Norwegian School of Economics
Bergen, Spring 2022

The Future of Hydrogen in the Norwegian Shipping Industry

An exploratory case study of the Norwegian shipping industry and its readiness for hydrogen short-sea vessels

William Strøm Dorp and Egil Øyri

Supervisor: Eirik Gaard Kristiansen

Master Thesis, Economics and Business Administration,
Financial Economics, Strategy and Management

NORWEGIAN SCHOOL OF ECONOMICS

Acknowledgements

This thesis is written as a part of our masters‘s degree in Economics and Business Administration at the Norwegian School of Economics (NHH), with majors in *Financial Economies* and *Strategy and Management*.

First and foremost, we would like to offer our warmest gratitude to our supervisor, Eirik Gaard Kristiansen, for his pivotal guidance, feedback, and support throughout the process. His knowledge and network within the field has been an immensely valuable to us. Second, we would like to thank Sigmund Størset at Enova and Pedram Nadim at Teco2030 for providing first-hand knowledge and information regarding their work within the Norwegian maritime sector and use of hydrogen technology. Finally, we would both like to thank our friends and families for unconditional support during this challenging and rewarding process.

Norwegian School of Economics

Bergen, December 2022

William Strøm Dorp	Egil Øyri

Abstract

With increasing greenhouse gas emissions from the shipping industry there is a need to find alternative fuels to reach climate targets. Hydrogen as a marine fuel is considered one of the promising solutions to reduce emissions from the maritime sector. At the same time, hydrogen technology for maritime application remains novel in Norway. Hence, the aim of this thesis is to provide valuable knowledge that could be used to facilitate a transition to hydrogen vessels, and is done with two goals.

The first goal is to provide understanding of important drivers and barriers for the transition, by using the PESTEL framework to analyse the macro environment in the sector. The results from the analysis discovered that authorities show commitment to the transition by establishing strategies and providing subsidies. Also, Norwegian maritime sector has facilities that could give a competitive advantage in the transition. However, both the cost of acquiring and operating a hydrogen vessel is substantially larger than alternative fossil vessels, and is therefore not an economically feasible option. Hence, the second goal is to analyse how CfD can be used by the Norwegian government to reduce barriers and accelerate deployment of hydrogen vessels.

Although it is unclear if the use of CfD is the most appropriate measure, the findings suggest that issuing CfDs would provide increased incentives for shipowners to invest in hydrogen vessels. This would also increase development and implementation of hydrogen technology, which contributes to reduced cost and increased competitiveness with fossil alternatives.

Keywords – Master Thesis, Shipping, IMO, Hydrogen, Fuel Cells, Environmental Policies, EU ETS, CfD

Contents

List of Figures

List of Tables

1 Introduction

The Intergovernmental Panel on Climate Change, IPCC, has stated that all sectors have the opportunity to at least halve emissions by 2030 (IPCC, 2022). This will require a substantial reduction in fossil fuels, and highlights the importance of hydrogen as an alternative energy carrier. If the world is going to limit global warming to 1.5°C, this means achieving global net zero carbon dioxide emissions in the early 2050s. Consequences of not reaching this international goal is extreme temperatures, droughts, lack of water availability, extreme precipitation, climate refugees and more (Buis, 2019). The risks of not reaching the 1.5°C goal therefore emphasizes the importance of reducing greenhouse gas (GHG) emissions.

The Norwegian government is pursuing an ambitious environmental policy with GHG reducing measures, in line with the Paris Agreement. The target stated in the Paris agreement is to reduce emissions by at least 50 per cent by 2030, compared to 1990 levels (Ministry of Climate and Environment, 2020). In order to reach this target, Norway must develop and start using technology that reduces emissions. It is for this reason that the Norwegian government in May 2020 announced their hydrogen strategy, which lays the foundation for how the government will develop and adapt policies in order to facilitate further development of hydrogen solutions. These solutions are meant to reduce emissions and also contribute to value creation.

The government states that hydrogen has the potential to be an important and relevant energy carrier in maritime shipping (Ministry of Climate and Environment, 2020). With products that cover the entire value chain, including design and technology development, the Norwegian maritime industry has a unique opportunity to contribute to both emission reductions as well as increased value creation. However, hydrogen shipping is still difficult to commercialise and the vessels that exists today are mostly pilot- and demo projects that are subsidized. The challenges are of economic and technological matter, which needs to be resolved before hydrogen vessels can become commercial feasible (Ministry of Climate and Environment, 2020). These problems are in the essence of this thesis. To explore the opportunities of hydrogen vessels and its challenges in a case-specific study, two research questions will be answered. The first one is:

To what extent does the economic and political environment support a transition to hydrogen vessels in the Norwegian shipping sector?

As the economical aspect is known to be one of the largest barrier, governmental measures taken to reduce this barrier becomes especially interesting. One of the measures used to support green investments and which has received a lot of attention, is contracts for difference. Therefore, it would be of large interest to investigate if CfD could be an appropriate measure to support the transition to hydrogen shipping. Hence, the second research question is:

How can the Norwegian government use CfD as a measure to increase investment in hydrogen vessels?

1.1 Motivation for Topic

In January 2021, Veidekke announced that they had initiated, as a part of DNV's Green Maritime Program, a hydrogen vessel project that was intended to transport asphalt, crushed stone and gravel along the Norwegian coast (Finansavisen, 2022). There were 31 shipping companies that were competing for this contract, indicating a large interest in hydrogen vessels within the shipping industry. However, only one year later the project was stopped by Veidekke because the risk became too high, and the economical commitments became too large and long-lasting. Veidekke also stated that "the hope for the realization of the project is not lost, if the public sector comes forward with better support schemes" (Finansavisen, 2022). This illustrates the current duality between the desire to invest in a transition to hydrogen vessels, and the barriers that hinders the companies to carry out desired investments.

The Norwegian government also address their aspiration to accelerate the transition from fossil fuel to hydrogen in the maritime industry through their official hydrogen strategy. However, at current time being, there are few hydrogen projects in realisation and the transition from fossil fuels to hydrogen is slow. Although there are studies and literature that focuses on specific technologies and challenges, there is a lack of literature that provide a broad analysis of the multiple barriers for the hydrogen shipping transition. It is useful for actors within the industry to understand the challenges across the whole industry environment, as they have to cooperate and coordinate activities in order to realize hydrogen vessels. This is especially true for the government, because they have the possibility to implement measures that could facilitate and accelerate the transition. Among the many measures that could be implemented by the government is CfD, which have gained increasing attention. In Germany and England, CfDs have successfully been used as an incentive to industry actors to invest in green energy, and have therefore been suggested as a measure that could be applicable in maritime sector as well (Kalland et al., 2022).

Hence, this study aims to provide empirical evidence from the Norwegian shipping industry in order to evaluate its readiness for a transition to hydrogen. And further on, use these findings to analyse whether CfD could be used by the government to accelerate the transition.

1.2 Constraints and Assumption

Although hydrogen technology could be applicable and relevant for different actors within the Norwegian maritime sector, this thesis focus on the short-sea shipping sector. The limitation of scope is partly due to the time constraint, and in order to achieve both depth and width to the paper. Additionally, hydrogen as marine fuel is considered to be most appropriate for shorter shipping routes due to limited storage capacity of fuel. The operations, systems and activities varies across the maritime sectors, and a limitation to short distanced shipping has allowed for a more case-specific and thorough analysis of opportunities and barriers for maritime hydrogen vessels.

Due to many different viable technological solutions in the maritime hydrogen market, this paper has chosen to analyze the most promising technology at this time being, rather than a broad analysis of multiple different technologies. Although other technologies are mentioned in areas where the prevailing technology is relatively more uncertain, the authors argues that by focusing on the most promising technology the analysis becomes more insightful. However, the thesis would be to some extent limited by the technology assumptions that will be further explained in chapter 2.2 Hydrogen technology.

It is assumed that a transition to hydrogen fueled vessels in short distance shipping in Norway would have a beneficial impact on the environment, even though this is a small industry in an international setting. However, in order to reduce global emission sufficiently, every sector must seek solutions to reduce their negative climate footprint. Additionally, a transition to hydrogen could have ripple effects by building competence and solutions that could be applicable in other maritime sectors, and even other industries. Therefore, this paper assumes that a transition to hydrogen fueled short-sea vessels in Norway will contribute to reducing global GHG emissions.

2 Background and literature review

This chapter will describe the Norwegian shipping industry and its most important characteristics. Further, hydrogen technology will be explained in addition to some relevant policies. This will provide the reader with necessary and vital information in order to understand both the challenges and opportunities with the transition to hydrogen vessels in Norway.

2.1 Norwegian Shipping Industry

The maritime industry is transporting a total of 80% of globally traded goods, making it the most vital way to transport commodities (Sirimanne et al., 2019). Whilst transporting by sea is the most affordable and practical method, it accounts for approximately 3% of the global greenhouse gas emissions each year (IMO, 2021). Earth is facing a huge challenge with fighting rising temperatures, as levels of greenhouse gas emissions in the atmosphere continues to increase. As a result, the Paris agreement was introduced to unite countries with the aim to stop the rise of global temperatures, and to keep it well below 2°C compared to pre-industrial levels (UNFCCC, 2020). In 2018 Norway pledged to IMO‘s new climate strategy to decrease CO_2 emissions from shipping with at least 50% by 2050 , relative to 2008 levels, in order to support the Paris agreement. In Norway the shipping industry accounts for 3.71% of the total emissions, and since 2008 emissions has increased with 12.1% (Norwegian Directorate for the Environment, 2022). Hence, finding solutions to reduce these emissions is important for Norway in order to comply with its pledge.

The Norwegian fleet consists of 2800 ships, and can be categorized into conventional, low-, and zero-emission ships. Conventional ships are those who use traditional fossil fuels, usually consisting of diesel or heavy oil, and accounts for 75.9% of the ships. These ships are dominating the long distance shipping routes. Further, 23.1% of the ships are low-emission ships using LNG- or LPG-gas as power source. These ships are mostly used in the offshore segment, where 70% of all ships use low-emission sources of energy. Further, these vessels are used to public transportation and aquaculture (Haugland, 2022). Commonly for all current low-emission vessels are that they operate on very short distances, for example as ferries or speedboats.

Compared to the global vessel-fleet with only 4.5% low-emission ships, Norway has already made a leap in this transition. Only 1% of the Norwegian vessels have zero-emission technology implemented, but if measured in tonnage the share is only 0.1% (Haugland, 2022). This implies that almost 50% of today's tonnage have to be de-carbonised by 2050 to reach the Paris-agreement. Additionally, the global shipping market is expected to increase according to IMO (2020), making the transition even more challenging and important.

To further investigate the Norwegian inbound shipping market, it is important to highlight the origin from where the CO_2 emissions occur. It is estimated that by 2030 the annual emissions from inbound freight will be approximately 4 million tonnes of CO_2 equivalents, if no government policies are introduced to change the trend (Rivedal et al., 2018). These 4 million tonnes are distributed based on the share of emissions occurring from each maritime sector. Additionally it is distinguished between three different ships, separated based on their operation time in the water on the scale from 0 to 100%. The expected amount of CO_2 emissions for each segment in 2030 is presented in Figure 2.1 below.

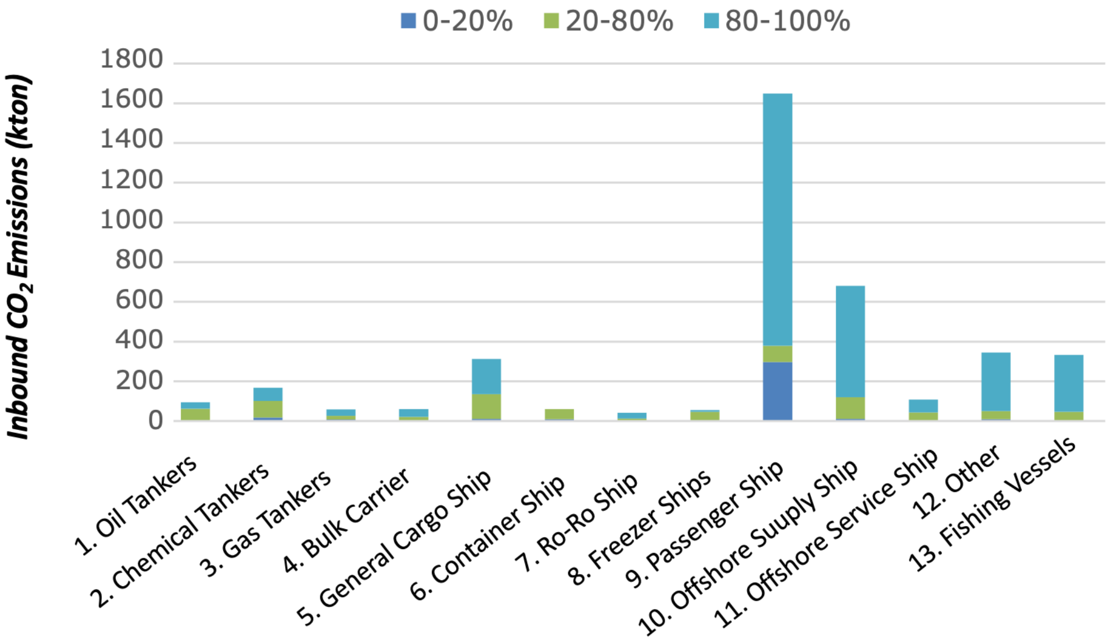


Figure 2.1: *CO2 Emissions from Norwegian Vessels. Source: Rivedal et al. (2018)*

Naturally, the ships producing the most emissions are those with 80-100% operation time. Further, passenger- and offshore supply ships are expected to produce approximately 2350 tonnes of emissions, accounting for the majority of the total share (Rivedal et al., 2018).

The shipping industry has previously been trough transitions, first from wind to steam, and then from coal to fossil fuels. Under these transitions all the ships made the same transitions, but this time the process is more challenging. Now, there are many alternative solutions in order to reduce emissions from ships like bio fuels, batteries, ammonia, hydrogen and more. Shipowners will probably choose different technologies which increases the complexity of the transition (Ovrum et al., 2022).

The fact that environmental sustainability has become a priority in the global maritime sector, has caused additional uncertainty for shipowners. Environmental regulations have directly influenced the dynamics and operations in global shipping. The IMO regulation from 2020 forced a 0.5% global sulphur cap on fuel content, causing an expected increase in fuel costs for container shipping of 10-15 billion dollars (Sirimanne et al., 2019). This shows that government policies can require shipowners to make drastic adaptations within short notice to become more environmental friendly. However, by thinking ahead there might be opportunities to get first-mover advantages and strengthen the position in the industry.

It is important that Norway succeeds to make this transition to maintain relevant in this industry. The maritime industry is one of the most important industries in Norway with a total of 160 billion kroner in created value each year (Haugland, 2022). The shipping companies accounted for 56% of the value created in 2021, and according to Haugland (2022) it is important that Norway facilitates for green innovation in the maritime industry. In addition to reaching Norway's climate goal, the transition could create opportunities to strengthen the Norwegian maritime industry.

The global shipping market was approximately 5500 billion kroner in 2021, and with Norway's 4.5% share of the market, there is potential for further growth. By investing early in this transition Norway could become an important exporter of green technologies, equipment, systems, ships, and fuels essential for hydrogen shipping. However, with the high entry barriers due to expensive technology and relatively cheaper fossil options there is a need for favorable government regulations, support, and incentives (Torvanger, 2021).

This paper will focus on hydrogen as a fuel option to de-carbonize the Norwegian maritime fleet. The worlds first hydrogen ferry was put into operation in Rogaland in 2022, and the government has decided that more will come (Norwegian Hydrogen Forum, 2022c). In order to make a thorough analysis later, the following section will elaborate different and relevant hydrogen technologies for maritime application.

2.2 Hydrogen Technology

One of the most effective ways to reduce greenhouse gas emissions in the shipping industry is to change from conventional fuels to greener alternatives, where one promising alternative is hydrogen due to low environmental impact (Atilhan et al., 2021). Hydrogen is an energy carrier that has to be produced from other energy sources and can be used to store, move and deliver energy. Hydrogen can also be used in fuel cells to generate energy (Satyapal, 2017).

This section will review the main hydrogen technologies suitable for application in the maritime industry. The objective is to provide insight about relevant technologies and set the scope of which technology that will be analysed in this thesis. There are three distinct aspects regarding the feasibility of hydrogen as a maritime fuel that further will be explained: production, storage and infrastructure.

2.2.1 Production, Storage, and Infrastructure

2.2.1.1 Hydrogen Production

The degree of how environmental friendly hydrogen is as a fuel highly depends on the method used to produce it, and is categorised as either green, blue, or grey. More than 95% of the global hydrogen is produced by reforming of fossil sources and classifies as grey, where half comes from steam reforming of natural or shale gas. If this process is done with implementation of carbon capture and storage solutions (CCS), up to 90% of the CO_2 emission occurring from the production can be captured, and the hydrogen will be designated as blue (Torvanger, 2021).

Neither grey nor blue hydrogen are considered as fully environmentally friendly because of GHG emissions occurring from its production. Emissions from grey hydrogen are estimated to be 9.3kg of CO_2 for each kilo hydrogen produced, which is more than gasoline at 9.1kg (Rapier, 2020). Further, green hydrogen is produced when a renewable source of energy is used to power the electrolysis, such as wind, solar, waterfalls or nuclear, making the production carbon neutral (Van Hoecke et al., 2021a).

In the transition to hydrogen fueled vessels, green and blue hydrogen would most likely be required to reach sufficient supply. However, the scope of this paper is limited to green hydrogen, and this has a tree-folded reasoning. First, due to the time constraints, including both methods would have been problematic because of the large technological and economical variations and implications of the production methods. Second, green hydrogen is the only production form that is carbon neutral, making it the most desirable production method. Last, there are currently planned five developments of hydrogen production and bunkering sites along the Norwegian coast that will be producing green hydrogen (Norwegian Hydrogen Forum, 2022a). This makes the green hydrogen production method especially relevant for Norwegian vessels.

Green hydrogen can be produced in an electrolysis by passing a high electrical current through water. The water will split into hydrogen- and oxygen gas by the following equation (Van Hoecke et al., 2021a).

$$H_2O + Current => H_2 + (1/2)O_2$$

Water electrolysis for production of hydrogen has an energy efficiency of approximately 70% and can be combined with the production of renewable energy from solar and wind, where the excess energy generated can be converted to hydrogen, thus functioning as a battery (Torvanger, 2021). This is a method to stabilize the intermittent character of solar- and wind power, which has been a disadvantage. Due to the high electricity demand from production, the cost of green hydrogen is substantial and ranging between 30-70 NOK/kg compared to cheaper grey and blue hydrogen that ranges between 20-55 NOK/kg (Rivedal et al., 2018). This implies that the CO_2 price needs to reach 230 USD/tonne to make green hydrogen competitive with fossil fuels, which is approximately four times higher than today (Collins, 2021). Hence, the availability of renewable energy is a critical factor determining the affordability of the fuel.

2.2.1.2 Storage of Hydrogen

There are several methods to store hydrogen, but there are mainly two that provides an acceptable amount of stored energy, which is compressed hydrogen ($\mathrm{CH_2}$) and liquefied hydrogen ($\mathrm{LH_2}$).

Compressed hydrogen is one of the most developed methods, where the gas is stored under high pressure ranging between 20-70 Mpa, depending on tank type. There are mainly five different types of tanks developed to store hydrogen numbered by the Roman numerals (I-V), representing the complexity of the tank (Van Hoecke et al., 2021a). However, compressed hydrogen storage causes some challenges. The energy density of hydrogen stored in gas cylinders is relatively low, requiring that large parts of the deck has to be used to the storage of the cylinders. Also, the low-density of hydrogen gas causes slow fuelling (Van Hoecke et al., 2021a).

Another method to store hydrogen is by liquification to LH_2. This requires a temperature of -253 °C in order to be stored in liquid form (Van Hoecke et al., 2021a). In the process of liquifying hydrogen high amounts of energy are consumed, where normally 30-40% of the lower heating value (LVH) of hydrogen are consumed (Cho et al., 2020). The low temperature requires the storage tanks to be maid of super isolating materials making them expensive, and still evaporation is a problem. Hence, this is a complicated and challenging method of storage.

Subsequently, $\mathrm{CH_2}$ is assumed to be the preferred method of storage, which allows for sufficient quantities of energy stored in order to power a vessel. Additionally, it requires less complicated solutions and appears more feasible.

2.2.1.3 Infrastructure of Hydrogen

In order to make hydrogen a feasible alternative for the Norwegian maritime industry, sufficient infrastructure has to be developed to enable distribution of hydrogen at low-cost. Usage of hydrogen also brings special cost and safety challenges in every distribution step, from production to end user. The reason for this is the low energy density, embrittlement, and safety concerns (DNV, 2022). Hydrogen are mostly transported in pipelines or in tanks, but the most effective and preferred way of transportation depends on the state of the hydrogen and the distance of transportation.

