Center for Maritime Economics and Logistics

Erasmus University Rotterdam

MSc in Maritime Economics and Logistics

2021/2022

Roadmap to Hydrogen-powered vessels in the EU by 2030

By

Syed Sharique Zeya

Acknowledgement

Foremost, I would like to express my sincere gratitude to my Supervisor Dr Michele Acciaro for his continuous support, patience, motivation, and enthusiasm throughout my research journey. I could not have imagined having a better mentor for my master's thesis. Besides him, I would like to thank all the lecturers at MEL who helped me in developing the required skill set and knowledge which helped me to pursue this journey competently.

I would like to extend my sincere gratitude to Maarten Fonteijn and Daniël Moolenburgh at ENVIU for inspiring me with their passion for a sustainable maritime industry. I am also thankful to Teddy, Ryan, and my other colleagues at Mavisoft for bearing with me so patiently and being flexible in all ways possible to ensure that my Office-work does not affect my academic work.

My sincere thanks also go to MEL Staff – Renee, Mariem, Felicia, and Martha for their unconditional support throughout my entire journey at MEL. My life in the past year has been full of surprises and has given me moments that I will cherish forever. To my friends in the MEL class, all this would have been much more difficult without you. Thank you all for your unwavering support and for reminding me to take breaks and have fun when I have been stressed out.

It is impossible to extend enough thanks to my family, especially my parents, who gave me the encouragement I needed throughout this process. I am deeply indebted to them for their support, appreciation, and their keen interest in my academic achievements.

Executive Summary

With the increasing pressure to reduce its harmful emissions, the shipping industry inevitably needs to shift away from fossil fuels. Studies suggest that zero-emission vessels must need to be entering into service by 2030 and should constitute a significant part of new builds if shipping has to meet its ambitious GHG reduction strategy in line with the Paris agreement. Hydrogen is under consideration as one of the most promising alternative sources of propulsion for the future fuel mix. However, it faces the challenge of higher costs and availability, and this competitiveness gap must be narrowed down to stimulate mass adoption of this zero-emission fuel in the maritime sector, which would go beyond demonstration projects and may have a real influence on lowering the industry's GHG emissions. Although a global approach led by the International Maritime Organization would be the most effective and thus preferable solution, the IMO's relatively slow progress has prompted the EU to take the lead in ensuring that maritime transport plays its role in accomplishing climate neutrality in Europe by 2050. One of the proposals is to include maritime transport in the EU Emissions Trading System, thus capping emissions, establishing a carbon price signal that should stimulate flexible and cost-effective GHG emission reduction, and generating revenues to battle climate change and boost innovation. In this study, we assess the impact of revenue recycling on the cost competitiveness of hydrogen-powered vessels. To do this, we developed a model to first calculate the existing competitiveness gap between hydrogen and conventional marine fuel. We then assessed the impact of policy measures by estimating the potential reduction in the competitiveness gap which could be achieved by recycling back the revenues generated by these policy measures. Our results suggest that combining the Market-Based measures with revenue recycling policies can lead to hydrogen-powered vessels becoming cost competitive even before 2030 while also mitigating its economic burden and supporting an effective and efficient transition. We found that recycling 88% of the generated revenues can make hydrogen cost-competitive by 2028. Also, by recycling 100% of the revenues, this goal can be achieved even before the end of 2027.

***Keywords**: GHG, IMO, EU ETS, Fit for 55, ETD, EU hydrogen strategy, Green Hydrogen, Lifecycle Assessment, Marginal Abatement Costs, Revenue Recycling*

Table of contents

List of Figures

List of Tables

1. Introduction

1.1. Background

Shipping contributes significantly to the equitable distribution of trade and commerce benefits. No country in this world can claim to be entirely self-sufficient and hence the maritime trade is relied upon by every country to sell what it produces and buy what it requires. With over 80% of the volume of international trade being carried out by sea, maritime transport is considered the backbone of global trade and economy(Ban Ki-moon, 2016).

Although shipping is considered the most energy-efficient mode of transportation, it still has a significant environmental impact. Shipping is responsible for 2.89 % of global anthropogenic greenhouse gas emissions expressed in terms of CO2e(IMO, 2020). The share of emissions has increased from 977 million tonnes of CO2e in 2012 to 1077 million tonnes in 2018, which is an increase of 9.6% in just 6 years. It is projected that the emissions will increase from about 90% of 2008 emissions in 2018 to 90-130% of 2008 emissions by 2050 depending on the global economic growth in future (IMO, 2020). To align international shipping with the Paris agreement temperature goals, IMO adopted an initial strategy for the reduction of GHG emissions from ships which aims at reducing average carbon dioxide (CO2) emissions per transport work by at least 40% from 2008 levels by 2030 and a reduction of 70% by 2050 (IMO, 2018a).

Despite adopting an ambitious target of reducing emissions by at least 50% by 2050 and pursuing GHG emission reduction pathways consistently with the temperature goals of the Paris agreement, the IMO has not yet been successful in enacting sufficient measures to be able to meet even its lowest emission level.

Fig. 1-1 Illustrates that the current framework of design and operational measures such as energy efficiency design index (EEDI) & ship energy efficiency management plan (SEEMP) is just not sufficient and hence Technologies powered by alternative fuels are the way forward.

Among various technologies under consideration to reduce harmful emissions from shipping, Hydrogen (liquefied or gaseous) has been identified as one of the most promising potential fuels for the decarbonised shipping industry. Hydrogen has emerged as an attractive carbon-neutral alternative for ship owners and operators.

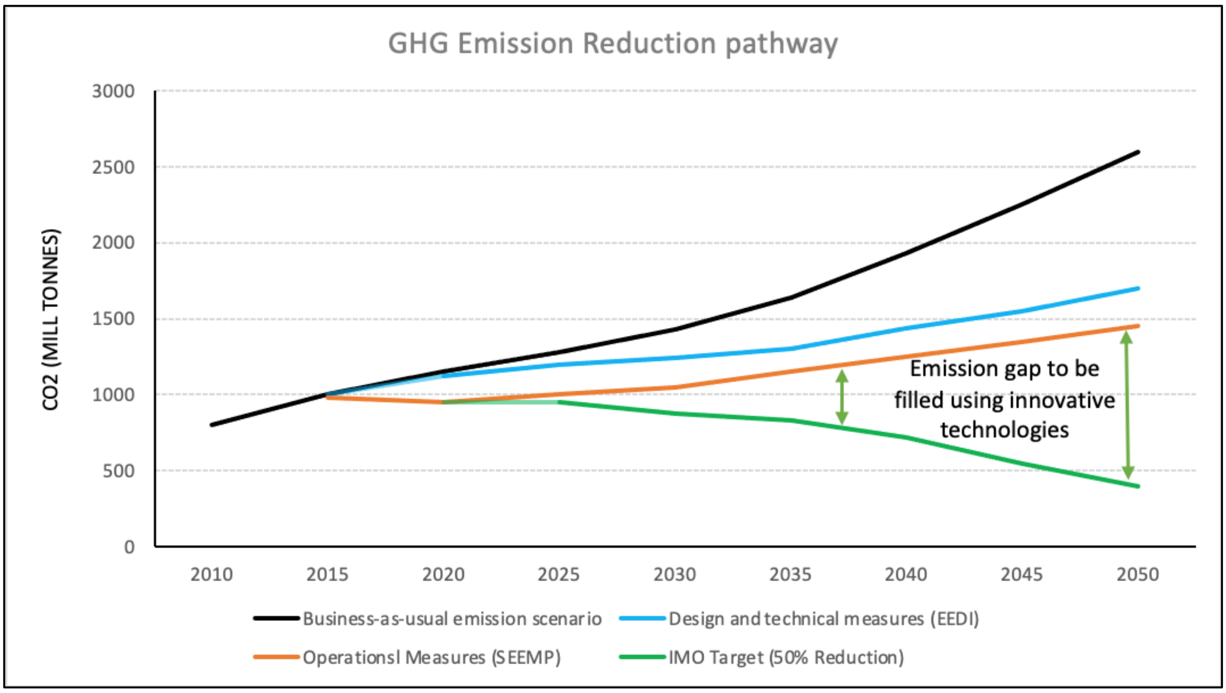


Fig.1-1: IMO's GHG Emission reduction pathway. Source: Adapted from (Hoenders, 2020)

1.2. Problem Identification

At the EU level, maritime transport is a significant CO_2 emitter, accounting for 3 to 4% (144 million tonnes) of total EU CO_2 emissions (European Commission, 2021). As per the second annual MRV Report on CO_2 emissions, container ships emerged as the largest emitter of CO_2 across different ship types as they accounted for 30% of the total emissions. These ships reported 44 million tonnes of CO_2 emissions originating from just 1801 ships from a total of 12117 ships in 2019 (European Commission, 2021).

The container vessels have the highest average propulsion power as they operate at a higher speed. There is an exponential relationship between speed and emission of the vessel as the speed of a vessel directly affects the fuel consumption and subsequently increases CO_2 emissions.

The results of the European Commission's analysis of EU MRV data show that intra-EEA voyages accounted for 32% of the total reported CO2 emissions in 2019. The report suggests that smaller ships have a higher share of their CO2 emissions from intra-EEA voyages. The study also found that CO2 emissions from short-sea shipping activities are primarily associated with intra-EEA voyages.

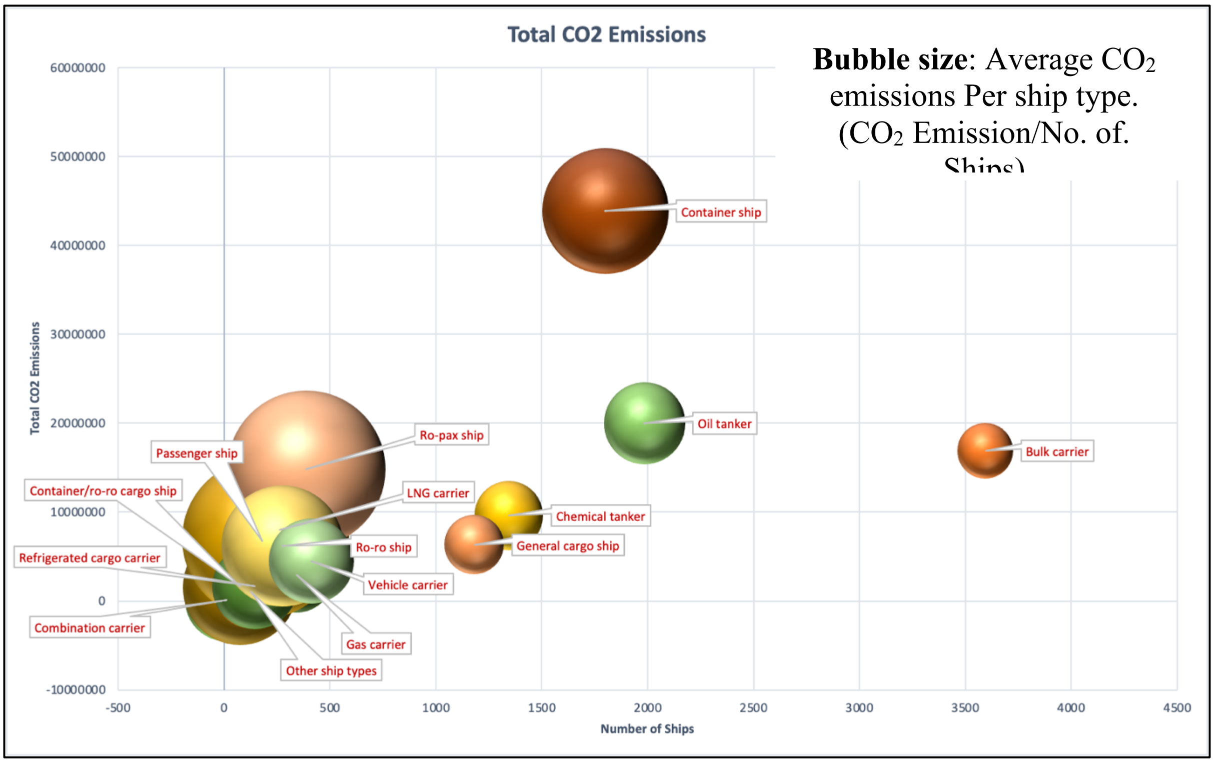


Fig. 1-2: Total CO2 emissions by ship type. Source: Adapted from EU MRV DATA

Hydrogen, although not a viable option for large ocean-going vessels yet, ticks all the right boxes to be an emission-free source of propulsion for smaller vessels engaged in these types of voyages. However, to become a competitive alternative fuel for the maritime industry, it faces the challenge of its higher cost as compared to the conventional fossil fuels being used. This competitiveness gap must be narrowed down to stimulate mass adoption of this zero-emission fuel in the maritime sector, which would go beyond demonstration projects and may have a real influence on lowering the industry's GHG emissions.

Although a global approach led by the International Maritime Organization (IMO) would be the most effective and thus preferable solution, the IMO's relatively slow progress has prompted the EU to take the lead and make new proposals to ensure that maritime transport plays its role in accomplishing climate neutrality in Europe by 2050. One of these proposals is to include maritime transport in the EU Emissions Trading System (ETS), thus capping emissions, establishing a carbon price signal that should stimulate flexible and cost-effective GHG emission reduction, and generating revenues to battle climate change and boost innovation (European Commission, 2021f).

Empirical evidence and modelling suggest that measures such as carbon pricing can support the decarbonisation of shipping by closing the competitiveness gap between fossil fuels and zero-carbon fuels such as hydrogen, but under the condition that the revenue is recycled back to the maritime sector to support investment in innovative technologies to trigger the uptake of zero-emission fuels. The question, however, remains whether this approach would lead to a smooth transition well in time to avoid carbon lock-in and stranded assets in the future. Studies suggest that zero-emission vessels must need to be entering into service by 2030 and should constitute a significant part of newbuilds if shipping must meet its ambitious GHG reduction strategy in line with the Paris agreement (Lloyd’s Register and UMAS, 2019)

1.3. Research Questions and Objectives

Persuaded by the identified problem as discussed in the previous section, this research attempts to answer the following main research question:

“Under what conditions could Hydrogen be a viable alternative fuel for container vessels operating within EEA by 2030?”

The study aims to provide a roadmap which could lead to hydrogen becoming a commercially viable alternative marine fuel in the EU by 2030. This would require us to develop a model which would allow us to first calculate the existing competitiveness gap between hydrogen and conventional marine fuel. We will then assess the impact of policy measures by estimating the potential reduction in the competitiveness gap which could be achieved by recycling back the revenues generated by the policy measures. The results will help the policymakers in designing effective policies which will incentivise the investment in alternative fuels to ensure that shipping meets its decarbonisation goals.

We have identified the following sub-research questions to get a comprehensive answer to our main research question and to achieve our research objectives:

1. What is the current competitiveness gap between conventional fossil fuels and Hydrogen?
2. What are the different technological and economic factors that significantly affect the competitiveness of hydrogen as an alternative marine fuel?

3. What are the different policy options that could help close this gap?
4. How can the revenues generated from the Market-Based Measures potentially be used to close the competitiveness gap to support the fuel transition?

