsion started on ships during the 1980s when semiconductor switching devices made opened up for the possibility of full rpm control of thrusters and propellers Hansen & Wendt (2015). However, the main motivation today for using electrically assisted propulsion in commercial shipping is fuel economy. This is because electric engines have a high degree of efficiency all the way from 5% to 100% of rated power, while for an internal combustion engine, max efficiency ($\sim 35-40\%$) are typically around 85%-90% of rated power Hannan et al. (2018). The electrical engine gives the opportunity to keep high propulsion efficiency in the entire operational range, while mechanically driven propulsion systems are designed and optimized for one specific operational point.

Table 5.1: Battery features



Battery	
Converter	Battery
Components	Electric motor Battery Battery management system
Key challenges	Size and weight High power charging requirements Cost
Maturity	1

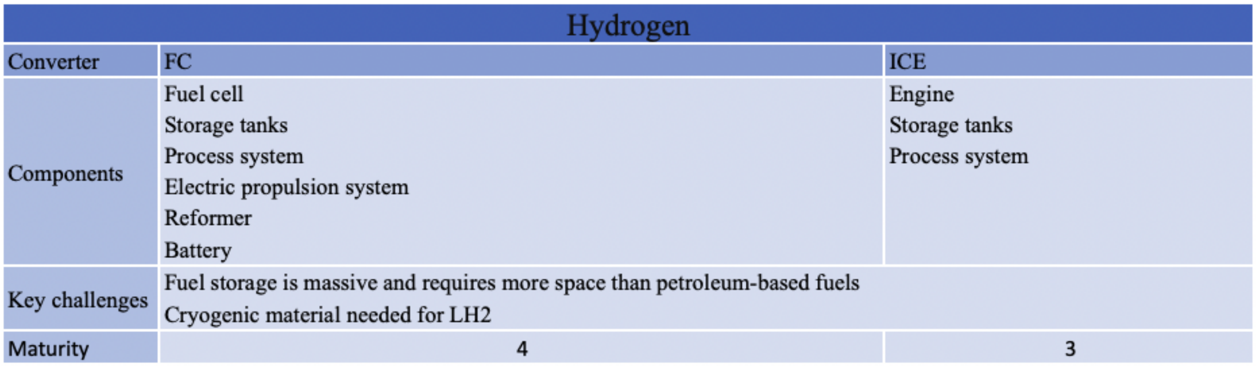
Today, the electric propulsion solutions vary depending on operational profiles, vessel types and the technology that was available at the time of construction. With increased environmental awareness, the electric propulsion fleet has grown three times as fast as the world fleet Pestana (2014). Although using hybrid-electric propulsion lowers emissions and increases efficiency significantly, it will still emit GHG as it is just an aid for the internal combustion engine which is the main power source. However, if the electricity comes from renewables, a fully electric vessel would have the benefit of zero-emission. However, battery can not as of today reach zero-emission in terms of life-cycle assessment as it contributes to emissions through its production and so on.There are others major drawbacks related to batteries that need to be overcome as well. Low energy density, high storage costs as well as relatively short lifetime makes fully electric vessels only viable for a limited amount of vessel sizes and types as well as only for shorter sailing distances, at least as of now. There are, however, progression in the field showcasing that making fully electric ships in the future is possible. "Ampere" is a fully electric fjord crossing battery ferry which is a pure zero-emission ferry.

5.2 HYDROGEN

Today, the shipping industry is almost exclusively using diesel engines. Oceangoing ships either use MDO or HVO as fuel, while inland waterway vessels - e.g. within the EU - often use commercial diesel fuel. At this point, the only other relevant options for the shipping industry are LNG, CNG or possibly batteries as e.g. "Ampere".

Like the aviation industry, the maritime industry is currently testing fuel cells as an on-board power supply. They already have been tested successfully under maritime conditions, and fuel cells are more efficient compared to diesel-generator sets, *Hydrogen Europe* (2019). Fuel cells do not only operate with hydrogen, but also with natural gas, diesel fuel or methanol. These have the perks of better availability as well as easier storage and lower price. They are converted into hydrogen by an external or internal reformer. Using hydrogen-powered fuel cells is still at a very early design phase, only tried at small scale passenger ships, ferries and recreational vessels. The most promising fuel cells for nautical applications as of this date is the high- and low-temperature fuel cells (PEMFC) as well as solid oxide fuel cell (SOFC). Fuel cells have not yet been scaled for and used on bigger commercial merchant ships. Another important aspect is that the technology is far too expensive today to sustainably implement it on a profitable ship.

Table 5.2: Hydrogen features



Hydrogen		
Converter	FC	ICE
Components	Fuel cell Storage tanks Process system Electric propulsion system Reformer Battery	Engine Storage tanks Process system
Key challenges	Fuel storage is massive and requires more space than petroleum-based fuels Cryogenic material needed for LH2	
Maturity	4	3

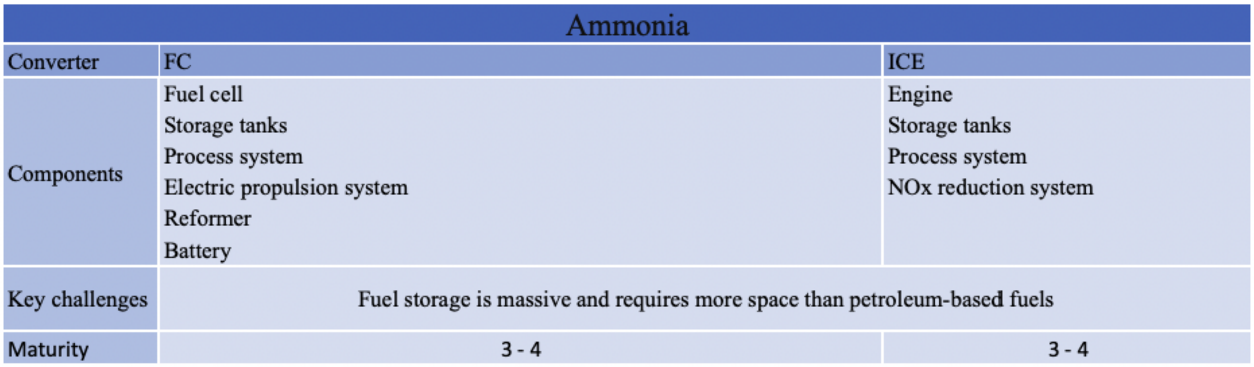
The advantage hydrogen has is that it has the opportunity to be completely zero-emission if produces from renewables. The anticipated energy transition on land to renewables is well in line with the future hydrogen production capacity. Until that transition has begun and well underway, hydrogen will mainly be produced by natural gas without carbon capture and storage. Besides the high costs related to hydrogen production, it also has some difficulties related to its applicability. The applicability at this time limits the ship segments where hydrogen can be used. For now, hydrogen is only applicable for shortsea shipping due to its limited range because of low density. It is also worth mentioning that additional costs related to safety systems and mitigating measures due to the flammability of hydrogen need to be accounted for as well. However, the specific costs of everything from installation, production, safety systems and operation will first be clear once the rules are thoroughly developed for using hydrogen as a fuel.

However, the production costs are still too high and the bunkering infrastructure is not sufficient at this point, Wold et al. (2019).

5.3 AMMONIA

The chemical formula for ammonia is NH_3. As one can see there is no carbon in ammonia, and with the future energy transition to renewable energy, ammonia has the potential of becoming a carbon-free energy carrier, but not emission-free. It has the benefit of having a higher density than hydrogen, granting the possibility of being feasible for deep-sea shipping. However, ammonia suffers from some of the same disadvantages as hydrogen, it is very expensive and has a low maturity level which consequently limits its feasibility as of now, as well as poor bunkering infrastructure. There are also extra costs related to implementing ammonia on ships as mitigating measures to avoid e.g. leakage of ammonia which is highly toxic, Brown (2018).

Table 5.3: Ammonia features

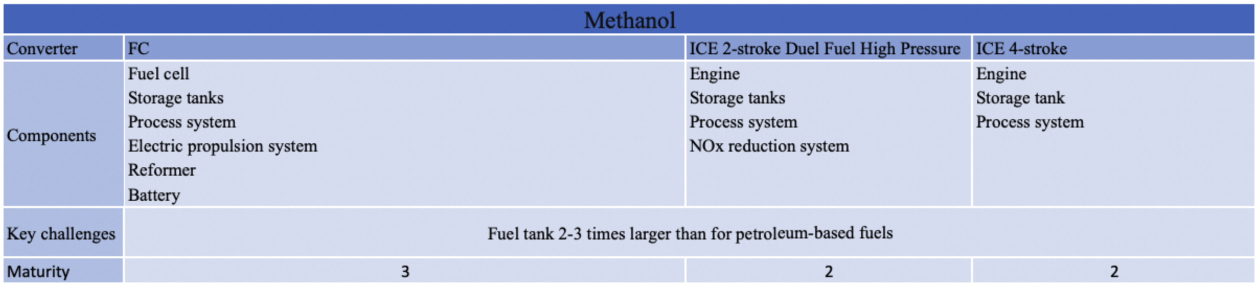


Ammonia		
Converter	FC	ICE
Components	Fuel cell Storage tanks Process system Electric propulsion system Reformer Battery	Engine Storage tanks Process system NOx reduction system
Key challenges	Fuel storage is massive and requires more space than petroleum-based fuels	
Maturity	3 - 4	3 - 4

5.4 METHANOL

Methanol has many upsides compared to the aforementioned fuels. It has relatively high applicability as it is able to utilize already existing converter technologies. It can be used as fuel in conventional engines like both a four-stroke and two-stroke diesel cycle engine or in a lean-burn Otto-cycle engine. Further on, methanol has a liquid form in the temperature range $-93^{\circ}C$ to $+65^{\circ}C$ at atmospheric pressure making it much easier to handle and cheaper to store compared to hydrogen, LNG, and ammonia. With its low tank costs comes low capital costs and it is in total a much cheaper alternative. However, even though methanol is very low on emissions of both sulfur oxides (SO_2), nitrogen oxides (NO_2), and particulate matter, but it is today produces mainly from fossil resources like coal or gas and has, therefore, a poor environmental performance as an alternative fuel compared to the aforementioned. Methanol has the possibility of being produced using other feedstocks, like renewable resources like black liquor from pulp and paper mills, agricultural waste, forest thinning or directly from CO_2 captured from e.g. power plants, Wold et al. (2019).