Compressed hydrogen is most effectively transported trough pipelines, where high quantities can be transported over long distances, making it the most cost-effective method. Hydrogen gas can be transported in its pure form or mixed with natural gas up to certain limits ranging between 2-8% depending on the type and quality of the pipelines. Mixing the two and utilising the existing 3 million km of global gas pipelines could be an affordable solution during the transition, which also could provide valuable knowledge towards a pure hydrogen grid according to DNV (2022).

The hydrogen used today is normally transported in bulk by trucks with 20-40ft containers holding a capacity of 1100 kg of hydrogen compressed to 500 bar[2] (DNV, 2022). Hydrogen can also be transported in liquid form via a carrier such as ammonia or LOHC, which today is the cheapest way to transport hydrogen over long distances (DNV, 2022). Globally, the lack of investments in infrastructure is considered to be one of the largest barriers to create a hydrogen eco-system (Van Hoecke et al., 2021a).

In Norway the hydrogen infrastructure is very limited due to low demand (Torvanger, 2021). But, in June 2022 Enova announced that they will support an establishment of five production facilities along the Norwegian coastline that will produce green hydrogen and function as fueling stations. All together these facilities will create a bunkering infrastructure, where they can supply 35-40 hydrogen powered ships (Norwegian Hydrogen Forum, 2022a). This is considered an important step towards making hydrogen a feasible alternative as fuel for the maritime sector in Norway according to SINTEF (2022).

The production, storage, and infrastructure of hydrogen is essential aspects in order to analyse the feasibility of whether the maritime industry can utilize hydrogen as a carbon neutral fuel. These three previous sections, describes hydrogen from production to end-use, and is summarized in the Figure 2.2 below.

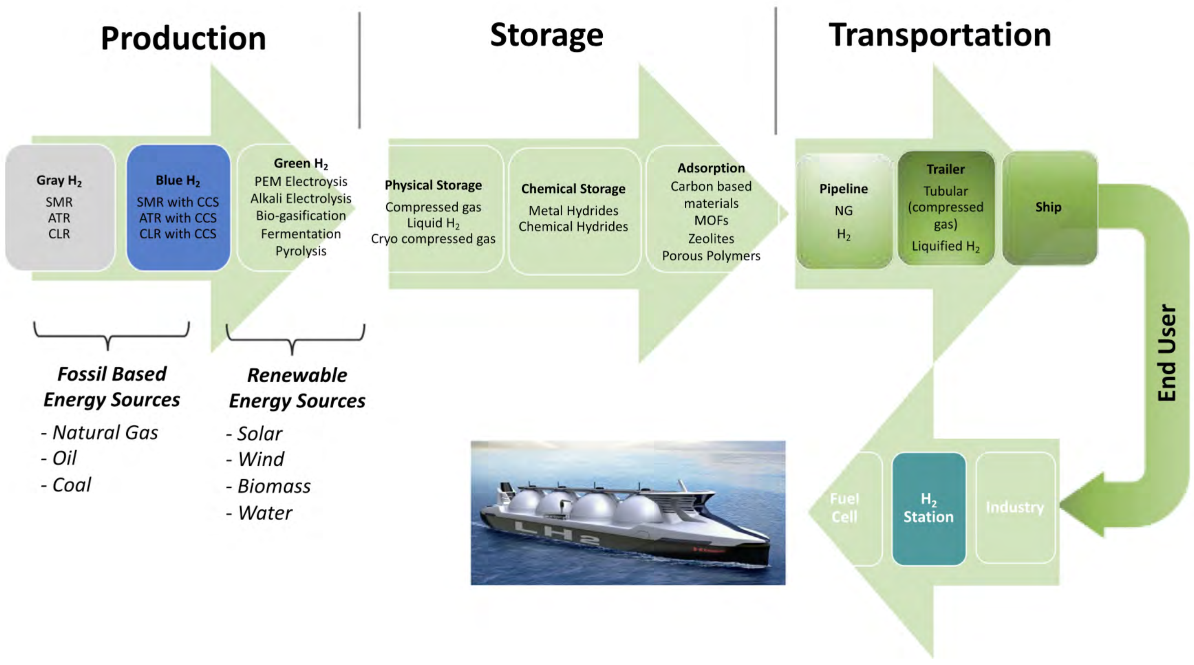


Figure 2.2: *Overview of the Hydrogen Process; Production to User. Source: Atilhan et al. (2021)*

2.2.2 The Hydrogen Fuel Cell

In the transition from fossil fuels to hydrogen the power unit also need to be adjusted and adapted in order to use hydrogen efficiently. As of today, diesel and natural gas engines are the most commonly used prime movers in the maritime sector, but fuel cells are considered a promising prime mover according to Mestemaker (2020). Fuel cells work in a reverse direction of an electrolyzer, where the hydrogen fuel is split into different components at the electrodes in the fuel cell generating electricity (Van Hoecke et al., 2021a). There are developed several different fuel cell technologies, but the most developed is the proton exchange membrane fuel cell (PEMFC) which according to Rivedal et al. (2018) is the most promising to maritime use.

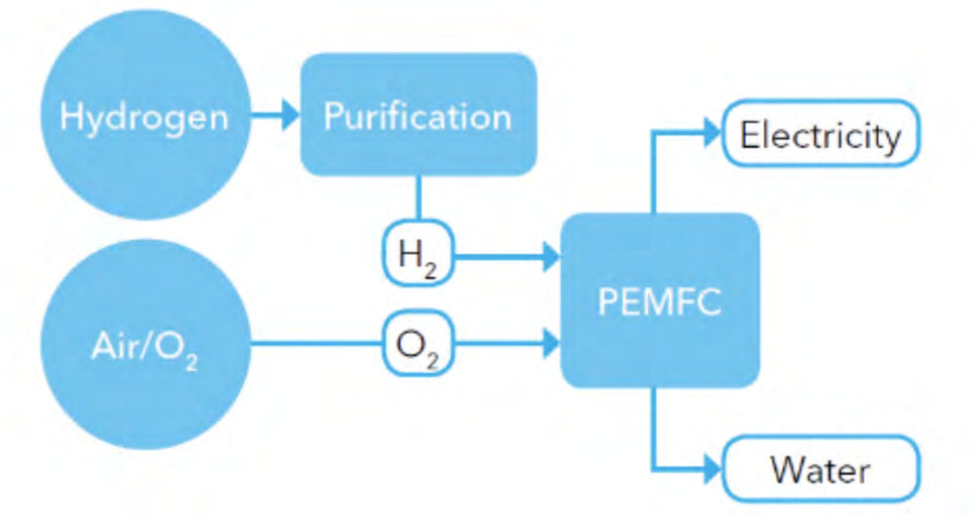


Figure 2.3: *Simple Illustration of PEMFC. Source: Rivedal et al. (2018)*

The proton exchange membrane technology is already used in transportation, mostly cars and busses. The technology is considered to be relatively matured and available, which increases the feasibility for the maritime industry to adapt the technology into vessels (Rivedal et al., 2018). However, due to the necessity of pure hydrogen in a PEMFC, the hydrogen used with this technology requires complex water treatment systems.

In order to utilize the PEMFC technology in the maritime industry, sufficient durability and operability is important. This was assessed by Xing (2021) where results show that the PEMFC has an expected lifetime of up to 40 000 hours. Also, DNV estimated the fuel cells lifetime in 2017 to be approximately 30 000 hours (Rivedal et al., 2018). The durability mainly depend on type of fuel cells, where different materials and design influence degradation of electrolyte, electrode, and bipolar plate. Further, degradation rates can be improved by focusing on maintenance trough the fuel cells operational lifetime. This is most relevant for larger ships and installations. The actual lifetime also depends on load cycle, thermal cycle, and quality of the fuel and air that influence the operational stability of the fuel cells (Xing, 2021). Some of the PEM-fuel cells requires longer start-up time than traditional engines, but this is not considered a problem for maritime applications according to Xing (2021).

The efficiency of the fuel cell is another important aspect in order to be used in the maritime industry. Efficiency is determined by the type of the fuel cell, materials, and fuel (DNV GL, 2019a). According to U.S. Department of Energy (2015) the PEM fuel cells can convert up to 60% of the energy contained in the hydrogen, while a traditional gasoline car is less than 20% efficient, corresponding to 50% reduction in fuel consumption. In a later assessment done by DNV in 2022 the efficiency was estimated to 68%, while also pointing out the importance of the load factor, where lower load results in higher efficiency from the fuel cell (Ovrum et al., 2022).

Another important aspect to make fuel cells feasible for maritime application is the cost of the technology. The development of maritime fuel cells started a long time ago when the high costs were considered the main reason for the technology not to be fully commercialised. The price of fuel cells is approximately 1800 USD/kW for PEMFC, with an estimated price of 400 USD/kW in 2025 due to higher production volumes (Rivedal et al., 2018). This is substantially more expensive than conventional diesel engines due to expensive materials and relatively low production volumes compared to conventional alternatives (Xing, 2021). However, because of substantial investments in PEM technology the cost has dropped (DNV GL, 2019a).

https://www.overleaf.com/project/631f03d7e97673a291dd977b

3 Theoretical Frameworks

The following section describes the theoretical framework that has been used to answer the first research question. The PESTEL framework will be presented, and its relevance to the research question will be explained.

3.1 PESTEL

The main objective of a PESTEL analysis is to highlight macroenvironmental forces that affects a corporation or industry, both non-market and market oriented, according to six different key categories. The categories are as follows: *Political, Economic, Social, Technological, Environmental* and *Legal* forces. (Johnson et al., 2018).

In this study, the research focuses on how the six forces affects a transition from fossil fueled vessels to hydrogen driven vessels in the Norwegian shipping industry. This allows for a broad analysis where not only economic factors are investigated, but political as well. This will increase the value of the findings, as it is more likely that the main drivers and barriers for hydrogen vessels will be exposed and investigated (Johnson et al., 2018).

Although a PESTEL analysis is more common in business analysis, it is also possible to apply it to industries. This framework is appropriate to investigate the research question as it allows for a broad analysis of the macroeconomic environment surrounding the chosen phenomenon, and it can discover key opportunities and threats of a transition to hydrogen vessels. For these reasons, a PESTEL analysis is an appropriate tool to investigate the first research question:

To what extent does the economic and political environment support a transition to hydrogen vessels in the Norwegian shipping sector?

In this section each of the six forces from the PESTEL analysis will be explained in further detail. It is also important to notice that these factors are not mutually exclusive in practise, which means that they could often interrelate with each other (Johnson et al., 2018).

Politics is the first factor within PESTEL, and focuses on the role of the government and other political factors (Johnson et al., 2018). In the analysis the role of the Norwegian government will be discussed, and also the role of EU as a legislator. Other public institutes that are subject to the Norwegian shipping sector, and have the possibility to promote or oppose hydrogen fueled vessels, will also be covered.

Economic forces comprise of the economic conditions within the industry (Johnson et al., 2018). The elements included in the analysis will be revolving around the cost of investing in hydrogen vessels. These are the initial investment costs and the operating costs. Further on, the costs of producing hydrogen and CO_2 emissions will be investigated, as these prices have great affect on the hydrogen price. It will also be discussed if there is a strategic first- or second-mover advantage based on the economic factors.

The *Social* forces encompasses elements as demographics, wealth distribution, geography and culture (Johnson et al., 2018). In the case of hydrogen vessels, the willingness to pay for zero-emission shipping by consumers will be analyzed. Additionally, the human capital required to carry out the transition and the industry ecosystem will be investigated.

Technological forces comprises of all changes in technological solutions, processes and systems (Johnson et al., 2018). In this part, the maturity and prospects of the technologies essential to hydrogen vessels will be investigated. The technologies analyzed are the hydrogen production, hydrogen storage, and hydrogen infrastructure.

The *Environmental* factor focuses on pollution and issues regarding the climate, and can be a great source of both opportunities and additional costs (Johnson et al., 2018). In the case of this study, the environmental aspect will address to what extent hydrogen as a fuel is environmental and ecological friendly. And, also to what extent hydrogen vessels imposes a risk to the environment.

The final element is *Legal*, which refers to how legislation and regulation affects the industry. Legal forces in the analysis will investigate legislative factors that either may support or hinder the transition to hydrogen.

It is important to notice that although the analysis will investigate the six parts of the PESTEL framework separately, in reality the parts are interconnected and have significant influence on each other. The authors have analyzed the topics considered the most important and relevant within each force. The elements in the analysis does not represent the boundaries of the discussion. Findings from the PESTEL analysis will also give a foundation to the investigation of the second research question.

4 Methodology

This chapter outlines the methodology framework, which comprises all the decisions made in order to answer the research question. It starts with a presentation of research design, followed by an explanation of the data collection process. Then the validity and reliability of the research will be discussed.

4.1 Research Design

Saunders et al. (2016) describes research design as the overall plan for the research project. The research design process involves multiple decisions that together makes the foundation necessary to answer the research problems (Saunders et al., 2016). Through an analysis of the macroeconomic environment of the Norwegian shipping industry, the purpose of our research is to investigate the opportunities and barriers of the transition to hydrogen vessels in Norway. Further, this will lay the foundation to evaluate CfD as a governmental measure that could increase investment in hydrogen vessels. To develop new insight into this topic, this study is constructed as a *mixed methods exploratory case study.*

4.1.1 Research Purpose

The research has an *exploratory* purpose, because it is seeking deeper insight into the phenomenon hydrogen shipping. Exploratory studies are valuable means to gain insight into a topic, especially if the nature of the topic is uncertain and have limited literature (Saunders et al., 2016). Because the purpose of this research is to gain a deeper understanding of hydrogen shipping in Norway, this makes the nature of the research project exploratory. In addition, because literature on hydrogen shipping often is narrowed and specialized rather than broad and extensive, it is currently lacking literature on how the macro environment of shipping affects the transition to hydrogen vessels. This supports the nature of the research to be exploratory.

The exploratory study has the benefit of allowing the research to commence with a broad focus, and become narrower as the research progresses (Saunders et al., 2016). This has been beneficial in this research because it allowed the research process to have a broad focus on the macroeconomic environment in the preliminary research, and later on narrow down and investigate the transition's most central opportunities and barriers in further detail. Saunders et al. (2016) also argues that one of the main advantages with an exploratory study is it's flexibility and adaptability to change. This became very useful for the researchers when deciding which of the barriers and opportunities to focus on. It allowed the researchers to adapt to new information and highlight the most important factors.

4.2 Research Approach

Mixed methods research combines the use of quantitative and qualitative data collection techniques and analytical procedures (Saunders et al., 2016). The researchers have simultaneously collected data and analyzed them using both methods, which allows for more diverse viewpoints and interpretations (Saunders et al., 2016). This has been important for the research in order to identify the most important forces affecting the transition to hydrogen shipping. In addition, by comparing data concurrently, the researchers have taken advantage of a concurrent triangulation design.

The secondary data collected have comprised of qualitative and quantitative data, and have laid the foundation for this research. Using the primary data as a starting point, the secondary have been used to further investigate the topics and viewpoints provided by the interviews. Secondary sources have been literature, online sources and case studies. The secondary data have provided broad, as well as in-depth, information about the opportunities and barriers for hydrogen vessels.

The approach is a combination of an inductive and abductive study. It is inductive when the researchers collects data to generate a better understanding of a phenomenon through analysing existing data (Saunders et al., 2016). Since the aim of this study is to investigate important drivers and barriers for a transition to hydrogen vessels, and whether CfDs could be used to accelerate the transition, an inductive approach is used. (Saunders et al., 2016) suggests that with an inductive approach, the researchers should analyse the data as it is collected and develop guidelines for the subsequent research. By applying an abductive approach as well, the researchers have obtained data that is sufficiently detailed and rich, in order to identify and explain patterns regarding the hydrogen shipping transition. The researchers then integrated these explanations in a overall conceptual framework, in order to investigate CfD as a government measure.

4.2.1 Research Strategy

The strategy chosen for this study is a *case study*, which is appropriate when the purpose of the research is to investigate a phenomenon and its context, and has the capacity to produce empirical descriptions and theories (Saunders et al., 2016). In this thesis, the phenomenon of interest is the transition to hydrogen short-sea vessels in Norway, with the underlying goal to reveal the most important barriers that prevent the transition. Saunders et al. (2016) argues that case studies have the possibility to create great understanding when investigating the interaction between a phenomenon and its surroundings. The authors therefore found this strategy applicable, because the aim is to investigate the shipping markets transition to hydrogen vessels through analyzing political, economic, social, technological, environmental and legal forces.

4.2.2 Research Objective

The main objective for this study is to identify and investigate the economic and non-economic forces affecting the Norwegian shipping industry's transition to hydrogen fueled vessels. The second objective is to explore how CfDs can increase investment incentives towards hydrogen vessels, and analyzing how the contracts should be designed given the industry‘s macro-economic environment.

In contrast to earlier literature, this study enlightens the specific opportunities and barriers of hydrogen fueled vessels in Norwegian shipping. Earlier research on this topic often undertake a narrow and thorough perspective within one of the several aspects of the macro-environment. The findings of this study however, contribute with a more extensive approach providing an overview of several macro-environmental forces, and analyzing if these could facilitate an opportunity or hinder the transition.

This research provides useful findings for both policy makers and industry participants who want to take part in the transition to hydrogen vessels in the Norwegian maritime industry. Additionally, it provides actors and the Norwegian government insight into how CfDs could facilitate the transition, and how it should be designed.

4.3 Data Collection Process

The main data source used in this research has been secondary data, mostly being raw and compiled qualitative and quantitative data. In addition, primary data have been collected through two semi-structured interviews and e-mail correspondence with actors within the shipping industry. This section will explain the two data sources in further detail.

4.3.1 Secondary Data

Secondary data have been collected from articles, journals, research publications, and government records. These sources have contributed as a medium for compiled secondary data, as well as raw secondary data for the data analysis. According to Saunders et al. (2016), secondary data have the ability to deliver high-quality data fast, leaving more time to analyze and interpret the data. This has been beneficial as the study aims to describe the industry's macro-environment, which is a very broad subject that requires extensive amount of data.

For example, scholar articles were of great importance when analyzing economic, socioeconomic, and technological factors. These topics are of great complexity, have been popular research topics recent years, and have provided insightful information about hydrogen fueled vessels and its challenges. Another example is DNV, who has provided a vast amount of data that have been of good use in the economic part of the analysis.

Grey literature have also been utilized. This is materials produced by all levels of government, academics, businesses and industries, both in print and electronic formats, which is not controlled by commercial publishers (Saunders et al., 2016). For example, assessments produced upon requests from the government, such as the Ministry of Climate and Environment, have contributed with thorough and up-to-date evaluation of several aspects of the macro-economic environment surrounding hydrogen and the maritime industry.

4.3.2 Primary Data

The primary data were gathered through semi-structured interviews with two different competent actors within the hydrogen shipping market. The interviews have been conducted through one-to-one conversations via internet online video calls. Two separate interview guides were constructed for each interview, which allowed the questions to be tailored to the interviewee‘s competence. The interview guides are meant to help the interviewers to gain a structure through the interview, as it consists of prepared questions as well as it opens for follow up questions and conversation. Hence, semi-structured interviews have the ability to give the interviewee the opportunity to explain and elaborate in their responses, whilst at the same time have a structured process that could easily be replicated (Saunders et al., 2016). This adds significance and debt to the data obtained, and is considered to be an appropriate method for data collection when conducting a case study (Marlisa and Wan Norhayate, 2015).

The first interview was conducted trough a video call with Sigmund Størset, Senior Market Advisor at Enova, who has large-scale hydrogen technologies as one of his main areas of research. Enova is a state enterprise owned by the Ministry of Climate and Environment in Norway, and their task is to promote reduction of greenhouse gas emissions, development of energy and climate technology and strengthen security of supply (Enova, 2018). Størset provided insightful and comprehensive information about the hydrogen shipping market, and played an important role in the preliminary research and throughout the analysis.

The second interview was conducted through a video call with Pedram Nadim. He holds the position as business developer within hydrogen technology at Teco2030. Teco2030 is located in Norway and is developing zero-emission technology for the maritime and heavy industry sectors, and have PEMFC as it‘s core product (Teco2030, 2022). This interview helped the researchers to comprehend the complex technology behind hydrogen fueled vessels and the context around it, which was crucial to the analysis. In addition, Nadim‘s contribution was also of great use in the economic part of the analysis.

4.4 Research Quality

Reliability and validity are two important elements when evaluating the research quality (Saunders et al., 2016). In this section, an assessment of these two factors will be covered and discussed.

4.4.1 Validity

The validity confirm the accuracy of the research, and if the methods in practise are measuring what they are supposed to (Brink, 1993). Validity is separated in to two different types; external and internal. Internal validity refers to the extent to which the findings are a true representation of the reality, while external validity addresses to which extent the representation of the reality are legitimately applicable across groups.