1.4. Research Design and Methodology

This research is concentrated on the quantitative analysis using secondary data (and a few reasonable assumptions) collected from various trusted sources which include, but are not limited to, shipping data providers such as Clarksons, Studies carried out by classification societies such as DNV and Lloyd's Register and several market players involved in projects related to alternative fuels and the latest MRV Report published by European Commission. A part of the thesis is also based on the literature review of various research studies carried out by experts and published by reputed publication houses such as MDPI and ELSEVIER as well as studies carried out by agencies such as IRENA, UMAS and Hydrogen Council etc.

Four sub-research questions have been identified to comprehensively answer the main research question. Sub-research question one (1) will help in establishing a model to calculate the exact competitiveness gap between a hydrogen vessel and a conventional low sulphur marine gas oil (LSMGO) fuelled vessel.

Sub-research question two (2) will help identify the main technological and economic factors that significantly affect the competitiveness of hydrogen and hence require innovations and investments.

Sub-research question three (3) will help in deciding the most effective policy package to drive both supply and demand of hydrogen fuel, which will be incorporated into the model to finally assess different options for closing the competitiveness gap.

Sub-research question four (4) will provide the results enabling the policymakers to design policies regarding the potential use of revenues generated by the Market-Based Measures for ensuring a cost-effective and efficient fuel transition by closing the competitiveness gap.

1.4.1. Thesis Structure

Chapter 1 provides a background for the study and identifies the problem and research questions followed by the methodology and a subsection showing the relevance of the study.

Chapter 2 constitutes a review of the existing literature and forms the theoretical background of the research where we shall explore and examine the academic work done in the fields relevant to the context of our research. A discussion of hydrogen and its maritime application will be carried out along with the demonstrations of the regulatory framework and potential policy measures at the global as well as EU levels.

Chapter 3 will detail the methodology and data used in building the model. This chapter will also explain the assumptions and relationship between the variables, followed by a discussion on the limitations of the model.

Chapter 4 will present the main findings and results from the model. We shall also carry out a sensitivity analysis to assess the effects of different values of variables on the results.

Chapter 5 will provide the conclusion and recommendations from the study followed by the limitation of the study and the scope for further research.

1.5. Relevance of the Study

Decarbonisation of the maritime industry is not possible without transitioning away from conventional fossil fuels (UNEP, 2020). Hydrogen appears to be one of the most dominant alternatives which have the potential to become a true-zero emission fuel for the maritime industry, provided it is produced from renewable sources of energy. However, there is a significant competitiveness gap between hydrogen and conventional bunker fuel (VLSFO/LSMGO) which requires additional R&D, innovative technologies, production scale-up, a reduced cost of renewable electricity and hence, additional Investments (Baresic et al., 2022). As a result, effective policy measures are required to close this competitiveness gap to support a cost-effective and efficient transition.

The policymakers need to design effective and efficient policies to drive both the demand and the supply side of hydrogen fuels. The demand can be boosted by capping the maritime transport emission, setting a maximum limit on the GHG content of the fuels, and implementing a carbon price on the emissions. The revenues thus generated can be recycled back for boosting innovations and R&D to accelerate the supply of hydrogen fuel.

Although there are studies which show that revenues generated from carbon pricing can be used to meet the decarbonisation goals of the maritime industry, As far as we are aware, there have not been any such studies carried out that quantitatively assess the potential usage of revenues generated by the economic instruments for improving the competitiveness of alternative fuels such as hydrogen and hence, will add novelty to the literature and will prove to be of great relevance to the academia, policymakers as well as other stakeholders in the maritime industry.

2. Literature Review

The existing literature contains a few studies that assess the viability of hydrogen by comparing it with other alternative fuels. (Gore et al., 2022) investigated the cost competitiveness of Green Hydrogen, Liquified Natural Gas (LNG), Methanol, and Green Ammonia, where green hydrogen emerged as the best alternative to meet the decarbonization goals but requires further reduction (by 60%) in its current price or a significantly high (275% higher than proposed) carbon tax (Gore et al., 2022). However, this study was carried out using NPV (Net Present Value) methodology which is not flexible enough to adapt decisions or to change the inputs (Acciaro, 2014). Another study was carried out by (Deniz & Zincir, 2016a), where a comparison was again made between Hydrogen, LNG, Methanol and Ethanol. Hydrogen again came out as a winner in terms of safety, bunker capabilities, adaptability to existing vessels and commercial effects criterion. However, these criteria were based on points given by experts and the report suggested that further studies and improvements were required. A techno-economic analysis conducted by (Horvath et al., 2018) shows that hydrogen fuel cells have the potential to replace the conventional combustion engine powered by fossil fuels by 2030 combined with a CO_2 price of around €60/tCO_2 and could even be competitive without a CO_2 price in 2040. Several other studies have identified the potential of hydrogen fuel cells for maritime use - (De-Troya et al., 2016; Inal & Deniz, 2020; Sohani et al., 2020; van Biert et al., 2016)

In another study, (Pomaska & Acciaro, 2022) used a real option model to analyze investment in hydrogen and observed that a low carbon tax could result in the slow uptake of technology and hence recommended setting higher carbon taxes at the early stages to close the competitiveness gap of hydrogen with conventional fossil fuels. Their study found that a tax of at least 28% of the fuel price would be required for a hydrogen-powered ferry in 2025 (Pomaska & Acciaro, 2022).

A recent study carried out by (Baresic et al., 2022) based on a techno-economic model estimated that an average carbon price of US$100/t$CO_2$ would be required in 2030 to achieve a 50% reduction in GHG emissions. They also suggested that this carbon price could be lower if the revenues generated are ‘recycled’ to further boost the decarbonization of the shipping industry. However, there is no literature present that investigates the potential reduction in the competitiveness gap of hydrogen (or other alternate marine fuel) that could be achieved by efficiently utilizing the revenues generated by the MBM.

This chapter further reviews the literature and forms the theoretical background of our study. We shall first discuss Hydrogen and its application in the maritime industry. The discussion will then be followed by various policy measures that could play a pivotal role in reducing GHG emissions and improving the competitiveness of alternative fuels for a decarbonized shipping industry.

2.1. Hydrogen

Hydrogen is abundantly found in nature as a compound of either water or methane. To obtain pure hydrogen, the element must be separated from these compounds. Under normal conditions, hydrogen is an odourless, colourless, tasteless, non-toxic, relatively nonreactive, and highly flammable gas with a wide range of flammability (ABS, 2021). Hydrogen can either be produced from fossil fuels such as Natural gas and Coal, or water through electrolysis.

2.1.1. Hydrogen production from Natural gas

Commercially, hydrogen is produced from natural gas by means of steam methane reforming (SMR) where methane from natural gas is heated along with steam. Methane reacts with steam under a pressure of 3-25 bar, usually with a catalyst to produce carbon monoxide and hydrogen.

$$CH_4 + H_2O \text{ (+ Heat)} \rightarrow CO + 3H_2 \quad \ldots\ldots\ldots\ldots\ldots (2.1)$$

The gas thus produced contains 12% of carbon monoxide which is further converted into carbon dioxide and more hydrogen using the following reaction.

$$CO + H_2O \rightarrow CO_2 + H_2 + \text{Heat} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.2)$$

In the final step called 'pressure-swing adsorption', CO_2 along with other impurities are removed, leaving pure hydrogen. This method of steam reforming can also be used to produce hydrogen from other fuel sources such as propane and ethanol.

2.1.2. Hydrogen production from coal

Hydrogen is produced from coal by means of gasification processes where carbon is converted into carbon monoxide and hydrogen as shown in the below equation. This reaction is endothermic and requires additional heat, the same as SMR.

$$C(s) + H_2O + Heat \rightarrow CO + H_2 \text{.....................}(2.3)$$

The carbon monoxide thus produced is further converted into carbon dioxide and hydrogen in the water-gas shift reaction same as equation 2.2.

2.1.3. Hydrogen production from water

Hydrogen can also be produced from water by electrolysis which is a process of splitting water into hydrogen and oxygen using electrical energy. This process is carried out in a unit called an electrolyser. The electrolyzer consists of an anode and a cathode separated by an electrolyte. There are four different types of electrolysers available today but only polymer electrolyte membrane (PEM) and alkaline electrolysers are commercially used (IRENA, 2020).

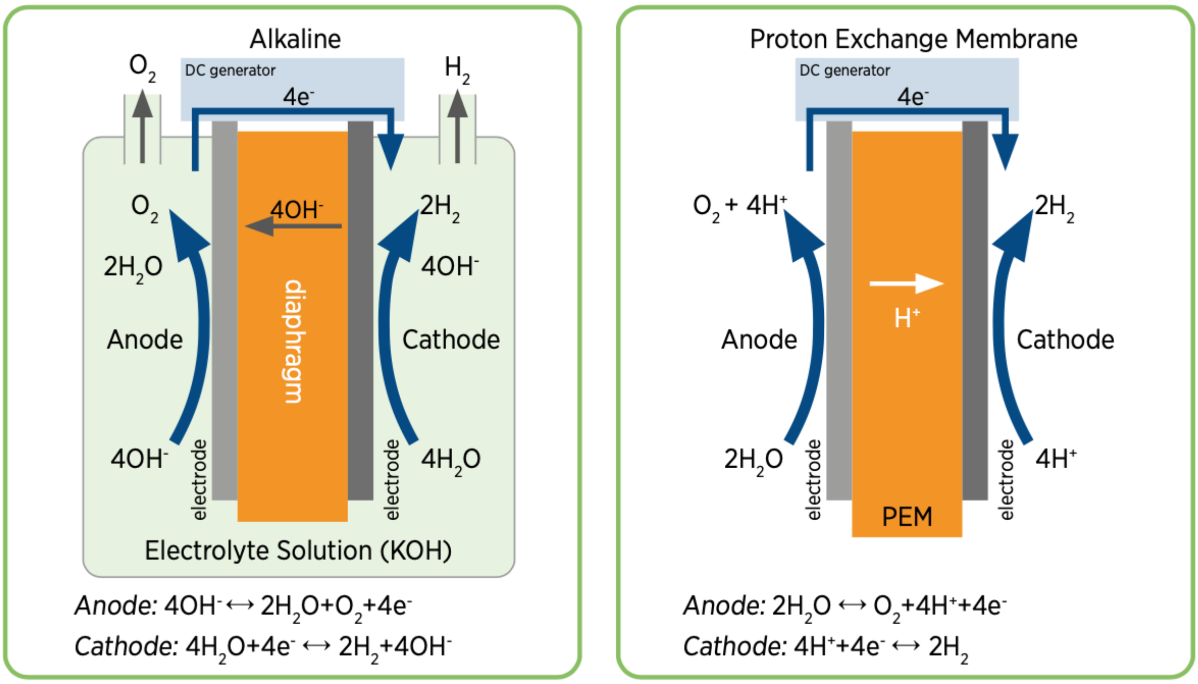


Fig. 2-1: Types of electrolysers commercially used. Source: (IRENA, 2020)

A. Polymer Electrolyte Membrane (PEM) Electrolysers:

The electrolyte in a polymer electrolyte membrane (PEM) electrolyzer is made up of specialized solid plastic material. At the anode, water reacts to produce oxygen and positively charged hydrogen ions. Electrons then travel through an external circuit, whereas hydrogen ions pass selectively across the PEM to the cathode. Hydrogen ions mix with electrons from the external circuit at the cathode to generate hydrogen gas (EERE, 2021).

Anode Reaction: $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$ ………………………(2.4)

Cathode Reaction: $4H^+ + 4e^- \rightarrow 2H$ ……………………………..(2.5)

B. Alkaline Electrolyzer:

Alkaline electrolysers work by transferring hydroxide ions (OH^-) from the cathode to the anode via the electrolyte, with hydrogen formed on the cathode side. For many years, commercially produced electrolysers used a liquid alkaline solution of sodium or potassium hydroxide as the electrolyte. On the lab scale, newer techniques that use solid alkaline exchange membranes (AEM) as electrolytes are showing great promise (EERE, 2021).

2.2. Hydrogen as an alternative marine fuel

The excellent physical and chemical properties of hydrogen make it a highly suitable emission-free source of propulsion for ships. As indicated in table 2-1, It has the highest energy content per mass of all the chemical fuels at 120.2 MJ/kg and thus, has 2.8 times the mass-energy of MGO and five to six times the mass-energy of alcohols (ABS, 2021).

This means that using hydrogen as fuel leads to improved engine efficiency and reduced specific fuel consumption. The high auto-ignition temperature of hydrogen plays a significant role in determining the compression ratio of the engine which affects its maximum power.

Table 2-1: Properties of hydrogen and other marine fuels

	UNIT	HYDROGEN	MGO	HFO	LNG	DIMETHYL - ETHER	METHANOL	ETHANOL	AMMONIA
BOILING POINT	℃	-253	180-360	180-360	-161	-25	65	78	-33
DENSITY	Kg/m^3	70.8	900	991	430	670	790	790	696
LOWER HEATING VALUE	MJ/kg	120.2	42.7	40.2	48	28.7	19.9	26.8	22.5
AUTO IGNITION VALUE	℃	585	250	250	537	350	450	420	630
FLASHPOINT	℃		>60	>60	-188	-41	11	16	132
ENERGY DENSITY LIQUID (H_2 GAS AT 700 BAR)	MJ/L	8.51 (4.8)	39.8	39.8	20.6	19.2	15.7	21.2	15.7
COMPRESSED VOLUME TO MGO (H_2 GAS AT 700 BAR)		4.51 (7.98)	1.0	0.96	1.86	2.0	2.45	1.81	2.45

Source: Adapted from (ABS, 2021)

However, Hydrogen has a lower volumetric energy density of hydrogen, necessitating the storage of larger volumes onboard. As a gas, hydrogen must be compressed and kept at extremely high pressures (approx. 700 bar); as a liquid, it must be stored at temperatures of -253° C using cryogenic technology (ABS, 2021). Because hydrogen is both explosive and flammable, ship system designs and Crew operational safety must be addressed.

2.2.1. Hydrogen as a fuel in internal combustion engines

There are several characteristics of hydrogen that contribute to its usage as a combustible fuel. The low ignition energy is crucial in combustion because the amount of energy required to ignite hydrogen is approximately one order of magnitude less than that necessary to ignite MGO. The high autoignition temperature of hydrogen is important in determining the compression ratio of the engine and influencing the maximum power output (i.e., mean effective pressure) that can be achieved. As per MAN energy solutions, the largest marine diesel engine manufacturer in the world,

internal combustion engines burning hydrogen have a significant economic advantage over other existing options and its potential is even growing as green hydrogen production is reaching a mature level (MAN Energy solution, 2022).
Hydrogen can be used directly in mono or dual fuel (DF) combustion engines. Mono fuel hydrogen engines require some modifications for optimization of combustion timing and reducing the engine knock (ABS, 2021). Hydrogen can also be used in combination with gas or other conventional fuels such as MGO. In DF applications, hydrogen is injected into the engine cylinder, compressed and then a very small quantity of pilot diesel fuel is added to commence combustion. Both, however, may require NOx reduction technologies such as Selective Catalytic Reduction (SCR) or Exhaust Gas Recirculation (EGR) depending on the Air/Fuel Ratio (Stępień, 2021).