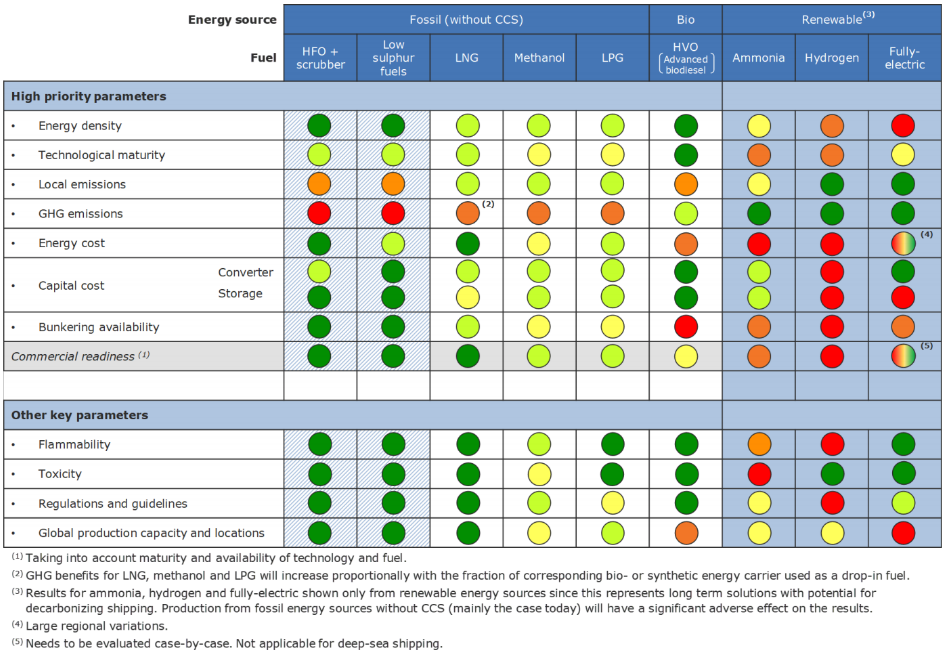
Table 5.4: Methanol features



Methanol			
Converter	FC	ICE 2-stroke Duel Fuel High Pressure	ICE 4-stroke
Components	Fuel cell Storage tanks Process system Electric propulsion system Reformer Battery	Engine Storage tanks Process system NOx reduction system	Engine Storage tank Process system
Key challenges	Fuel tank 2-3 times larger than for petroleum-based fuels		
Maturity	3	2	2

5.5 CURRENT STATUS AND FEASIBILITY

The aforementioned fuels have multiple advantages and disadvantages both compared with each other and compared to today's MDO and HFO. Figure 5.2 shows an illustration made by DNV GL giving an overview of some alternative fuels they have seen as relevant for the future. This figure emphasizes the advantages and disadvantages related to the different fuels. Methanol is for instance relatively good on all points, besides possibly the most important one, at least related to this thesis, namely GHG emissions. When looking at those with the potential of being 100% emission-free, one can easily see that there is still a way to go in terms of infrastructure, technology, and regulations. However, as the market realizes that the demand for these alternative fuels is high, the infrastructure will eventually become better. To speed up this process, help from governments in terms of facilitating for a change to happen are needed. Companies will ultimately make decisions upon where they can earn money. Building an infrastructure to a technology that is not yet available is not very attractive. It is also not attractive to spend a lot of money and resources on new technology that where it is a total lack of infrastructure. Until the infrastructure is ready, bridging fuels are an option that can be evaluated.



Energy source		Fossil (without CCS)					Bio	Renewable[3]		
Fuel		HFO + scrubber	Low sulphur fuels	LNG	Methanol	LPG	HVO (Advanced biodiesel)	Ammonia	Hydrogen	Fully-electric
High priority parameters										
• Energy density		🟢	🟢	🟩	🟩	🟩	🟢	🟡	🟠	🔴
• Technological maturity		🟩	🟩	🟩	🟡	🟡	🟢	🟠	🟠	🟡
• Local emissions		🟠	🟠	🟩	🟩	🟩	🟠	🟡	🟢	🟢
• GHG emissions		🔴	🔴	🟠[2]	🟠	🟠	🟩	🟢	🟢	🟢
• Energy cost		🟢	🟩	🟢	🟡	🟩	🟠	🔴	🔴	◐[4]
• Capital cost	Converter	🟩	🟢	🟩	🟩	🟩	🟢	🟩	🔴	🟢
	Storage	🟢	🟢	🟡	🟩	🟩	🟢	🟩	🔴	🔴
• Bunkering availability		🟢	🟢	🟩	🟡	🟡	🔴	🟠	🔴	🟠
Commercial readiness [1]		🟢	🟢	🟢	🟩	🟩	🟡	🟠	🔴	◐[5]
Other key parameters										
• Flammability		🟢	🟢	🟢	🟩	🟢	🟢	🟠	🔴	🟢
• Toxicity		🟢	🟢	🟢	🟡	🟢	🟢	🔴	🟢	🟢
• Regulations and guidelines		🟢	🟢	🟢	🟩	🟡	🟢	🟡	🔴	🟩
• Global production capacity and locations		🟢	🟢	🟢	🟡	🟩	🟠	🟡	🟡	🔴

(1) Taking into account maturity and availability of technology and fuel.

(2) GHG benefits for LNG, methanol and LPG will increase proportionally with the fraction of corresponding bio- or synthetic energy carrier used as a drop-in fuel.

(3) Results for ammonia, hydrogen and fully-electric shown only from renewable energy sources since this represents long term solutions with potential for decarbonizing shipping. Production from fossil energy sources without CCS (mainly the case today) will have a significant adverse effect on the results.

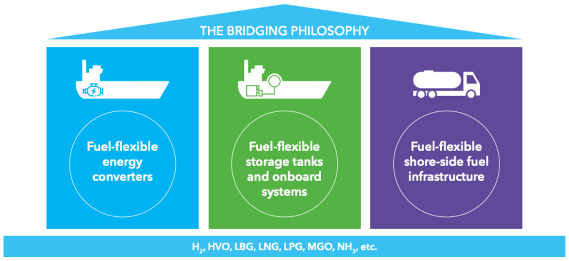
(4) Large regional variations.

(5) Needs to be evaluated case-by-case. Not applicable for deep-sea shipping.

Figure 5.2: An overview of the maturity of a set of alternative fuels, *DNV GL* (2018)

5.6 LNG AS BRIDGING FUEL

According to *The world merchant fleet - statistics from Equasis* (2019), there are currently approximately 11 000 ships in the world fleet, where the majority are powered by diesel engines. Changing an entire world fleet over from traditional fuel over to low-emission alternative fuels will, of course, be a very time-consuming process. To reach the goal of reducing emissions by 50% within 2050, the world fleet needs to go through a transition, and the transition needs to happen smoothly over a period of time to ensure stability in the market. In order to reach the 50% goal within 2050, changes need to happen now. However, the technology to accomplish zero-emission is not ready this time, and this is where the idea of a bridging fuel comes in.



H_2, hydrogen; HVO, hydrotreated vegetable oil; LBG, liquid biogas; LNG, liquefied natural gas
LPG, liquefied petroleum gas; MGO, marine gas oil; NH_3, ammonia
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Figure 5.3: The model on bridging philosophy, by DNV GL

Bridge fuels are fuels that facilitates the possibility of implementing zero-emission fuels in the future when technology is ready. It is a way of smoothening the transition from today's use of MDO and HFO to more gentle fuels, typically natural gas. In *Maritime Forecast to 2050* by DNV GL, *The Bridging Philosophy* is brought up. They have made a model on how one should facilitate for by future zero-emission fuels based by implementing three pillars based on different aspects of fuel flexibility; infrastructure, onboard systems, and energy converters as shown in the Figure 5.3 below.

In the same report, LNG and LPG were used as examples of such bridging fuels, illustrating how a possible transition could look like. In Figure below, one can see that if LNG is chosen, it is easy to later transition to blending in Bio-LNG and hydrogen into the fuel mixture reducing emissions further, as shown in Figure 5.4. Going for LPG and then transition into using ammonia is also a possibility, but will not be further assessed now.

LNG consists mainly of methane, CH_4, which is the hydrocarbon with the lowest carbon content. This gives LNG a huge potential in reducing CO_2, roughly a 26% reduction if compared with HFO, *Alternative Fuels Insight* (2019), and the production process of LNG ensures that there are no SO_x emissions either. LNG has approximately 18% higher energy density (LHV in MJkg) than HVO and also a lower volumetric density (43% of HFO). However, LNG has to be stored in cylindrical tanks, so these advantages get washed away resulting in approximately the same potential of storing energy onboard a ship.