Internal Validity

The research has taken several measures to strengthen the internal validity, and one of these is the use of a descriptive framework. The researchers have used the PESTEL framework to structure the analysis of the macroeconomic environment of hydrogen shipping, as this is the purpose of the framework. This has allowed the case study to follow a structure, that is the six forces of the PESTEL framework. The framework is widely used for case studies, and strengthens the research internal validity.

During the primary data collection, the internal validity was strengthened by asking clarifying questions when needed. Saunders et al. (2016) explains that semi-structured interviews have the potential to achieve high level of validity because of its nature. By asking multiple questions and probing for answers, the chances of understanding the opinions and viewpoints of the interviewee are increased. As a result, the interviews provided data with strong internal validity.

The utilization of multiple secondary data sources, both qualitative and quantitative, increases internal validity due to the *triangulation effect* (Saunders et al., 2016). The purpose of this is to ensure that the data are reliable and correct through comparing independent data sources with each other. The researchers therefore put alot of work into validating information about barriers and opportunities across data sources, incorporating rival viewpoints as well. Through comparisons between multiple secondary sources and the interviews, the internal validity was strengthened since it became possible to confirm information across separate and independent sources.

The internal validation of the interviews was strengthened through participant confirmation. This is when the researchers sent the research data back to the interviewee for comment and validation (Saunders et al., 2016). In order to achieve this effect, a list of citations from the interview was sent to each participant to be confirmed or corrected.

One concern by using secondary data is that it could reduce the internal validity, due to the fact that the research was conducted for another purpose (Saunders et al., 2016). However, this threat has been counteracted through careful selection and evaluation of the research behind each data source. In addition, great emphasis has been placed on validating and securing the different sources, which is important when using secondary data (Saunders et al., 2016). In the process both the methods of collecting data, and the quality of the various sources have been essential to validate and evaluate.

External Validity

Case studies are often criticised for their weak external validity, since context plays an integral part in the analysis, and the findings are often context-dependent. In this research, the case being the hydrogen shipping transition and the population being Norwegian actors, findings could be difficult to generalize to other industries and countries. The reason for this is that the factors within each industry and country could generate very diverse results. However, Yin (2013) argues that in case studies it is the analytical generalisation that should be considered when measuring external validity, rather than the statistical. Therefore it is suggested that the generalisation should be made to theory, not population, and is to which degree the theory can be used to explain similar phenomenon in similar scenarios Saunders et al. (2016).

The study has given an extensive description of the context, analysis, methodology and findings, and therefore gives generalisability for the reader. The readers of the research could easily detect the transferability of the study if they want to investigate its relevance while studying a similar scenario. Therefore, rich and detailed descriptions of background, methodology and analysis have contributed to external validity.

4.4.2 Reliability

Reliability is concerned with the consistency and the repeatability of the data collection method, and could be difficult to control Brink (1993). Reliability could also be divided into internal and external reliability.

The *internal reliability* refers to the consistency during the research project. One way to secure this is by using more than one researcher. More than one researcher reduces the chances of researcher error and bias (Saunders et al., 2016). Therefore, because this study is conducted by two researchers, this has contributed to ensuring internal reliability. In addition the researchers have maintained consistency through extensive discussions of findings, and by investing a lot of time clarifying and formulating concepts, definitions, and objectives.

External reliability is concerned about how easy it is to replicate the techniques and analyses to reveal the same results. This have been secured through careful preparations before the interviews were carried out. These preparations, in addition to the interview guides, should make it easy for other researchers to conduct these interviews in similar ways. In addition, most of the secondary sources are available online, which makes it easier to replicate the study. Most importantly, this research is aimed to be fully transparent in order to allow others to replicate the study.

5 Analysis of PESTEL

This section will analyse the macroeconomic environment of the Norwegian shipping industry, and by doing so investigate the elements that could hinder or promote a transition to hydrogen vessels. The analysis will follow the PESTEL framework, as presented in section 3.1, in order to conduct a structured and thorough analysis. This chapter will examine the first research question:

To what extent does the economic and political environment support a transition to hydrogen vessels in the Norwegian shipping sector?

5.1 Political

The first step in PESTEL is to analyse the political environment that affects our research question. Both national and international political factors that influence implementation of hydrogen vessels in Norway will be examined. The Norwegian government has a major influence over the Norwegian economy and industries, including the maritime industry, with a great interest in facilitating the transition to lower greenhouse gas emission solutions. This in order to reach the goal to halve emissions by 2030 and be climate neutral by 2050 (Norwegian Shipowners Association, 2022).

5.1.1 Norway's Policy Frameworks

The Norwegian government introduced a hydrogen strategy document in 2020 that portrays possibilities within the hydrogen field. The strategy seeks to contribute to prioritising investments where Norway may have market advantages in order to build a competitive hydrogen industry. An important goal of this strategy is to increase the number of pilot projects to generate technology development and commercialize the hydrogen technology (Norwegian Ministry of Petroleum and Energy & Norwegian Ministry of Climate and Environment, 2020). The government further acknowledges that the expensive and immature technology is a significant barrier today, and will therefore continue to support research and development of hydrogen technology.

However, the strategy has not received major support from the industry. Jon Erling

Fonneløp (2020) from Energi Norge stated that "the strategy only points on existing instruments", and that the industry need "more precise measures to accelerate hydrogen investments" (Fonneløp, 2020). In the strategy document the government especially see potential for hydrogen as a marine fuel. But according to the manager of the Environment foundation Zero, Marius Holm (2020), the strategy does not provide sufficient measures to generate investments. This causes Norway to loose terrain against comparable countries and EU, which now invests heavy and by more specific measures (Holm, 2020). Despite these weaknesses, the hydrogen strategy was incorporated in "Veikartet" presented in 2021, where the work towards a greener industry continues.

Today's political foundation is based on "Hurdalsplattformen", which is a political platform that describes the intended and desired politics from our current sitting-government. The government wants to contribute in building a continuous hydrogen value chain where production, distribution, and usage are developed simultaneously with specific production targets for green hydrogen by 2030 (Arbeiderpartiet & Senterpartiet, 2021). This indicates that the government is taking measures to facilitate hydrogen technology implementation, and there is several relevant parliamentary resolutions that has been proposed to the current government to generate hydrogen developments. However, the government turned down a proposed resolution to start a "large scale investment on Norwegian hydrogen- and ammonia development" which included an encouragement to "considerate new instruments that accelerates projects regarding hydrogen and ammonia, including contract-for-difference" (Haltbrekken, 2022). This may indicate that the government is not fully committed, and that earmarked funds to the transition are limited.

In addition to policies and strategies, the Norwegian Government is heavily invested in Norwegian industries with direct ownership in 70 companies, that combined accounts for a value of 1179 billion kroner (Norwegian Government, 2022). According to the government there is a need for public involvement, because the private sector alone will not give the best socio-economic result. In October 2022 the government presented an updated ownership-policy that strengthens their focus on sustainability to reach the Paris Agreement, which includes more focus on investments in green technologies (Norwegian Government, 2022).

One of the companies that interferes with the market on the governments behalf is

Enova, which recently granted 219 million kroner to Wilhelmsen and their Topeka project of building a hydrogen vessel (Enova, 2020). According to Wilhelmsen's Senior Vice President, Jan Eyvin Wang (2020), this grant is a huge deal for the maritime industry in Norway and to further explore hydrogen as a future fuel alternative. Further, Enova also announced in June 2022 that they will support five hydrogen production facilities with a total grant of 669 million kroner. These facilities will be located along the Norwegian coast, with the capacity to supply 40 hydrogen vessels with renewable hydrogen (Norwegian Hydrogen Forum, 2022b). Enova assigns these grants on the behalf of the government with the intention to reduce existing barriers (Enova, 2022a). This illustrates how the government, through companies with state ownership, commits to facilitate, invest, and accelerate the implementation of hydrogen technology.

Another aspect of the political landscape that affect innovation in the Norwegian maritime sector is wealth tax. Compared to international maritime industry, the Norwegian shipping companies have relatively larger private ownership. The wealth tax forces owners to extract dividends from the companies to pay the tax, instead of reinvesting capital in emission reducing technology. This reduces the competitiveness of privately owned shipping companies in Norway (Norwegian Shipowners Association, 2022). To build a strong and innovative maritime sector, it is important that the political frameworks provide stable, predictable, and international competitive conditions. According to the Norwegian Shipowners Association (2022) 50% of the Norwegian shipping companies are experiencing that wealth tax causes negative impact on their green transition.

5.1.2 Emission Taxation and Quotas

One of the most important tools for the authorities to regulate and secure less GHG emissions is carbon tax and quotas.

Carbon Tax

The carbon tax was introduced in 1991 in Norway with the intention to efficiently reduce CO_2 emissions cost (Norwegian Government, 2020). The CO_2 tax has also become a central instrument to accelerate the transition to low emission solutions. Whether hydrogen will be utilised as an energy carrier in shipping, largely depends on the alternatives that exist, such as fossil fuels. Hence, the price of carbon is important in making hydrogen competitive (Norwegian Ministry of Petroleum and Energy & Norwegian Ministry of Climate and Environment, 2020).

Today the CO_2 tax is approximately 760 NOK/tonn, and there is broad political agreement in Norway that the tax should increase steadily towards 2000 NOK/tonn by 2030 (Kalland et al., 2022). There has been many studies that show strong theoretical evidence that increases in carbon taxes causes a reduction in emissions. In Norwegian politics this has been an important economic mechanism to reduce emissions since 1991, when it first was introduced (Haug et al., 2022). This emphasizes the importance and relevance of carbon taxes in order to reduce emissions, and guide industries into more sustainable solutions such as hydrogen.

The continuation of the carbon tax increase will cause companies that emit substantial amounts of carbon, like shipping, to experience a reduction in profitability (Haug et al., 2022). This is an important mechanism of the tax that could close the profitability gap between hydrogen and fossil vessels. Further, a study by Ahmadi et al. (2022) suggests that the income generated from the carbon taxes could be systematically reinvested by the government into emission reducing projects to accelerate the transition. The CEO of the Norwegian Shipowners Association, Harald Solberg (2022), also share this idea to strengthen the commitment towards renewable projects. He argues that today we see new technology being developed and introduced to the market, but when applied and used, the public subsidies disappears and slows down the transition in Norwegian maritime industry (Norwegian Shipowners Association, 2022). This may be a weakness in the current transition instruments, whereas reinvesting the tax income from emissions could contribute to a more large scale implementation of green technology in the industry.

Emission Quotas and EU Taxonomy

Another way of pricing GHG emissions is trough emission quotas. Since 2008 Norway has been a part of the EU Emission Trading System (EU ETS), which is the European system for trading GHG emission quotas (Øvrebø, 2022). This works by setting a limit on the total amount of greenhouse gases emissions allowed each year, where entities within the system receive or buy emission permits. ETS is EU´s key tool to reduce GHG emissions, and the cornerstone in their policy to fight climate change (European Commission, 2022). However, the maritime sector is not included in the EU ETS system. Since the Norwegian shipping industry to a large extent operates internationally, it has been challenging to regulate their emissions due to the possibility to bunker fuel in jurisdiction without GHG taxes (Haug et al., 2022). This may have caused relatively less incentives for the Norwegian marine sector operating internationally to invest in emission reduction solutions, compared to other comparable sectors included in the EU ETS system.

There has been much debate whether the greenhouse gas emissions from maritime transport should be included in the EU Emission Trading System. In July 2021 the European commission proposed to extend the EU ETS system to also cover the maritime sector, but the proposal was rejected. However, in June 2022 a compromised solution was approved that expands the EU ETS to include maritime transportation from 2024 (Hagberg, 2022). According to Skjelmo and Hagberg (2021) this extension will result in a price signal that incentivizes low-carbon solutions, and will reduce the price difference between alternative fuels and traditional maritime fuels. This also coincide with the theoretical studies preformed on how pricing emissions also cause them to decline. The inclusion of maritime sector to the EU ETS system is expected to generate several billion kroner to the Norwegian government, and according to the Norwegian Shipowners Association (2022) this capital should be reinvested in CO2 reducing maritime projects. By doing so, both the reinvested capital and the EU ETS mechanism could be a incentive for the shipowners to invest in emission reducing solutions such as hydrogen vessels, and could accelerate the transition.

Increased CO_2 prices gives alternative renewable fuels better competitiveness, and makes hydrogen relatively more profitable. However, to make substantial impact on the maritime industry with today's instruments the CO_2 price needs to increase drastically to trigger the hydrogen transition (Kalland et al., 2022). Since the Norwegian government does not control the ETS prices, they need to find a balance between giving strong enough incentives to invest in emission free vessels, while simultaneously not weaken the competitiveness of Norwegian fossil vessels operating internationally. This is likely to be a huge challenge, and of great importance to maintain the relevance of this important industry. It could be argued that too much reliance on the CO_2 tax to drive the transition may threaten the industry, and that other supplementary instruments therefore are necessary.

In order to realise new hydrogen projects in the maritime industry, it is necessary to have sufficient capital available. The introduction of the EU Taxonomy, that classifies the sustainability of the companies, is meant to redirect capital towards sustainable projects which also applies to the maritime sector (Directorate-General for Mobility and Transportation, 2022). Hence, companies that comply with the taxonomy will access competitive green capital which will be key to develop new technology and solutions necessary to de-carbonise the shipping industry (Johansen and Folkestad, 2022). For Norwegian shipping companies that desires to make substantial investments in hydrogen vessels this could be an important channel to acquire capital, and an incentive to make the transition.

The use of carbon taxation clearly provide incentives for shipowners to reduce their emissions, and could incentivize a transition to hydrogen as an alternative maritime fuel. The inclusion of the marine sector in the EU ETS system in 2024, further penalize ships with high emissions and strengthens the effect of pricing carbon emissions. Hence, the Norwegian and European tax-framework is likely to facilitate a transition to hydrogen ships.

5.1.3 Summary of Political Analysis

The Government's Hydrogen Strategy

The hydrogen strategy document that the Government introduced in 2020 demonstrate that the government, regardless of the parties it comprises of, aspires to support hydrogen projects and investments Størset (2022). Although this alone may support the transition to hydrogen within the shipping industry, the government‘s vision must be manifested in specific measures to facilitate the transition.

On one side, Enova has awarded several grants to hydrogen projects such as the Topeka project and the five hydrogen hubs along the coast project, two projects that develops the Norwegian hydrogen market. On the other side, multiple industry leaders claims that the strategy is too ambiguous and that the government is not fully committed to their strategy goals. The governments ambitions and goals are therefore an opportunity for hydrogen shipping. However, there could be argued that there is a lack of measures, which in turn reduces the effect of this opportunity.

Wealth Tax

Norwegian shipping companies are relatively more private owned and the owners face a higher wealth tax, compared to other countries. This operate as a barrier because the shipowners experience that capital which could have been invested in renewable solutions, such as hydrogen, instead must be used to pay wealth tax.

Taxes and Quotas

The price of carbon is an important political instrument to accelerate the transition to low emission solutions. The projection for the carbon tax levied by the Norwegian government will increase incentives for green projects in the future, including hydrogen vessels. The EU ETS quota system on the other hand have not incorporated the maritime sector, which have reduced incentives for the maritime industry to invest in green solutions. However, as this will change in 2024, the Norwegian shipping sector will face stronger incentives to invest in hydrogen.

Therefore, both the Norwegian carbon tax and the EU quota benefits green investments, creating an opportunity for Norwegian hydrogen shipping. Nevertheless, balancing the carbon tax with the EU quota system will demand careful considerations, in such way that the carbon tax does not threaten the Norwegian competitiveness.

5.2 Economic

This section will analyse the economic forces within the sector that affects implementation of hydrogen vessels. Both the micro-economic and macro-economic environment will be investigated to compare the cost of a hydrogen vessel with a fossil vessel. Hence, identifying the most important cost components of hydrogen vessels will be assessed.

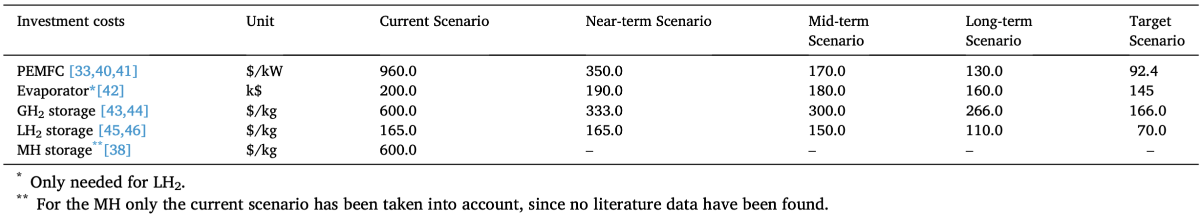
The focus in this paper is to investigate whether the environment is sufficient for implementation of hydrogen short-sea vessels. Hence, the economic analysis will be facilitated towards the short-sea shipping segment. This is important to notice because of the large differences between shipping segments within maritime transportation due to different applications and operating patterns, requiring different technologies and properties.

5.2.1 Capital Expenditures

The amount of capital that is required to be invested by ship owners to acquire a hydrogen vessel is an important aspect to determine whether it is a financial viable option. To make this assessment it is helpful to understand the hydrogen cost components required in a general cargo vessel, compared to a similar fossil vessel.

The power train component is an essential part of capital expenditures (CAPEX). The PEM fuel cell technology is one of the most developed fuel cell technologies for maritime today. However, compared to conventional power train systems, the technology is still very expensive (Størset, 2022). According to a recent study performed by Di Micco et al. (2022), the investment cost for the PEM fuel cell power train system for marine use is approximately 1.6 times the price of a diesel engine system. This fuel system include both the cost of storing the compressed hydrogen onboard and the PEM fuel stacks which is the electrocatalyst. The PEM fuel stacks itself is substantially more expensive than conventional diesel power plants, largely explained by the platinum layers in the fuel stacks that accounts for 56% of the total cost (Sürer and Arat, 2022a).

The study indicate that in addition to the technology being relatively novel, it requires expensive materials that causes the hydrogen power system to be expensive. With an average capital cost of diesel engines equal to approximately 480 USD/kW and 960 USD/kW for fuel cell stacks, the hydrogen PEMFC power system is not cost competitive today from a CAPEX point of view. However, the costs of PEM fuel cell stacks is expected to decrease rapidly in the future as the technology get more developed and production increases (Di Micco et al., 2022). The expected price reduction for PEMFC components is presented below in Table 5.1 with a current, near-term, mid-term, long-term, and target scenario, which corresponds to respectively 2020-2050.



Investment costs	Unit	Current Scenario	Near-term Scenario	Mid-term Scenario	Long-term Scenario	Target Scenario
PEMFC [33,40,41]	$/kW	960.0	350.0	170.0	130.0	92.4
Evaporator* [42]	k$	200.0	190.0	180.0	160.0	145
GH_2 storage [43,44]	$/kg	600.0	333.0	300.0	266.0	166.0
LH_2 storage [45,46]	$/kg	165.0	165.0	150.0	110.0	70.0
MH storage** [38]	$/kg	600.0	–	–	–	–

* Only needed for LH_2.

** For the MH only the current scenario has been taken into account, since no literature data have been found.

Table 5.1: *Projection for PEMFC Components. Source: Di Micco et al. (2022)*

The interview with Teco2030 also provided insight of the price trajectory of PEM fuel cell technology. According to their estimations the technology price will fall from today's 1250 USD/kW to 600 USD/kW in 2030, mainly driven by a reduction in manufacturing cost as the production quantity increases (Nadim, 2022). This indicates a price reduction of approximately 50% by 2030. Although the estimated price reduction is less than in Di Micco et al. (2022) study, both indicate that the technology becomes significantly cheaper in the future. Enova also believes that the PEM technology will be much cheaper in the future as it will be further developed and implemented in industries (Størset, 2022). Although this is very beneficial for investments in PEM hydrogen vessels, it could cause shipowners to postpone their investments until the technology becomes cheaper, providing a second-mover advantage.

Although the estimates are uncertain and highly depends on the specifics of different vessels, it still provides a realistic picture of the relative difference in CAPEX for a hydrogen fuel cell and diesel engine. In addition to the power train component, it is also important to analyse the total capital expenditures to acquire a general cargo vessel powered by hydrogen, relative to the diesel alternative.

A case study performed by Olsen et al. (2020) investigated if a hydrogen fueled vessel, that was supposed to sail a distance of approximately 550nm with a sailing cargo of 5500 metric tons, could be financial competitive. Three different types of general cargo vessels were examined in addition to a comparable marine gasoil (MGO) ship. The cost of the newbuild hydrogen ships were estimated to 18.5, 21, and 24.1 million euros, and corresponding MGO ships to 10.8, 13.2, and 16.5 million euros. Another similar study constructed by Papadias et al. (2019) estimated that CAPEX for a diesel and PEM hydrogen vessel was respectively 12.8 and 19.4 million euros.