2.2.2. Hydrogen fuel cell

Hydrogen can also be used as fuel cells (see *Fig. 2-2*) which convert hydrogen's energy into electricity and heat which can be used to power the ship's propulsion system. These fuel cells can constantly supply energy as long as they are fed with fuel, which is a great advantage over batteries that must be recharged. Additionally, the same source of hydrogen can also be utilized to meet the auxiliary power demand of the ship. (Sohani et al., 2020) carried out an application-based performance optimization study and found that fuel cells can dramatically reduce emissions and have higher efficiency than combustion engines.

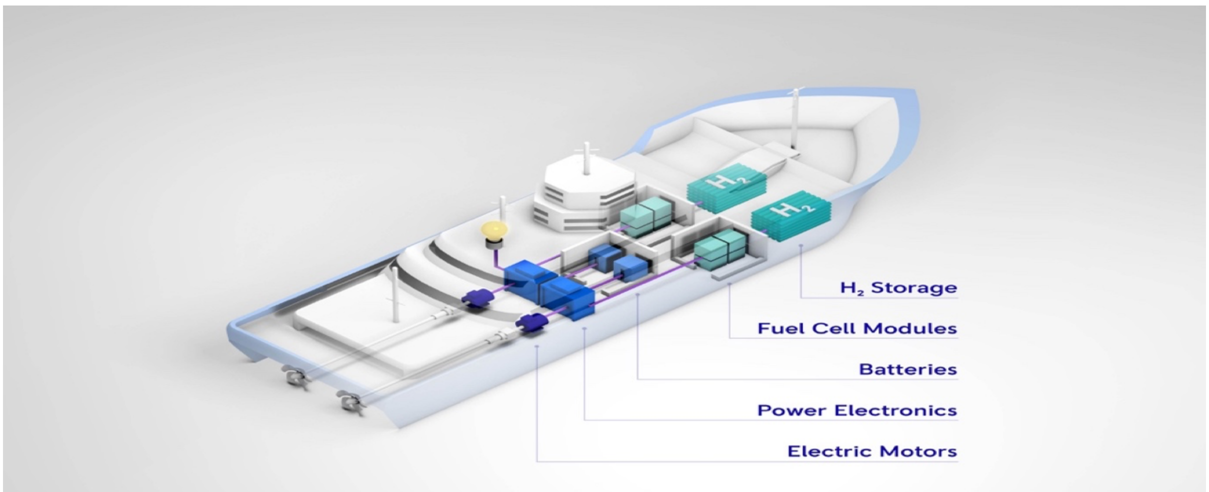


Fig. 2-2: Illustration of a simple Hydrogen fuel cell layout. *source:*(MTU, 2021)

The classification of fuel cells is based on the type of electrolyte used (De-Troya et al., 2016). This classification defines the type of electrochemical processes that take place in the cell, the type of catalysts needed, the temperature range at which the cell functions, the fuel required, and other criteria. These properties influence the type of applications for which these cells are most suited (EERE, 2022). *Table:2-2* shows the summary for different fuel cell types.

Table 2-2: Fuel cell type summary

Fuel Cell Type	Fuel Options	Emissions	Efficiency	Operation Temperatures
Alkaline Fuel Cell (AFC)	Hydrogen	Water	50-60 %	50-230 C
Proton Exchange Membrane Fuel Cell (PEMFC)	Hydrogen	Water	40-60 %	50-130 C
Solid Oxide Fuel Cell (SOFC)	Natural Gas, Diesel, Hydrogen	Water + CO_2 if carbon included fuel is used.	40-70 %	500-1000 C
Phosphoric Acid Fuel Cell (PAFC)	Natural Gas, Diesel, Hydrogen	Water + CO_2 if carbon included fuel is used.	40-50 %	150-220 C
Molten Carbonate Fuel Cell (MCFC)	Natural Gas, Diesel, Hydrogen	Water + CO_2 if carbon included fuel is used.	30-70 %	600-700 C

Source: Adapted from (Inal & Deniz, 2020)

Of all the different options, the most relevant fuel cell types for maritime use are PEMFC and SOFC (Tjalve Svendsen, 2022). The fuel cell technology has progressed significantly, and the solid oxide fuel cell shows high potential for maritime application because of its large energy density (Terun, 2020).

2.3. Life-cycle emissions of Hydrogen

When used in combustion engines or as fuel cells, hydrogen has the right potential to be a zero-emission marine fuel with the only by-product of combustion being water.

When compared to other alternative marine fuels available, hydrogen is capable of reducing CO2 emissions by up to 100%.

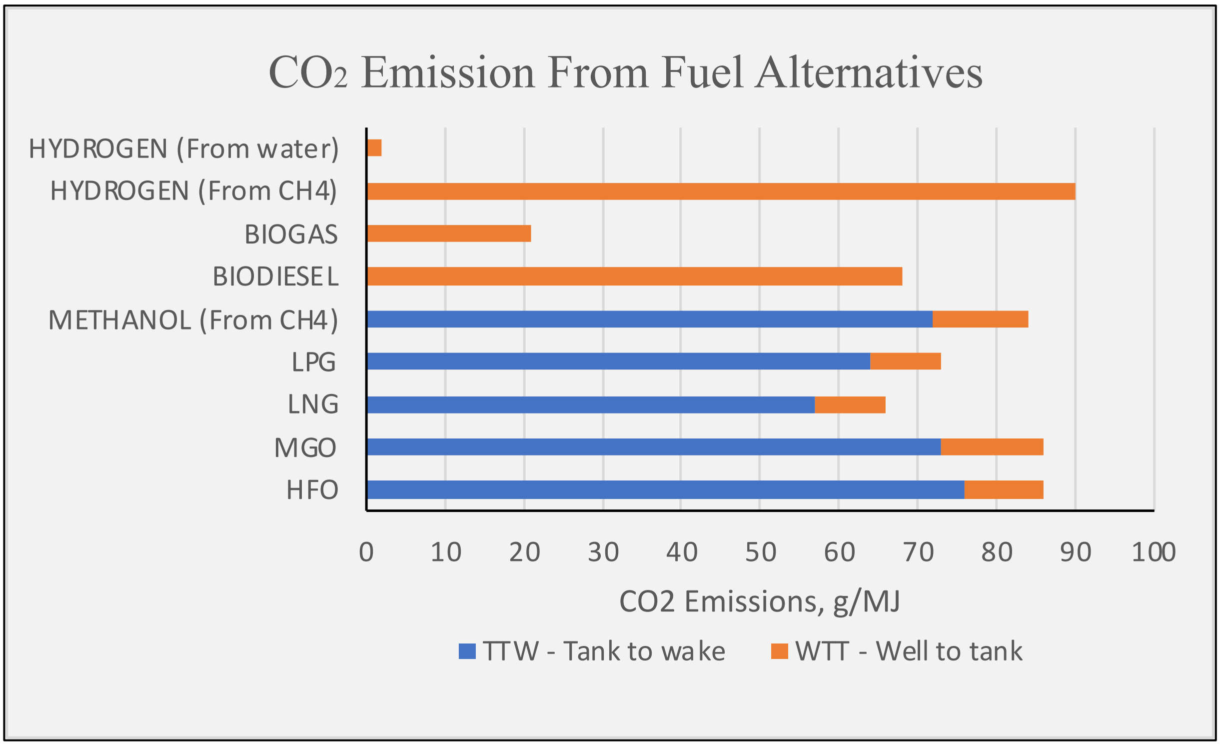


Fig. 2-3: CO2 emissions of alternative marine fuels. *Adapted from* (DNV, 2018)

However, it is important to account for emissions from the entire lifecycle of the fuel as the use of a tank-to-wake approach would understate its total health and climatic implications. The emissions (CO2, Sox, NOx, CH4 & PM10) throughout the life cycle of the fuel can be classified as follows:

A. Well-to-Tank (WTT) – Emissions as a result of the production process of the fuel from the feedstock to a ship's fuel tank
B. Tank-to-Wake (TTW) – Emissions due to the combustion process of the fuel on the ship
C. Well-to-Wake (WTW) – Emissions throughout the lifecycle of the fuel from its production until it is used to fuel a vessel. This includes WTT and TTW.

2.3.1. Not all Hydrogen is carbon neutral

While there is no tank to wake emission, the process by which the hydrogen is produced has a significant impact on its entire life cycle emissions. Based on the method of production, hydrogen fuel has been assigned colour codes as follows:

Fig. 2-4: The different colours of hydrogen. *Adapted from* (Castigliego Joshua, 2021)

Most of the hydrogen (96%) available today is produced from fossil fuels, particularly from the SMR of natural gas and the gasification of coal (Howarth & Jacobson, 2021). This method of production of hydrogen is very carbon-intensive as it leads to emissions of between 71 kg CO2 /MJ H2 for natural gas to 166 kg CO2 /MJ H2 for coal, however, these emissions can be reduced or eliminated by implementing the CCS technology(ABS, 2021). Only green hydrogen is produced in a carbon-neutral way and has the potential to help achieve net zero by 2050 (WORLD ECONOMIC FORUM, 2021).

2.3.2. Economic considerations for Hydrogen

Apart from the environmental impacts and technological readiness, the commercial viability of green hydrogen will also play a significant role in realising its true potential. (Lamas et al., 2015) conducted an emission analysis of different alternative fuels and found that hydrogen is the best performer when it comes to emission reduction. However, it is too expensive to be considered a viable option. Several other studies are available in the literature which show a similar outcome - (Abraham, 2021; Deniz &

Zincir, 2016b; Gore et al., 2022). In this section, we investigate the cost analysis of hydrogen-powered ship propulsion systems.

2.3.3. Capex for Hydrogen as an alternative fuel

Table 2-3: Capital investment costs for fuel technologies

Component	Retrofit Cost (US$/kW)	New Build Cost (US$/kW)	Lifetime
Propulsion systems			
ICE Diesel, Biodiesel	-	460	30 years
ICE, Methanol	328	505	30 years
ICE, Ammonia		600	30 years
ICE, LNG, LBG, Hydrogen	900	850	30 years
Fuel cell, SOFC	-	4000–9000	7–12 years
Fuel cell, PEMFC	-	730–2860	7–12 years
Fuel storage system			
Gas supply system + tank, LNG, LBG (USD$/kg)	270–420	270–420	30 years
Gas supply system + high pressure tank (700 bar), Hydrogen (USD$/kg)	-	576–868	30 years

Source: Adapted from (Wang et al., 2021)

Two components that make up the initial capital cost are the capital cost of the main propulsion system and the costs associated with the storage and distribution system (Wang et al., 2021). New Vessels require to be equipped with a gas-powered engine to be able to use hydrogen as fuel. Existing fuel oil engines can also be retrofitted to use hydrogen. These additional costs associated with the hydrogen fuel system are expected to be similar to that of the LNG fuel system as both of them deal with pressurized and cryogenic liquids. However, the additional costs of hydrogen storage tanks will be more expensive as the requirement of extremely low temperature requires better insulation quality. Additionally, the cost for fuel cells will be more than when hydrogen is used in internal combustion engines. The high capital investment and a shorter expected lifetime of the fuel cells are the barriers to their wide adoption in shipping.

2.3.4. Fuel price

Most of the hydrogen in production today is grey hydrogen and is produced using natural gas and coal. The production cost of grey hydrogen is as low as $1/kg in the low gas/coal price areas such as middle east, North America and Russia and it is below $2/kg in Europe whereas, the cost of green hydrogen is in the range of $2.5-6/kg (KPMG, 2021). This means that green hydrogen is more Expensive today as compared to its blue and grey alternative. However, the green hydrogen production cost has gone down by 50 % since 2015 (IHS Markit, 2020). The hydrogen council estimates that the cost of green hydrogen will be further reduced by up to 50% by 2030 (Hydrogen Council, 2020).

The EU Hydrogen Strategy aims to reduce the cost of producing green hydrogen in Europe from 3.5 to 5.5 euros per kilogram to 1.1 to 2.4 euros per kilogram by 2030 (Leibreich Michael, 2020).

2.4. Maritime application of Hydrogen – State of the art

March 2021 Global Maritime Forum research assessed 106 projects focusing on zero emissions in maritime shipping around the world and discovered that roughly half of these activities relied on hydrogen as a low-carbon fuel source (Reinsch, 2021). While large sea-going ships have not been tested with hydrogen, hydrogen-powered ferries and smaller shipping vessels have been tested in the United States, Belgium, France, and Norway (Hersher, 2019). FLAGSHIPS, a European innovation project, was awarded 5 million Euros from the European Union's Horizon 2020 Research and Innovation program to support the deployment of two commercially operated vessels which will be fuelled by hydrogen produced from renewable energy, laying the groundwork for future local zero-emission transportation deployment (The Maritime Executive, 2019). These vessels are expected to start their operations soon.

The MF HYDRA is another zero-emission vessel to be powered by liquid hydrogen, which operates between Hjelmeland, Nesvik and Skipavik. This 82m long vessel has a capacity of 300 passengers as well as 80 cars. The vessel operates at a speed of 9 knots and can operate for up to three weeks without the need for refuelling (FuelCellWorks, 2021). This first-of-its-kind vessel was also awarded the ship of the year award by the Norwegian president on 8 September 2021. TOPEKA, a zero-emission shipping company, has received NOK 219 million (USDM 25) for building two zero-emission vessels. The two identical vessels will be powered by liquid hydrogen and hydrogen fuel cells and are expected to enter into service by 2024 (Bahtic, 2021).

Shell recently announced that it has reached its final investment for its ambitious project “Holland Hydrogen 1”, which would be Europe’s largest green hydrogen plant and will commence its operation in 2025. The 200MW electrolyzer plant will have a daily production capacity of 60,000 kg. The electrolyzer will be powered by renewable energy from Shell's offshore wind farm ‘Hollandse Kust’ (Shell, 2021).

Additionally, European Commission has approved a 5.4-billion-euro hydrogen project jointly funded by 15 EU countries and 35 companies focused on the scaling up of hydrogen production, Fuel cells, storage, and transportation particularly in the mobility sector (REUTERS, 2022). The long list of various ambitious projects and feasibility studies clearly highlights hydrogen's potential as an alternative fuel in maritime transportation. However, in the absence of policy or regulatory intervention, hydrogen is unlikely to become a viable alternative to traditional fossil fuels (Pomaska & Acciaro, 2022).

2.5. Policy context

2.5.1. The pressing need for policies for a decarbonised shipping industry

Shipping would rank as the 6th largest greenhouse gas emitter if it was a country (WORLD ECONOMIC FORUM, 2018). Despite adopting an ambitious target of reducing emissions by at least 50% by 2050 and pursuing GHG emission reduction pathways consistently with the temperature goals of the Paris agreement, emissions from shipping are expected to increase from 90-130% of the 2008 level by 2050 (Faber, Zhang, et al., 2020). To achieve the Paris Agreement's objective, the industry must rapidly decarbonize and begin emissions reductions in the 2020s, leveraging energy-efficient technology in the short term and swiftly transitioning to SZEFs in the mid-to-long term (Parker et al., 2021). Furthermore, due to the longer asset lifespan and energy density required to propel ships, shipping is usually regarded as a difficult-to-abate sector (Deloitte, 2020). A recent study by (Baresic et al., 2022) highlights the need for policy intervention to deal with the competitive disparity between fossil fuel and its zero-emission alternatives.