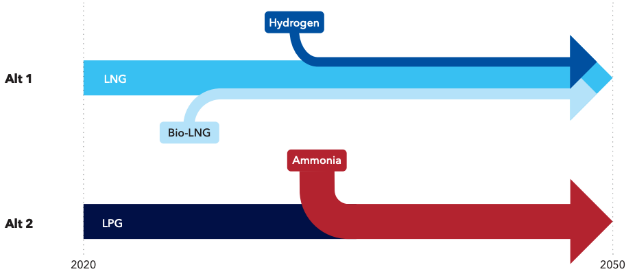
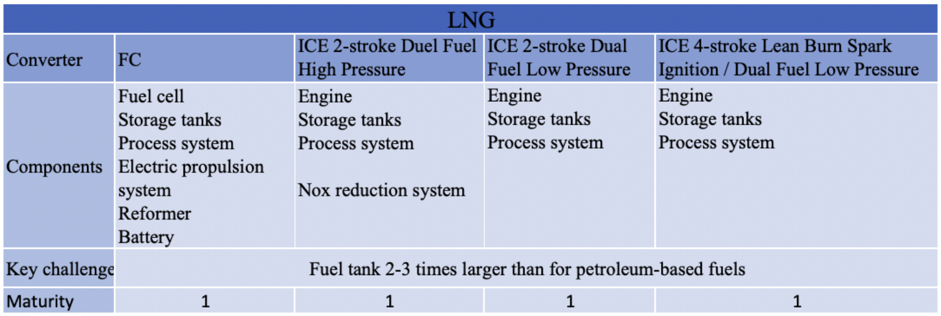


Figure 5.4: Two alternative fuel paths for LNG and LPG

LNG as a fuel is highly flexible and the maturity is relatively high as seen in Table 5.5. The flexibility gives many possible opportunities in the future, as LNG can use multiple different energy converters. Today, a regular ICE is what is most relevant, however, fuel cells might be interesting as well as technology proceeds. This opens up the possibility of creating a zero-emission ship, which is an opportunity that an ICE doesn't possess. Due to the high temperature in the combustion process, nitrogen coming from the air will produce NO_x, making NO_x-emissions inevitable for combustion engines.

Table 5.5: LNG features



LNG				
Converter	FC	ICE 2-stroke Duel Fuel High Pressure	ICE 2-stroke Dual Fuel Low Pressure	ICE 4-stroke Lean Burn Spark Ignition / Dual Fuel Low Pressure
Components	Fuel cell Storage tanks Process system Electric propulsion system Reformer Battery	Engine Storage tanks Process system Nox reduction system	Engine Storage tanks Process system	Engine Storage tanks Process system
Key challenge	Fuel tank 2-3 times larger than for petroleum-based fuels			
Maturity	1	1	1	1

6 DECISION SUPPORT TOOLS

6.1 KPI

A set of different alternative fuels have now been reviewed. However, making a solid decision might require more than this, especially when deciding upon something that is supposed to last an entire lifetime of a ship. Decision support tools can, therefore, be useful. These tools can help to quantify the problems making it easier to point out the advantages and disadvantages of the different solutions. However, there are some attributes that harder to quantify than others, for instance, eco-friendliness. In that case, introducing key performance indicators hereby referred to as KPI can be beneficial. Any business that wishes to improve both efficiency and cost-effectivenessn needs to have a clear way of measuring success. This relates especially to shipping, where big companies that own large fleets need to track and analyze performance. To understand how your fleet performs and to easily identify areas for improvement, setting KPIs for your fleet is a good way of measuring your fleet accurately. KPIs can be divided into high- and low-level KPI. High-level KPI can, for example, be big goals for the overall performance of the business, while a low-level KPI may be weekly goals related to amount sales, etc. However, a KPI is only as valuable as the actions it aspires. Defining KPIs are not enough on their own, but are very valuable as a way of measuring performance and as a decision-making tool. Another important aspect of KPI is that it helps in sorting relevant data. Using KPI helps to limit the amount of useful data, making it easier to act on the information received. In the maritime business, KPIs are often related to costs, emissions, efficiency, delivery time, profits, failure response time and more.

6.2 RISK MITIGATION

An important aspect to assess when deciding upon a project, is the risk involved with the different choices. One way of assessing the risk related to a project is to create a risk matrix. Risk is calculated using Equation (6.1):

$$Risk = Likelihood \cdot Consequence. \tag{6.1}$$

A risk matrix is used to make the problem tangible as the parameters are hard to quantify:

Table 6.1: Risk matrix evaluating the different combinations of consequence and probability.

Risk Classes	**Highly unlikely**	**Unlikely**	**Likely**	**Very likely**
Catastrophic	Medium	High	High	High
Critical	Low	Medium	High	High
Major	Low	Low	Medium	High
Minor	Low	Low	Low	Medium

This is an example of how a risk matrix could look like. The green fields represent tolerated risks, yellow fields represent marginal risks, and the red fields represent risk that are not tolerated. The severity of the consequences are described in Table 6.2 below.

Table 6.2: Classification of the consequences based on their severity.

Consequence	Description
Catastrophic	The ship is found unfit for operation and/or additional costs are unbearable.
Critical	The ship must undergo extensive reconstructions in the shipyard and/or additional costs are very high.
Major	The ship has to delay operation due to minor reconstructions or repair and/or additional costs are substantial.
Minor	Minor adjustments can be made under normal operation and/or additional costs are low.

The risk probabilities are classed as low, medium, and high and are further described in Table 6.3 below:

Table 6.3: Classification of the risks.

Risk Class	Description
Low	The risk should be kept fresh in mind, but no precautions are made
Medium	Precautions should be strongly considered
High	Unacceptable risk level where significant precautions or design changes must be made

6.3 EPOCH-ERA ANALYSIS

Ships are subjected with a wide variety of missions, where requirements to capabilities and functionalities varies. However, something that always will be the case, is that every ship is subjected to a change in technology, climate, rules and regulations, oil price, and much more over the its lifetime. These factors among others are considered as uncertainty related to ship design. These are only few out of many factors that will have an impact of the performance of a ship through its lifetime. This is where an Epoch-era analysis (EEA) can be helpful. By employing an EEA, these potential circumstances can be to a certain extent be dealt with, or at least, approached with sense and reason. An EEA can be used to maximize the chances for the ship to uphold an adequate utility rate during its operational years.

EEA was developed by Ross et al. (2008) as a systems engineering technique where providing a structured way of representing temporal complexity of a system is the goal. The life-cycle of a ship is named an era, and an era is build up by epochs. The epochs are time periods throughout the life-cycle of a ship where there are a given set of static variables. When conducting an EEA, multiple epochs are constructed with a given set of epoch-variables. The epoch-variables are decided by evaluating what factors that will have an impact on the performance of the design. These are often related to physical design parameters, change in regulations or technology. When the epoch-variables are decided, these epoch-variables can take different values and construct multiple eras. Now one can evaluate the performance of the different designs by looking at each era. An era represents a combination of possible future scenarios, and the design that performs the best throughout all the constructed eras are considered as the optimal design.

7 MODEL AND CASE

The main goal of this thesis is to explore the possible benefits of implementing adding flexibility to the design that allows retrofitting from a commercial fuel to an alternative fuel in a cost-efficient manner. The question that needs to be answered is;

> *Should one design a flexible ship in a way that allows cheap and quick retrofitting in the future or should one design a ship the conventional way if minimizing costs is the goal?*

There is no obvious way to answer this question because this question raises a lot of other questions that first need to be answered. To what extent should flexibility be implemented? Change out parts continuously or at a given point? Is a passive approach better than an active one? To make a choice related to this, one needs to have a look into the future to see what it might hold. Changes in the market, regulations, and technology are three very important aspects that need to be assessed when deciding what design to go for.

One way to approach the question raised in the previous section can be to create an illustrative case. The illustrative case is made to make the question into a tangible problem. The case could be something along these lines:

You are a shipowner, and you are going to order a new chemical tanker. You have to decide if you want to build a cheap ship with a conventional engine running on MDO or if you should invest in an LNG-driven ship that much easier can be retrofitted to run on an alternative fuel in the future?

In order to find out what is the best decision, one needs to find a design that performs best over time. A way of finding the best performing design is by comparing them up against each other using key performance indicators.

7.1 INTRODUCING KPIS

Establishing key performance indicators (KPI) can in many cases be a good way of measuring something up against each other. This paper has a focus on decreasing emission in the future of shipping, and therefore, a suiting KPI must be relevant. Emissions are highly relevant and CO_2-emissions per tonne mile are, therefore, a suiting KPI. Another highly relevant KPI is the cost of fuel per tonne mile as most shipowners wish to minimize costs to maximize profits. These are the two KPIs that will be assessed further in this thesis.

7.1.1 CO_2-EFFICIENCY

CO_2-efficiency is a combination of the 2 performance indicators (PI) emitted mass of CO_2 and transport work and as defined by *Shipping KPIs* (2019), the KPI is calculated as follows:

$$\mathrm{KPI}_{\mathrm{CO_2-efficiency}} = \frac{\mathrm{PI}_1}{\mathrm{PI}_2} \times 10^6. \tag{7.1}$$

This gives the following KPI-unit:

$$\mathrm{KPI}_{\mathrm{CO_2-efficiency}} = \left[\frac{\mathrm{gCO_2}}{\mathrm{tonnes} \cdot \mathrm{mile}}\right] \tag{7.2}$$

Table 7.1: Comparison of KPI of MDO and LNG

	MDO	**LNG**	**Ammonia**	**Hydrogen**
$\mathrm{KPI}_{\mathrm{CO_2-efficiency}}$	320	248	0	0

As one can see, there is a big difference in the $\mathrm{KPI}_{\mathrm{CO_2-efficiency}}$. LNG is already a 22.5% decrease compared to MDO. However, both hydrogen and ammonia have det benifit og 0 CO_2-emissions as it does not contain any hydrocarbons.

7.2 POSSIBLE FUTURE SCENARIOS

As mentioned earlier, possible changes that come in the future needs to be accounted for when deciding on which solution to go for. External factors that are most likely to make an impact on the KPIs need to be identified. In other words, what are the opportunity drivers and risks beyond the shipowner's control? Creating possible future scenarios and then checking how the different designs perform within those scenarios are valuable information for the shipowner in a decision-making process. One way of approaching this problem can be to divide the future into segments and then evaluating the separate segments using a risk matrices. Here, segments of 10 years at a time have been evaluated.