Based on these studies, investing in a new hydrogen vessel causes CAPEX to increase by 6.7-7.8 million in this short-sea segment, or in average by 56%, compared to a new corresponding diesel vessel. This result also coincide with the study by Sürer and Arat (2022a), who estimates that hydrogen fuel cell ships on average is between 1.5 to 2 times more expensive.

It is important to acknowledge that these calculations could deviate from the reality due to the general approximation of the studies. Størset (2022) also pointed out that even within the short-sea segment the variations in CAPEX for these vessels is large. However, the investment costs for a hydrogen vessel generally are much higher than alternative fossil vessels. This is because a hydrogen vessel requires additional elements like specialised fuel tanks, motors, and catalysators to generate the electrical power (Olsen et al., 2020). Subsequently, this analysis provide sufficient evidence that investing in a hydrogen vessel is significantly more expensive than in an equivalent fossil vessel.

5.2.2 Operational Expenditures

To further investigate if hydrogen powered vessels are a viable option for the Norwegian maritime sector, the operational expenditures (OPEX) associated with operating a hydrogen vessel is important to investigate. This section will analyse the main operational cost drivers that causes hydrogen vessels to be more expensive than fossil vessels.

When investors evaluate a business case of operating a hydrogen fuel cell vessel, the major OPEX difference compared to a fossil vessel is fuel cost (Pomaska and Acciaro, 2022). Enova also considers the fuel price as the main cost barrier when operating a hydrogen ship (Størset, 2022). Hence, this subsection will focus on analyzing the cost effects from hydrogen price.

Cost of Producing Hydrogen

As mentioned in section 2.2.1.1, There are mainly three different types of hydrogen depending on production method used, and this thesis only analyze use of green hydrogen. Since green hydrogen is produced from water electrolysis, where high amounts of electrical power are required, the price of hydrogen highly depends on price of electricity. Given the historical price average on electricity in Norway of 0.3-0.35 NOK/kW, 70% of the hydrogen production cost occurs from the electricity price (Størset, 2022). Further the need for compression and transportation also contribute to increase the price (DNV GL, 2019a).

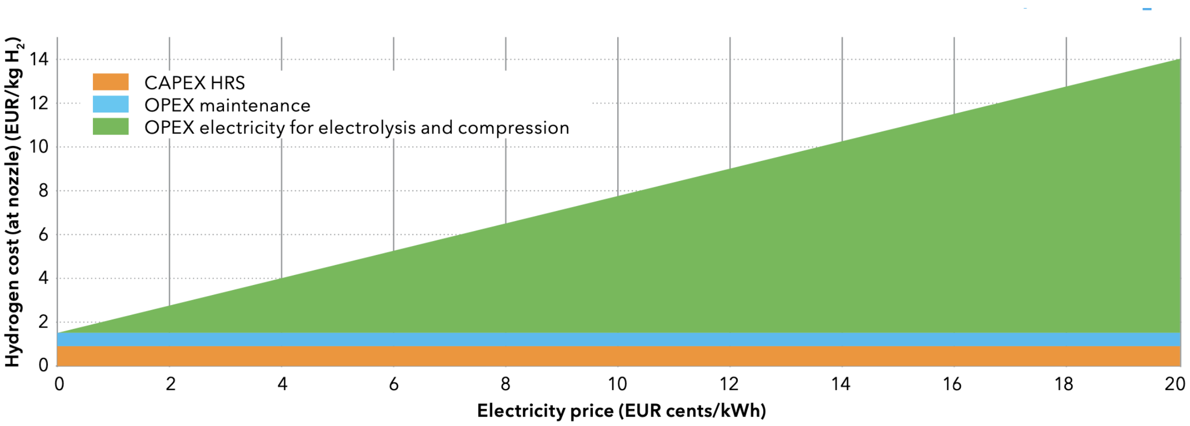


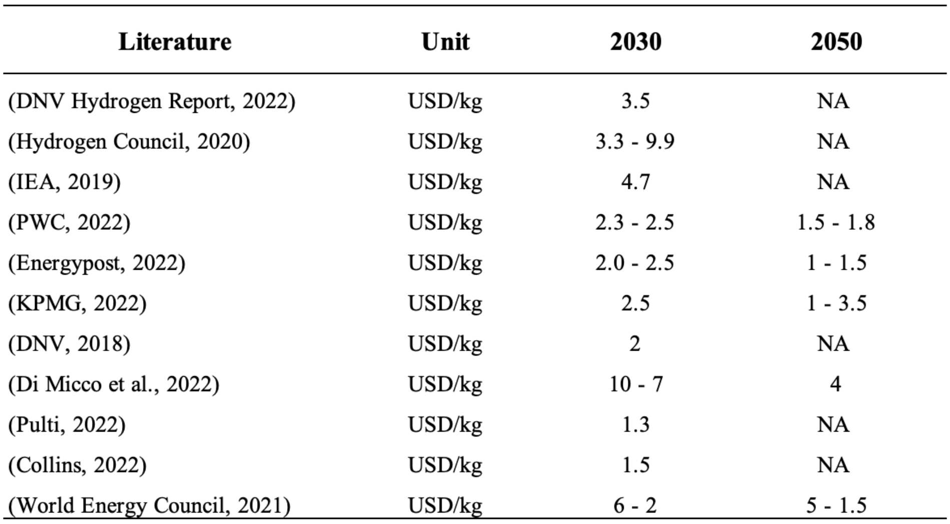
Figure 5.1: *Hydrogen Price Sensitivity. Source: DNV GL (2019a)*

From Figure 5.1 we observe that toady's CAPEX and OPEX cost from producing green hydrogen gives a hydrogen price of approximately 1.75 EUR/kg (1.74 USD/kg), isolated from the electricity price. It is expected that the price of electrolysers will decrease in the near future, reducing CAPEX and consequently drives the consumer price of hydrogen down for any given electricity price (DNV GL, 2019a). However, the largest cost determiner for hydrogen is the electricity price.

Hydrogen Price Competitiveness and Expectation

From a shipowner's perspective, the deciding factor regarding operational expenses (fuel price) will be the cost parity price for hydrogen, compared to fossil alternatives. According to Hydrogen Council (2021) PEM fuel cell vessels powered by renewable hydrogen from electrolysis could achieve cost parity at approximately 2.6 USD/kg. Torvanger (2021) estimates that a hydrogen price of 2 USD/kg could make green hydrogen cost-competitive given a MGO price at 0.5 USD/kg. This is due to the higher energy density of hydrogen and higher efficiency of a PEM fuel cell, compared to fossil engines. Papadias et al. (2019) estimates the break-even fuel cost for a hydrogen vessel to be 2.03 USD/kg. This also corresponds to the same price range found in the previous section, and further emphasizes the importance of reaching a competitive price level for hydrogen.

At this time, the price of green compressed hydrogen is approximately 9 USD/kg, but has been very volatile lately due to the current energy crisis which has led to high electricity prices. At the most the hydrogen price has reached 16.5 USD/kg (Penrod, 2022). This volatility causes uncertainty and is a considerable risk to ship owners when considering investing in hydrogen vessels. Additionally, the price of hydrogen fuel has to become much lower in order to be competitive with fossils. To further analyze whether the hydrogen price can reach required levels to become cost-competitive, several estimates of the future green hydrogen price have been collected from different studies. This has been done because of the large variation in estimations.



Literature	Unit	2030	2050
(DNV Hydrogen Report, 2022)	USD/kg	3.5	NA
(Hydrogen Council, 2020)	USD/kg	3.3 - 9.9	NA
(IEA, 2019)	USD/kg	4.7	NA
(PWC, 2022)	USD/kg	2.3 - 2.5	1.5 - 1.8
(Energypost, 2022)	USD/kg	2.0 - 2.5	1 - 1.5
(KPMG, 2022)	USD/kg	2.5	1 - 3.5
(DNV, 2018)	USD/kg	2	NA
(Di Micco et al., 2022)	USD/kg	10 - 7	4
(Pulti, 2022)	USD/kg	1.3	NA
(Collins, 2022)	USD/kg	1.5	NA
(World Energy Council, 2021)	USD/kg	6 - 2	5 - 1.5

Table 5.2: *Estimated Future Hydrogen Price from Litterature*

Table 5.2 shows that the average expected hydrogen price is calculated to be 3.57 USD/kg in 2030 and 2.48 USD/kg in 2050. Based on these estimations, it could be expected that hydrogen could become more cost-competitive in the period between 2030 and 2050. According to Hydrogen Council (2021) green hydrogen production may become cost-competitive by 2035. This will require that the electricity prices returns to more normal levels, and that the expected improvements in electrolysis technology actually occurs. However, it should be noted that the estimates vary substantially, which indicates a large uncertainty connected to future hydrogen prices.

Based on EU´s hydrogen strategy and goals for 2030, it is likely to be a deficit of electrolysers that produces green hydrogen (Størset, 2022). This potential limitation of supply, could increase the price target for green hydrogen in 2030 and 2050. The current global energy crisis also is expected to slow down investments in production facilities in the short-term. Long-term projections are however still indicating that hydrogen prices should continue to fall as technology is further developed and the scale of production grows (Penrod, 2022).

Fuel Cell Efficiency

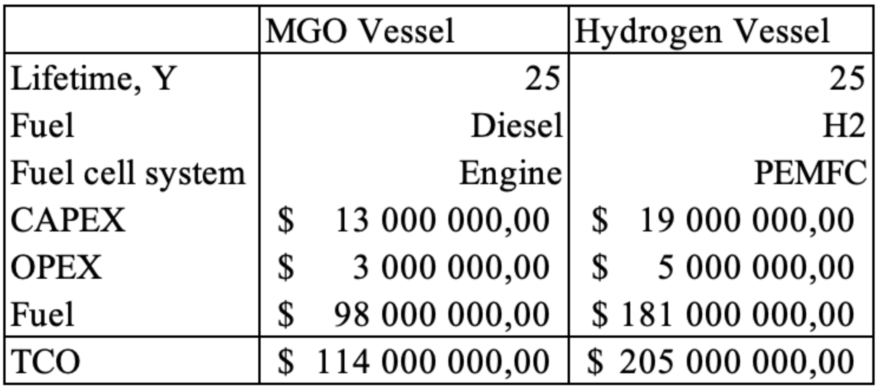
Another important aspect that is decisive for the profitability of a hydrogen powered vessel, is the efficiency of the PEM fuel cell. Today the average efficiency of fuel cells is approximately 50%, but could potentially reach 60% with new and promising technologies under development. This increase in efficiency will reduce OPEX directly due to less fuel required (Størset, 2022). Maximizing the efficiency is an important measure to reduce OPEX and increase the profitability of hydrogen vessels. According to Nadim (2022) the fuel cells reach the highest efficiency when running on lower rpm, and when running on full speed efficiency could drop as much as 10%. Since the hydrogen price is such a large part of the operational expenses, measures to increase fuel cell efficiency under sailing could be an important factor to reduce OPEX and make hydrogen vessels profitable.

5.2.3 Total Cost of Ownership Analysis

This section seeks to further analyze, based upon the analysis above, the relative impact CAPEX and OPEX have on the total cost for a shipowner, when both investing in and operating a hydrogen vessel. This is done by analyzing the total cost of ownership (TCO), which measures the cost of buying and operating an asset over its lifetime (Alexandra Twin, 2021).

A study by Papadias et al. (2019) found that the TCO for a hydrogen vessel was approximately twice as high than a similar fossil vessel over a lifetime of 25 years. With the assumption of a MGO price equal to 0.7 USD/kg and 4.0 USD/kg for hydrogen, the fuel cost alone accounted for 88.6%, the remaining OPEX accounted for 4.8%, and CAPEX accounted for 9.3%. The study also assumed that the PEM fuel cell had an efficiency of 57%.

Table 5.3 summarises the key inputs and results used in the study by Papadias et al. (2019).



	MGO Vessel	Hydrogen Vessel
Lifetime, Y	25	25
Fuel	Diesel	H2
Fuel cell system	Engine	PEMFC
CAPEX	$ 13 000 000,00	$ 19 000 000,00
OPEX	$ 3 000 000,00	$ 5 000 000,00
Fuel	$ 98 000 000,00	$ 181 000 000,00
TCO	$ 114 000 000,00	$ 205 000 000,00

Table 5.3: *Key Inputs and Results from Study by Papadias et al. (2019)*

These results illustrates the major TCO gap between MGO and hydrogen vessels. However, the analysis is performed with a hydrogen price of 4 USD/kg, which is much lower than toady's price level of approximately 9 USD/kg. The hydrogen price has been volatile because of uncertainty in energy markets, where green hydrogen reached a price of 16.8 USD/kg in late July 2022 (Penrod, 2022).

Therefore, a sensitivity analysis was performed to analyse how a hydrogen vessels TCO is affected when electricity and hydrogen prices change. This is done by using the inputs and results from Papadias et al. (2019) study, and DNV GL (2019a) model for hydrogen price as a function of electricity price. The sensitivity analysis is shown in Figure 5.2 below and shows that TCO is highly affected by changes in electricity and hydrogen prices.

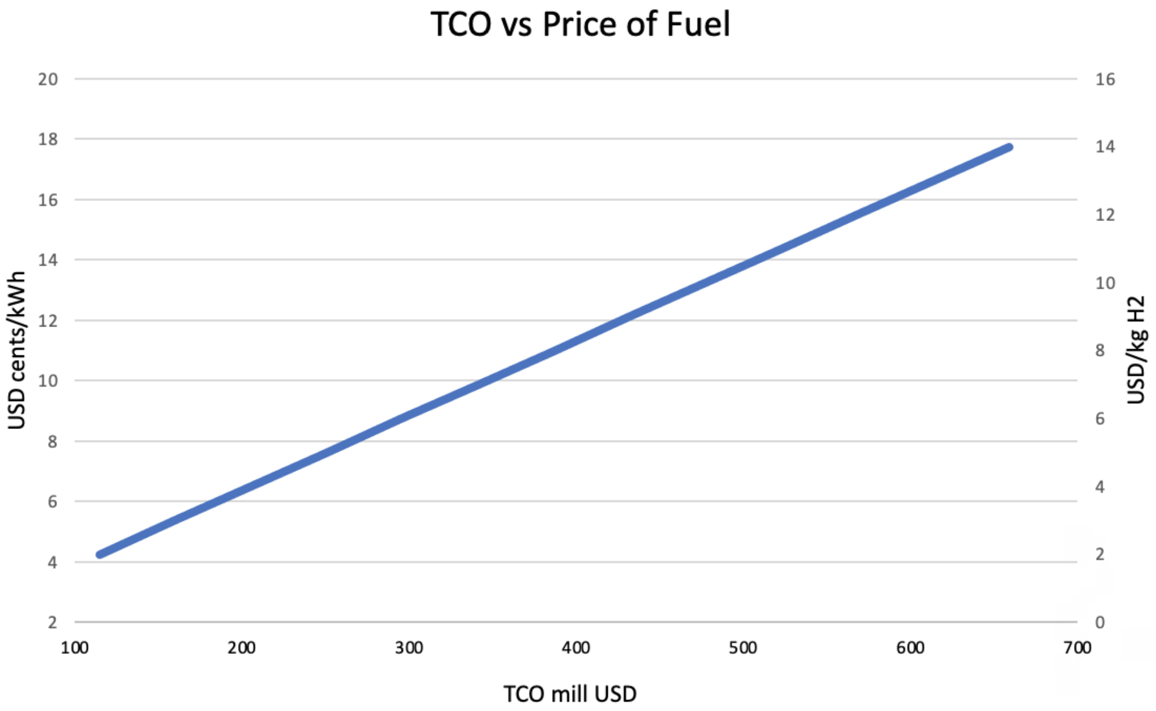
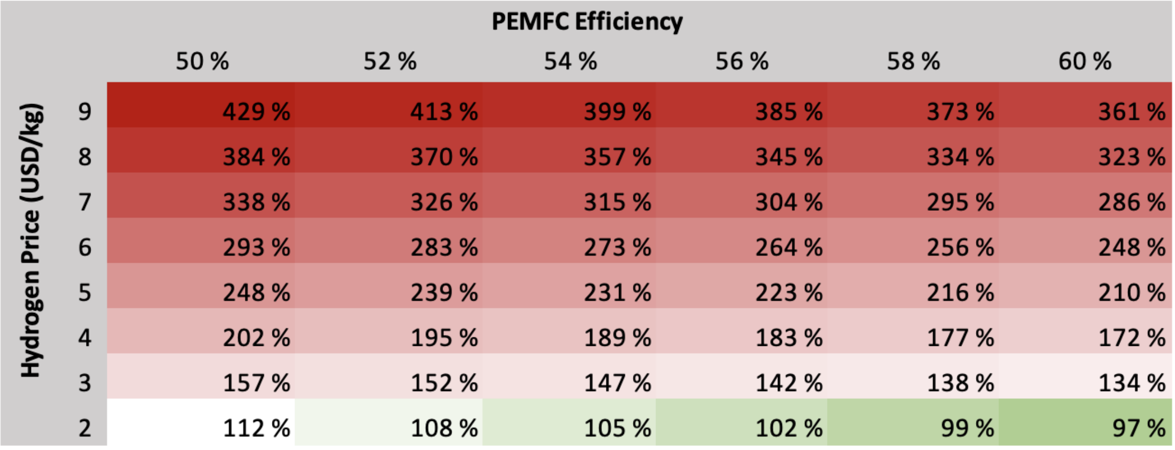


Figure 5.2: *Sensitivity Analysis of Electricity and Hydrogen Price Effect on TCO*

In addition to high uncertainty attached to the fuel and electricity price, the efficiency of the fuel cell is important in order to reduce costs. The fuel cell efficiency can vary between 50-60% depending on speed, and the technology is expected to evolve rapidly and increase efficiency. Hence, a second sensitivity analysis was performed to investigate how the TCO for a hydrogen vessel is affected when both hydrogen price and fuel cell efficiency changes, based on the results and inputs from the study by Papadias et al. (2019). The analysis presents the total cost of ownership in a hydrogen vessel as a percentage of a similar fossil vessel, illustrated in figure 5.3.



Hydrogen Price (USD/kg)	PEMFC Efficiency 50 %	52 %	54 %	56 %	58 %	60 %
9	429 %	413 %	399 %	385 %	373 %	361 %
8	384 %	370 %	357 %	345 %	334 %	323 %
7	338 %	326 %	315 %	304 %	295 %	286 %
6	293 %	283 %	273 %	264 %	256 %	248 %
5	248 %	239 %	231 %	223 %	216 %	210 %
4	202 %	195 %	189 %	183 %	177 %	172 %
3	157 %	152 %	147 %	142 %	138 %	134 %
2	112 %	108 %	105 %	102 %	99 %	97 %

Figure 5.3: *Sensitivity Analysis of Hydrogen Price and PEMFC Efficiency on TCO*

The sensitivity analysis indicates that we can only achieve a competitive TCO when hydrogen price is below 3 USD/kg and the fuel cell efficiency is close to 60%. Despite this analysis assuming fixed fuel cost in each scenario, which is highly unlikely over 25 years, it still illustrates the magnitude of the cost difference caused by hydrogen price and fuel cell efficiency. With an expected price of hydrogen in 2030 of 3.57 USD/kg, this would give a TCO of approximately 160% compared to a fossil vessel, depending on PEMFC efficiency. This indicates that hydrogen vessels will not be cost-competitive in 2030. However, assuming an expected hydrogen price of 2.48 USD/kg in 2050 the vessel could become cost-competitive with a fuel cell efficiency close to 60%. Due to the assumptions and general approach of the analysis, it does not provide accurate estimates, but it provides a realistic insight of the importance of the hydrogen price and fuel cell efficiency. Hence, results may indicate a need for operational subsidies that can reduce fuel cost for hydrogen vessels.

5.2.4 First vs Second Mover

Shipping companies considering investing in hydrogen vessels face a strategic challenge, because the economic outcome of such an investment would depend on the timing. The strategic choice between entering the market as a first-mover, or wait with entrance and become second-mover, is an important decision. Hence, if it becomes too beneficial strategically to delay investment and wait for other actors to enter the market first, this could create a barrier for the hydrogen shipping transition.

CAPEX

On the one hand, being a first-mover in the market could lead to valuable competence and knowledge of hydrogen technology and vessel development. Accumulation of such knowledge would give a first-mover a competitive advantage, because as the market grows they would have more advanced technology than their competitors. In addition, a company that is a first-mover would get the opportunity to build a customer base and a brand as a hydrogen shipping company, which could in turn secure a large market share as entrants challenge the incumbent. Therefore, taking the position as a first-mover could be viewed as an opportunity for Norwegian shipping companies.