Market-Based Measures (MBMs) had been a part of IMO's discussions from 2006 to 2013 and several proposals including an emission trading system (MEPC 60/4/12, 60/4/22, 60/4/26, 60/4/41) were submitted during this time (IMO, 2019). However, in 2013, instead of pursuing MBMs, the IMO adopted the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP), both of which entered into force in 2013. IMO also adopted a Data Collection System (DCS) regarding the fuel consumption of vessels, which entered into force in 2018 (Parker et al., 2021).

The IMO has established a timeframe for considering various measures as part of the Initial IMO GHG Strategy. The Strategy provides a non-exhaustive list of short-, mid-, and long-term policy measures that could be implemented between 2018 and 2023, 2023 and 2030, and beyond 2030, respectively (IMO, 2018b). The short-term measures are primarily focused on improving energy efficiency, and in June 2021, MEPC 76 adopted regulations that will apply technical efficiency standards to existing ships (Energy Efficiency Existing Ship Index, EEXI (IMO, 2021). Ships must also meet an annual operational Carbon Intensity Indicator (CII) target. MBMs have been identified as a prospective measure for debate in discussions on mid-term measures, which will commence soon.

The necessity for additional decarbonisation policies in shipping is obvious. However, the lack of IMO regulation that is stringent enough to make a material difference to GHG emissions in shipping has created a regulatory void into which the EU has stepped, and thus the inclusion of shipping in the EU ETS represents a significant regional push toward decarbonising shipping and the application of an MBM to the shipping sector(Parker et al., 2021).

2.5.2. The EU Emissions Trading System

The EU's Emission Trading System is a market mechanism that puts a price on CO2 and provides incentives for emissions to be reduced in the most economical way. Since its implementation in 2005, it has succeeded in reducing emissions from energy-intensive industries and power generation by 42.8% (European Commission, 2021b). The EU ETS has a "cap-and-trade" strategy: the EU sets a ceiling on the annual emission of greenhouse gases, and businesses are required to hold the European Emission Allowance (EUA) for each tonne of CO2 they emit over the course of a year. They can trade these permits after receiving or purchasing them (Appunn, 2021).

This 'hard cap' ensures that emissions drop at a linear rate aligned with the EU's climate targets across all ETS sectors. In practice, this is accomplished by limiting the number of permits available to firms each year. These permits are known as European Union Allowances, or EUAs, and provide the holder with the right to release GHG equivalent to one tonne of CO2 equivalent (tCO2e). The steady reduction, known as the 'linear reduction factor,' allows businesses to gradually adjust to meeting the increasingly aggressive overall objective for carbon reductions. The cap is falling annually at a reduction factor of 2.2% in the current phase 4 of the ETS (2021-2030) (European Commission, 2021b).

Whenever possible imbalances in the supply and demand for allowances occur, the ETS contains extra design features to address them. The Market Stability Reserve (MSR), which commenced operation in 2019, allows the regulator to shift a major number of allowances to the reserve rather than allocating them. This occurs when an excess of allowances in the system threatens to undermine the ETS's price and investment signal, and MSR is likely to play an important role in ETS operation over the next decade (Osorio et al., 2021).

2.5.3. The EU's proposal to include Shipping in the EU ETS

On 14th July 2021, the European Commission adopted the 'Fit for 55' package aimed at reducing GHG emissions by at least 55% by 2030 compared to 1990 levels and extending the emission trading system (ETS) is one of the few proposals that were made to address the climate impact of maritime transport (European Commission, 2021f).

Since its publication, the Commission's proposal has been the topic of intense debate in the European Parliament and the European Council, but on 7 June 2022, the process nearly came to a halt when the European Parliament decided to reject a proposed revision of the EU ETS. However, a compromise solution was found on June 22, 2022, and the European Parliament has officially endorsed their position on the revision of the EU Emissions Trading System (ETS), including the application of EU ETS to maritime transportation (Hagberg, 2022).
The approach now taken by the European Parliament differs significantly from the initial proposal made by the EU Commission in July last year (Hagberg, 2022).

a) Maritime transportation will be included in the EU ETS beginning in 2024 rather than in 2023.
b) There will be no phase-in period, as initially envisaged, which means that shipping companies will be required to surrender credits equivalent to 100% of verified emissions recorded for each calendar year beginning in 2024.
c) Emissions from maritime transportation carried out by ships of 5,000 gross tons and above will be included for the period 2024-2026, however, this will be reduced to 400 gross tons and above beginning in 2027.
d) The EU ETS will be expanded to include methane (CH4) and nitrous oxide (NOx) and not just CO_2
e) 75% of the revenues generated from marine allowances will go to an Ocean Fund to aid in the transition to an energy-efficient and climate-resilient EU maritime sector.
f) The "shipping company" (the ISM DOC holder) remains the responsible body, but emissions costs should be conveyed on to charterers to ensure that the "polluter pays principle" is properly observed and to stimulate the adoption of efficiency measures and cleaner fuels.
g) The proposal for the period 2024-2026 remains that the EU ETS cover 100% of emissions from intra-European routes and 50% of emissions from extra-European routes to and from the EU. However, the proposal also states that if the distance to or from the EU port is less than 300 nautical miles, 100% of the emissions from that voyage will be included in the annual emissions computation. The goal is to avoid "evasive port calls in neighbouring non-EU countries" (Bradley Beth & Hoyland Rachel, 2022).

h) Emissions from all voyages (intra- and extra-European) will be covered 100% beginning in 2027, with possible exceptions for non-EU nations, where coverage could be cut to 50% according to certain criteria. These conditions apply only when a third country has a carbon pricing mechanism that is at least equivalent to the EU ETS, or when a third country is a Least Developed Country or a Small Island Developing State with a GDP per capita lower than the EU average and includes emissions in its nationally determined contributions under the Paris Agreement (Bradley Beth & Hoyland Rachel, 2022).

2.5.4. The EU's policy mix beyond ETS

The EU aims to decarbonize shipping through a policy mix that includes, in addition to the maritime ETS, the 'FuelEU' carbon standard for shipping fuel (European Commission, 2021d), the Alternative Fuels Infrastructure Regulation (AFIR), which requires an onshore power supply and LNG bunkering infrastructure by 2025 (European Commission, 2021c), and the Energy Taxation Directive (ETD), which will lift a ban on bunker taxation for global shipping (European Commission, 2021e).

The FuelEU proposal will limit the GHG intensity of ship fuel by setting maximum limits by year with respect to the fleet average in 2020. These restrictions will gradually increase as follows: 2% by 2025, 6% by 2030, 13% by 2035, 26% by 2040, 59% by 2045, and 75% by 2050. In contrast to measures proposed and discussed at IMO targeted at improving technical and operational efficiency, the targets address the carbon content of the fuel consumed rather than the efficiency of the vessel or its operation. However, these reductions are unlikely to permit a shift to SZEF in the short term (Parker et al., 2021).

The revised AFIR establishes an EU-wide mandate for the implementation of sustainable fuel infrastructure across all forms of transportation. For shipping, it mandates that a broader selection of seaports (TEN-T 'comprehensive' ports) provide Onshore Power Supply to container and ro-ro ships by 2030, mirroring the demand-side requirement in Fuel EU. The Commission's proposal also maintains a mandate for major seaports to have LNG bunkering facilities by 2025, a measure that could be scrutinized in the upcoming EU legislative review (Pierre-Louis Ragon et al., 2022).

A revision to the ETD that incorporates fuels from the maritime industry has been proposed as part of the Fit For 55 package. Maritime bunker fuel has been tax-free in the EU until now, but beginning in January 2023, all bunker fuel sold in the EU and consumed on voyages within the EU will be taxed. The directive establishes a minimum tax rate for each fuel category, with fossil fuels paying the highest (€10.75/GJ) and electricity, advanced sustainable biofuels and biogas, and renewable fuels paying the lowest (€0.15/GJ). Over a 10-year transition period, sustainable and alternative fuels in the maritime sector will have a zero minimum tax rate (NAPA, 2022).

2.5.5. Carbon Price Required to close the gap

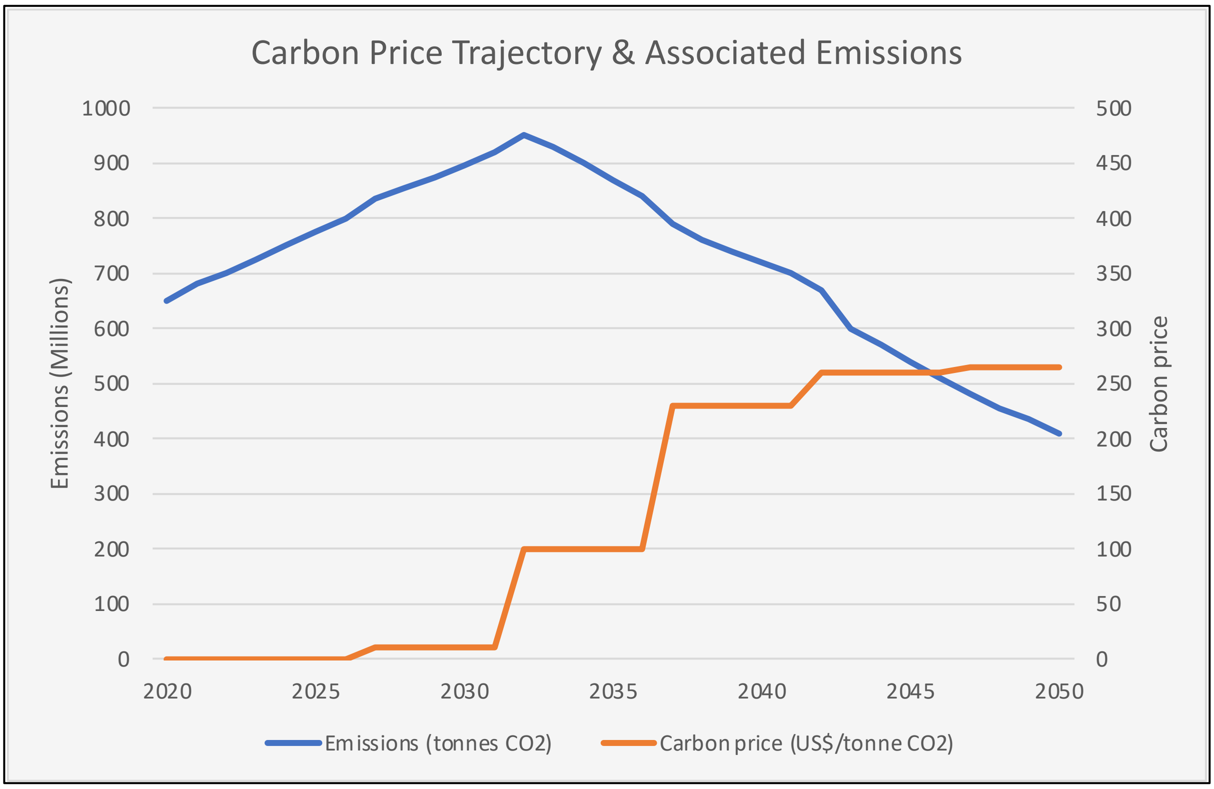


Fig. 2-5: Carbon Price Trajectory *and Associated emissions projected for IMO'S lowest ambition scenario. Adapted from* (Baresic et al., 2022).

(Lloyd's Register and UMAS, 2019) highlighted that Scalable Zero Emission Fuels (SZEFs) are required to achieve the IMO's levels of ambition as well as the price gap, which is at best expected to be almost double the price of LSFO in the 2030s and 2040s. According to the report "Closing the Gap" by (Baresic et al., 2022) which is based on the scenario and techno-economic modelling conducted by (Smith et al., 2019) for the UK Department for Transport, an average carbon price of US$173/tonne CO2 would be required to achieve the IMO's Initial Strategy's lowest ambition of reducing ships' GHG emissions by 50% by 2050 compared to 2008. To decarbonize shipping completely by 2050, the average carbon price would only need to be marginally higher: roughly US$191/tonne CO2.

Fig 2-5 shows the assumed carbon price trajectory, which begins in the mid-2020s at a relatively low carbon price of US$11/tonne CO2 to phase in carbon pricing.

This would not result in overall emissions reductions, while some owners may find it cost-effective to invest in energy efficiency equipment (Baresic et al., 2022). To incentivize the transition to low- and zero-carbon fuels/energy, the global carbon price would need to rise to roughly US$100/tonne CO2 in the early 2030s, and then hover around US$230-260/tonne CO2 between 2035 and 2045.

2.5.6. Implications of Revenue recycling on competitiveness

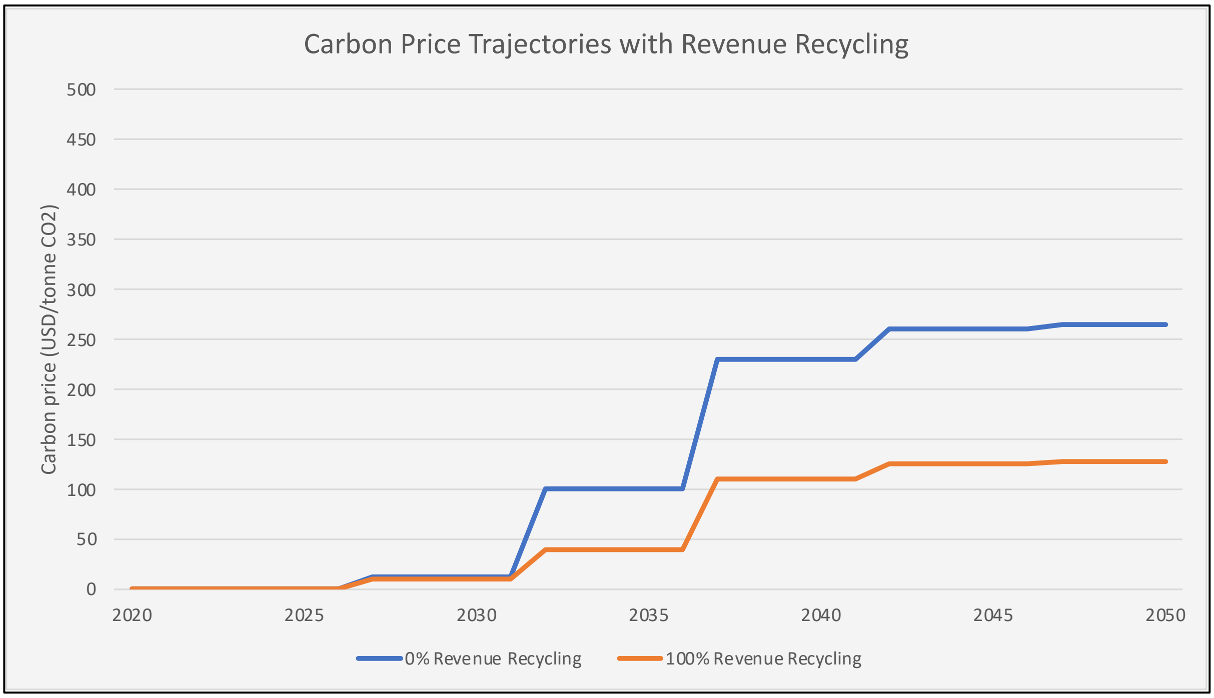


Fig. 2-6: Carbon Price Trajectory based with revenue recycling. *Adapted from* (Baresic et al., 2022).

Revenue recycling can be used to accomplish the same environmental goals while reducing the sector's economic burden. While having a higher-than-necessary carbon price earlier on signals to the industry that it needs to hit the brakes on its BAU trajectory, there are still R&D difficulties to overcome, and the revenue recycling strategy gives a buffer to allow zero-carbon fuels to take off (Parker et al., 2021).