7.3 ALTERNATIVE 1: MDO

One of the alternatives in the illustrative case was business as usual. Order a chemical tanker powered by MDO. This is the cheapest choice, but do not have the same flexibility in terms of retrofitting in case of future changes, and thus more sensitive to changes and a higher risk.

7.3.1 TECHNOLOGY

In an interview by *SAFETY4SEA* (2018), Mr. Eirik Nyhus, Director, Environment DNV GL, mentioned three key elements to decarbonization: increased efficiency, improved logistics, and carbon-neutral fuels. Increased efficiency can help reduce emissions from ships running on MDO, however, as MDO is a fossil fuel, a ship running on MDO will never be emission-free. So, in order for MDO to become a greener fuel, it is the efficiency that needs to be improved as better logistics won't do much either.

Table 7.2: The risk of change in technology or lack thereof evaluated by consequence and likelihood.

New technology making MDO not competetive	**Consequence**	**Likelihood**	**Risk**	**Precautions**
0-10 years	Major	Unlikely	Low	None
10-20 years	Major	Likely	Medium	None

A potential threat for MDO is that new technology becomes widely available and on a scale that makes prices for alternative fuels competitive pushing MDO off the market. Here, this kind of change in technology has been evaluated as unlikely to happen during the next 10 years. However, it has been evaluated as likely within the next 20 years.

7.3.2 REGULATIONS

Business as usual is not the option anymore if one wants to achieve the 50% goal within 2050. In order to change business as usual, new regulations are needed to drive the change in the right direction. New technology and new alternative fuels also need regulations. These regulations can make it harder for conventional ships today, running on e.g. MDO. Some potential future scenarios are evaluated using the risk matrix introduced in Section 6.2.

Table 7.3: The risk of change in regulations or lack thereof evaluated by consequence and likelihood.

Increased ECA	**Consequence**	**Likelihood**	**Risk**	**Precautions**
0-10 years	Major	Likely	Medium	None
10-20 years	Major	Very likely	High	None
Stricter emission regulations	**Consequence**	**Likelihood**	**Risk**	**Precautions**
0-10 years	Critical	Likely	High	None
10-20 years	Critical	Very likely	High	None
Zero emissions requirements	**Consequence**	**Likelihood**	**Risk**	**Precautions**
0-10 years	Catastrophic	Highly unlikely	Medium	None
10-20 years	Catastrophic	Unlikely	High	None

ECAs today are shown in Figure 7.1, excluding the coast outside China. There are however discussed increasing the ECA to include the Mediterranean, and with the increasing focus on the environment, it is not unlikely they will increase even more. This will affect ships that were build before the ECAs were decided, limited the ship's operational area and thus reducing potential income. An increase in ECA has, therefore, been evaluated as a major consequence, as this would result in either extra costs to retrofit or lost profits. During the next 10 years, it has been evaluated as a likely scenario and a very likely scenario within the next 20 years.

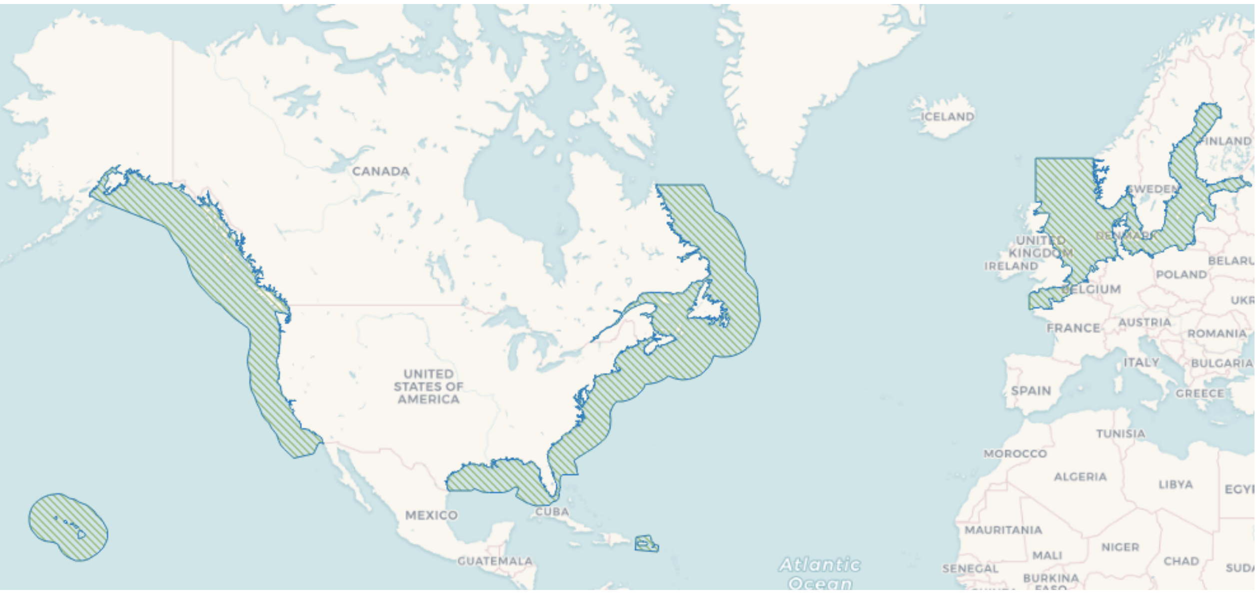


Figure 7.1: ECA, retrieved *Alternative Fuels Insight* (2019)

Stricter emissions regulation can be misunderstood as somewhat similar to ECA areas, but this is thought of as e.g. increased taxes for high polluting ships or taxes on fossil fuels making it more expensive and less attractive. This has been evaluated as critical, as this would affect the margins for the shipowners greatly in terms of extra costs, no matter the operational area. In order to reach the 2050 goal, new regulations are inevitable and are, therefore, evaluated as likely to happen within the next 10 years and very likely to happen within the next 20 years. This will, therefore, be a high risk related to choosing alternative 1.

Zero-emissions requirements are on the other hand evaluated as highly unlikely and unlikely for the next 10 and 20 years, respectively. However, this would have catastrophic consequences for a ship on fossil fuels as this would make the ships unfit for operation and have to undergo extensive retrofitting.

7.3.3 MARKET

The market can be seen as a function of the two aforementioned segments, as the trends in the market are ruled by the most efficient technology as well as the market has to follow the regulations that are relevant.

Table 7.4: The risk of change in market or lack thereof evaluated by consequence and likelihood.

Alternative fuels are competitive	**Consequence**	**Likelihood**	**Risk**	**Precautions**
0-10 years	Major	Unlikely	Low	None
10-20 years	Major	Likely	Medium	None
MDO price increase	**Consequence**	**Likelihood**	**Risk**	**Precautions**
0-10 years	Critical	Highly unlikely	Low	None
10-20 years	Critical	Unlikely	Medium	None

The future scenario where the alternative fuels have matured is set to unlikely within the next 10 years. This is because there is still extensive work that needs to be put down to make most of those fuels competitive. This includes infrastructure, prices, supply, and demand. This scenario has been evaluated as giving major consequences for a shipowner owning ships running on fossil fuels as his competitive advantage is lost, assuming that advantage was offering low rates due to low fuel costs. The risk of this happening the next 10 years is set to low, and medium for the 20 year-perspective as it is more likely to be alternative fuels ready during this time frame.

When it comes to an increase in MDO prices, this is meant by an even larger price gap than the last scene where they were somewhat similar. Here, it is assumed that the MDO prices have risen due to a lack of supply as a result of increased taxes. This highlights also the connection between regulations and the market. This price change has been evaluated as a critical consequence for a shipowner, as this would not make the shipowner's ship not competitive.

7.4 ALTERNATIVE 2: LNG

Alternative 2 in the illustrative case was to invest in an LNG driven chemical tanker. This comes with an additional cost compared to MDO, however, going for an LNG-driven ship comes with extra flexibility. Going from LNG to e.g. synthetic LNG is easier and will significantly reduce downtime as well as extra costs related to retrofitting. In this case, the LNG will follow the potential pathway explained in Figure 5.4. The extra cost of investing in an LNG system can be seen as the cost of reducing risk.

In order to evaluate Alternative 2, one has to have a look into the future and evaluate the expected performance.

7.4.1 TECHNOLOGY

Today, LNG is already rated as a relatively mature fuel and several ships are already running on LNG. What needs to progress in the field to make it a competitive alternative at this point in time is a cheaper way of storing the fuel. Today, the LNG must be stored in insulated tanks for cryogenic purposes, Wold et al. (2019).

To evaluate if LNG is a viable choice, a risk assessment considering some potential future scenarios are looked at.

Table 7.5: The risk of change in technology or lack thereof evaluated by consequence and likelihood.

No technology improvement	**Consequence**	**Likelihood**	**Risk**	**Precautions**
0-10 years	Minor	Unlikely	Low	None
10-20 years	Minor	Highly unlikely	Low	None

7.4.2 REGULATIONS

LNG is still a relatively new fuel compared to the conventional ones like HVO and MDO and will therefore not have the same thorough regulations. However, new regulations are coming, strengthening the viability and integrity of LNG compared to MDO and HVO.

Table 7.6: The risk of change in technology or lack thereof evaluated by consequence and likelihood.

Zero emission requirement	**Consequence**	**Likelihood**	**Risk**	**Precautions**
0-10 years	Major	Very unlikely	Low	None
10-20 years	Major	Unlikely	Low	None
Stricter storing regulations	**Consequence**	**Likelihood**	**Risk**	**Precautions**
0-10 years	Major	Unlikely	Low	None
10-20 years	Major	Unlikely	Low	None

The scenarios that have been assessed here are a zero-emission requirement, banning all fuels that emit any emissions, and a stricter regulation related to storage of LNG. The first scenario would give major consequences as LNG is not a zero-emission fuel and would, therefore, have to undergo a retrofit of the machinery. However, this is believed to be very unlikely to happen in the next 10 years, and still unlikely the next 20 years as well, thus resulting in a low risk. When it comes to the second scenario, stricter storing regulations are absolutely possible, but still evaluated as unlikely. This evaluation stands for both the next 10 and 20 years, resulting in a low risk. The consequence of this happening would potentially be a shorter period of downtime to install safety equipment or similar.