On the other hand however, taking the position as a first-mover could also be expensive. First off, as explained earlier, the CAPEX costs are expected to decrease in the years to come. This makes it more advantageous to withhold the investment, even if this allows competitors to invest first. With this perspective, first-movers would pay high prices to manufacturers of parts and equipment such as fuel cells. As these actors scales up, and are able to leverage of economies of scale benefits, the price of hydrogen auxiliaries will be lower for second-movers.

OPEX

Considering the OPEX costs, it is also expected that these will decrease in the future, creating a second-mover advantage. The reason partly comes from the fact that the world is faced with an energy crisis driving up the price for electricity, and therefore also hydrogen. Further, there are relatively few established hydrogen production facilities, resulting in low supply. Nevertheless, these high electricity prices are expected to come down to more normal levels, and with further development and investments in hydrogen infrastructure, the price of hydrogen is likely to drop in the future. Hence, it could be argued that this will only temporarily contribute to a second-mover advantage.

Fuel cells are expected to become more efficient as explained earlier, and this also benefits the second movers. First-movers would have to invest in fuel cells that are less efficient so that the fuel cell manufacturers could improve the technology. In addition, the production of green hydrogen is also expected to become less expensive. The hydrogen available at the market today comprise mostly of gray and blue hydrogen, and to a lesser extent green.

Because there has been a limited demand of green hydrogen, it has also been limited supply, making green hydrogen a scarce resource (Sürer and Arat, 2022a). However, if the demand for green hydrogen would increase, the hydrogen producers would be able to scale up the production and gain economies of scale benefits. Ultimately this would lead to cheaper hydrogen, which therefore also creates a temporary second-mover advantage.

5.2.5 Summary of Economic Analysis

High Costs

The cost associated with investing in hydrogen fueled vessels is currently much higher than the fossil fueled equivalent. Several studies concludes that the severe cost difference are currently one of the biggest barriers in the transition to hydrogen vessels. Operating costs are also creating a large barrier, since using hydrogen as fuel is much more expensive than fossil fuels.

Uncertain Future

The hydrogen price is expected to decrease as electricity prices declines and production methods are further developed. However, future hydrogen price estimations are uncertain and varies substantially, which makes it difficult to predict future cost of operating hydrogen vessels. This uncertainty makes calculating the profitability of a hydrogen shipping project difficult for shipping companies. Because the TCO of a project is heavily affected by the hydrogen price, this uncertainty creates a significant barrier for hydrogen vessels.

Second-Mover Advantage

The benefits of entering the hydrogen shipping market is associated with building up competence, systems and technology, that can secure larger market shares in the long run. However, because the high investment and operating costs are expected to decrease after the first-movers enters the market, there is a large incentive to wait until these cost barriers are reduced. Therefore, the second-mover advantage could be viewed as a barrier to the transition as it is strategically better to postpone the investments.

Nevertheless, there has been several initiatives from shipping companies to invest in hydrogen vessels. Although these initiatives have been subsidized by the government, it also highlights the willingness to become a first-mover.

5.3 Social

Social factors that have an impact on the transition to hydrogen vessels will be analyzed in this chapter. Customers willingness to pay for green shipping, social acceptance, human capital and eco-system are among the social factors.

5.3.1 Willingness to Pay

The additional costs of hydrogen vessels compared to fossil fuel vessels were explained in chapter 5.2 Economics. However, if the end consumers are willing to pay an additional cost on the products they buy, then hydrogen could be profitable even with higher costs. This additional price consumers pay for environmentally friendly projects is known as a “green premium” (Energy, 2022), and if the public is willing to pay a green premium, then this would make hydrogen vessels more profitable and beneficial.

One study compared people’s willingness to pay (WTP) for a t-shirt depending on if it had been transported environmentally friendly or not (Schniederjans and Starkey, 2014). Their findings suggested that consumers were willing to pay more for the environmentally friendly t-shirt than the one with regular transportation. However, through a separation between intentions and actions, they also found that the consumer had to be sufficiently convinced in order to take action and buy the environmentally friendly t-shirt. These findings therefore suggests that consumers could be willing to pay extra for products that have been transported with hydrogen vessels, but only if they are sufficiently convinced that hydrogen vessels are environmentally friendly.

Another study investigated whether decarbonization of maritime shipping and the whole value chain is valued in the consumers perception and affects their WTP, employing coffee as an example (Bek, 2022). They also found that consumers have a willingness to pay the green premium for environmental friendly shipping, and even more if the whole supply chains emissions were reduced. These results suggest that green hydrogen vessels have the potential of collecting a green premium for the freight they transport and could use this to cover some of the additional cost that hydrogen vessels imposes. It should be mentioned however, that the study was conducted in America, and that environmental preferences and WTP for green premiums are varying across countries. In addition to this, the willingness to pay for green premium by consumers is likely to be dependent on the product itself, making it difficult to calculate these premiums in advance.

The willingness to pay for emission free or reduced transport by Norwegian freight owners, are somewhat low according to a report by the Norwegian Department of the Environment (DNV GL, 2019b). This assessment argues that the reason is that there are few or no emission reduction requirements for the freight owners, making them less willing to pay a green premium for hydrogen shipping. Likewise, Størset (2022) argues that the discussion about whether hydrogen fueled vessels could achieve better rate-conditions is disputed within the market.

5.3.2 Public Opinion

Historically, hydrogen has experienced some unfortunate incidents of explosions, which have led to a bad reputation of safety. The fear for hydrogen can be attributed to several incidents of explosions, especially the Hindenburg incident in 1937 (Van Hoecke et al., 2021b). This was the destruction of an airship, which struck the public with a fear of hydrogen usage.

Hydrogen still imposes some risk because of its easily flammable features. However, according to a study conducted by Garcia (2017) about European countries opinions about hydrogen, Norwegians social acceptance of the deployment of hydrogen technology and shipping as safety technologies scores 7, on a scale from 1 to 10. Since 2016 there have been no accidents, and the Norwegian government has released a hydrogen strategy plan without being met by safety concerns from the public. Therefore, even though hydrogen have other safety concerns than fossil fuels, this is mainly regarded as a challenge for those who are in charge of safety design on-board, and not a general public concern.

5.3.3 Human Capital

Capabilities and Competence

The Norwegian shipping industry has a history of being innovative within the industry, and known to be in the very front of change processes (Haugland et al., 2022). Competence has been built up specializing in tailoring ship design and prototypes. The ship manufacturers have achieved great capabilities with problem solving within innovative ship design, mainly because the orders have demanded special adaption and flexibility. In the transition to hydrogen shipping, there are several technological challenges that needs to be solved regarding ship design. Among these challenges are the design of the storage tank and the design behind refueling, which will be further discussed in 5.4 Technology. These challenges emphasizes the importance of innovation and novel solutions when designing hydrogen vessels. Therefore, because Norway has built up innovative capabilities and know-how in ship design over time, this has the potential to give Norwegian hydrogen shipping a competitive advantage.

The maritime Norwegian work culture can also be considered to be facilitating a transition to hydrogen vessels (Haugland et al., 2022). The structure is known to be flat with minimal hierarchy and short decision processes, which is beneficial because it makes it easier for shipping companies to make changes and be flexible during the building process. Studies show that flexibility, autonomy, and open communication are factors that facilitates innovation (Martins and Terblanche, 2003). Therefore, the Norwegian maritime work culture presents itself as an opportunity for hydrogen shipping, as it is promoting innovation.

Education

Although Norway is equipped with human capital that already possesses capabilities about hydrogen production and ship development, there exists many knowledge and competence gaps that needs to be filled. Confederation of Norwegian Enterprise (2021), along with several other industry companies, expresses the need for competence-building measures within hydrogen technology. These measures would be further education of workers with exiting capabilities, as well as new education programs which specializes in hydrogen. Although the lack of hydrogen specialized workers is not currently a problem, taking measures now to strengthen hydrogen competencies could result in a competitive advantage. Especially due to the expected future growth of the industry (Størset, 2022).

On-Board Work Environment

Maritime transport is known for difficult job conditions where workers are exposed to certain elements that impose health problems, and one of these factors are noise pollution

(Özdemir, 2022). Studies have found that noise pollution can lead to hearing loss and cause high heart rate, which in turn can lead to acute medical conditions such as high blood pressure and heart risks (Özdemir, 2022). However, hydrogen vessels using fuel cell technology will have significantly reduced noise pollution due to no moving parts in the engine (Sürer and Arat, 2022a). Therefore, hydrogen fueled vessels could become an attractive workplaces because of its reduced health hazards associated with noise pollution. This could be viewed as an opportunity for hydrogen vessels as it could attract more skilled employees, giving the hydrogen fueled vessels a competitive advantage.

5.3.4 Ecosystems

Hydrogen is a novel fuel with a need for innovative technological solutions regarding the operationalization of hydrogen in shipping, and a well-functioning eco-system would therefore be beneficial. This will require a value-chain where the different actors work together and collaborate in an ecosystem.

The Norwegian value chains in the maritime industry are, with some exceptions, complete. Innovation takes place to a large extent between the actors in the value chains, where the shipping companies are customers and ship designers, equipment manufacturers, system integrators, and shipyards work together to develop new vessels and new technological solutions (Haugland et al., 2022). The R&D activity is often integrated into the construction process. Due to the integrated and cooperative value chain, Norway has a unique opportunity to develop hydrogen vessels.

Actors in the maritime cluster have the advantage of close relationships between each other with a high level of trust. This relationship is characterized by informal processes of information sharing, made possible because of the short geographical distances and an interdependency between the actors in the cluster (Haugland et al., 2022). These characteristics enables cooperation and coordination between the several actors in the market. As a result, the Norwegian maritime cluster facilitate an interdependent ecosystem that is able to cooperate, which is beneficial in the transition to hydrogen vessels.

5.3.5 Summary of Social Analysis

Green Premium

Because a hydrogen vessel is environmentally friendly, consumers could be willing to pay a green premium for transported goods. This premium could potentially cover some of the increased costs associated with hydrogen fueled vessels. Hence, increased WTP could be an important driver in order to make hydrogen vessels profitable, although there is no consensus in the market about such green premiums existing today.

Shipping Innovation

Norwegian shipping companies have knowledge and experience with shipping innovation. In addition, industry culture in Norway is facilitating innovation and cooperation. This human capital is beneficial for shipping companies that want to invest in hydrogen vessels and is unique for Norway, meaning that it could be used to gain an international competitive advantage. Still, there are many knowledge and competence requirements needed in the hydrogen market, which raises the need for education. This leaves Norwegian actors with an unique opportunity to invest in hydrogen vessels, as long as the industry and government secure the needed education.

Hydrogen Ecosystem

The actors within the Norwegian maritime market have a history of close interaction and coordination. The value chain is to a large extent complete, and there are innovative solutions taking place between actors in the value chain. These characteristics are supporting a developed ecosystem that cooperates and are able to innovate, resulting in an opportunity for the hydrogen shipping transition.

5.4 Technological

This part of the analysis is going to address the technological aspects of hydrogen vessels. Comparing different technologies and discussing benefits and disadvantages of the multiple technologies is not within the scope of this paper. However, based on the assumptions in 2.3 technology, the maturity and prospects of the given technologies are analyzed. There are several technologies that influences the transition to hydrogen vessels, this paper analyzes hydrogen production, infrastructure, and fuel cells.

5.4.1 Hydrogen Production

The focus of this paper is green hydrogen, and the most common production technique is through the process of water electrolysis. As long as the electricity used during the electrolysis is green, then the whole process from production to on-board hydrogen use becomes emission free (Sürer and Arat, 2022a). The method that today are believed to be the superior technique is the proton exchange membrane electrolysis (PEME), which has been suggested by several studies as the best electrolysis technique regarding social, environmental and economic costs (d'Amore Domenech et al., 2020). PEME is also categorized as the most advanced technology within electrolysis, and will in this paper be considered as the method used to produce hydrogen.

Nevertheless, there are some challenges with this electrolysis method today. The first challenge arises from the material use in the electrolysis, which includes precious metals that are both scarce and expensive (Nadim, 2022). These metals, combined with other scarce materials being used in PEME production, are hindering the technology's extensive application (Anwar et al., 2021). This makes green hydrogen production two to three times more expensive than gray production, and as a consequence, 95 percent of the hydrogen produced today is grey (Sürer and Arat, 2022a). However, extensive research is being conducted in order to overcome this challenge and make PEME more appropriate for commercial application (Anwar et al., 2021). At this time however, the required expensive materials create a barrier to the hydrogen shipping transition, although this may change in the future.

5.4.2 Fuel Cells

In this paper, it is assumed that hydrogen ships are utilizing fuel cells to extract electricity from the hydrogen on board. These fuel cells work in a reverse direction of the electrolyzer system (Nadim, 2022).

There are several fuel cells technologies, among these are three systems that are applicable for maritime use: the proton exchange membrane fuel cell (PEMFC), the molten carbonate fuel cell, and the solid oxide fuel cell (Van Hoecke et al., 2021b). Among these, the PEMFC is the most used fuel cells system. This is because it has features as being partly less costly and relatively more mature than the other technologies (Sürer and Arat, 2022a). The technology has already been used for several years in other vehicles, such as busses, and is feasible to maritime usage (Nadim, 2022).

Even though the technology is viable and ready to be deployed on-board, there are some challenges. First of all, one of the biggest limitations of PEMFC is the need for very pure hydrogen. As for now, such pure green hydrogen are a very scarce resource (Sürer and Arat, 2022b). This implies that even though the technology is mature, it is difficult to scale up because of the scarcity of hydrogen. Hence, further development and improvement of the technology in order to allow less pure hydrogen as fuel would be beneficial, and would reduce the barrier.

However, scaling up production of this technology is expected to encounter some challenges, where acquiring fuel cells for vessels could become a bottleneck in the transition (Størset, 2022). Because PEM fuel cells and the PEM electrolyzers are based on the same technology just reversed of each other, this increases the demand of the precious metals required. This is likely to increase the price of the fuel cell, which makes it less attractive to invest in hydrogen vessels for shipowners. Despite these challenges, Teco2030 aims to reduce the overall cost of PEM fuel cells through a large production scale (Nadim, 2022). This is expected to reduce the cost of producing the fuel cells, which further reduces the investment costs of hydrogen vessels.

5.4.3 Storage

Storage challenges are often referred to as one of the largest challenges when it comes to hydrogen vessels. Although liquid hydrogen and compressed hydrogen are two possible technologies, this paper is focusing on compressed hydrogen as mentioned in the introduction. This storage method has proven to be cheaper and technologically more feasible, although it also has some challenges.

The first challenge arises from large storage necessity due to low volume density in the gas cylinders. Therefore, cylinders will require large areas of the ship's deck in order to store gas cylinders. Additionally, the fuelling time is very slow because of the hydrogen gas is of such low density (Van Hoecke et al., 2021b). These challenges are contributing to increase the cost of hydrogen vessels and work as a barrier against the transition.

There is uncertainty associated with what is the most efficient design of a hydrogen vessel (Nadim, 2022). Storage containers are of some hazard due to the explosive nature of hydrogen, which requires safety considerations when designing the ship. Because there are no procedures of how to design a ship with such safety concerns, shipping companies must develop their own design and apply for approval (Nadim, 2022). Until the market has reached an industry standard, this challenge will work as a barrier in the transition. Likewise, the fuelling method of gaseous hydrogen lack an industry standard (Størset, 2022). Absent industry standards are problematic for shipping companies due to two reasons. Firstly, the design process requires more time and money compared to conventional vessels. Secondly, when choosing the design there is a risk that a better design will emerge in the future and become the industry standard, making the initial vessel outdated and incompatible with the infrastructure. However, when the market standard gradually emerges, this will reduce this uncertainty and lay the foundation for a faster transition.

5.4.4 Infrastructure

Similar to other countries in Europe, there are very little hydrogen infrastructure in Norway at the time being. Infrastructure that facilitates hydrogen fueling is important, especially because hydrogen fuel will require more frequent bunkering than conventional diesel fuel due to the limited storage capacity of hydrogen fuel. Norwegian hydrogen vessels is also dependent on hydrogen infrastructure in Europe to become a feasible alternative to fossil vessels. This is because some operate on shipping routes from the North Sea to Northern Europe.

In order to achieve a sufficient infrastructure for hydrogen bunkering, it will require cooperation between hydrogen producers, shipping companies and the government. This is because neither hydrogen producers nor shipping companies can operate without each other, and according to Størset (2022) it is important to achieve a good balance between the expansion of both of them. Therefore, cooperation between these actors must occur in order to efficiently make the transition economical and technological feasible. The government is granting funds to green projects, and must also be able to allocate the funds in a way that enables simultaneous and equal development of the two (Størset, 2022).

Consequently, action has been made by the government to develop the hydrogen infrastructure in Norway. Enova has granted five different hydrogen production facilities projects along the Norwegian coast at a total of NOK 669 million (Enova, 2022b). These five projects are located in Glomfjord, Rørvik, Hitra, Florø and Kristiansand, which are illustrated in Figure 5.4.

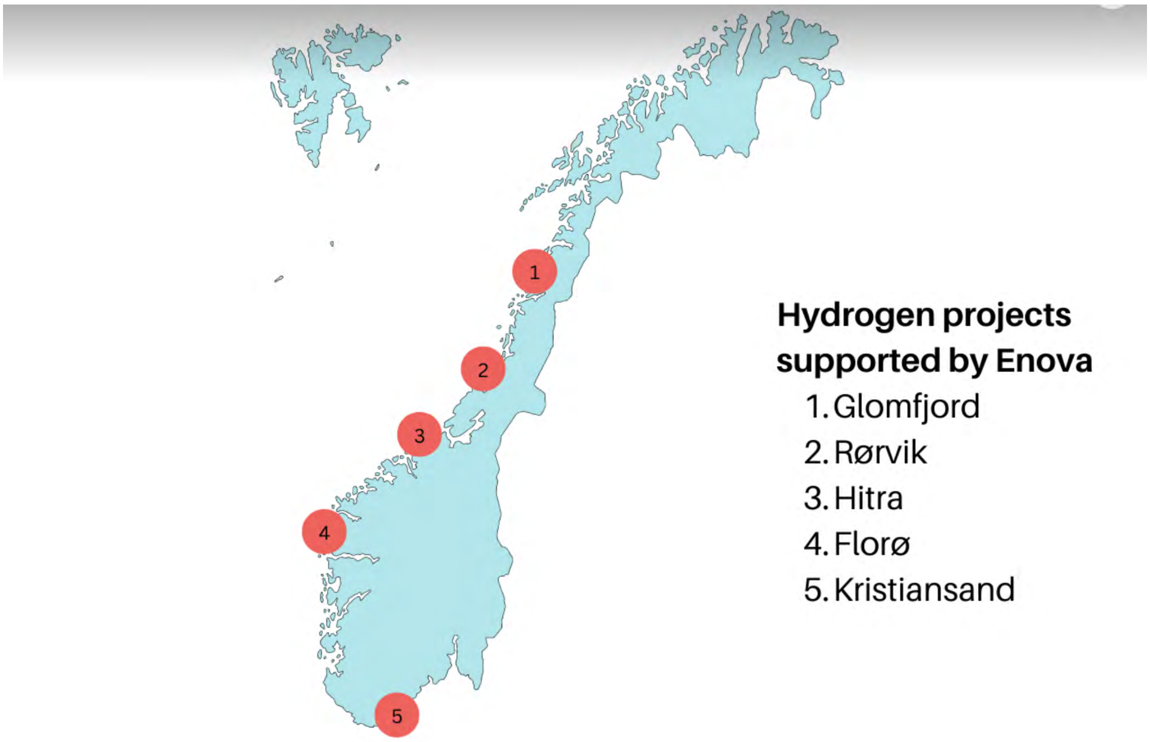


Figure 5.4: *Location of Five Hydrogen Production Facilities Subsidised by Enova*

Some of these plant facilities will be built from scratch, and some are already existing and will use the grants to expand its production (Enova, 2022b). As a result, the Norwegian hydrogen infrastructure is being developed and strengthened, which facilitates a transition to hydrogen vessels in the years to come.

5.4.5 Technological Opportunities for Norway

There are some technological factors that could create a competitive advantage in a transition to hydrogen vessels in Norway. First, it is beneficial for both shipping companies and hydrogen producers to have access to local fuel cell producers such as Teco2030 (Størset, 2022). This gives a unique opportunity to share information and knowledge with each other. Further, if fuel cell producers like Teco2030 is willing to prioritize local demand, the risk for shipowners not being able to acquire fuel cells is reduced and would reduce the bottleneck barrier. Currently, Teco2030 primarily aims to deliver fuel cells to the European market, due to low demand in Norway. However, this might change as Norwegian demand increase.

Additionally, Norway has the advantage of large access to renewable power and renewable energy sources, which is an important resource in the production of green hydrogen. Further, Norway has the experience with hydrogen production from electrolysis, production of electrolysers, and installation of complete electrolysis plants (Confederation of Norwegian Enterprise, 2021). Experience with these technologies could make Norway better positioned to produce green hydrogen, which also supports a potential expansion of hydrogen infrastructure.