Revenue 'recycling' in the context of the EU ETS would use the revenue raised from shipping company allowances to further support closing the competitiveness gap between SZEFs and fossil fuels through various subsidies such as funding R&D into alternative fuels and technology, financing the construction of fuel bunkering infrastructure, or directly subsidizing alternative fuels. The 'Closing the Gap' report by (Baresic et al., 2022)estimates the carbon price required to close the competitiveness gap between fossil fuels and SZEFs, considering variable degrees of revenue recycling. The '0% carbon price' in *Fig. 2-6* is the carbon price required if there was no revenue recycling and thus no subsidy. The '100% carbon price,' on the other hand, anticipates that all revenues generated by a carbon pricing mechanism will be recycled through subsidies to support zero-carbon marine fuels. If 100% of the revenue collected by a carbon pricing mechanism was reinvested back into the sector by subsidizing SZEFs and associated infrastructure, the carbon price required to bridge the competitiveness gap between fossil fuels and SZEFs could theoretically be reduced by half.

2.6. Findings From the Literature Review

- Of all the different methods of production available today, only hydrogen produced from renewable sources (Green Hydrogen) has the potential to reduce total well-to-wake CO_2 emission by up to 100%
- Green hydrogen ticks all the right boxes to be the emission-free source of propulsion but loses competitiveness because of its low volumetric density and high production cost. However, the cost is expected to reduce by up to 50% by 2030
- The large storage volume due to its low volumetric efficiency may compromise the cargo space making it a less favourable option for large ocean-going ships
- Hydrogen fuel cells are more efficient than conventional diesel engines and can potentially replace them. However, innovation is required to further reduce the cost and to become competitive with other alternatives
- The long list of various ongoing maritime projects and feasibility studies clearly highlights hydrogen's potential as an alternative fuel in maritime transportation
- Policy intervention is urgently required to deal with the competitive disparity between fossil fuel and its zero-emission alternatives

- The slow progress by IMO has created a regulatory void into which the EU has stepped
- The European Union has proposed to include maritime transport into the EU ETS along with other policy measures such as FuelEU, AFIR AND ETD as a part of its wider 'Fit for 55' package
- EU has also proposed to recycle back 75% of the revenues generated from marine allowances to an 'Ocean Fund' to aid in the transition to an energy-efficient and climate-resilient EU maritime sector
- A study carried out by (Baresic et al., 2022) suggests that recycling back the revenues generated through various economic instruments into R&D and innovation for alternative fuel technologies in the maritime industry can lead to an efficient and cost-effective fuel transition
- Our research will highlight the importance of effective policymaking for enabling an effective and efficient transition. Assessing the impact of effective policies for making hydrogen-powered vessels a reality, will also provide a novel approach for assessing the potential of other alternative fuels and will complement the existing literature

3. Methodology

In this chapter, we discuss the methodology regarding Data collection, assumptions, and the development of a model for assessing the competitiveness gap between hydrogen and conventional fossil fuel, and the potential reduction in this gap by implementing correct policy measures. First, we will assess the existing competitiveness gap between the hydrogen-powered vessel and the vessel powered by conventional marine fuel oil. We shall then evaluate various policy options and estimate the potential revenues generated by the economic instruments. Finally, we will assess the impact of revenue recycling on the cost competitiveness of hydrogen-powered vessels every year over the period of 2023-2030.

3.1. Competitiveness gap between Hydrogen and Conventional fossil fuel

In this section, we will compare the cost of owning and operating a conventional diesel-fuelled container vessel vs the cost of owning and operating the same vessel on hydrogen fuel. For doing this, we will first select a model container vessel based on the EU MRV data. We will then estimate and compare the total sum of annual fuel cost and the amount of yearly fixed investment cost for these vessels. For comparing the fixed investment costs, only the costs of the propulsion system and fuel storage tanks are taken into consideration as other investment costs are expected to be equal for both vessels. Similarly, only the fuel cost has been considered as variable OPEX as other costs like crewing, stores, spares,
and insurance etc. are assumed to be equal in both cases and have been excluded. Finally, we will estimate the cost of abatement per ton of CO_2 using hydrogen. This section addresses the first and second sub-research questions of our study.

3.1.1. Vessel particulars

We have selected a 2000 TEU capacity feeder vessel for our research as the low volumetric density of hydrogen requires large volumes to be stored on board and hence compromises the cargo carrying capacity of larger vessels(van Hoecke et al., 2021). The selected vessel operates within the EU and does a round trip of 1350 Nautical miles in a total time of 7 days (Maersk, 2022). The average engine capacity for these types of vessels is 12000 kW (European Commission, 2021a) (see appendix:1) and their average operating speed is 18 knots while running at 55% MCO (MAN B&W Diesel A/S, 2019).

Table 3-1: Vessel particulars of the diesel-fuelled vessel

Propulsion power (kW)	Speed (Knots)	Output %	Round trip distance (NM)	Total time for 1 round trip	Sailing time for 1 round trip	No. of trips in a year	Aux Engine cap. (kw)	Aux Engine Load Factor (%)
12000	18	55	1350	168 (hrs)	75 (hrs)	50	850	60

Source: Author's rendering of (European Commission, 2021a; MAN B&W Diesel A/S, 2019)

3.1.2. Annual fuel cost calculation

Energy needs for sailing

In order to calculate the annual fuel demand, we need to find the energy need of the vessel per year as it is advisable to base the calculations on energy consumption when reviewing the benefits and drawbacks of a new energy source(Goodwin & Hildre, 2015). We have used a simple formula for calculating the energy consumption which is a multiplication of the engine output, output percentage and total sailing time in the year. This is illustrated as follows:

Energy consumption per year (sailing) = Total power output* x *Output %* x *Time **…….. (3.1)**

Energy needs at Berth

Ships require auxiliary engines to be still running at berth to meet the energy requirement for auxiliary services. This results in significant amount of annual fuel consumption and cannot be ignored. We have calculated this as follows:

Energy consumption per year (at Berth) = Aux. engine power capacity* x *Load factor (%)* x *Time at Berth **…….. (3.2)**

Fuel demand

The fuel demand for the selected route is calculated as the total amount of fuel required to operate the chosen vessel per year. We use the energy content of the fuels and the engines' energy efficiency to translate consumed energy into fuel demand for the chosen vessel. Diesel engines cannot use all the energy in the fuel because some of them are lost inside the combustion chamber and some outside the system due to heat dissipation and transmission losses. Since the vessel is expected to operate in emission control areas (ECA) requiring the sulphur content to be less than 0.1%, we have used low sulphur marine gas oil (LSMGO) as a reference fuel for our research. The following equation illustrates our method for determining fuel demands based on the route's energy requirement:

$$\textit{Annual Fuel demand} = \frac{\textbf{Energy cons. (kWh per year)}}{\textbf{Energy content of fuel(kwh per kg)}\ X\ \textit{Engine efficiency}} \quad \textbf{.... (3.3)}$$

For our calculations, we have used the following factors:

- Energy content for LSMGO: 11.944 kWh/kg (Aronietis et al., 2016)
- Diesel Engine efficiency: 50% (Wärtsilä, 2022)
- Energy content for Hydrogen: 33.33 kWh/kg (Enapter, 2022)
- Hydrogen Fuel Cell efficiency (PEMFC): 60% (Pollet et al., 2016)

Fuel Cost

One of the most critical aspects for this type of study is fuel price estimates. Predicting the future of shipping is heavily reliant on forecasting fuel prices and how different technologies will grow to become more cost-effective.

LSMGO prices are determined by multiplying the historical ratio between fuel price and the Brent crude price by the oil price forecast from (Deloitte, 2022) study whose data sources include EIA, OPEC, ARC Energy and Marex Spectron (see appendix: 2). These prices, however, are not inclusive of any carbon pricing.

Table 3-2: Expected LSMGO price (excluding carbon price)

Year	2023	2024	2025	2026	2027	2028	2029	2030
Price ($/MT)	732.53	657.24	624.36	636.90	649.88	662.86	675.85	689.26

Source: Author's adaptation from (Deloitte, 2022; macrotrends, 2022; Ship & Bunker, 2022)

As discussed in the previous chapters, only green hydrogen has the potential of zero well to wake emission; hence, our calculations are based on the price of green hydrogen. In Europe, green hydrogen is currently available at a price of $5 - $7 per kg (S&P Global, 2022) and is expected to fall to a price of $3 per kg by 2030 as per a 2022 study carried out by UK-based Aurora Energy Research (Diermann, 2022). There are several other predictions found in market outlooks as well as literature which suggest the same such as (Burgess, 2022; IEA, 2019; Sonnichsen, 2022). Since we could not find price predictions for every year, we have used linear interpolation to determine the prices of green hydrogen for those years (see appendix:3 for the graph). The following prices for green hydrogen over the years are, however, based on the anticipated natural rate of technological developments and can be further reduced under ambitious circumstances by boosting innovation and investment which we have analysed in the later sections of this study.

Table 3-3: Expected Green Hydrogen price

Year	2023	2024	2025	2026	2027	2028	2029	2030
Price ($/kg)	5.00	4.70	4.45	4.15	3.90	3.60	3.30	3.00

Source: Author's adaptation from (Diermann, 2022; S&P Global, 2022)

The annual fuel cost is finally estimated as follows:

$$\textit{Annual fuel cost} = \textit{Fuel price} \times \textit{Annual Fuel demand} \quad \ldots\ldots\ldots \quad (3.4)$$

3.1.3. Annual fixed investment cost calculation

The amount of annual fixed investment cost is calculated using the formula for the equivalent annual cost (Kenton, 2020)given by:

$$EAC = \frac{\textit{Asset Price X Discount Rate}}{1-(1+\textit{Discount Rate})^{-\#period}} \quad \ldots\ldots\ldots \quad (3.5)$$

The investment cost is calculated based on the economic life of 10 years as this would allow us to develop a worst-case scenario which means that if the investment is economically viable in short term, it would prove to be a much more attractive option in the long run. Also, it is crucial to take into consideration the sale of the vessel before the end of its lifetime (Pomaska & Acciaro, 2022). The actual discount rate may vary depending on the risk and the project's lifetime but is set at 6% in this study. The investment is thus discounted over a 10-year period at a 6% discount rate, resulting in an annual cost to the operator to pay back the investment.

3.1.3.1. Asset price calculation for vessels

The asset price is calculated as

$$\textit{Asset price} = \textit{Cost of propulsion system} + \textit{Cost of storage tanks} \quad \ldots\ldots\ldots \quad (3.6)$$

The different components of the propulsion system, storage tanks and their costs used in this study are explained further in the following sections. For calculating the asset price, only the costs of the propulsion system and fuel storage tanks are taken into consideration as other investment costs are expected to be equal for both vessels.

Hydrogen fuel cell

As discussed in section 2, Proton Exchange Membrane Fuel Cell (PEMFC) has been successfully used in maritime applications and has several advantages over other types of fuel cells such as low operating temperature, better efficiency, and relatively lower cost because of matured technology (DNV-GL, 2017). The PEM fuel cell is currently available at a price of about 2000 USD/kW. As per “The Future of Hydrogen” study carried out by the International Energy Agency, the cost of hydrogen fuel cells is expected to reduce to a price of 1000 USD/kW in 2050 (IEA, 2020) at the natural rate of technological cost reduction. We have assumed an exponential drop (i.e., sharply dropping in the early stage and slowly dropping near 2050) in the price for these fuel cells and have used the ‘exponential’ graph function in excel (see appendix: 4) to derive an exponential equation for calculating the expected costs for the years in between. The average life of hydrogen fuel cells is 40,000 hrs which translates to 10 years for the vessel. The following table shows the expected price of hydrogen fuel cells in the upcoming years at the anticipated natural rate of technological development.

Table 3-4: Expected Hydrogen fuel cells price

Year	2023	2024	2025	2026	2027	2028	2029	2030
Price ($/kW)	2000	1950	1900	1850	1800	1760	1715	1670

Source: Author’s adaptation from (IEA, 2020)

Drivetrain and associated equipment costs

The (IEA, 2020) study predicts the cost of an electromotor to be 70$/kW in 2020 as well as in 2030, which makes our CAPEX for the electromotor to be USD 840,000. The costs for other equipment such as converters, inverters and batteries are based on a study carried out by (Bob et al., 2021) as illustrated in the following table.

Table 3-5: Drivetrain and associated equipment costs

	Electromotor	Converter	Inverter	Battery
Price (USD)	840,000	135,000	67,500	270,000

Source: Adapted from (Bob et al., 2021; IEA, 2020)

Hydrogen storage tank

The vessel does a roundtrip of 75 hours (sailing time) and hence requires at least 25000 kgs of hydrogen to be stored on board (equation 3.1 & 3.2) if the vessel is to bunker once in every voyage. The (SmartPort, 2020) study shows that the current cost of Hydrogen storage is 1180 Euro/GJ. This makes the CAPEX for the storage tank as high as USD 2,102,760. However, there is very little information available about the costs of these storage tanks and the value of USD 2,102,760 can be an overestimation because this value is based on smaller tanks, and it would be unfair to linearly interpolate the cost for a large tank as is required in our case.

Instead, an alternative way forward would be to bunker at least two times during every trip reducing the need for storage thus reducing the CAPEX for the storage tank by 50%.

DWT Loss due to Hydrogen implementation

Due to the lower volumetric density of hydrogen and extra space required by the fuel cell stack, there would be a loss in the cargo carrying capacity of the vessel which is estimated as 0.26 t/MWh by a study carried out by Lloyd's Register and University College London (Smith et al., 2014). In our case this would be equal to:

[Total power output (MW) **x** ***Output %*** **x** ***Annual sailing time(hrs)]*** **x** ***0.26 Tonnes***

…… (3.7)

This loss in cargo carrying capacity is adjusted as an additional operation cost calculated in terms of the loss of revenue of the hydrogen-powered vessel every year.

Internal combustion engine

The accurate cost data for ICE are not widely published. A study carried out by (SmartPort, 2020) shows the price of marine diesel engines as 636 Euro/kW which is equal to 763 USD/kW (using an exchange rate of 1.2). Another study by (Papadias et al., 2019) shows the cost of a marine diesel engine used in a ferry as 480 USD/kW. For our calculations, we have used a value of 620 USD/kw which is an average of the two above-mentioned values. The price for the ICE is assumed to be the same in 2030 as well however, the price for fossil fuel-powered engines is expected to increase in the near future due to environmental taxations (European Environment Agency, 2022).

LSMGO storage tank

Assuming that the vessel is bunkered once in every voyage, the volume of fuel required to be stored on board is 100 MT (equations 3.1 & 3.2). The cost of storing LSMGO is comparatively very less as this does not require any special material or coatings. Moreover, the LSMGO is stored at atmospheric pressure and usually, the storage tanks are part of the ship's structure with additional heating coils and some piping arrangements. The cost of LSMGO storage tanks used in this study is 108$/MT as used in the 'Power-2-Fuel Cost Analysis' report by (SmartPort, 2020).