7.4.3 MARKET

When assessing the possible market change related to LNG, the same applies here as mentioned in Section 7.3.3. Here, two scenarios have been evaluated.

Table 7.7: The risk of change in technology or lack thereof evaluated by consequence and likelihood.

No improvement in infrastructure	**Consequence**	**Likelihood**	**Risk**	**Precautions**
0-10 years	Minor	Unlikely	Low	None
10-20 years	Minor	Highly unlikely	Low	None
No LNG available	**Consequence**	**Likelihood**	**Risk**	**Precautions**
0-10 years	Catastrophic	Highly unlikely	Medium	None
10-20 years	Critical	Highly unlikely	Low	None
LNG price rice	**Consequence**	**Likelihood**	**Risk**	**Precautions**
0-10 years	Major	Likely	Medium	None
10-20 years	Major	Likely	Medium	None

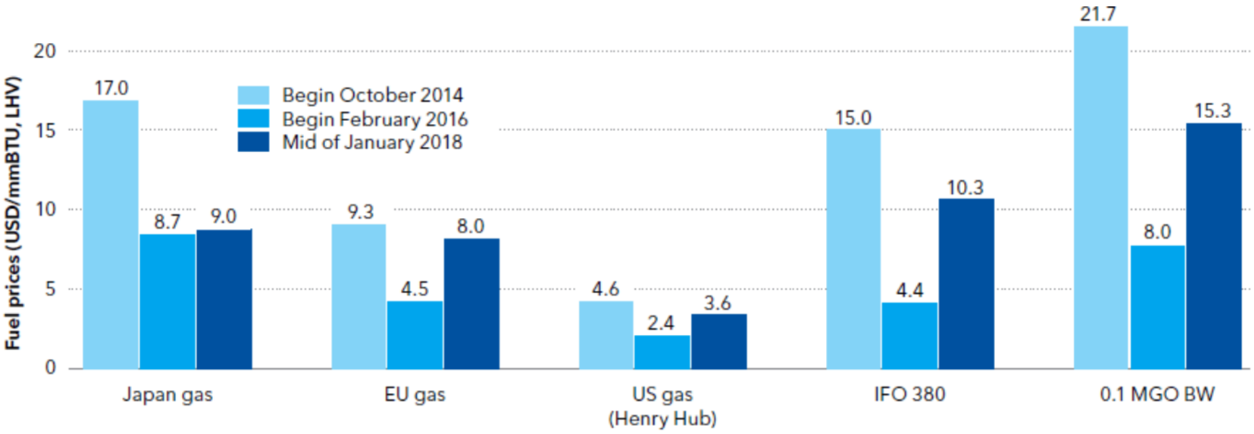
The first is related to a lack of improvement to the current infrastructure. Today, the LNG infrastructure can be divided into two segments:

- 1. Full-scale.
- 2. Small-scale.

The full scale spans from the big import terminals, with tanks with capacity up to $100000m^3$, to the large liquefaction facilities. This part of the infrastructure is already fairly well established, both in terms of technology and commercially. The second one, small-scale, are LNG distribution sources like import terminals and the end consumers. This part is not yet very well developed, but it is an emerging industry *LNG Ready* (2019). As the infrastructure is already at a decent level, the consequence of no further improvement has been set to minor and the related risk is low.

When it comes to the second scenario, "NO LNG available", a consequence of that would, of course, be catastrophic, at least early on. However, LNG as a bridging fuel can be blend with both LBG (BIO-LNG) and hydrogen. With no LNG, one of these could have been used instead of the same energy converter already installed. However, hydrogen is very expensive and has a low maturity at this point in time, resulting in a possibly catastrophic consequence if during the first 10 years. In a 20 year scenario, the consequence has been set to critical assuming that the maturity of hydrogen has progressed and made it cheaper and more available. However, this scenario is evaluated as highly unlikely to happen and will therefore not represent any particular risk.

The third potential scenario is a significant increase in LNG prices making LNG ships less competitive. As seen in Figure 7.2, the prices have been somewhat volatile ranging from 2.4 to 21.7 USDmmBTU which is a difference of 804.2%, making this a likely scenario.



Source: DNV GL

Figure 7.2: LNG prices

8 EPOCH-ERA ANALYSIS

8.1 EPOCH CHARACTERIZATION AND ERA CONSTRUCTION

As introduced in Section 6.3, an Epoch-era Analysis is a systems engineering tool help making design choices under uncertainty. First, a set of suiting epoch-variables for the relevant problem needs to be defined. When this is done, these epoch-variables needs to be tested in different future scenarios to see which design performs best. The alternatives that are being evaluated are MDO and LNG as in the illustrative case as well as both ammonia and hydrogen. These two are chosen as they both have great potential. Ammonia is ahead on the TRL, albeit, hydrogen is still very interesting with its potential of reaching zero-emission.

8.1.1 EPOCH-VARIABLES

An overview of the epoch-variables assessed in this thesis are shown in Table 8.1 below:

Table 8.1: Epoch variables

Epoch variable		Unit	Values
Technology parameters	Ammonia	[-]	[Low, medium, high]
	Fuel cells	[-]	[Low, medium, high]
Market parameteres	Ammonia price decrease	[-]	[Low, medium, high]
	Hydrogen price decrease	[-]	[Low, medium, high]
	MDO price	[-]	[Low, medium, high]
Reglulation-related parameters	CO2-taxes	[-]	[Low, medium, high]
	NOx-taxes	[-]	[Low, medium, high]
	ECA-increase	[-]	[Low, medium, high]
Availability	Ammonia infrastructure improvement	[-]	[Low, medium, high]
	Hydrogen infrastructure improvement	[-]	[Low, medium, high]

In Table 8.1, one can see that the variables are divided into four categories; Technology, market, regulations and availability. The value they are given ranges from low to high. Low, medium and high does not give adequate information, and will need a further elaboration.

Table 8.2: Description of technology-related parameters.

Value	Description
Low	Low to no improvement to current TRL. No to little impact.
Medium	An improvement of significance. Will make an option more viable and competitive.
High	Technology breakthrough. A very low TRL-fuel will become competitve.

Related to the technology parameters, low means no to very little progress made to the technology available today. This means that a low improvement to technology for one fuel will not have the same impact as for another. The reason for this is that the fuels discussed have a different TRL. This means that a low improvement to a fuel with a very low TRL, e.g. hydrogen, will not have a significant impact and remain not competitive. On the other hand, a low improvement to a fuel with a mediocre TRL like ammonia, will possibly be the little edge it needed to become competitive in a certain degree.

Medium means that there has been a significant progress to the technology that makes the option more viable than it is today. It is not specified what kind of progress, and can therefore be everything from weight optimization or higher energy efficiency. For instance, a medium improvement to technology to a very low TRL-fuel will render the fuel more competitive than before but still an inferior choice.

High is meant to be the extreme case where there has been a significant breakthrough related to the respective technology. As before, it is not specified what this is, but its significance is of the sort that the technology now is highly competitive, if not a superior choice to today's standard. This can be improved efficiency, weight optimization and more. The starting point is still relevant as in the two others, meaning that a high improvement to the technology of a very low TRL-fuel will now render the fuel competitive. A mid tier TRL-fuel will now be better than most alternatives, and a high improvement to an already high TRL-fuel will make it the clear choice out of all alternatives.

Table 8.3: Description of market-related parameters.

Value	**Description**
Low	Low to no change in price. No to little impact.
Medium	A significant change in price. Can make an option more viable and competitive.
High	An extreme price change. Will make e.g. hydrogen very competitive.

The market parameters are related to the price of the relevant fuels. The market category is also divided into low, medium and high. These values are, as similar to the ones technology-related, relative. Low price decrease means a very low to no decrease resulting in no significant impact. A medium price decrease, however, can potentially be the tipping point between to already competitive fuels. A high price decrease will on the other hand, mean a significant change. This would make an option that is today out of the loop, a viable option, albeit not necessarily the best option.

The third group of parameters are the ones related to regulations. Tax-increases, more specifically taxes related to both CO_2- and NO_x-emissions. The third parameter is related to emission control area and potential expansions of these. These parameters are relevant because they have an impact on the design choice. CO_2-taxes will have an impact on engines running on fossil fuels, NO_x-taxes will have an impact on all combustion engines no matter what fuel, and an increase in ECA will have an impact on both. The same scale has been used, ranging from low to high. Low will mean no to very little change than what it is today. A medium change will have an impact on the choice, albeit a low impact. A high change will once again be a significant change having huge impacts. This would significantly reduce the operational areas of different ships, as well as making some fuels not viable at all.

Table 8.4: Description of regulations-related parameters.

Value	**Description**
Low	Low to no change. No to little impact.
Medium	Will have an impact. Restricting operational areas. Can make an option more viable and competitive.
High	Extreme strict regulations. Emissions highly restricted. Fossil fuels and ICE not competitive.

The last two parameters are related to availability, more specifically, availability of ammonia and hydrogen. These represents how easy it would be for a ship to access a site for refueling. Production facilities are not included, but it is assumed that the refuel-station always can provide fuel.

These parameters are also valued from low to high. Low will mean that there are a very limited amount of refuel points available, meaning that a ship would need to travel a long distance to refuel, and thus be a very limiting factor in its operations. Medium would say that the infrastructure have improved significantly and that there is refuel stations available in every big city. High improvement would imply that the availability would not be a limiting factor of any kind. Refuel stations are available close to all large ports and with good capacity.

Table 8.5: Description of availability parameters.