All these factors creates a unique opportunity for Norway to invest in hydrogen vessels, relatively to other countries. These technological benefits have the potential of re-enforcing one another and create a competitive advantage within the hydrogen sector. Through producing green hydrogen and fuel cells, a foundation for hydrogen vessels is strong in Norway compared to other countries.

5.4.6 Summary of Technological Analysis

Maturity

Technological maturity is essential for the hydrogen vessels to be feasible, and the degree of the maturity will affect the economic costs. Both production, fuel cells and storage have reached the level of practical feasibility. Still, there is some ambiguity of which technology that will dominate in the future regarding fuel cells and storage methods, which imposed some uncertainty for shipping companies. Therefore, further development will be decisive for which technology that becomes most cost efficient. However, given the technology that the market is leaning towards, it is feasible to use and expected to impose reduced costs in the future.

Infrastructure and Suppliers of Technology

One of the advantages for Norwegian shipping companies that intends to invest in hydrogen vessels, is the planned infrastructure of five bunkering sites. Also, having a fuel cell producer located in Norway is beneficial as it builds domestic competence and offer potential collaboration. This could also provide competitive advantages in the transition for Norwegian shipping companies.

5.5 Environmental

This section includes the environmental factors that affects the transition to hydrogen vessels. First, the environmental benefits associated with hydrogen vessels will be addressed. Thereafter, the environmental risks that occurs when using hydrogen vessels will be examined.

Environmental Benefits

The climate crises are stressing the need to find energy carriers that do not produce GHG emissions, and hydrogen is considered to be one of the promising candidates as a zero-emission fuel (Depken et al., 2022). In addition to be emission free at on-board level, green hydrogen from electrolysis is also emission free, causing the whole hydrogen life-cycle to be emission free (Van Hoecke et al., 2021b). Moreover, hydrogen vessels do not produce substances that create air pollution. This is beneficial when sailing into large ports close to cities where the shipping traffic is high, and when sailing near populated areas that struggles with air pollution (Nadim, 2022).

Hydrogen Hazards

Although hydrogen is considered to be environmental friendly in terms of GHG emissions, it also imposes some environmental hazards. Hydrogen gas is recognized to be a highly flammable fuel, due to the fact that the ignition energy required is low, combined with a wide limit of flammability (Van Hoecke et al., 2021a). This makes hydrogen more likely to explode than conventional fossil fuels, and could lead to economic end ecological damage (Sarı et al., 2021). The environmental damage of an explosion would vary depending on the size and type of the ship, and also what type of cargo it is transporting (Kim et al., 2020).

Hydrogen molecules are very small, which makes gaseous hydrogen more susceptible to leakage (Sarı et al., 2021). In addition, hydrogen is odourless and invisible, making it difficult for humans to detect. Mixing odour into hydrogen in order to make it easier to detect by humans are not possible, mainly due to the fact that fuel cells require very pure hydrogen as mentioned in section 5.4 (Depken et al., 2022).

However, hydrogen itself is not toxic for humans or the environment, and the only direct danger it imposes to humans is a suffocation effect through displacing oxygen from the environment (Depken et al., 2022). In case of leakage, a number of detectors exists that can detect hydrogen leakages, each with its own advantage and disadvantage. Nevertheless, the disadvantages might be compensated by using a combination of different detectors (Depken et al., 2022), and reduces the risk of suffocation by leakage (Rigas and Amyotte, 2013). The indirect hazard of fire or explosion due to leakage is also reduced by installing detectors, as they are able to detect leakage at levels 100-fold lower than the explosion limit (Van Hoecke et al., 2021a).

Another hazard from pressurized hydrogen storage is the risk of rupture of the vessel, often as a result of fire in the vessels surroundings (Depken et al., 2022). Such a fire makes the temperature inside the vessel rise drastically, and increases the pressure until the vessel ruptures. The initial fire could then make the hydrogen explode. However, the tank could easily overcome this challenge by a pressure relief device that prevents this from happening (Depken et al., 2022). Although safety measures must be implemented, this hazard is not in itself a barrier to the transition to hydrogen.

5.5.1 Summary of Environmental Analysis

Green Energy

The main rationale for making a transition from fossil to hydrogen fuel is the environmental benefit. Hydrogen fueled vessels that utilize green hydrogen are emission free through the whole value chain, and are therefore one of the most environmentally friendly and attractive energy carriers. In addition, it does not cause any air pollution, and relatively little noise pollution.

Risk of Leakage

Since hydrogen is odorless and invisible, leakage is difficult to detect. However, with the appropriate detectors potential leakes will be detected relatively fast, and will therefore not impose a severe risk. The problem with a potential leakage is still challenging regarding the design of the ship, because a leak can have such major consequences. Without establishing standards for ship design within the hydrogen shipping industry, receiving government approval for ship designs could be a potential challenge for shipping companies.

5.6 Legal

This last section of PESTEL is going to examine the regulatory and legislative environment that affects implementation of hydrogen vessels. Weak or lacking frameworks could cause uncertainty regarding implementation of hydrogen technology. There will first be an assessment of the international regulations that are developed by the International Maritime Organisation (IMO). Thereafter, relevant national regulations of the Norwegian maritime sector will be assessed.

5.6.1 International Regulations

IMO is an international maritime organisation governed by FN to regulate international shipping, where Norway has been a member since 1958 (United Nations Association of Norway, 2022). IMO regulations covers a broad spectre of international shipping, which include ship design, construction, equipment, operation, and disposal (DNV, 2021). The implementation of hydrogen as a fuel to the maritime sector is not an easy task, where navigating the regulatory landscape is challenging due to IMO´s regulatory framework, class rules and different national regulations that have to be considered (Frithiof, 2021).

The international Convention for the Safety of Life at Sea (SOLAS) is one of the conventions governed by IMO, which has constructed requirements regarding construction, equipment, and operation of ships to ensure sufficient safety. The main code applicable to hydrogen-fuelled vessels is the IGF Code, covering vessels that use gases or other low-flashpoint fuels (DNV GL, 2019a). However, specific regulations are not covered for the use of hydrogen as a marine fuel, causing developers to choose an "Alternative Design" approach when designing hydrogen vessels, which is based on a risk-based approval process that requires equivalent safety levels as for conventional vessels. This approach is expected to cause a comprehensive and expensive process for hydrogen fuelled vessels, with a high degree of uncertainty (DNV, 2021).

Further, there has been no work by IMO to cover storage of hydrogen as a fuel on vessels according to DNV (2021). This illustrates some of the legislative challenges the maritime sector is facing when considering development of hydrogen vessels, where weak and unspecific frameworks might cause confusion and uncertainty for developers and investors.

Although the lack of regulations causes implications for development of hydrogen vessels, there are existing regulations for fuel cells application. The DNV GL class rules for fuel cell implementation for vessels include standards for design, material requirement, and safety system (DNV GL, 2019a). There exist two different class notations that are possible to obtain by ships, FC(Power) when design requirements are fulfilled, and FC(Safety) when environmental and safety requirements are satisfied. The intention is to secure safe and reliable operation of the fuel cell power unit (DNV, 2021). The existence of such class rules can ease the above mentioned Alternative Design approach by giving more clear guidelines for standards and requirement.

Since hydrogen has been used in several industries for a long time, there are existing international hydrogen standards that also could be relevant for the use of hydrogen as a maritime fuel. One of the leading organisations for setting hydrogen standards is ISO, with its Technical Committee who constructs standards for hydrogen technology. However, this is not providing any specific requirements for hydrogen vessels.

In addition to mentioned technological and safety regulations, there are also relevant regulations that might affects the incentives within the maritime sector. The International Convention for the Prevention of Pollution from Ships (MARPOL), governed by IMO, constructs regulations aimed to prevent and reduce maritime pollution (Julian and Michael, 2022). The introduction of Annex VI limiting sulfur content of ships from 2020 has caused increased interest in hydrogen fuel cell technology to satisfy emission regulations (DiRenzo, 2022). There has also been introduced strict measures from several countries to reduce marine emissions, where some marine areas only allow emission free vessels. According to Enger (2021) implementation of hydrogen vessels could be a solution to overcome such restrictions.

5.6.2 National Regulations

In addition to being an instigator for the development of IMO´s international shipping regulations, Norway also has national regulations affecting the shipping industry. The most important laws that provide guidelines for national shipping are the Ship Safety Act, Pollution Act, and Ports and Waters Act (Norwegian Ministry of Climate and Environment, 2019). These three Acts provide emission regulations, with the intention to create new markets for renewable solutions and products in the Norwegian maritime industry.

The Ship Safety Act

The Ship Safety Act regulates vessels sailing with the Norwegian flag and foreign flag ships sailing in Norwegian territorial waters, and is customized according to IMO´s MARPOL. The act regulates environmental safety, and includes a number of ship-specific requirements (Norwegian Ministry of Climate and Environment, 2019). This could be beneficial for investments in Norwegian hydrogen vessels operating in both national and international waters, since they have to adapt to the same regulations regarding design, safety, and operation requirements, which reduces the complexity of developing and operating such a vessel.

However, separate and strict requirements have been implemented for the North Sea that vessels have to comply with. Further, Norway has the possibility to regulate its own territorial waters in order to protect the environment. An example of this is prohibiting vessels running on heavy oil near Svalbard, implemented by Norway. Such restrictions could increase incentives to implement hydrogen vessels. In addition, Norway has the possibility to regulate its own waters more aggressively, to force shipowners to transition towards emission reducing technologies, such as hydrogen.

The Pollution Act

Regulation of emissions occurring from Norwegian harbors is regulated by The Norwegian Pollution Authority, and is covered in the Pollution Act. This act regulates fuel, noise, and air pollution occurring from Norwegian harbours (Norwegian Ministry of Climate and Environment, 2019). Although this not directly targets ships, the regulation has the possibility to introduce technological requirements that could support hydrogen vessels docking at the harbours, such as hydrogen fuelling stations.

The Port- and Waters Act

The Port- and Waters Act is supposed to facilitate responsible use and management of Norwegian waters, including environmental requirements for ships (Norwegian Ministry of Climate and Environment, 2019). This has been used as an instrument to regulate emissions from the Norwegian maritime sector. According to DNV GL (2018), these national requirements illustrates the governments willingness to facilitate a transition towards a greener maritime sector in Norway.

5.6.3 Summary of Legal Analysis

Legal requirements affecting implementation of hydrogen vessels exist, but there is a lack of specific regulations. The International Maritime Organisation has a procedure that developers can utilize which makes it legally feasible. This being a non-specific procedure for hydrogen vessels causes complexity and uncertainty, where establishment of specific laws for hydrogen vessels could reduce these barriers. However, there are established requirements and laws regarding fuel cells and international hydrogen standards that can be used to ease the approval process needed to construct the vessels. Also, MARPOL has implemented measures to regulate emissions from the maritime industry, which is favorable for hydrogen vessels. Norway has adopted IMOs regulatory framework, which reduces the complexity for Norwegian vessels, and has enforced stricter requirements regarding pollution in some territorial waters.

6 Analysis of CfD Implementation

The PESTEL analysis presented above, has highlighted some of the key opportunities and barriers of the macroeconomic environment affecting the transition to hydrogen vessels in Norway. Based on this analysis, this section will further focus on contracts for difference as a government policy that may increase investments in the transition to hydrogen vessels. This is done by discussing the second research question.

How can the Norwegian government use CfD as a measure to increase investment in hydrogen vessels?

The research question will be discussed by first analyzing how CfDs can increase investment incentives towards hydrogen vessels. Thereafter, analyzing how the contracts should be designed in order to operate as a effective policy implementation by reducing risk regarding the hydrogen price.

6.1 CfD and Investment Incentives

This section will analyze how contracts for difference can operate as an effective policy implementation to facilitate and accelerate the development of hydrogen vessels, by increasing investment incentives. The analysis will be based on the discovered drivers and barriers from the PESTEL analysis, and aims to investigate how CfD could provide as a solution to overcome some of them.

A Contract for Difference is a type of incentive-based policy, and designed to induce changes in the behaviour of organisations or individuals by using financial means. Incentive-based policies are constructed by authorities where rules and objectives are determined to motivate emitting companies to implement emission reducing technologies. Simultaneously, allowing sufficient freedom for usual commercial incentives. Such policies could motivate polluters to reduce environmental risks posed by their facilities, processes or products (Anderson & Robert, 2002). A CfD is an instrument that allows two parties to construct a financial agreement based on the price difference between a commodity price and a reference price (Corporate Finance Institute, 2022).

CfDs main feature is the ability to reduce the risk attached to a commodity by paying the difference between a predetermined reference price reflecting the old technology and a strike price (Pandey et al., 2022). As we have discovered, there is a huge price gap in the price of fossil fuels and green hydrogen, making the operation of a hydrogen vessel very expensive compared to fossil fuel alternatives. Further, uncertainty regarding how the price gap will evolve in the future is likely to reduce the investment incentives, as investments in vessels are a committing long-term investment. Currently, government subsidies have been given to hydrogen marine projects trough institutions like Enova, and in the form of investment support to reduce CAPEX. Hence, OPEX related uncertainties and barriers are still remaining. According to Ovrum et al. (2022) CfDs provide stable and predictable terms for developers by guaranteeing a strike price over a fixed period. Implementation of CfDs could be used to both reduce the cost gap between conventional fuels and hydrogen, and to reduce the risk of future price fluctuation. Consequently, this instrument could reduce some of the main uncertainty attached to developing and implementing hydrogen vessels.

Marine hydrogen technology is currently in an emerging phase, with just a few existing projects (Størset, 2022). As discussed in section 5.2, increased development and use of hydrogen technology is expected to reduce the cost of both CAPEX and OPEX due to scaling effects. CfDs can be used as a government policy to reduce the price gap between conventional and hydrogen technology in the short term, until hydrogen becomes more competitive. By stimulating the investment incentives in the early phase, the market can reach competitiveness earlier. Hence, CfDs may also be a suitable instrument to faster reach the climate goals set for the Norwegian maritime sector.

A challenge with analyzing the contracts effect on investment incentives towards hydrogen vessels is that such an instrument has not been used in Norway yet. However, Great Britain has been using CfDs as an instrument to secure investments in renewable energy (Kalland et al., 2022). According to the UK Department for Business, Energy, and Industrial Strategy (2022) these contracts provide developers of projects with high CAPEX and long lifetimes with direct protection from volatile and uncertain prices, which is crucial for profitability, and has been their main mechanism to incentivize such investments. Hydrogen vessel projects share many of the same characteristics as the granted CfDs in UK, with high CAPEX and uncertain hydrogen prices that will determine the vessels profitability. This may indicate that the instrument, with appropriate figuration, could be used to efficiently increase investment incentives in Norwegian hydrogen vessels.

Further, a review of the CfDs effect in UK was performed by KPMG in 2019. The result shows that the contracts have caused cost reduction within the industry and increased development. This supports that CfDs can serve as an effective instrument to incentivize such investments. Subsequently, these results indicate that Norway could implement CfD as a measure to increase investment incentives in hydrogen vessels by eliminating some of the main barriers attached to fuel price.

6.2 Appropriate design of CfD

The design of a contract for difference can be done in multiple ways. This section seeks to discuss how the government could design the contracts to efficiently increase investments in hydrogen vessels in Norway. This is done by evaluating the most essential design options; target, reference price, and allocation of the CfDs.

6.2.1 Target of CfD

The target of the contracts is an important consideration for the government when designing CfDs. The government can provide CfDs to producers of hydrogen to reduce cost of production, or directly to hydrogen vessel owners in order to compensate for the price difference between hydrogen and alternative fuels.

Production of green hydrogen is expensive due to the high amounts of energy required, which further causes expensive hydrogen for users as discussed in section 5.2. The intention with issuing CfDs to hydrogen production facilities is to provide predictable and competitive terms, which further generates additional investments. This is expected to reduce hydrogen costs and increase demand in end use (Ovrum et al., 2022). It could be possible to construct the contracts to reduce production cost risk by using the market price of electricity and determining an appropriate strike price, where the government pays the difference between the two. As a result the producer will not risk paying more than the strike price for electricity. Alternatively, the government could use the CfD to guarantee the producers a certain strike price for the sold hydrogen. The producers would sell hydrogen and receive the market price, and receive the potential difference between market and strike price from the government (Byenstuen & Hentschel, 2022).

In this analysis the consumer of hydrogen is determined to be the shipping companies that operate the hydrogen vessels. Issuing CfDs directly to ships that consumes hydrogen could be an effective instrument to accelerate new projects of hydrogen ships. The contracts will function as a hedge, reducing the shipowners risk of paying a high additional cost from consuming hydrogen, compared to other conventional fuels. As discovered in section 5.2, both OPEX and TCO are very sensitive to changes in fuel expenses. According to Rilling et al. (2022) targeting the specific projects with CfDs could make investments and implementation of the technology happen faster. Hence, issuing CfDs to the shipping companies could serve as an effective instrument to accelerate development of the technology, especially in an early face.

For policy-makers, it is important that the CfDs generates an optimal balance between vessel and infrastructure development, since investments in hydrogen vessels require sufficient infrastructure and vice versa. According to Størset (2022) this is one of the most challenging aspects of the transition to hydrogen in the Norwegian maritime industry. Hence, it is important to emphasize whether issuing CfDs to shipowners or hydrogen production facilities will be more efficient in order to facilitate the transition and secure good balance withing the sector. Issuing CfDs to both should also be considered

In theory, the decision to either issue CfDs to the producer or consumer should be irrelevant since both fill the cost gap between green hydrogen and high-carbon alternatives (Byenstuen & Hentschel, 2022). However, there might be some important differences between the two methods. Targeting the consumers with CfDs will directly increase investment incentive for the receiver, and in turn the whole value chain as demand for hydrogen increases. This could possibly provide motivational effects due to the close attachment between developer and instrument (Kalland et al., 2022). Targeting producers to upscale hydrogen supply and infrastructure could also provide benefits outside the shipping sector, which according to Pandey et al. (2022) would improve energy security and provide cost competitive fuel to a diversity of consumers. Moreover, this may result in a larger hydrogen market in Norway and commercialize hydrogen as a fuel, which also would be beneficial to hydrogen vessels.

6.2.2 Appropriate Reference Price

The reference price is an important dimension of the contracts, and determines which difference that should be paid to the project owners. CfD is a financial agreement between two parties, where the difference between a reference price and the strike price is payed as compensation (Kalland et al., 2022). Hence, it is important to determine a reference price that gives accurate foundation for the payed subsidy, ideally an observable market price. This analysis assumes that there is mainly two approaches to determine a reference price, either based on the project costs or the carbon price.

Contracts constructed where the strike price is determined on the basis of the CO_2 price as reference, are called Carbon Contracts for Difference (CCfD), and offer assurance against the future trajectory of carbon prices (Gerres & Linares, 2020). As discovered in section 5.1.1, the inclusion of shipping in the EU ETS system, will force Norwegian fossil vessels to pay carbon taxes and increase their operational expenses as the carbon price increases. Hence, the decision to invest in hydrogen or fossil vessels will be greatly dependent on the current and future carbon price, where low carbon prices reduces incentives to invest in low-carbon vessels. From an investment perspective, the cost of hydrogen vessels has to be lower than the price of emitting carbon, since the alternative is to emit CO_2 with a fossil vessel and pay carbon credits. Therefore, CCfDs can be used as an hedging instrument against the carbon price.

The CCfD can be constructed as a one-way contract where the government pays the difference when the CO_2 price is lower than the strike price, or as a two-way contract where the agent also has to pay the government when the CO_2 price exceeds the strike price (Gerres & Linares, 2020), as illustrated in Figure 6.1.