3.1.4. Abatement cost

Abatement costs are the overall opportunity costs incurred by a potential emitter when reducing emissions from a business-as-usual level to a reduced emission level (Requate, 2013). In our case, the abatement cost corresponds to the additional costs associated with hydrogen implementation divided by the total amount of CO2 reduced. The additional cost associated with hydrogen implementation is calculated as the difference between the sum of annual fixed investment cost and annual fuel cost for both types of vessels. The following equation shows the cost of abatement per ton of CO_2.

$$\boldsymbol{AC} = \frac{\begin{array}{c}(\textbf{Total annual cost for hydrogen powered vessel} - \\ \textbf{Total annual cost for diesel powered vessel})\end{array}}{\boldsymbol{t\ Co2/year}} \quad \ldots\ldots\ldots \quad \textbf{(3.8)}$$

Where,

$$\textbf{Total annual cost} = \textbf{Annual fuel cost} + \textbf{Annual fixed investment cost} \quad \ldots\ldots\ldots \quad \textbf{(3.9)}$$

3.2. Policy measures to close the competitiveness gap

Economic instruments or Market Based Measures, direct regulatory approaches, voluntary initiatives, and national and regional actions are all potential measures to achieve decarbonisation in shipping (Baresic et al., 2022). There can be a variety of policy options for closing the competitiveness gap between fossil and zero-emission fuels and enabling an efficient and cost-effective transition. However, we have considered the following policy package as the potential way forward based on existing literature and regulatory policy outlook. This section addresses the third sub-research question of our study.

A. **Direct regulatory approaches:** This would give an unequivocal signal to the market that a fuel shift is inevitable in the long run.
B. **Adoption of Market-Based Measures (MBM):** This could incentivise emission reductions and investments in readily available GHG mitigation technologies. This has the potential to generate a significant amount of revenue.
C. **Combination of MBM with effective revenue recycling policies:** This has the potential to boost both demand for and supply of zero-emission fuels.

3.2.1. Direct Regulatory Approaches

Regulatory approaches were the first environmental policies, and they continue to play an essential role in environmental and climate policy around the world (Somanathan et al., 2014). They are sometimes referred to as command-and-control measures because they prescribe the actions that a company must do or the environmental objectives that it must attain (Sills & Jones, 2018).

The FuelEU Maritime proposal aims to accelerate the decarbonization of the maritime industry through the use of renewable and low-carbon fuels and technology, as well as goal-based reductions in Greenhouse Gas (GHG) energy intensity beginning in 2025. The draft Regulation includes ambitious targets for reducing the GHG intensity of marine fuels (Open access Government, 2022). As discussed in section 2.4.4, The FuelEU proposal will limit the GHG intensity of ship fuel by setting maximum limits by year with respect to the fleet average in 2020. These restrictions will gradually increase as follows: 2% by 2025, 6% by 2030, 13% by 2035, 26% by 2040, 59% by 2045, and 75% by 2050. In contrast to measures proposed and discussed at IMO targeted at improving technical and operational efficiency, the targets address the carbon content of the fuel consumed rather than the efficiency of the vessel or its operation. However, these reductions are unlikely to permit a shift to SZEF in the short term (Parker et al., 2021). We have included this in our calculation in section 3.2.2.4.

3.2.2. Market-Based Measures

Regulators adopt MBMs to internalize the costs of pollution resulting from economic activity, resolve market inefficiencies, and reduce price discrepancies between fossil fuels and alternatives. MBMs can help to decarbonize shipping by closing the competitiveness gap between fossil fuels and zero-emission fuels by increasing the expense of using fossil fuels through carbon pricing. This mechanism could incentivise emission reductions and investments in readily available GHG mitigation technologies, as well as fuel switching once alternative zero-emission fuels are widely available. A maximum emissions target is set by regulators and an emissions market is established in the form of a cap-and-trade system, in which a cap is set in place and gradually reduced. The allowances are distributed or auctioned to market players. The market reaction to a cap raises the price of fossil fuel consumption, encouraging emissions reductions and the transition to alternate fuels. However, determining a suitable cap is critical to efficacy.

3.2.2.1. Carbon price prediction

To ensure that a carbon pricing mechanism achieves its goals, the carbon price must be set at the 'optimal' level. There are multiple approaches to determining the 'optimal' level, depending on the goal of the carbon pricing mechanism. Since the goal here is to establish the carbon prices required to meet the set level of emission reduction, the most suitable approach is to employ target-consistent carbon prices. This is commonly done using techno-economic modelling and/or marginal abatement cost curves, which depict the relationship between overall GHG emission reduction and cost efficiency for particular abatement measures (Faber, Lee, et al., 2020). While there are still major uncertainties, this approach is thought to be more certain than establishing the social cost of carbon values (Rogelj & Shindell, 2019). A techno-economic analysis carried out by (Baresic et al., 2022) suggests that a carbon price of approximately USD 100/t CO_2 would be required in early 2030, to incentivise the transition into zero-emission fuels. As per a 2022 forecast by S&P Global, the carbon price for EU ETS would average USD 90.29/t CO_2 between 2022 – 2025 and USD 105.27/t CO_2 between 2026-2030 (Lin, 2022). A similar range of carbon prices is predicted by (Bloomberg, 2021) and (Simon, 2021). Based on the above predictions and forecasts we have considered the following carbon price scenario for our study.

Table 3-6: Carbon price predictions

Year	2024	2025	2026	2027	2028	2029	2030
USD / t CO_2	92.00	94.50	96.50	98.80	101.00	103.00	106.00

Source: S&P Global (Lin, 2022).

3.2.2.2. Revised Energy Taxation Directive

The present energy taxation directive (ETD) has technically been in effect since 2003, making it out of date and incompatible with the EU's climate goals. A revision to the ETD that also includes fuels from the maritime industry has been proposed as part of the Fit For 55 package. Maritime bunker fuel has been tax-free in the EU until now, but beginning in January 2023, all bunker fuel sold in the EU and consumed on voyages within the EU will be taxed. The directive establishes a minimum tax rate for each fuel category, with fossil fuels paying the highest (€10.75/GJ) and electricity, advanced sustainable biofuels and biogas, and renewable fuels paying the lowest (€0.15/GJ) (European Commission, 2021g). For maritime fuels, a minimum tax rate of €0.9/GJ is proposed, resulting in an additional USD 43/MT for LSMGO from 2023 onwards (Faber et al., 2021). Furthermore, sustainable, and alternative fuels will be tax-free for a transitional period of 10 years.

3.2.2.3. Potential Revenue generation

Since our purpose is to assess the impact of revenue cycling on the competitiveness gap between Hydrogen and fossil fuel (LSMGO), we have only considered the revenues generated by the similar type and sizes of vessels (container vessels of up to 40000 DWT) and operating within the EEA based on the EU MRV data published by European Commission.

The annual report on CO_2 emission from marine transport suggests that container vessels were responsible for the largest share of emissions which were 30% in 2019 and 31% in 2018 respectively. According to the findings of their analysis, smaller ships emit a greater proportion of their CO2 emissions during intra-EEA voyages. The study also confirmed that CO2 emissions from short-sea shipping are primarily associated with intra-EEA voyages (European Commission, 2021a). The Following figure shows the CO_2 emission per ship size and voyage type for the container vessels.

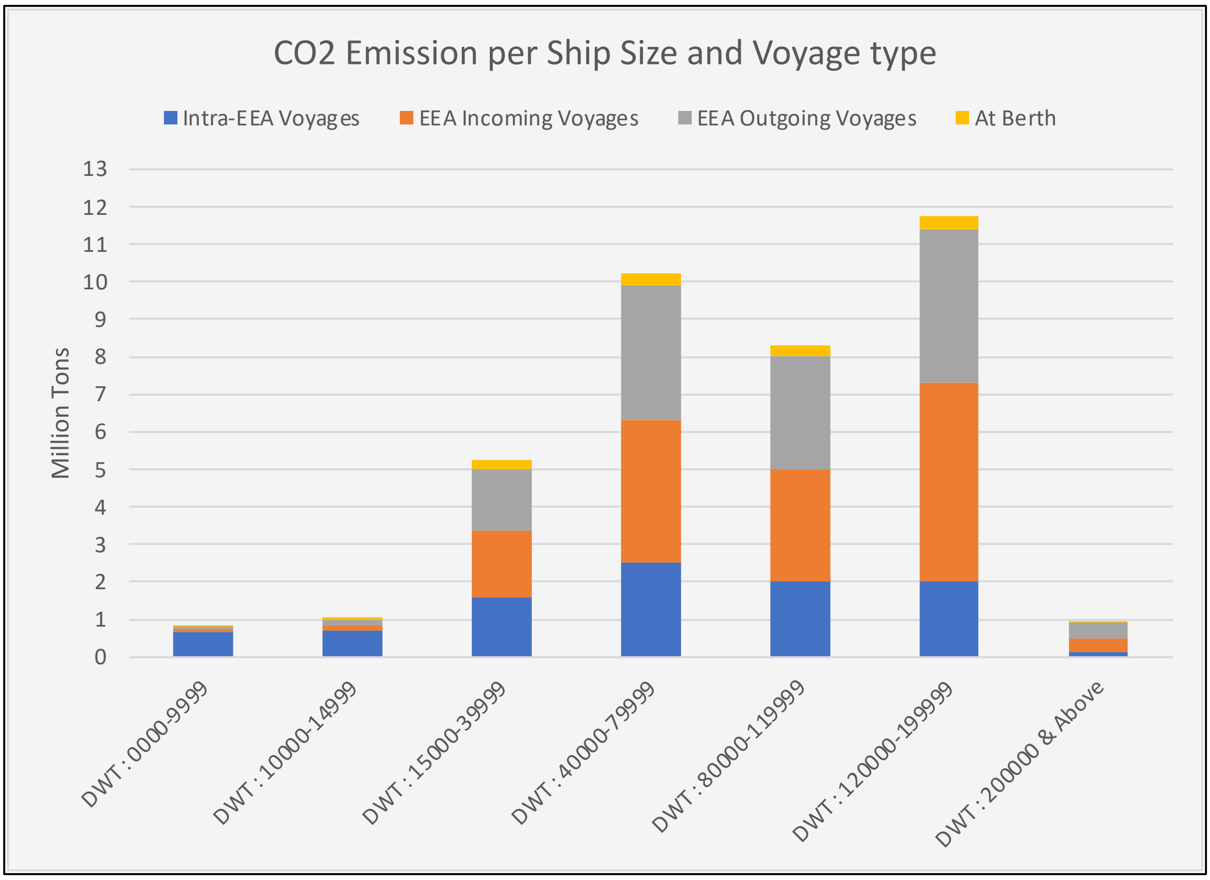


Fig. 3-1: CO2 emission per ship size and voyage type for container vessels. Adapted from (European Commission, 2020a)

The potential revenue generated is thus calculated as follows:

***Annual Revenue = Expected Carbon Price* X *Total Annual Emissions*…….. (3.10)**

Where,

Total Annual emissions (from similar ship sizes) can be calculated as:

Annual emissions from Intra-EEA voyages + Annual emissions at EEA berth

………. (3.11)

3.2.2.4. No. of ships transitioning away from fossil fuels every year

A carbon tax on the use of fossil fuels and subsequent revenue recycling for boosting the energy transition would provide an incentive to the ship owners to transition away from fossil fuels and start investing in alternative technologies such as Hydrogen.

To estimate the no. of vessels which would be decommissioned and replaced by Hydrogen powered vessels, we have used the following formula:

No. of vessels to be replaced = % of fleet older than 15 years* X *Total No. of similar size and type of vessels ………….. **(3.12)**

Our analysis is based on the EU MRV data for 2019 and the ships which are older than 15 years of age in 2019 will be over 25 years by the end of 2030. As per the 2020 annual EU MRV report published by European Commission, 11% of all container vessels that were reported in the EU MRV database for 2019 were over 15 years old. Considering this, we assume that at least 11% of the vessels of similar size and type (container vessels of up to 40000 DWT) would need to be replaced by the end of 2030. We have done so by replacing equal no. of vessels every year over the period of 2024-2030. This will also be in line with the FuelEU proposal which, if enforced, will limit the

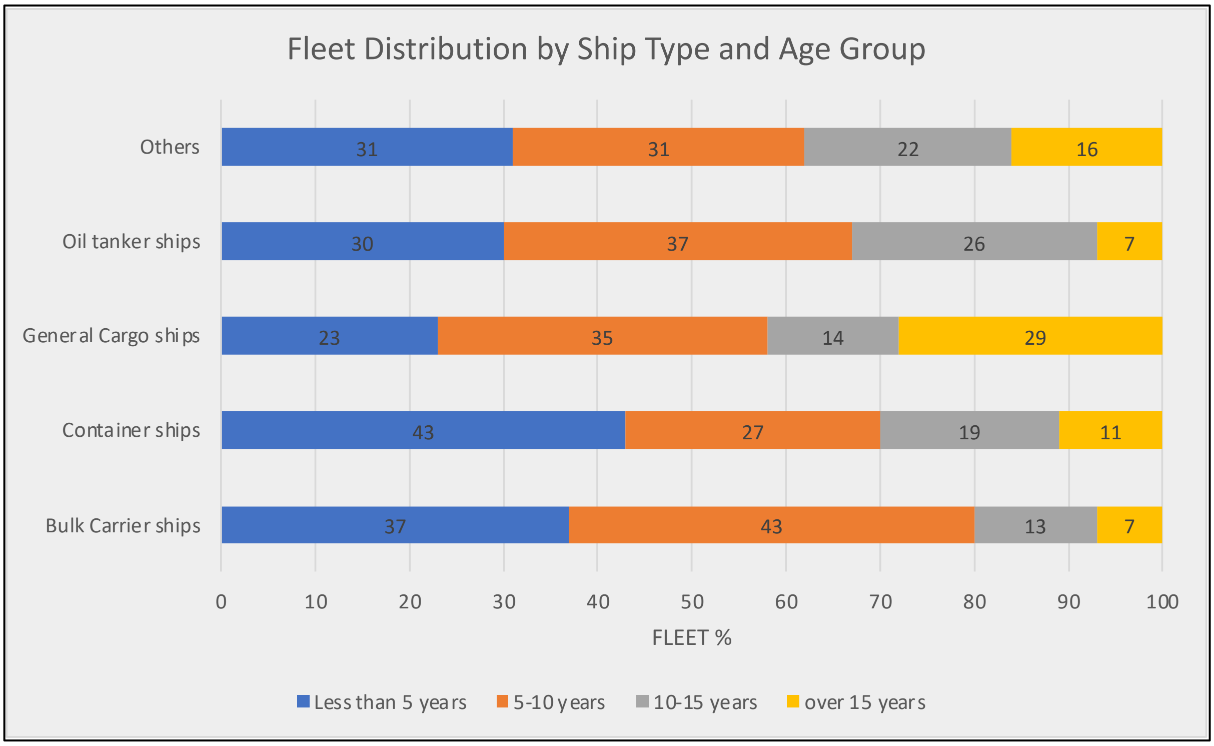


Fig. 3-2: Fleet Distribution by ship type and age group. *Adapted from* (European Commission, 2020).

GHG intensity of ship fuel by setting maximum limits by year with respect to the fleet average in 2020. The proposed limits in FuelEu are as follows: 2% by 2025, 6% by 2030, 13% by 2035, 26% by 2040, 59% by 2045, and 75% by 2050. The replacement is further discussed in the next section. Fig 3-2 shows the average fleet distribution by vessel types and age group.