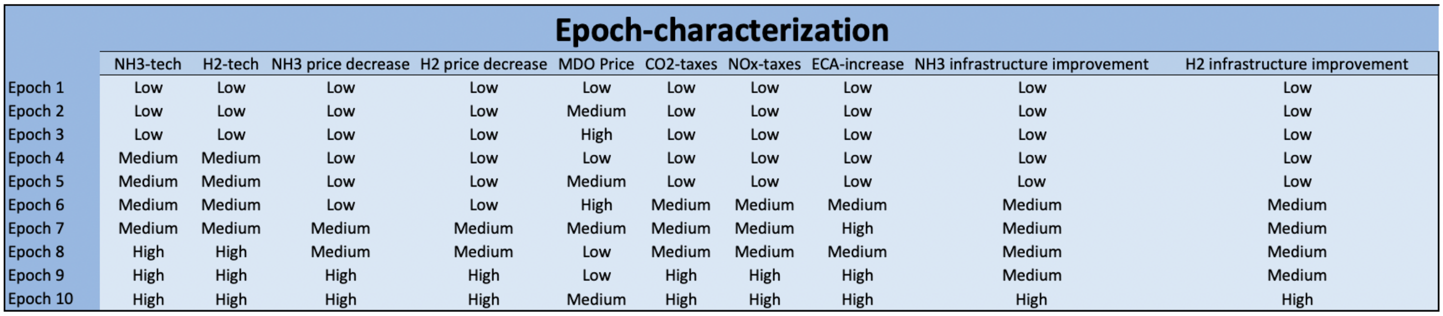
Value	**Description**
Low	Only a handful available refuel stations. Huge limiting factor for operations.
Medium	Refuel stations available at every large city. Still a limiting factor.
High	Infrastructure fully developed. Refuel stations available close to every port.

8.1.2 EPOCH-CHARACTERIZATION

After the epoch variables are decided, epochs where constructed. There are 10 epochs constructed where the first one is the most conservative and the tenth and last one is a somewhat far-fetched scenario where technology has increased a lot. This is however not very likely to happen the first few years, but an important aspect to consider nonetheless.

The first epochs are made the way they are with the intention of checking the performance of MDO and business as usual up against the up and coming technologies when the MDO price is changing. The next epochs are representing a gradual increase in technology and infrastructure before the last ones represent a far future where restrictions are high, new technology is mature and the availability in terms of infrastructure and production is greatly improved.

Table 8.6: Epoch-characterization



Epoch-characterization

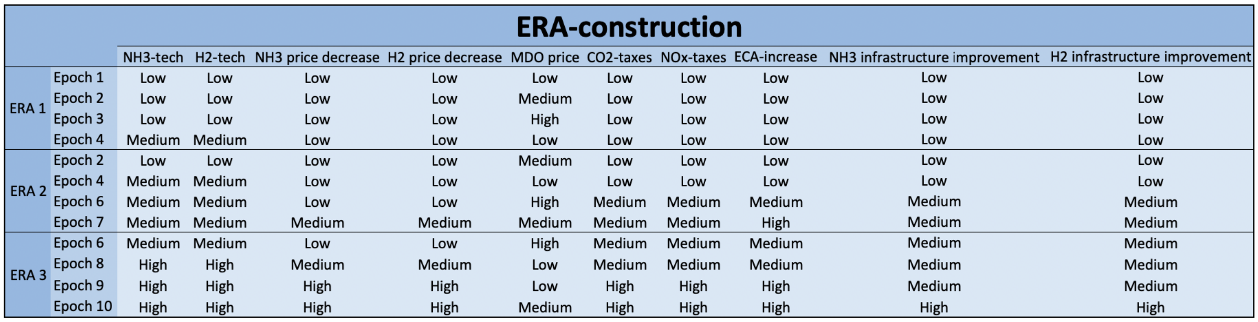
	NH3-tech	H2-tech	NH3 price decrease	H2 price decrease	MDO Price	CO2-taxes	NOx-taxes	ECA-increase	NH3 infrastructure improvement	H2 infrastructure improvement
Epoch 1	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
Epoch 2	Low	Low	Low	Low	Medium	Low	Low	Low	Low	Low
Epoch 3	Low	Low	Low	Low	High	Low	Low	Low	Low	Low
Epoch 4	Medium	Medium	Low	Low	Low	Low	Low	Low	Low	Low
Epoch 5	Medium	Medium	Low	Low	Medium	Low	Low	Low	Low	Low
Epoch 6	Medium	Medium	Low	Low	High	Medium	Medium	Medium	Medium	Medium
Epoch 7	Medium	Medium	Medium	Medium	Medium	Medium	Medium	High	Medium	Medium
Epoch 8	High	High	Medium	Medium	Low	Medium	Medium	Medium	Medium	Medium
Epoch 9	High	High	High	High	Low	High	High	High	Medium	Medium
Epoch 10	High	High	High	High	Medium	High	High	High	High	High

8.1.3 ERA-CONSTRUCTION

In order to conduct an EEA, eras need to be constructed. Each era contains four epochs from the 10 epochs characterized, and a total of 3 eras are constructed. In an effort to try to create a likely future, 2 of the eras are made up by most of the conservative epochs, while the third era represents a period some time into the future where technology has come a far way. The epochs have been constructed as shown in Table 8.7 below.

The first epochs are very conservative, and the reason for that is to show that MDO performs good in a market with no incentives to use alternative fuels. No significant emission-taxes, poor infrastructure, and a technology that can not compete due to its maturity render both ammonia and hydrogen not very competitive, and the first epochs are meant to highlight just that.

Table 8.7: ERA-construction



ERA-construction

		NH3-tech	H2-tech	NH3 price decrease	H2 price decrease	MDO price	CO2-taxes	NOx-taxes	ECA-increase	NH3 infrastructure improvement	H2 infrastructure improvement
ERA 1	Epoch 1	Low	Low	Low	Low	Low	Low	Low	Low	Low	Low
	Epoch 2	Low	Low	Low	Low	Medium	Low	Low	Low	Low	Low
	Epoch 3	Low	Low	Low	Low	High	Low	Low	Low	Low	Low
	Epoch 4	Medium	Medium	Low	Low	Low	Low	Low	Low	Low	Low
ERA 2	Epoch 2	Low	Low	Low	Low	Medium	Low	Low	Low	Low	Low
	Epoch 4	Medium	Medium	Low	Low	Low	Low	Low	Low	Low	Low
	Epoch 6	Medium	Medium	Low	Low	High	Medium	Medium	Medium	Medium	Medium
	Epoch 7	Medium	Medium	Medium	Medium	Medium	Medium	Medium	High	Medium	Medium
ERA 3	Epoch 6	Medium	Medium	Low	Low	High	Medium	Medium	Medium	Medium	Medium
	Epoch 8	High	High	Medium	Medium	Low	Medium	Medium	Medium	Medium	Medium
	Epoch 9	High	High	High	High	Low	High	High	High	Medium	Medium
	Epoch 10	High	High	High	High	Medium	High	High	High	High	High

8.2 PERFORMANCE EVALUATION

Each epoch have been evaluated with a score of low, medium, or high giving a score of 1, 2, or 3 respectively. After every epoch have been evaluated individually, one can find the performance through an entire era by calculating the average score. To see which option did the best overall, an average of every epoch have been calculated.

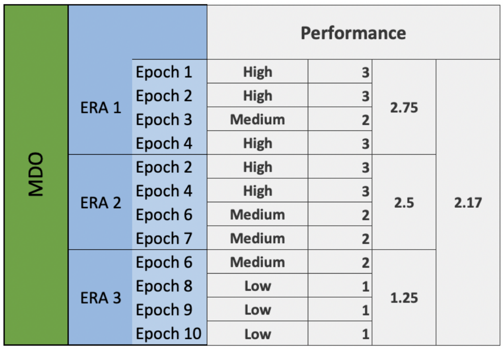
8.2.1 MDO PERFORMANCE

In Table 8.8 the performance of MDO is showcased. MDO scores high in three out of the four first epochs. This is because of the low to medium fuel price as well as the competing technologies are not competitive at this stage. LNG is still a good option here, albeit MDO is a cheaper investment, and as there are no emission-taxes or ECA-increase, there are no incentives for investing in an LNG-driven ship. The last score in the first era was evaluated as medium. This is because the price for MDO is high and therefore less competitive, making space for LNG to come into the market.

The second era grants MDO two scores of medium and two high. The reason it has been evaluated as high twice again, is still that the other alternatives are not competitive in terms of both technology and availability as well as there are no strict emission-regulations present. However, MDO was also evaluated medium in two epochs. In these epochs, other technologies have advanced, emission-taxes are being introduced and an increase in ECA will limit the operational areas of MDO-driven ships.

The third era is the worst era for MDO. In this era, strict regulations combined with a significant advance within competing technologies make MDO simply a poor choice. ECA have increased significantly resulting in very limited operational areas, high emission-taxes drives operational costs up and there is no evident reason to choose MDO.

Table 8.8: MDO performance



			Performance			
MDO	ERA 1	Epoch 1	High	3	2.75	2.17
		Epoch 2	High	3		
		Epoch 3	Medium	2		
		Epoch 4	High	3		
	ERA 2	Epoch 2	High	3	2.5	
		Epoch 4	High	3		
		Epoch 6	Medium	2		
		Epoch 7	Medium	2		
	ERA 3	Epoch 6	Medium	2	1.25	
		Epoch 8	Low	1		
		Epoch 9	Low	1		
		Epoch 10	Low	1		

8.2.2 LNG PERFORMANCE

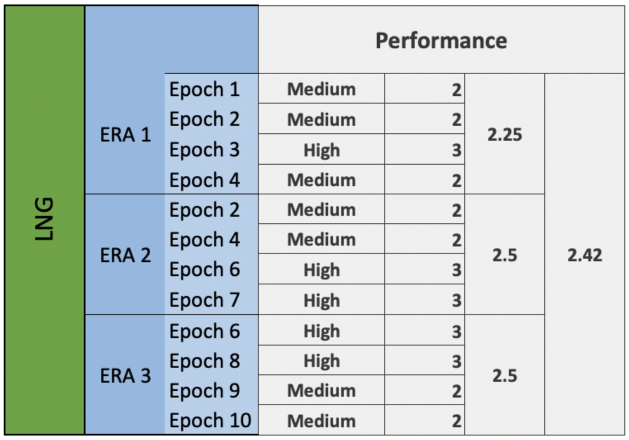
The next alternative to be evaluated is LNG. The evaluated performance is showcased in Table 8.9.