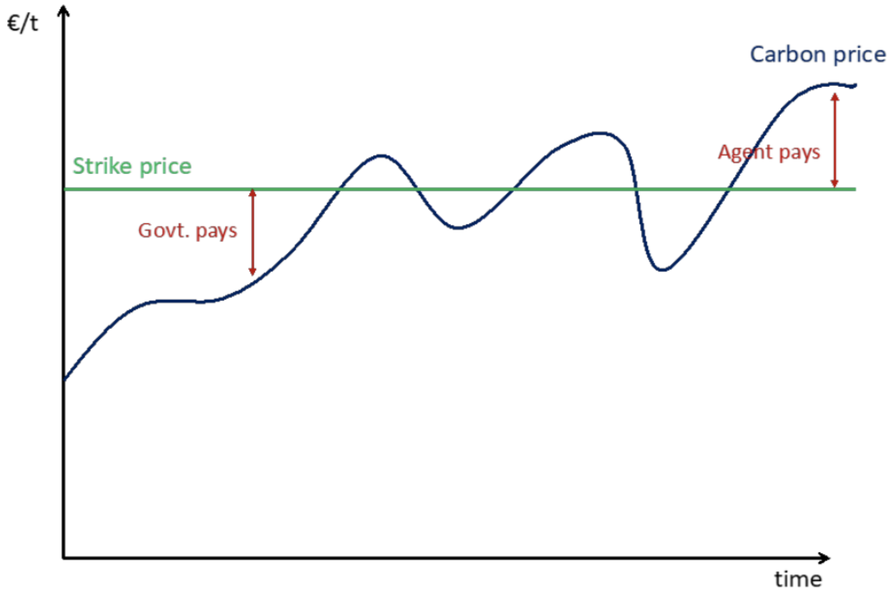


Figure 6.1: *Simple Illustration of CCfD Mechanism. Source: Gerres & Linares (2020)*

According to a study by Chiappinelli and Neuhoff (2020) CCfDs also works as a commitment device for the government by giving strong incentives for governments to maintain carbon prices high. When carbon prices are high, the gap to the strike price will be less than for lower carbon prices. Hence, the governments expenses is reduced and the incentives to innovate is maintained for both sides. This could be an appropriate reference price for hydrogen vessels since it covers their opportunity cost compared to fossil vessels.

To issue CCfD to the hydrogen producers, it would be necessary to estimate a theoretical CO_2 reduction caused by the facility, in order to link the production cost with CO_2 (Kalland et al., 2022). It may be difficult to make precise estimations, due to the possibility that there will be different vehicles and industries consuming the hydrogen. Changes in the carbon price does not necessarily affect the cost of producing hydrogen, which weakens the intention of the CCfD.

Another approach is to determine the reference price based on the cost of the projects. In the maritime sector the price of conventional fuels, like MGO, would be appropriate as a reference price (Kalland et al., 2022). By setting the strike price equal to the cost of hydrogen, the difference payed by the government would account for the additional cost of running on hydrogen. As discovered in section 5.2, the largest share of operational expenses for a hydrogen vessel is the fuel cost, which is significantly more expensive than for fossil vessels.

According to Department for Business, Energy Industrial Strategy (2021) the difference in a CfD should cover the actual barrier that prevents a project from being realised, which this CfD configuration could achieve for hydrogen vessels. Determining a reference price based on the project's production cost could also be appropriate for hydrogen production facilities Kalland et al. (2022). The important aspect to emphasise when determining an appropriate reference price is to mitigate the chances for over- and under compensation from the CfDs, in order to maximize the effect of the government subsidy.

6.2.3 Allocation of CfD

The allocation procedure is another important dimension of the instrument design. There are mainly two different methods of awarding the CfDs that will be assessed in this analysis, which is either through a competitive process or by an individual application procedure.

Awarding CfDs based on an application procedure allows for multiple criteria to be evaluated in each specific project, such as feasibility, degree of innovation, and technological maturity (Rilling et al., 2022). This could be a significant strength in order to pick the most promising hydrogen vessel projects, while also evaluating possible synergies with other projects. There is also large regional differences in the Norwegian power supply and power grid capacity that is important to account for when considering power-intensive projects (Kalland et al., 2022). This is something an application process could take into account.

A challenge with the process is that it could become very complex and time-consuming due to the multiple criteria that requires thorough evaluation. It would also require a large dedicated team to execute the process and ensure sufficient transparency, which would be expensive. Therefore, an application procedure could be preferable if the only objective is to find the hydrogen projects that reduces emissions with highest efficiency, without emphasising costs. Likewise, if there are relatively few applicants, this method could be preferred.

Next, the CfDs could be allocated trough a competitive auction. Constructing predictable criteria for the projects auctioned would ensure good competition between applicants according to Kalland et al. (2022), which is one of the strengths with the process. This method has been used by UK when allocating CfDs, where the auctions include a technology-specification restricting which projects eligible to bid. Those who meet the requirements would make strike price bids and the project with the lowest bid is granted the contract (Oxera, 2014). The auction will construct an upward-sloping supply curve, where more projects are expected to be financially viable as the strike price increases (Department for Business, Energy Industrial Strategy, 2021). This is illustrated in figure 6.2, where the curve shows the estimated MW capacity for different production facility projects that could be built at different strike prices.

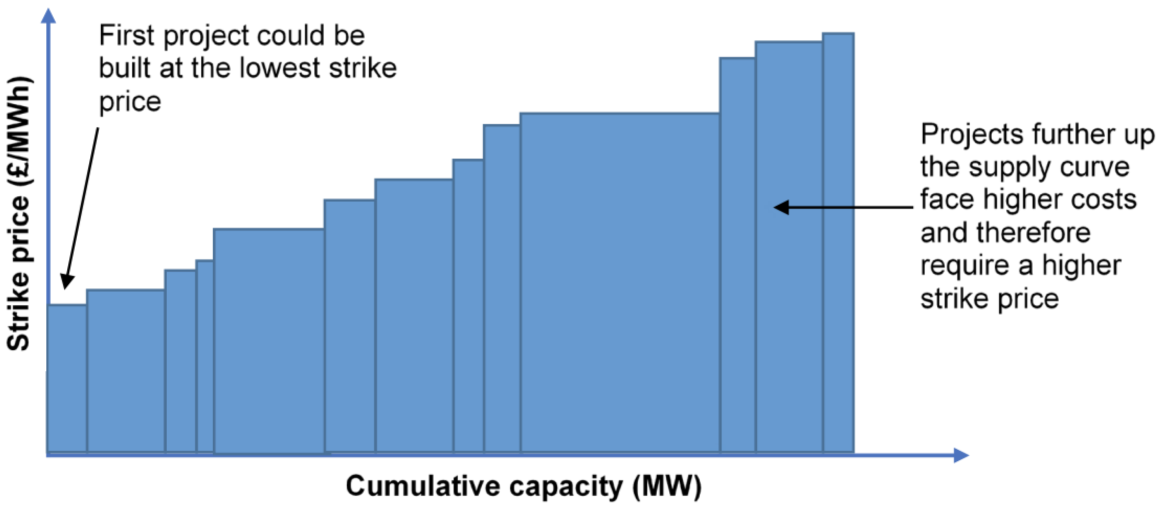


Figure 6.2: *Illustration of Competitive CfD Auction. Source: Department for Business, Energy Industrial Strategy (2021)*

This method would award the project that is the most cost-competitive and can be realised with the lowest amount of subsidy. However, a competitive auction allocation procedure does require many bidders for each project in order to arrive at the most efficient allocation (Oxera, 2014). Since the Norwegian hydrogen vessel market is in a very early phase with few projects, this might not be the most suitable allocation method in the short term. Regardless of which allocation method preferred, the overall objective should be to maximize the effect of the subsidy provided trough CfDs in order to accelerate the transition to hydrogen vessels.

7 Discussion

7.1 PESTEL Results

The analysis of PESTEL has discovered opportunities for the implementation of hydrogen vessels in Norway. The government has facilitated and subsidised the five hydrogen hubs along the Norwegian coastline, which provides an important infrastructure that hydrogen vessels can utilize. Through an ambitious hydrogen strategy the government show great commitment to invest and facilitate for hydrogen solutions in the maritime sector, providing reduced risk, uncertainties and possible cost reductions for shipowners as hydrogen technology and infrastructure further develops. Further, future projection for the Norwegian carbon tax is favourable for operating hydrogen vessels, as emissions will be more expensive. The inclusion of shipping in EU ETS will provide additional incentives to reduce emissions, lowering barriers for hydrogen vessels. The fact that Norwegian shipping companies possesses market leading competences and experiences could provide a competitive advantage. This is further supported with a culture within the industry which facilitates innovation. Also, environmental awareness by customers makes them willing to pay green premiums for goods transported without emissions, and increased environmental awareness could contribute to amplify demand for low-emission goods transported by hydrogen vessels, thus increasing willingness to pay for such goods. Finally, being a first-mover can contribute in building a strong brand and knowledge that can give a competitive advantage when others enter the market.

Despite great political ambitions and commitment exists, there is discovered a lack of incentives to develop hydrogen vessels. Participants in the maritime sector have expressed that there is a lack of sector-specific political measures, that is not consistent with the governments strategy. Additionally, the Norwegian wealth tax weakens their ability to reinvest capital into renewable solutions, such as hydrogen. Further, hydrogen technology and fuel cells are expected to evolve rapidly to become more efficient. There is also uncertainties attached to which hydrogen technology that will dominate in the future, causing developers to hesitate. However, the main barrier for implementation of short-sea hydrogen vessels appears to be the economic. Both CAPEX and OPEX is drastically more expensive than for comparable fossil vessels. This is mainly due to expensive fuel, and the fact that constructing a hydrogen vessel requires expensive materials and occupies large spaces on deck, which reduces the load capacity. High uncertainty regarding future prices of hydrogen creates a large risk for the profitability of the vessels. Additionally, the lack of specific regulations for use of hydrogen as a maritime fuel causes a complex and expensive approval process, which reinforces the barriers. Subsequently, the barriers appears to be so significant that they exceeds the benefits, resulting in postponing implementation of hydrogen vessels.

The PESTEL analysis does not provide a numerical weighting of the five different factors. The authors therefore assumes that the barriers outweigh the possibilities of short-sea hydrogen vessel implementation in Norway. The main findings from the analysis is highlighted in Figure 7.1 below.

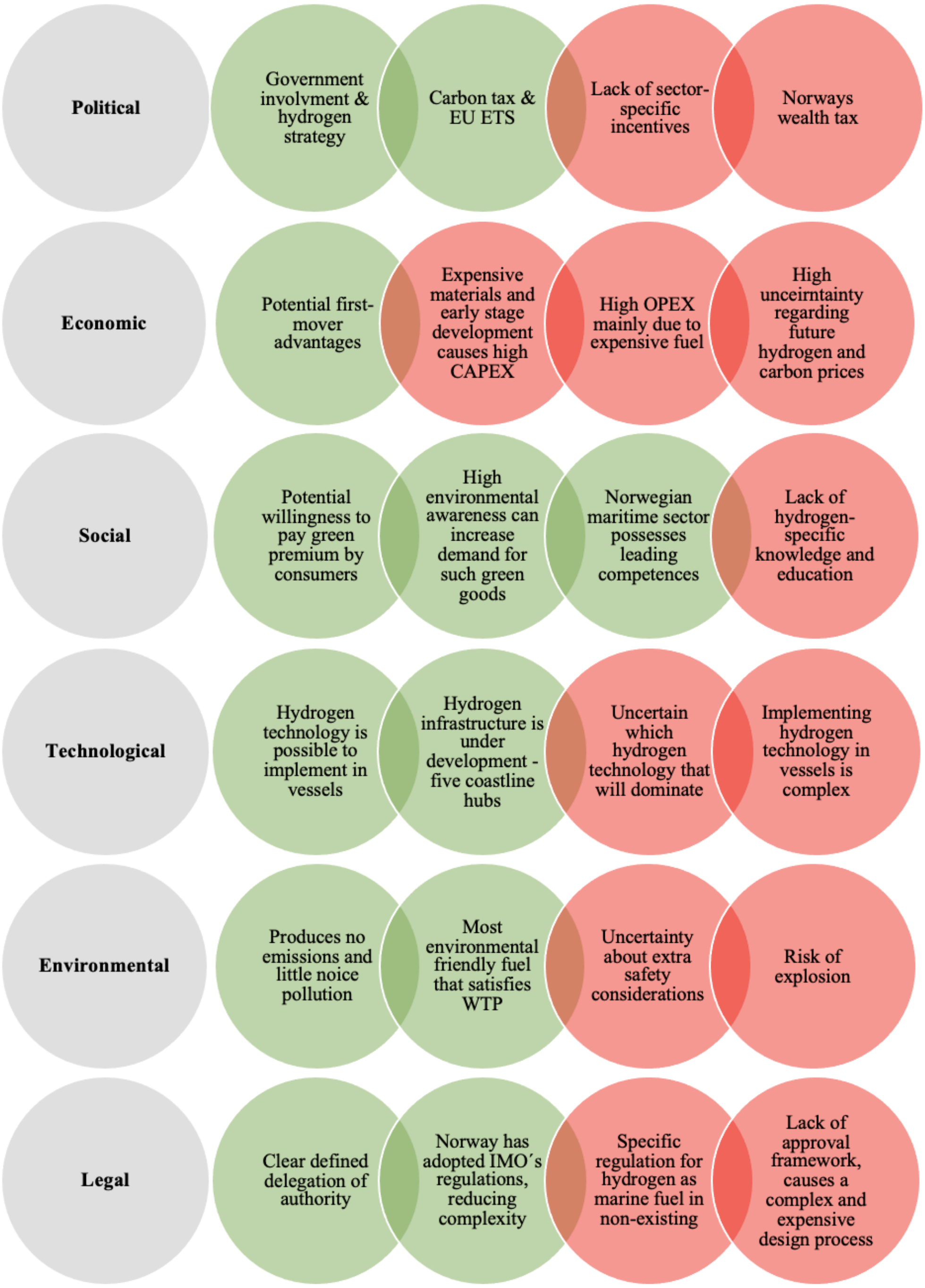


Figure 7.1: *Main Drivers and Barriers from PESTEL Analysis*

7.2 Evaluation of CfD

In terms of increasing incentives, the use of CfDs show clear potential to reduce some of the largest barriers for implementing hydrogen vessels. The contracts can be used to limit expenses towards hydrogen fuel and therefore reduce one of the largest barriers which is OPEX. Further, a CfD has the ability to reduce the risk towards uncertain and volatile hydrogen prices by providing predictable terms, which is one of the main risk shipowners experience. CfDs could operate as a suitable attribution to cash subsidies, since although it reduces CAPEX, some projects are still not executed due to uncertain and expensive fuel costs. The introduction of such an instrument is also expected to increase investments towards hydrogen vessels, which would increase demand for hydrogen fuel and technology. An up-scale of the development is necessary in order to improve technology efficiency and affordability in order for hydrogen vessels to be commercialised.

To the extent this instrument efficiently could increase incentives, also depends on the design of the contracts. The option to either issue CfDs to producers of hydrogen, or directly to shipowners has both each it´s strengths. Targeting producers will reduce hydrogen cost and increase demand, resulting in reduced fuel costs for shipowners and other consumers. By targeting shipowners directly the OPEX barriers will be immediately obliterated and accelerate investments in hydrogen vessels. Hence, targeting shipowners directly is evaluated as the most efficient way in order to accelerate implementation of hydrogen vessels.

Further, CfDs can efficiently reduce the fuel price barrier by using MGO as reference price, which guarantees a limit of what shipowners pay for hydrogen fuel above the MGO price. Likewise, using carbon as reference price can also mitigate the price risk regarding this gap. Additionally, a CCfD function as a commitment device for the government, both reducing the fuel barrier and reinforces their commitment to the ambitious hydrogen strategy. Subsequently, these findings suggest that the most appropriate reference price is the carbon price.

Lastly, how these contracts get allocated and awarded to projects is an important consideration. A competitive auction will force increased competition between projects in order to receive the CfD. This will encourage the competitors to strive for solutions that requires vessels to become more affordable and therefore require less subsidies. Hence, a competitive auction could reduce both the economic barriers, but also technological. Further, this method has been used by UK and proven to award projects that are more cost-competitive to efficiently use available subsidy. However, this method requires that there is many competitors for the contracts. The alternative approach is to use an application procedure, allowing the government to evaluate multiple and specific criteria for each project. This could be beneficial in order to strategically pick the projects most suitable to develop the Norwegian hydrogen maritime sector. Despite that this process can become complex and time consuming, this approach is preferred.

8 Conclusion

Through two research questions, the purpose of this study has been to explore the transition from fossil fuels to hydrogen for the Norwegian shipping industry:

To what extent does the economic and political environment support a transition to hydrogen vessels in the Norwegian shipping sector?

How can the Norwegian government use CfD as a measure to increase investment in hydrogen vessels?

The research that has been conducted has been an exploratory case study. Through investigation of the Norwegian shipping market, the opportunities and barriers for a transition to hydrogen vessels have been discovered. The analysis and finding are based on an extensive amount of data, and provide both economic and non-economic factors that have an influence on the transition to hydrogen vessels. The findings suggest that there currently are large economic barriers, mainly due to hydrogen prices and expensive technology. Although predictions suggest that these prices would decrease in the future, the uncertainty of the hydrogen makes the investment decision very challenging for shipping companies. Although the government hydrogen strategy is ambitious and have led to an improvement and development in the hydrogen market, it has not yet had the desired effect in the Norwegian shipping market.

Further on, based on the current state of the macro environment, the research findings suggest that a CfD offered by the government would be beneficial and have the potential to accelerate the transition to hydrogen vessels. In addition, CfDs most appropriate reference price is the carbon price and should be awarded through application procedure.

This thesis is build upon several assumptions that have been necessary to make, and whether these assumption are true or not will decide the relevance of the findings provided by this research. However, several indicators across the macroeconomic environment are suggesting that Norway both have the potential to be a pioneer within hydrogen shipping, and a strong foundation to build competitive advantage relative to other countries. Therefore, this thesis conclude that the Norwegian government should continue their support to hydrogen projects, and consider implementing CfDs as an incentive policy to accelerate development of hydrogen vessels. Doing so would be an important step in the process of reducing the Norwegian CO_2 emissions and strengthen the chances of fulfilling the Paris Agreement.

9 Limitations and Future Research

9.1 Limitations to the Study

This section will address some of the most important limitations and weaknesses of the study.

Technology Assumptions

In order to limit the scope of the analysis, several technology assumptions were made, and have the potential to limit the value of the findings. As explained earlier, there are many novel technology practices in the hydrogen market and the prevailing technology is currently undetermined. This implies that the technology that are assumed in this thesis could become inferior to other technologies in the future, which would limit the value of this thesis findings.

Cost Analysis

Given the novelty of the topic, the cost calculations were challenging and demanded several simplifications and assumptions. Although the assumptions have been based on several data sources, there is a large uncertainty connected to the costs of developing and operating a hydrogen ship. Although the researchers have tried to counter the uncertainty with a sensitivity analysis, there are still simplified variables that are uncertain. Further, the CAPEX, OPEX, and TCO analysis are based on averages within the short-sea sector, and does not represent case specific adaptation. This is a limitation because costs vary substantially between cases.

Framework Limitation

Although the PESTEL framework provided structure to the analysis when identifying barriers and opportunities within hydrogen shipping, it also has some limitations. First, the PESTEL framework does not offer a numerical value of the importance of the different forces that are identified. This means that the researchers must do a weighing of the magnitude of each opportunity and barrier, which could lead to researcher bias. This means that the research are exposed to the risk of being influenced by the researchers, and therefore make the findings less valuable.

There was no theoretical framework in the second part of the analysis when CfDs was discussed, which could be a potential limitation. The researchers based this analysis on the PESTEL findings, which left the researchers to structure the analysis as they deemed it most appropriate. However, without a theoretical framework, the analysis could be affected by researcher bias and reduce the quality of the findings.

Data Sources

Secondary sources have provided most of the data used in the analysis, which can be argued to be a limitation. Secondary sources are originally conducted for other purposes, and have the possibility of be outdated. Primary sources can counter this limitation, and have therefore been used. However, this paper could also have conducted more interviews with industry participants to gather more primary data. The absence of an interview with a Norwegian shipping company could also be a source tolimitation of finding.

9.2 Future Research

There are several topics within the findings of this research that could be further researched. For example, it could be interesting to complete a more comprehensive cost analysis of CfDs. There is a need for research that investigates how the government should calculate the appropriate reference price, and it could be interesting to conduct studies on how investments incentives varies with different reference prices.

Currently, there is a lack of policy studies for hydrogen shipping, especially based on the macro-environment. Because of scope limitation, this study only investigates CfDs as a measure that the government could use to increase investments in the hydrogen shipping transition, although there are many other policies that could be utilized. It could be interesting to see how these policies fits with the overall macro-environment, in order to find the most efficient way to support the transition to hydrogen shipping.

This research only investigate hydrogen in the shipping industry, although hydrogen could also be applicable in other maritime sectors. The passenger ship sector has the largest CO_2 emissions in the maritime industry, and hydrogen vessels could therefore be relevant for this sector. Although electricity are among the most prominent technology for short distances, as it also is emission free, hydrogen could be applicable for longer distances.

Therefore, hydrogen in the passenger ship industry is also a field of interest that should be further studied.

Another field of interest is blue hydrogen. Due to scope limitations, blue hydrogen has to a large extent been omitted from the analysis throughout this paper. However, green hydrogen production has been claimed to not provide sufficient supply to the market alone in the short term, implying that blue hydrogen production will most likely be important in the hydrogen transition. Nevertheless, the interdependence of green and blue hydrogen production is understudied, and the government could benefit from developing a strategy where the production methods are interrelated. Hence, more research are needed for the interaction of blue- and green hydrogen.