Similarly, for estimating the no. of similar size and type of container vessels, we have used the following data from the same EU MRV annual report which shows the no. of container vessels as per vessel size and engine capacity as illustrated below:

Table 3-7: No. of container vessels as per ship size and engine capacity

	2018		2019	
DWT	Average engine power (kw)	No. of ships	Average engine power (kw)	No. of ships
0000-9999	7520	108	7302	104
10000-19999	9463	199	9397	215
20000-39999	17888	404	17841	392
40000-79999	40432	439	39978	408
80000-119999	56947	312	56704	305
120000-199999	60653	310	59570	350
200000 & above	59504	20	63970	27

Source: Adapted from (European Commission, 2020).

3.2.3. Revenue Recycling and its impact on the competitiveness gap

The competitiveness gap between hydrogen and fossil fuels can be narrowed or even closed by simultaneously increasing the costs of using fossil fuels (carbon pricing) and decreasing the costs of zero-emission fuels and related technologies (revenue recycling). The EU has proposed to direct ETS revenue from shipping to an Ocean Fund for low-carbon innovation initiatives, However, the current proposal does not guarantee that sufficient funding will be channelled to shipping to promote R&D and scale-up production of zero-carbon fuels and related technologies in shipping through supply-side policies. Given the EU ETS's inability to create a solid financial case for SZEF investment this decade, supply-side policies are critical for ensuring a cost-effective and efficient transition in the short timespan required to ensure zero emissions vessels enter service by 2030 (Parker et al., 2021).

Our analysis in section 3.1 finds that the Costs of green hydrogen and Hydrogen fuel cells are the two factors that greatly impact the cost competitiveness of hydrogen-powered vessels and must be brought down to facilitate the transition. In this section, we will assess how the revenues generated from the economic instrument (Carbon price) can best be used to fund the investments required for making hydrogen-powered vessels economically viable by 2030. For doing this, we will first estimate the amount of investment required to reduce the costs of green hydrogen as well as hydrogen fuel cells. We will then assess the potential of revenue recycling for funding these investments. This section addresses the fourth sub-research question of our study.

3.2.3.1. Green hydrogen cost reduction and Investment required

In terms of decarbonisation, hydrogen produced from fossil fuels without capturing the CO2 emissions does not meet the criterion of renewable energy, although accounting for the majority of hydrogen production today and green hydrogen is the key to environment-friendly shipping. For a long time, it was regarded to be an unaffordable option, but society has begun to recognize that if we want to avoid climate change, there are no real alternatives. This realization has only been accelerated by recent geopolitical developments. The good news is that the cost of green hydrogen has begun to reduce, and in the long term, it will most certainly fall below the cost of today's fossil alternatives (de Groot, 2022). However, green hydrogen is still 2-3 times more expensive than blue hydrogen, which is produced from fossil fuels with carbon capture and storage. As a result, additional cost reductions are required.

The main cost drivers of green hydrogen are Electrolyser Capex, Plant efficiency and the cost of renewable electricity (Blanco & Maigret, 2022) . The cost of the renewable electricity required to run the electrolyser unit on-site represents the single highest cost component. Therefore, the low cost of electricity is a requirement for producing cost-competitive green hydrogen. Low electricity costs alone, however, are insufficient for competitive green hydrogen production, and electrolysis facility costs, which make up the second largest cost element, must also be reduced (IRENA, 2020). An aggressive electrolyser deployment pathway, when combined with low energy costs, can make green hydrogen cheaper than any low-carbon alternative before 2040. Green hydrogen is forecasted to become competitive with blue hydrogen by 2030 if rapid scale-up occurs over the following decade (IRENA, 2020).

A. Investment required for Electrolyser's cost reduction

Increasing stack production to GW-scale manufacturing facilities can result in significant cost savings. The stack accounts for around 45% of the total cost at lower production rates, although it can be reduced to 30% at higher production rates. This scale-up allows for a cost reduction of about 50% in stack manufacturing (IRENA, 2020). Also, the cost of the associated plant is just as essential as the cost of the electrolyser stack, and savings can be achieved by standardizing system components and plant design. However, the cost is not the only issue dictating plant size because each technology has its unique stack design that varies between manufacturers. The application that drives system performance in areas such as efficiency and flexibility also influence optimal system design.

The "Hydrohub" project (Hydrogen Hub, 2022) has developed an advanced concept for a GW-scale green-hydrogen plant that would employ alkaline water electrolysis (AWE) and would be built and operational in a Dutch port region by 2030. This project demonstrates that the predicted total investment cost levels for AWE of 730 €/kW are within reach (ISPT, 2022). Thus, the CAPEX required will be roughly half that of the 2020 state-of-the-art design. This is based on available operating hours in accordance

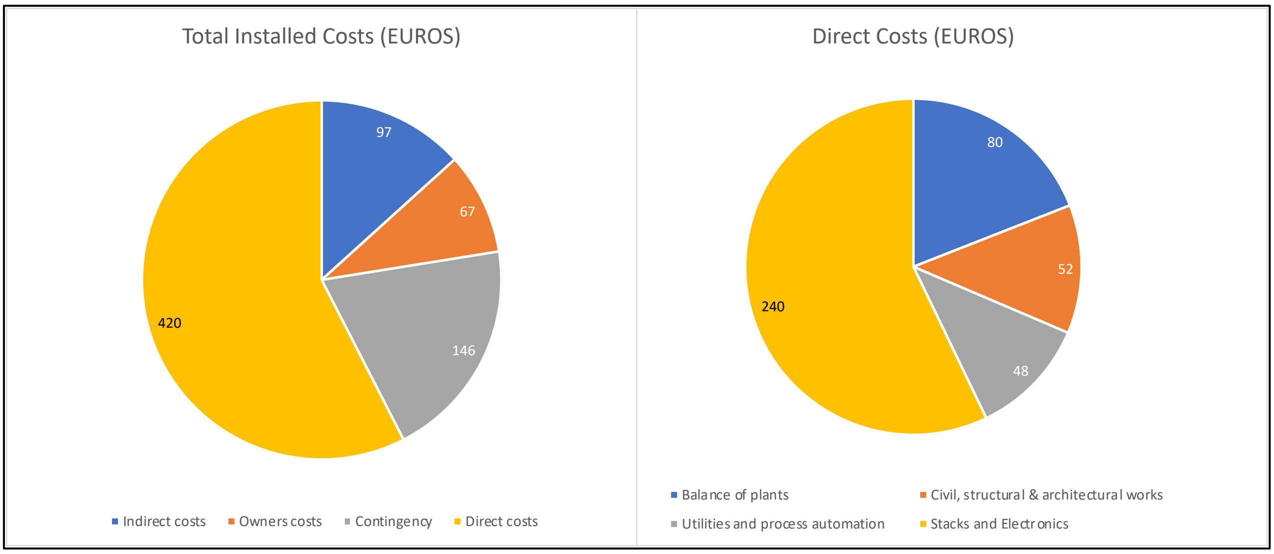


Fig. 3-3: Total installed costs and direct costs breakdown for a GW-Scale Green Hydrogen plant in the EU. *Adapted from* (ISPT, 2022).

with the wind pattern (4,000 full load h/a), needed availability of 94%, and system efficiency. The estimated efficiency at full load is around 98%. Fig. 3-3 exhibits a more extensive breakdown of total installed costs, separating direct costs from total installed costs, which include indirect costs, owner charges, and contingency.

B. Investment required for scaling up Renewable Electricity

As discussed in the previous section, Electricity produced from Renewable sources is the major cost component of green hydrogen. A study carried out by the International Renewable Energy Agency shows that The Levelized cost of electricity for onshore wind is becoming competitive and expected to decline further to a price of USD 0.03/kWh by 2030 and USD 0.02/kWh by 2050 (IRENA, 2019). The "Hydrogen generation in Europe" study carried out by European Commission further suggests that the investment required for achieving this cost in 2030 would be 0.704 million EUR/MW (European Commission, 2020b). This would require a total amount of € 704 million for the beforementioned 1 GW electrolysis plant with an efficiency of 98% as given by (ISPT, 2022).

3.2.3.2. Green Hydrogen price in accordance with the above developments

Cost of renewable hydrogen with varying LCOE and load factors USD/kg H2

< USD 2/kg | USD 2-3/kg | USD 3-4/kg | > USD 4/kg | Viable medium-term (<2030)

LCOE / Capex electrolyser	USD 750/kW					USD 500/kW					USD 250/kW				
UDD 0/MWh	5.7	2.8	1.9	1.4	1.1	4.2	2.1	1.4	1.1	0.9	2.8	1.4	0.9	0.7	0.6
USD 10/MWh	6.1	3.3	2.4	1.9	1.6	4.7	2.6	1.9	1.5	1.3	3.2	1.9	1.4	1.2	1.0
USD 20/MWh	6.6	3.8	2.8	2.4	2.1	5.2	3.0	2.3	2.0	1.8	3.7	2.3	1.9	1.6	1.5
USD 30/MWh	7.1	4.2	3.3	2.8	2.5	5.6	3.5	2.8	2.5	2.2	4.2	2.8	2.3	2.1	2.0
USD 40/MWh	7.5	4.7	3.8	3.3	3.0	6.1	4.0	3.3	2.9	2.7	4.6	3.2	2.8	2.6	2.4
USD 50/MWh	8.0	5.2	4.2	3.7	3.5	6.5	4.4	3.7	3.4	3.2	5.1	3.7	3.2	3.0	2.9
USD 100/MWh	10.3	7.5	6.5	6.1	5.8	8.9	6.7	6.0	5.7	5.5	7.4	6.0	5.6	5.3	5.2
Load factor	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%

Fig 3-5: Renewable hydrogen from electrolysis production cost scenarios. *Source:* (Hydrogen Council, 2020a).

By scaling up the electrolysers and Renewable electricity generation plants, the cost of green hydrogen will drop faster than anticipated. In the previous sections, we saw that the cost of electrolysers can be reduced to a price of USD 250/kW by 2030. Also, renewable electricity could be produced at a price of USD 30/MWh in 2030.

Figure 3-5 depicts an info graph outlining the cost parameters and resulting hydrogen pricing estimates (Hydrogen Council, 2020a). Based on our findings on the electrolyzer and renewable electricity costs, we have estimated the cost of hydrogen production in 2030 using this model.

Using the electrolyser price of USD 250/kW and the levelized cost of electricity for onshore wind as USD 30/MWh, we can conclude that the cost of green hydrogen in 2030 would be USD 2/Kg H_2. Considering the expected green hydrogen price of USD 5/Kg H_2 in 2023, we have interpolated the costs in the years between 2023-2030 (see appendix: 5) as follows.

Table 3-8: Expected Green Hydrogen costs

Year	2023	2024	2025	2026	2027	2028	2029	2030
Price ($/kW)	5.00	4.60	4.15	3.70	3.30	2.85	2.40	2.00

Source: Author's Calculations

3.2.3.3. Hydrogen fuel cell cost reduction and Investment required

The expected key cost-cutting driver for the fuel cell stack and system is economies of scale. Improvements in performance and material innovation are also likely to play a significant role in cost reduction (APCUK, 2022). To date, major improvements have been achieved by technological innovations and product enhancements. Manufacturers might save 60-65% on fuel cell costs with even a slight increase in annual manufacturing volumes (Pocard Nicolas, 2022). Such cost savings will be generated mostly by the industrialisation of the fuel cell system, because, unlike batteries, fuel cells are generally unreliant on commodities. Instead, fuel cell systems are mostly made of carbon, steel, and aluminium elements (Pocard Nicolas, 2022).

TECO 2030 is currently constructing a hybrid innovation centre and factory in Narvik, northern Norway, where they will manufacture hydrogen fuel cells. The TECO 2030 Innovation Centre in Narvik will be Norway's first large-scale hydrogen fuel cell production facility. TECO 2030 estimates total investments in the Narvik facility to reach USD 100 million over the next ten years (Hellenic Shipping News, 2021). The following table exhibits the production output and costs per kW over the years as reported by (TECO 2030, 2022).

Table 3-9: Expected production output and price for hydrogen fuel cell

Year	2023	2024	2025	2026	2027	2028	2029	2030
Production output (MW)	15	120	400	800	900	1000	1200	1600
Price ($/kW)	1500	1440	1140	960	900	840	780	720

Source: Adapted from (TECO 2030, 2022).

3.2.3.4. Subsidy on Capex for hydrogen-powered vessel

Although the prices for green hydrogen and hydrogen fuel cells are expected to fall in the coming years, they will take at least a few years till they come into effect as the green hydrogen production plants, renewable energy plants as well as hydrogen fuel cell production facilities need some time to scaleup and operate at their required efficiency rate. This means that ship owners will not find it profitable to invest in hydrogen-powered vessels. As discussed in section 3.2.2.4, the ship owners need to replace a part of their fleet which is already older than 15 years with hydrogen-powered vessels. Hence, in order to incentivise the ship owners to invest in hydrogen-powered vessels in the years when the competitiveness gap is still significant, we will need to give subsidies on their investment in the new builds. These subsidies will be given from the same revenues that are generated from carbon pricing.

4. Results and analysis

This section presents the results and findings of the study. The results are categorised in order to address the sub-research questions of the study. First, we estimate the existing competitiveness gap between hydrogen and LSMGO at the current rate of technological development and existing policy measures and identify the major cost drivers for this Gap. We then assess the impact of policy measures and estimate the amount of revenues that can be generated through these Market-Based Measures. We then go on to assess the potential of revenue recycling for closing the competitiveness gap.

4.1. Competitiveness Gap at the current rate of technological development and existing policy measures

Our analysis suggests that, at the current rate of technological development and with existing policy measures, there exists a huge competitiveness gap between hydrogen and conventional marine fuel (LSMGO). This gap, although appears to narrow down in the future but not to the extent that hydrogen can become an economically viable alternative zero-emission fuel by 2030. The abatement cost per MT of CO_2 emission in 2030 is still more than USD 200 which translates into an additional USD 640/MT on the price of conventional fuel oil as illustrated in the following figure.

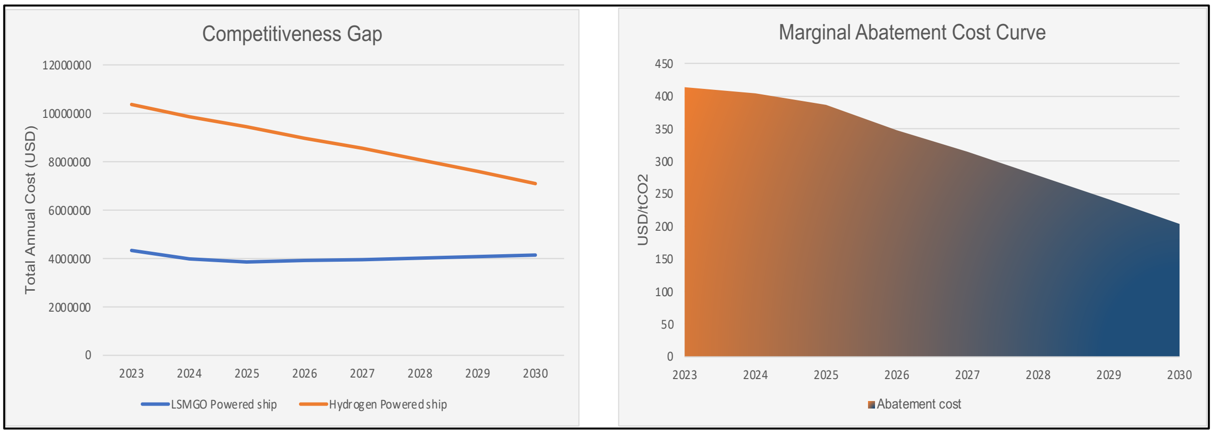


Fig. 4-1: Competitiveness Gap and Marginal abatement cost curve under existing policy measures and the Natural rate of technological development. *Source: Author*

This calculation is based on the comparison of total annual costs of owning and operating a 2000TEU container vessel operating within the EU Ports. Total annual costs include the Fuel cost as OPEX and Equivalent Annual cost (EAC) of assets as CAPEX as explained in sections 3.1.2 and 3.1.3. While comparing these costs, our analysis shows that both the CAPEX and OPEX for hydrogen-powered vessels are significantly higher than that of LSMGO-powered ships. The cost difference is found to be reducing over time but that is mainly because of the expected decrease in the cost of green hydrogen and the CAPEX difference is still significant in 2030 hindering the adoption of Hydrogen as an alternative marine fuel.