In the first era, LNG has been evaluated medium in three out of four epochs. The reason for this is linked with the reason why MDO scored high in three out of four epochs in the same era. MDO is a cheaper alternative than LNG, and with no incentives to invest in cleaner technology, the cheaper option comes out on top. The epoch where LNG is evaluated high is the same epoch where MDO was evaluated medium due to high MDO price.

The second era, LNG has been evaluated with two medium and two high and again, opposite of MDO. Where MDO is evaluated high, LNG is evaluated medium and vice versa. This is because these two are reckoned to be the two most relevant options in the two first eras. LNG is getting in front because of ECA-increase and high MDO-prices.

In the third era, LNG is still doing good with two out of two high and the two other mediums. In this era, MDO performs very poorly making LNG the best option for a while. However, as the regulations get stricter, in terms of taxes on NO_x-emission, as well as both ammonia and hydrogen technology have significantly improved, LNG performs somewhat less optimal and is, therefore, evaluated as a medium.

Table 8.9: LNG performance



			Performance			
LNG	ERA 1	Epoch 1	Medium	2	2.25	2.42
		Epoch 2	Medium	2		
		Epoch 3	High	3		
		Epoch 4	Medium	2		
	ERA 2	Epoch 2	Medium	2	2.5	
		Epoch 4	Medium	2		
		Epoch 6	High	3		
		Epoch 7	High	3		
	ERA 3	Epoch 6	High	3	2.5	
		Epoch 8	High	3		
		Epoch 9	Medium	2		
		Epoch 10	Medium	2		

8.2.3 AMMONIA PERFORMANCE

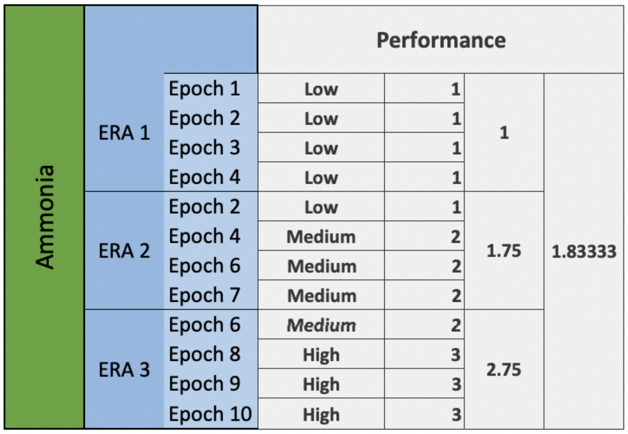
Ammonia has been evaluated low throughout the entire first era. This is because of the low TRL, no technology improvement in sight, and poor infrastructure. Ammonia is not a viable option as of yet, and will remain that way as long as the technology does not advance.

In the next era, ammonia is advancing but still performs poorly. It is evaluated medium in three out of four epochs and low in the remaining epoch. The low is a result of no technology improvement and the three medium evaluations are a result of both technological advances as well as higher MDO prices and stricter emission regulations.

In the third era, ammonia receives high in three out of four epochs and medium in the one remaining. As technology progresses, ammonia will be a great option as an alternative fuel. The first epoch in era 3, ammonia still struggles with both technology and infrastructure, albeit it is a viable option due to its nice emission spectrum. No CO_2-emissions and very low NO_x-emission with the correct accessories e.g. scrubber. However, by using an internal combustion engine, there will always be emissions and fuel residues. Although, these emissions are close to negligible when compared to a conventional ICE running on MDO or even LNG. Ammonia has still been evaluated high in the epoch where NO_x-taxes are set to high, as the NO_x-emissions are can be taken care of by adequate machinery.

Despite being evaluated high in the last epoch in era 3, H2 will have an edge on ammonia because of the aforementioned. However, in this case, the assumption is based on the technologies being at the same TRL, thus giving hydrogen the edge on ammonia. On the other hand, when looking at their current TRL, ammonia seems to be ahead and therefore probably more likely to succeed, at least in the short run.

Table 8.10: Ammonia performance



			Performance			
Ammonia	ERA 1	Epoch 1	Low	1	1	1.83333
		Epoch 2	Low	1		
		Epoch 3	Low	1		
		Epoch 4	Low	1		
	ERA 2	Epoch 2	Low	1	1.75	
		Epoch 4	Medium	2		
		Epoch 6	Medium	2		
		Epoch 7	Medium	2		
	ERA 3	Epoch 6	*Medium*	2	2.75	
		Epoch 8	High	3		
		Epoch 9	High	3		
		Epoch 10	High	3		

8.2.4 HYDROGEN PERFORMANCE

The last evaluated fuel is hydrogen and the performance is shown in Table 8.11.

Because of low the TRL and very little technology improvements as well as no improvement to infrastructure related to hydrogen, it has been evaluated as low throughout the first two eras making it the lowest scoring option the two first eras.

However, the last era where technology has come a far way and the infrastructure is adequate, hydrogen is scoring higher than any of the three others in the last era. This is because of its huge potential including its energy capacity as well as the possibility of achieving zero-emission, unlike the other three alternatives. This is infact true for the entire life-cycle for hydrogen if produced using clean energy. If the hydrogen used is produced from hydropower from Norway or possibly thermopower from Iceland, there will be no emissions throughout the entire life-cycle of hydrogen. On the other side, if the hydrogen is produced from fossil energy sources like e.g. coal, hydrogen becomes one of the worst contenders, even worse than HFO. This is because hydrogen production demands very much energy, and if that energy is not clean, the end product will not be either.

Table 8.11: Hydrogen performance

			Performance			
Hydrogen	ERA 1	Epoch 1	Low	1	1	1.5
		Epoch 2	Low	1		
		Epoch 3	Low	1		
		Epoch 4	Low	1		
	ERA 2	Epoch 2	Low	1	1	
		Epoch 4	Low	1		
		Epoch 6	Low	1		
		Epoch 7	Low	1		
	ERA 3	Epoch 6	Low	1	2.5	
		Epoch 8	High	3		
		Epoch 9	High	3		
		Epoch 10	High	3		

9 RESULTS

In this report, a multitude of alternative fuels has been discussed. Two of them, namely MDO and LNG have been further assessed and compared against one another in an illustrative case. These were chosen because MDO is representing today's business as usual while LNG was chosen because of its maturity. The other fuels are highly interesting but lack technological maturity to be considered for application on a vessel as of now. In addition to its maturity, LNG was also chosen due to its flexibility. It has proven to be a potential bridging fuel as LNG can use an energy converter that holds the opportunity to burn both bio-LNG as well as hydrogen when readily available to further decrease the emissions.

This paper also introduced the concept of risk to assess the value of flexibility. Is higher flexibility worth the extra investment to mitigate risks related to market-, regulation- or technology change? The goal was not to give an explicit answer, but rather present a way of approaching the problem by introducing an illustrative case where two alternatives were proposed:

- Alternative 1: Cheap ship with low flexibility running on MDO.
- Alternative 2: Invest in an LNG driven ship with higher flexibility to mitigate risk.

Moreover, the case was then evaluated up against different future scenarios related to possible changes in regulations, the market, and technology for both the next 10 years as well as 10 years after that. The risk involved with both alternatives were evaluated up against 6 different future scenarios and given a risk of either low, medium, or high.

Table 9.1: The accumulated risk score of Alternative 1

Alternative 1: MDO	**Risk**
0-10 years	Medium
10-20 years	High

Table 9.2: The accumulated risk score of Alternative 2

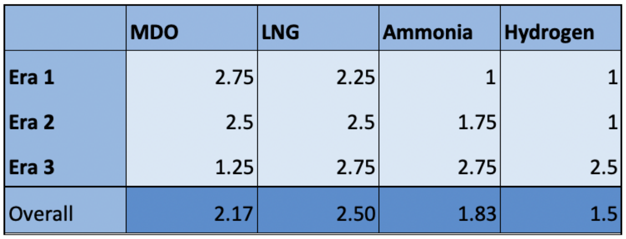
Alternative 2: LNG	**Risk**
0-10 years	Low
10-20 years	Low

The accumulated risk related to the two different alternatives are presented in Table 9.1 and Table 9.2 above. The risk was evaluated up against both potential significant downtime which means a loss in revenue as well as extra costs related to retrofitting.

In addition to the illustrative case, an epoch-era analysis was also conducted, and this analysis included both ammonia and hydrogen as well as MDO and LNG. This was done to further assess the possibility of utilizing alternative fuels on a ship in the near future. Epoch variables were defined and epochs were characterized and put together to eras. The goal was to see how the different alternatives would perform up against each other in a set of different potential futures with static conditions.

The epochs were created in a way using today's business as usual as the status quo, and gradually increase the up until a technology level where one can consider the technology to be fully developed and fully operational.