References

Ahmadi, Y., Yamazaki, A., and Kabore, P. (2022). How do carbon taxes affect emissions? plant-level evidence from manufacturing. *Environmental and Resource Economics*, pages 1–41.

Alexandra Twin (2021). Total cost of ownership: What's included and an example.

Anderson & Robert (2002). Incentive-based policies for environmental management in developing countries.

Anwar, S., Khan, F., Zhang, Y., and Djire, A. (2021). Recent development in electrocatalysts for hydrogen production through water electrolysis. *International Journal of Hydrogen Energy*, 46(63):32284–32317.

Arbeiderpartiet & Senterpartiet (2021). Hurdalsplattformen. In *For en regjering utgått fra Arbeiderpartiet og Senterpartiet - 2021-2025.* Retrieved 25.10.2022 from: https://www.arbeiderpartiet.no/aktuelt/hurdalsplattformen/.

Atilhan, S., Park, S., El-Halwagi, M. M., Atilhan, M., Moore, M., and Nielsen, R. B. (2021). Green hydrogen as an alternative fuel for the shipping industry. *Current Opinion in Chemical Engineering*, 31:100668.

Bek, U. (2022). Pricing sustainable shipping of coffee: Consumers' preferences and willingness to pay for emission reductions and offsets. *Junior Management Science*, 7(3):543–568.

Brink, H. I. (1993). Validity and reliability in qualitative research. *Curationis*, 16(2):35–38.

Buis, A. (2019). A degree of concern: Why global temperatures matter. *Retrieved from: https://climate.nasa.gov/news/2865/a-degree-of-concern-why-global-temperatures-matter/.*

Byenstuen & Hentschel (2022). How can contracts for difference kick-start a norwegian hydrogen market?

Chiappinelli, O. and Neuhoff, K. (2020). Time-consistent carbon pricing: The role of carbon contracts for differences.

Cho, S., Park, J., Noh, W., Lee, I., and Moon, I. (2020). Developed hydrogen liquefaction process using liquefied natural gas cold energy: Design, energy optimization, and techno-economic feasibility. *International Journal of Energy Research.*

Collins, L. (2021). Not even a carbon price of €200 would make green hydrogen cost-competitive this decade. In *RECHARGE.* Retrieved from: https://www.rechargenews.com/energy-transition/not-even-a-carbon-price-of-200-would-make-green-hydrogen-cost-competitive-this-decade/2-1-1037262.

Confederation of Norwegian Enterprise (2021). Anbefalinger for flaggskipsprosjekter for storskala produksjon av grønt hydrogen. In *Dokumentarkiv.* Energi Norge.

Corporate Finance Institute (2022). Contract for difference (cfd). *Retrieved 14.11.22 from: https://corporatefinanceinstitute.com/resources/derivatives/contract-for-difference-cfd/.*

Department for Business, Energy Industrial Strategy (2021). Methodology used to set administrative strike prices for cfd allocation round 4. *Contract for Difference.*

Depken, J., Dyck, A., Roß, L., and Ehlers, S. (2022). Safety considerations of hydrogen application in shipping in comparison to lng. *Energies*, 15(9):3250.

Di Micco, S., Mastropasqua, L., Cigolotti, V., Minutillo, M., and Brouwer, J. (2022). A framework for the replacement analysis of a hydrogen-based polymer electrolyte membrane fuel cell technology on board ships: A step towards decarbonization in the maritime sector. *Energy Conversion and Management*, 267:115893.

Directorate-General for Mobility and Transportation (2022). Maritime taxonomy: new study contributes to definition of sustainable economic activity. In *Mobility and Transport.* Retrieved 29.10.2022 from: https://transport.ec.europa.eu/news/maritime-taxonomy-new-study-contributes-definition-sustainable-economic-activity-2021-05-04_en.

DiRenzo, J. (2022). Imo 2020: Hydrogen's future in maritime. *Marine Link.*

DNV (2021). Handbook for hydrogen-fuelled vessels.

DNV (2022). Hydrogen forecast to 2050.

DNV GL (2019a). Assessment of selected alternative fuels and technologies.

DNV GL (2019b). Reduksjon av klimagassutslipp fra innenriks skipstrafikk.

d'Amore Domenech, R., Santiago, O., and Leo, T. J. (2020). Multicriteria analysis of seawater electrolysis technologies for green hydrogen production at sea. *Renewable and Sustainable Energy Reviews*, 133:110166.

Energy, B. (2022). Where to innovate first - the green premium. *Retrieved from: https://breakthroughenergy.org/our-approach/the-green-premium/.*

Enger, T. (2021). Nytt konsept fra teco 2030 gjør at skip kan seile helt utslippsfritt. Retrieved 12.11.2022 from : https://kommunikasjon.ntb.no/pressemelding/nytt-konsept-fra-teco-2030-gjor-at-skip-kan-seile-helt-utslippsfritt?publisherId=17847477releaseId=17909289.

Enova (2018). About enova. *Retrieved 11.10.22 from: https://www.enova.no/about-enova/.*

Enova (2020). Sjøsetter hydrogensatsning med hydrogenfartøy i fast rute. In *Enova.* Retrieved 25.10.2022 from: https://presse.enova.no/news/sjoesetter-hydrogensatsing-med-hydrogenfartoey-i-fast-rute-417761.

Enova (2022a). Enova støtter hydrogenprosjekter i maritim sektor med 1,12 milliarder kroner. Retrieved 10.10.2022 from: https://presse.enova.no/pressreleases/enova-stoetter-hydrogenprosjekter-i-maritim-sektor-med-112-milliarder-kroner-3190840.

Enova (2022b). Enovastøtte til 15 hydrogenprosjekt i maritim transport. In *Enova.* Retrieved 20.10.22 from: https://presse.enova.no/pressreleases/enovastoette-til-15-hydrogenprosjekt-i-maritim-transport-3130758.

European Commission (2022). Eu emission trading system (eu ets). In *Climate Action.* Retrieved 29.10.2022 from: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en.

Finansavisen (2022). Veidekke dropper hydrogenskip: – risikoen ble for høy. *Retrieved from: https://www.finansavisen.no/nyheter/shipping/2022/01/14/7802947/veidekke-dropper-hydrogenskip-risikoen-ble-for-hoy?*$zephr_s so_o tt = PIt56L$.

Fonneløp, J. E. (2020). Hydrogenstrategi uten tydelig retning. In *Norges Energi*. Retrieved 28.10.2022 from: https://www.energinorge.no/fagomrader/fornybar-energi/nyheter/2020/hydrogenstrategi-uten-tydelig-retning/.

Frithiof, N. (2021). Five lessons to learn on hydrogen as ship fuel.

Garcia, D. A. (2017). Analysis of non-economic barriers for the deployment of hydrogen technologies and infrastructures in european countries. *International Journal of Hydrogen Energy*, 42(10):6435–6447.

Gerres & Linares (2020). Carbon contracts for differences: their role in european industrial decarbonization. *Climate Friendly Materials Platform*.

Hagberg, H. (2022). Update on the extension of eu ets to include maritime transportation. In *Legal Developments*. Retrieved 30.10.2022 from: https://www.thommessen.no/en/news/extension-of-eu-ets-to-include-maritime-transportation.

Haltbrekken, N. . (2022). Innstilling fra energi- og miljøkomiteen om representantforslag om en storstilt satsning på norsk hydrogen- og ammoniakkutvikling. Retrieved 25.10.2022 from: https://www.stortinget.no/no/Saker-og-publikasjoner/Publikasjoner/Innstillinger/Stortinget/2021-2022/inns-202122-274s/?all=true.

Haug, Reiakvam, and Solheim (2022). Avgifter på utslipp er fortsatt lave som andel av produksjonsverdi. In *Norges Bank*. Retrieved 30.10.2022 from: https://www.norges-bank.no/bankplassen/arkiv/2022/avgifter-pa-utslipp-er-fortsatt-lave-som-andel-av-produksjonsverdi/.

Haugland, A., Berle, H., and Jakobsen, N. (2022). Norske skipsverft – aktivitet, konkurransesituasjon og rammebetingelser.

Haugland, Abrahamoglu, F. B. J. (2022). Grønn maritim 2022.

Holm, M. (2020). Hydrogenstrategi får kritikk: - en tapt mulighet for norge. In *DN*. Retrieved 28.10.2022 from: https://www.dn.no/energi/norge/tina-bru/sveinung-rotevatn/hydrogenstrategi-far-kritikk-en-tapt-mulighet-for-norge/2-1-818893.

Hydrogen Council (2021). Path to hydrogen competitiveness - a cost perspective.

IMO (2020). Fourth greenhouse gas study 2020.

IMO (2021). Preliminary results: Impact of ship´s biofuling on greenhouse gas emissions.

IPCC (2022). The evidence is clear: the time for action is now. we can halve emissions by 2030. *Retrieved from: https://www.ipcc.ch/2022/04/04/ipcc-ar6-wgiii-pressrelease/.*

Johansen and Folkestad (2022). The eu taxonomy in the maritime transport industry. In *Wikborg Rein*. Retrieved 31.10.2022 from: https://www.wr.no/en/news/publications/green-shipping-update-may-2022/the-eu-taxonomy-in-the–maritime-transport-industry/.

Johnson, G., Whittington, R., Scholes, K., Angwin, D., and Regnér, P. (2018). *Fundamentals of strategy*, volume 4. Pearson.

Julian and Michael (2022). Marpol 73/78: the international convention for the prevention of pollution from ships. *Maritime Studies*, (113).

Kalland, G., Schjølset, S., and Aasland (2022). Differansekontrakter for hydrogen. ZERO.

Kim, H., Koo, K. Y., and Joung, T.-H. (2020). A study on the necessity of integrated evaluation of alternative marine fuels. *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, 4(2):26–31.

Marlisa, A. R. and Wan Norhayate, W. D. (2015). The case study method in business. *Scholars Journal of Arts, Humanities and Social Sciences*, 3(1):105–109.

Martins, E.-C. and Terblanche, F. (2003). Building organisational culture that stimulates creativity and innovation. *European journal of innovation management.*

Mestemaker, Heuvel, C. (2020). Designing the zero emission vessel of the future: Technologic, economic and environmental aspects. Retrieved 10.10.2022 from: https://www.sintef.no/siste-nytt/2022/produksjon-og-bruk av-hydrogen-i-norge-skaleres-opp/.

Ministry of Climate and Environment (2020). The norwegian government's hydrogen strategy. *Retrieved from: https://www.regjeringen.no/contentassets/8ffd54808d7e42e8bce81340b13b6b7d/hydrogenstrategien-engelsk.pdf.*

Nadim, P. (2022). Interview with teco2030. (W. Dorp E. Øyri, Interviewer).

Norwegian Directorate for the Environment (2022). Klimagassutslipp fra transport i norge.

Norwegian Government (2020). Co2-avgiften. Retrieved 28.10.2022 from: https://www.regjeringen.no/no/tema/okonomi-og-budsjett/skatter-og-avgifter/veibruksavgift-pa-drivstoff/co2-avgiften/id2603484/.

Norwegian Government (2022). Et grønnere og mer aktivt statlig eierskap - statens direkte eierskap i selskaper. In *Meld. St. 6 (2022-2023*. Retrieved 24.10.2022 from: https://www.regjeringen.no/no/dokumenter/meld.-st.-6-20222023/id2937164/?ch=1.

Norwegian Hydrogen Forum (2022a). 669 millioner kroner til produksjon av fornybart hydrogen langs kysten. *Retrieved from: https:https://www.hydrogen.no/aktuelt/nyheter/maritim-gladmelding-fra-enova.*

Norwegian Hydrogen Forum (2022b). 669 millioner kroner til produksjon av fornybart hydrogen langs kysten. Retrieved 12.11.2022 from: https://www.hydrogen.no/aktuelt/nyheter/maritim-gladmelding-fra-enova?fbclid=IwAR1Ts34LgoEsXD4rYv5lbNwh3zLe802Z6fn70LbbDRYHZC1Dd$_hWNJGb1GM$.

Norwegian Hydrogen Forum (2022c). Maritim sektor - bruksområde. Retrieved 30.09.22 from: https://www.hydrogen.no/bruksomrader/nytt-bruksomrade.

Norwegian Ministry of Climate and Environment (2019). Regjeringens handlingsplan for grønn skipsfart.

Norwegian Ministry of Petroleum and Energy & Norwegian Ministry of Climate and Environment (2020). Regjeringens hydrogenstrategi - på vei mot lavutslippssamfunnet. Norwegian Ministry of Petroleum and Energy & Norwegian Ministry of Climate and Environment.

Norwegian Shipowners Association (2022). Konjunkturrapport 2022. Norwegian Shipowners Association.

Olsen, H., Fougner, , Valstrand, R., and Nyland (2020). Can a hydrogen fuelled vessel be financially competitive and technically feasible? *Grønt Skipsfartprogram.*

Ovrum, Longva, H., Rivedal, E., and Eide (2022). Maritime forecast to 2050.

Oxera (2014). Cfd auctions, bidding strategies, and insights from auction theory. *Advancing economics in business.*

Özdemir, Ü. (2022). The effects of ship-borne noise pollution on the crew. *Available at SSRN 4111279.*

Pandey, Søgaard, B., and Spiegelenberg, M. (2022). How eu contracts for difference can support zero-emission fuels. *Getting to Zero Coalition.*

Papadias, D., Ahluwalia, R., Connelly, E., and Devlin, P. (2019). Total cost of ownership (tco) analysis for hydrogen fuel cells in maritime applications–preliminary results.

Penrod, E. (2022). Green hydrogen prices have nearly tripled as energy costs climb: Sp. Retrieved 06.11.2022 from: https://www.utilitydive.com/news/green-hydrogen-prices-global-report/627776/.

Pomaska, L. and Acciaro, M. (2022). Bridging the maritime-hydrogen cost-gap: Real options analysis of policy alternatives. *Transportation Research Part D: Transport and Environment*, 107:103283.

Rapier, R. (2020). Estimating the carbon footprint of hydrogen production. In *Energy*. Forbes.

Rigas, F. and Amyotte, P. (2013). Myths and facts about hydrogen hazards. In *13th International Symposium on Loss Prevention and Safety Promotion in the Process Industries, Florence, Italy (May 12-15, 2013).*

Rilling, A., Anatolitis, V., and Zheng, L. (2022). How to design carbon contracts for difference-a systematic literature review and evaluation of design proposals. In *2022 18th International Conference on the European Energy Market (EEM)*, pages 1–8. IEEE.

Rivedal, Endresen, and Sverud (2018). Analyse av tiltak for reduksjon av klimagassutslipp fra innenriks skipstrafikk. : https://www.miljodirektoratet.no/globalassets/publikasjoner/M1027/M1027.pdf.

Sarı, A., Sulukan, E., Özkan, D., and Uyar, T. S. (2021). Environmental impact assessment of hydrogen-based auxiliary power system onboard. *International Journal of Hydrogen Energy*, 46(57):29680–29693.

Satyapal, S. (2017). Hydrogen: A clean, flexible energy carrier. Office of Energy Efficiency Renewable Energy.

Saunders, M., Lewis, P., and Thornhill, A. (2016). *Research Methods for Business Students*, volume 7. Pearson.

Schniederjans, D. G. and Starkey, C. M. (2014). Intention and willingness to pay for green freight transportation: An empirical examination. *Transportation Research Part D: Transport and Environment*, 31:116–125.

SINTEF (2022). Produksjon og bruk av hydrogen i norge skaleres opp. In *SINTEF*. Retrieved 10.10.2022 from: https://www.sintef.no/siste-nytt/2022/produksjon-og-bruk-av-hydrogen-i-norge-skaleres-opp/.

Sirimanne, S. N., Hoffman, J., Juan, W., Asariotis, R., Assaf, M., Ayala, G., Benamara, H., Chantrel, D., Hoffmann, J., Premti, A., et al. (2019). Review of maritime transport 2019. In *United Nations conference on trade and development, Geneva, Switzerland*. UNCTAD.

Skjelmo, I. and Hagberg, H. (2021). The eu emissions trading system to be extended to cover maritime transport emissions. In *Legal Developments*. Retrieved 30.10.2022 from: https://www.thommessen.no/en/news/the-eu-emissions-trading-system-to-be-extended-to-cover-maritime-transport-emissions.

Størset, S. (2022). Interview with enova. (W. Dorp E. Øyri, Interviewer).

Sürer, M. G. and Arat, H. T. (2022a). Advancements and current technologies on hydrogen fuel cell applications for marine vehicles. *International Journal of Hydrogen Energy*, 47(45):19865–19875.

Sürer, M. G. and Arat, H. T. (2022b). Advancements and current technologies on hydrogen fuel cell applications for marine vehicles. *International Journal of Hydrogen Energy*, 47(45):19865–19875.

Teco2030 (2022). Teco 2030 have signed a loi with avl on behalf of an undisclosed truck customer for delivery of fuel cell stacks to 30 trucks based on the avl hytruck platform, delivery to start end of next year. *Retrieved 15.11.22 from: https://teco2030.no/news/teco-2030-have-signed-a-loi-with-avl-on-behalf-of-an-undisclosed-truck-customer-for-delivery-of-fuel-cell-stacks-to-30-trucks-based-on-the-avl-hytruck-platform-delivery-to-start-end-of-next-year-17945022/.*

Torvanger (2021). Hydrogen for shipping - opportunities for norway. In *CICERO´s strategic incentives - Hydrogen*. CICERO Center for International Climate Research.

UK Department for Business, Energy, and Industrial Strategy (2022). Contracts for difference. Retrieved 14.11.22 from : https://www.gov.uk/government/publications/contracts-for-difference/contract-for-difference.

UNFCCC (2020). Paris agreement. In *Report of the Conference of the Parties to the United Nations Framework Convention on Climate Change (21st Session, 2015: Paris). Retrived December*, volume 4. Retrieved 25.10.22 from: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

United Nations Association of Norway (2022). Den internasjonale sjøfartsorganisasjonen (imo). Retrieved 15.10.2022 from: https://www.fn.no/om-fn/fns-organisasjoner-fond-og-programmer/den-internasjonale-sjoefartsorganisasjonen-imo.

U.S. Department of Energy (2015). Fuel cells fact sheet. In

Energy Efficiency Renewable Energy. Retrieved 17.10.2022 from: https://www.energy.gov/sites/prod/files/2015/11/f27/fcto$_{f}uel_{c}ells_{f}act_{s}heet.pdf$.

Van Hoecke, L., Laffineur, L., Campe, R., Perreault, P., Verbruggen, S. W., and Lenaerts, S. (2021a). Challenges in the use of hydrogen for maritime applications. *Energy & Environmental Science*, 14(2):815–843.

Van Hoecke, L., Laffineur, L., Campe, R., Perreault, P., Verbruggen, S. W., and Lenaerts, S. (2021b). Challenges in the use of hydrogen for maritime applications. *Energy Environmental Science*, 14(2):815–843.

Xing, Stuart, S. C. (2021). Fuel cell power systems for maritime applications: Progress and perspectives. In *Sustainability*. MDPI.

Yin, R. K. (2013). Validity and generalization in future case study evaluations. *Evaluation*, 19(3):321–332.

Øvrebø, O. A. (2022). Kvotemarkedet: Eu og verden. In *Energi og Klima*. Retrieved 29.10.2022 from: https://energiogklima.no/klimavakten/kvotemarked-eu-og-verden/.

Appendix

A1 Interview Guide Enova

The question asked is aimed to work as a starting point for conversation and discussion.

Questions:

- Which shipping segment, short- vs deapsea, is most feasible for implementation of hydrogen vessels?
- Is there currently existing obvious political barriers in Norway for implementation and development of hydrogen vessels?
- Today, is it profitable to develop and operate hydrogen vessels?
- Which components within development and operation of hydrogen vessels is viewed as the largest barriers today?
- Is it viewed to be more attractive to act as a first- or second mover?
- Which technology is considered to become superior for powering a hydrogen vessel?
- How is the access of fuel cell technology, and how does is affect the transition to hydrogen vessels?
- How important is hydrogen infrastructure in order to make hydrogen vessels feasible, and is it sufficient in Norway and Europe?
- How do you evaluate the risk attached to the rate of change in hydrogen technology, is it a threat?
- Which environmental risks is associated with implementation of hydrogen vessels?
- How do you view the potential and relevance for CfD to incentives investments in hydrogen vessels?

A2 Interview Guide Teco2030

The question asked is aimed to work as a starting point for conversation and discussion.

Questions:

- What is the core business of Teco2030?
- How is your approach to PEM technology?
- How is demands for fuel cells in the market?
- What is the largest challenges with implementing and using PEM fuel cell technology?
- How does implementation of PEM fuel cells in vessels affect the available capacity for carrying goods, compared to fossil alternatives?
- Can you share specific key inputs for the cost of PEM fuel cells?
- How do you expect the future price of PEM fuel cells to evolve?
- How is today's efficiency of PEM fuel cells, and how do you expect it to evolve?