Table 9.3: Overall Performance



	MDO	LNG	Ammonia	Hydrogen
Era 1	2.75	2.25	1	1
Era 2	2.5	2.5	1.75	1
Era 3	1.25	2.75	2.75	2.5
Overall	2.17	2.50	1.83	1.5

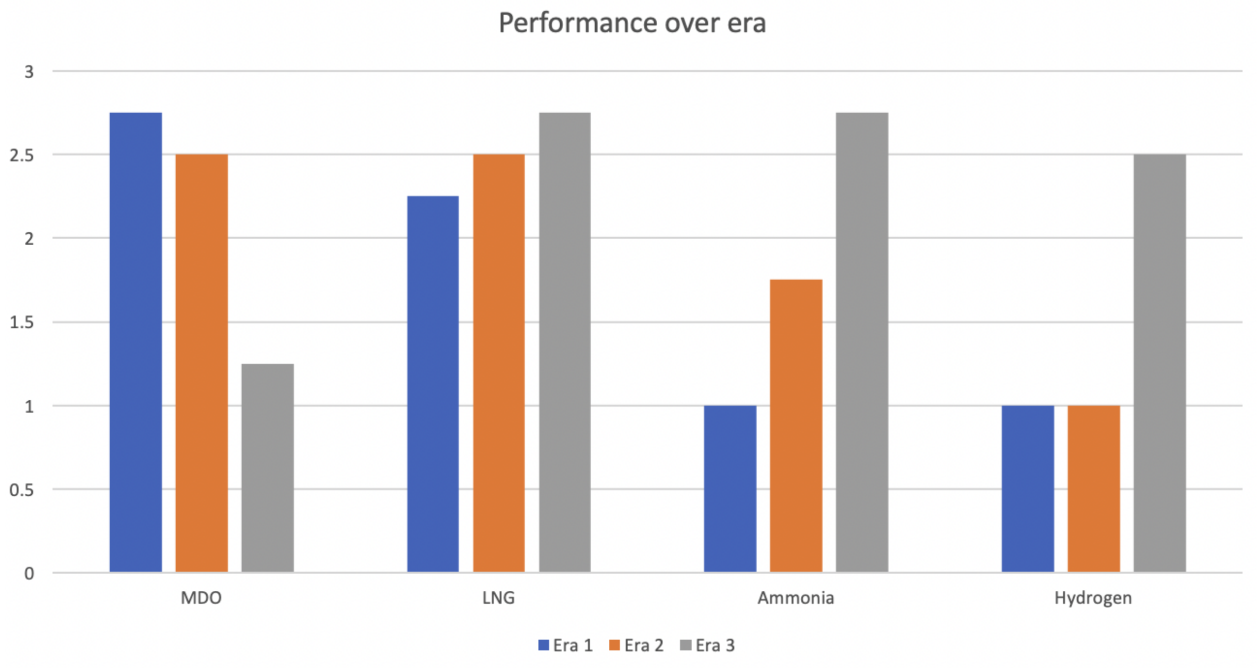


Figure 9.1: Performance overview over eras.

In Table 9.3 and in Figure 9.1 one can see the performance of each fuel up against each other. LNG got the overall highest score, MDO second highest and ammonia and hydrogen are numbers three and four, respectively.

As expected, conventional MDO and LNG perform overall very well. Albeit, MDO has a drop in performance in the third and last era. This is because of the strict regulations that would make it very little profitable to operate an MDO-driven ship due to high taxes. In addition to this, the competitors have become significantly stronger and are now to be considered as very viable options. LNG performs well already from era one and have continuous growth in performance throughout every era. This is because it has a fairly good emission-spectrum as well as it very flexible in terms of a potential retrofit in the future. Another reason is that it is already a well-rounded technology with a functional infrastructure.

Because of low TRL both ammonia and hydrogen struggles in the first eras. However, already in era two, ammonia begins to advance even though both MDO and LNG are still evaluated higher. Hydrogen is still not viable in era two but has spiked in performance in era three making it a highly viable choice, although beaten by ammonia and LNG.

10 DISCUSSION

The overall aim of the master thesis is to review the different options related to alternative fuels in order to reach the emission goals of 2050, using Epoch-era analysis early in the design phase with a goal of minimizing risk in terms of early choices.

A ship has traditionally an operational lifetime of up to 30 years, and in some rare cases even more. This means that 2050 will be within the operational lifetime of a ship that is being designed today. Minimizing cost and maximizing profits is a priority for ship owners, and because of that, investing in a ship that will in a few years be useless due to new and strict regulations or other exogenous factors is not an option. Shipowners are usually very dependent on a high level of operability of a ship, thus being forced to decommission a ship would be detrimental and in the worst case mean bankruptcy. However, this is inevitably a risk when designing a ship as one can not predict the future. Unforeseen events with huge impacts on the industry can occur. Even though the chances of a catastrophic incident that causes the entire shipping industry to shut down are extremely low, one needs to have an idea of what are the risks involved with building a ship. Is it best to go for the cheapest solution and hope that it will be able to operate a full lifetime, or invest in a more expensive and sophisticated design with a higher level of flexibility that can help you overcome difficulties in the future? This question is an important question, but not always very easy to answer. The answer often depends on whether you are risk-averse or not among other factors. No matter what option is chosen, it is important that this question is being raised. Having an understanding of the risks involved are crucial when, as the consequences can be extremely comprehensive.

To get a better understanding of what risks are involved with a shipbuilding process, it is smart to review the options that are available and have a look at the possible outcomes and consequences of choosing one or another. In this thesis, an illustrative case was created to make the problem more tangible. The question raised in that particular case was:

> *Should one design a flexible ship in a way that allows cheap and quick retrofitting in the future or should one design a ship the conventional way if minimizing costs is the goal?*

The way this problem was approach was to evaluate the risks of losing revenue in terms of downtime throughout their lifetime. Technological changes, market changes, and regulations changes were taken into account. Here, it was concluded that going for higher flexibility would be the better choice. A reason for this is that there has been much focus on environmental impacts and climate change the last years which leads to anticipating stricter rules and regulations related to emissions. Stricter rules and regulations can potentially take a ship out of service. If it is cheaper to get rid of the ship and build a new one, rather than retrofitting to meet the new rules and regulations, the smart thing would be to scrap the ship and build a new one. However, this can be avoided by taking this possibility into account when designing the ship. Investing in a more expensive ship with a higher level of flexibility might in this case be the most cost-efficient option.

Another question that should be answered is: When should flexibility be prioritized over cost? Neither is this easy to answer, although there are some important factors the one should consider when answering. A longer lifetime means a higher degree of uncertainty, however, some uncertainties can be to some extent neglected. For instance, when looking at the emission control areas and where they are located today, one can have an idea of where they will expand to or where to expect new ones. Deep-sea shipping, for instance, is not very affected by the emission control areas, as these areas often are close to shores. Short sea shipping, on the other hand, is. Therefore, building a ship running on MDO might not be a bad choice when deep-sea shipping is the purpose. If short sea shipping is the operational area, MDO might not be the best choice as the risk of being affected by new ECA are present.

A number of alternative fuels have been discussed in this thesis, and those who were found relevant have been further assessed. MDO and LNG were compared up against each other in an illustrative case, but there were a few more fuels of interest due to their potential. An epoch-era analysis was conducted where the performance of MDO, LNG, ammonia, and hydrogen was checked up against each other. All four alternatives were each evaluated in different future scenarios with static conditions to see what performs best overall eras. As the results show, LNG seemed to have the edge on MDO while ammonia came third and hydrogen last. Ammonia and hydrogen coming last was to be expected as both these technologies are yet to mature.

While MDO was the best option in the early epochs and hydrogen and ammonia did great in the last one, an interesting point to make is that LNG performed very well through all the eras. The reason for this might be that LNG has been available a decent time already, thus the technology has matured, and there is a functioning infrastructure. One could also say that it is a relatively safe bet considering its possibilities. It is more expensive compared to MDO, but it has the ability to be used as a bridging fuel as talked about earlier. This capability makes LNG very flexible because if the regulations get stricter, the ship already has much of the needed piping infrastructure to use for instance a hydrogen mix. However, this is dependent on how far the infrastructure related to hydrogen has come. If the regulations come before an adequate hydrogen infrastructure, synthetic LNG is also an option. All these possibilities make LNG a safer choice in terms of risk.

However, as the thesis title implies, the goal is to reach zero-emission. This is not an easy task, and seeing the results from the epoch-era analysis, it does not seem to come the few next years either. Although zero-emission might be a hairy goal, it is possible. When it is going to happen, it is hard to say, but hydrogen holds all the possibilities to achieve it. The technology needs to mature as well as governments need to facilitate a change to happen. The industry will not invest in hydrogen as long as the infrastructure is not there. In order to speed up the maturity for both ammonia and hydrogen, governments need to facilitate for this to happen.

There haven't been done many calculations on the topic, but rather a methodology on how the problem can be solved. This has, of course, some weaknesses related to it, but the results are not the essence of this thesis. It is about how one can make a problem tangible and reflect upon it to further support a decision-making process.

11 CONCLUSION

In order to reach the 50% goal within 2050, change needs to happen. Achieving zero-emission seems at this point hard to accomplish due to the low maturity level for the fuels with zero-emission potential, especially hydrogen. There is however a multitude of options of how one can reduce emissions drastically compared to today's standard. LNG is for instance a great option for newbuildings with an already functioning infrastructure, a high degree of maturity and availability makes it more than viable. Ships running on LNG will also have improved flexibility compared to ships on conventional MDO or HFO. This is because a ship on LNG will already have the correct composition of components in order to later implement both bio-LNG and hydrogen. Both MDO and LNG are typically using and ICE as an energy converter. The difference between them is the system composition, more specifically storage tanks. Both LNG and hydrogen require circular cryogenic tanks which a ship on MDO or HFO doesn't.

To answer the question about flexibility is wanted or not, this paper experienced that there is far less risk involved with choosing LNG. The regulations are getting stricter each year, therefore, hedging yourself from risk by choosing LNG would seem reasonable. It is hard to recommend the best practice, but something that can be recommended is doing a thorough assessment of possible future scenarios to ensure resilience and robustness in the final choice.

However, as the thesis title implies, the goal is to reach zero-emission. This is not an easy task, and seeing the results from the epoch-era analysis, it does not seem to come the few next years either. Although zero-emission might be a hairy goal, it is possible. When it is going to happen, it is hard to say, but hydrogen holds all the possibilities to do so.

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