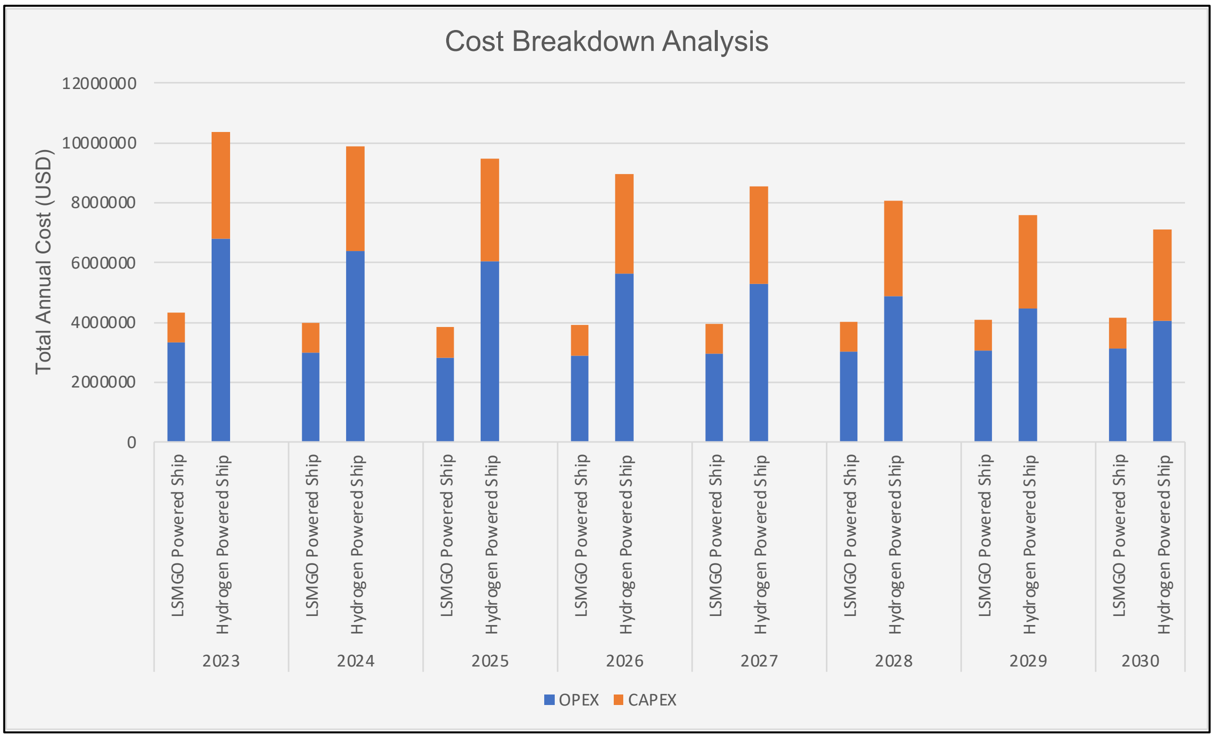


Fig. 4-2: Cost breakdown Analysis for both types of vessels over the years.
Source: Author

The above comparison highlights the pressing need for rapid scale-up of technologies and policy intervention to support an efficient and cost-effective transition. The scaling up of technology combined with strict policy measures will boost both the supply and demand side of hydrogen as an alternative fuel.

4.2. Impact of Market-Based Measures on the competitiveness gap

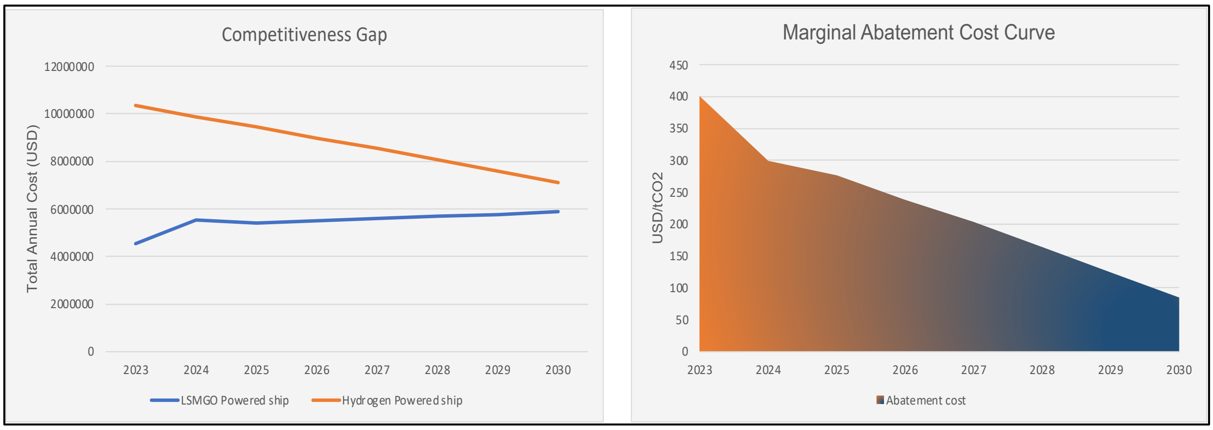


Fig. 4-3: Competitiveness Gap and Marginal abatement cost curve after implementation of MBMs. *Source: Author*

As illustrated in Fig 4-3, our analysis shows that the EU's decision of including shipping into the EU ETS combined with the revised Energy Taxation Directive (ETD) significantly affects the competitiveness gap between hydrogen and conventional marine fuel. As proposed by the European Commission, shipping will be included in the EU ETS in 2024 which is illustrated in the above graphs as a sudden increase in the total annual costs of LSMGO-powered vessels, thus reducing the competitiveness gap and resulting in the lower abatement cost. This is further explained below with the help of a cost breakdown analysis (Fig. 4-4).

The inclusion of shipping into EU ETS combined with the revised ETD increases the cost of conventional fossil fuel resulting in higher OPEX for our analysis. The analysis further suggests that although the Market-Based Measures result in a narrowed competitiveness gap between hydrogen and conventional marine fuel, these measures are not enough to facilitate the transition into hydrogen fuels in a cost-effective manner. The abatement cost per MT of CO_2 emission in 2030 for this scenario is still USD 85 which translates into an additional USD 272/MT on the price of conventional fossil fuel.

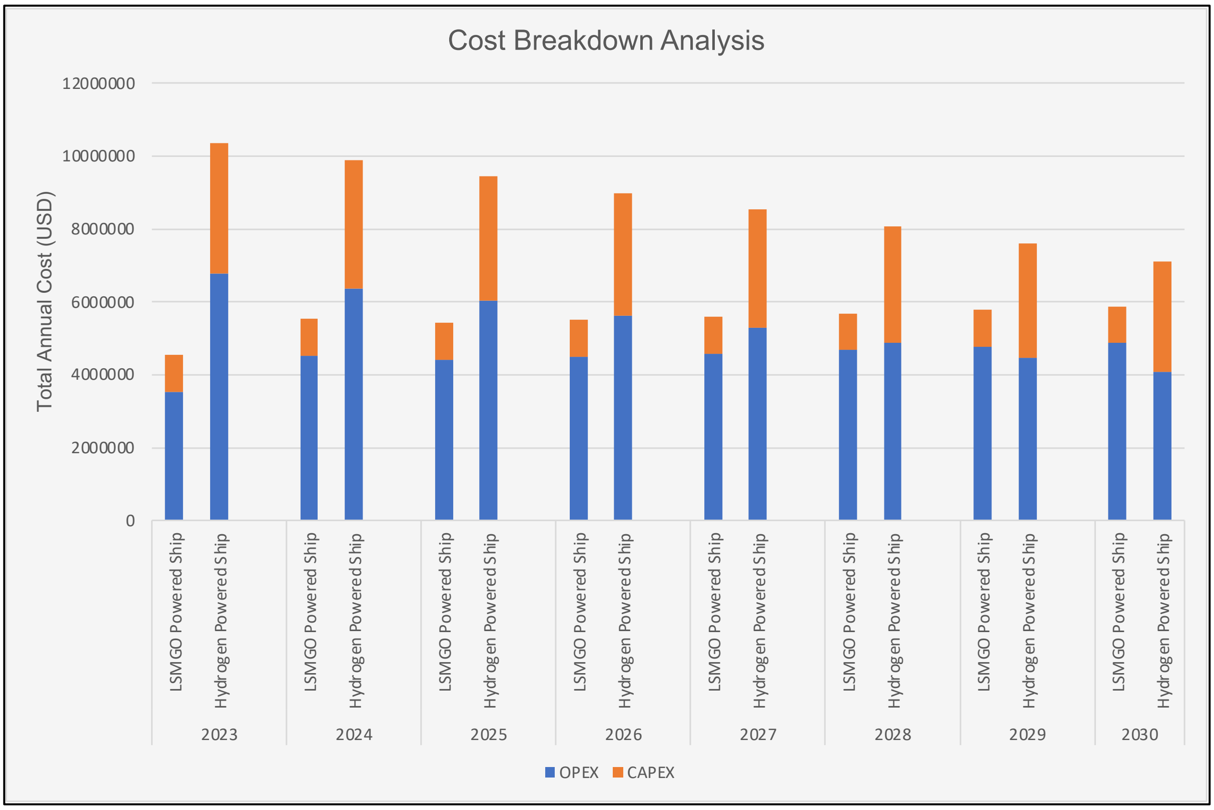


Fig. 4-4: Cost breakdown Analysis for both types of vessels after the implementation of MBMs. *Source: Author*

4.3. Potential Revenue Generation from Market-Based Measures

The carbon price not only penalizes polluters using fossil fuels but also generates a significant amount of revenue. Fig. 4-5 illustrates the potential revenues generated from similar types of vessels as explained in section 3.2.2.3 using equations (3.10) and (3.11). The revenues are calculated based on the total emissions by the whole fleet of similar types of vessels while sailing as well as when at berth as per the EU MRV data.

Although the Carbon price is expected to rise every year, the CO_2 emissions and the resulting revenues follow a downward trend because of the transitioning away of vessels older than 15 years from LSMGO and being replaced by Hydrogen-powered vessels as explained in section 3.2.2.4.

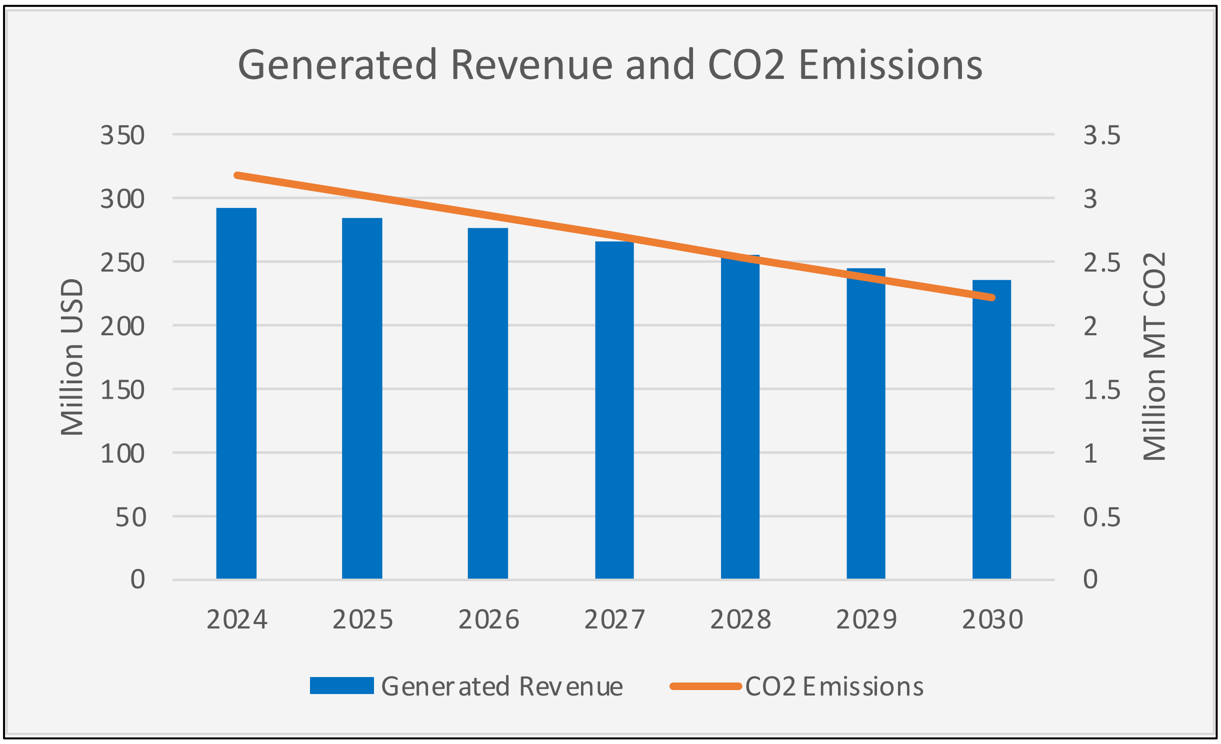


Fig. 4-5: Cost breakdown Analysis for both types of vessels after the implementation of MBMs. *Source: Author*

4.4. Revenue recycling for closing the Competitiveness Gap

As discussed in section 3.2.3, The competitiveness gap between hydrogen and conventional fossil fuel can be narrowed or even closed by simultaneously increasing the costs of using fossil fuels (carbon pricing) and decreasing the costs of zero-emission fuels and related technologies (revenue recycling). We have analysed the impact of revenue recycling by investing back the revenue generated through MBMs into the research and innovations required for scaling up the Hydrogen to be used as an alternative marine fuel. Our analysis in the previous sections shows that both the CAPEX as well as OPEX for hydrogen-powered vessels are high enough to hinder the uptake of hydrogen. Studies carried out by various market players and experts suggest that scaling up the electrolysers and renewable electricity as well as increasing the production volume of Hydrogen fuel cells combined with some innovation in designs have the potential of reducing the costs significantly as explained in section 3.2.3. Our analysis for the same shows that recycling back the revenues results in sharp reductions in both CAPEX as well as OPEX of the hydrogen-powered vessel as illustrated below in Fig. 4-6.

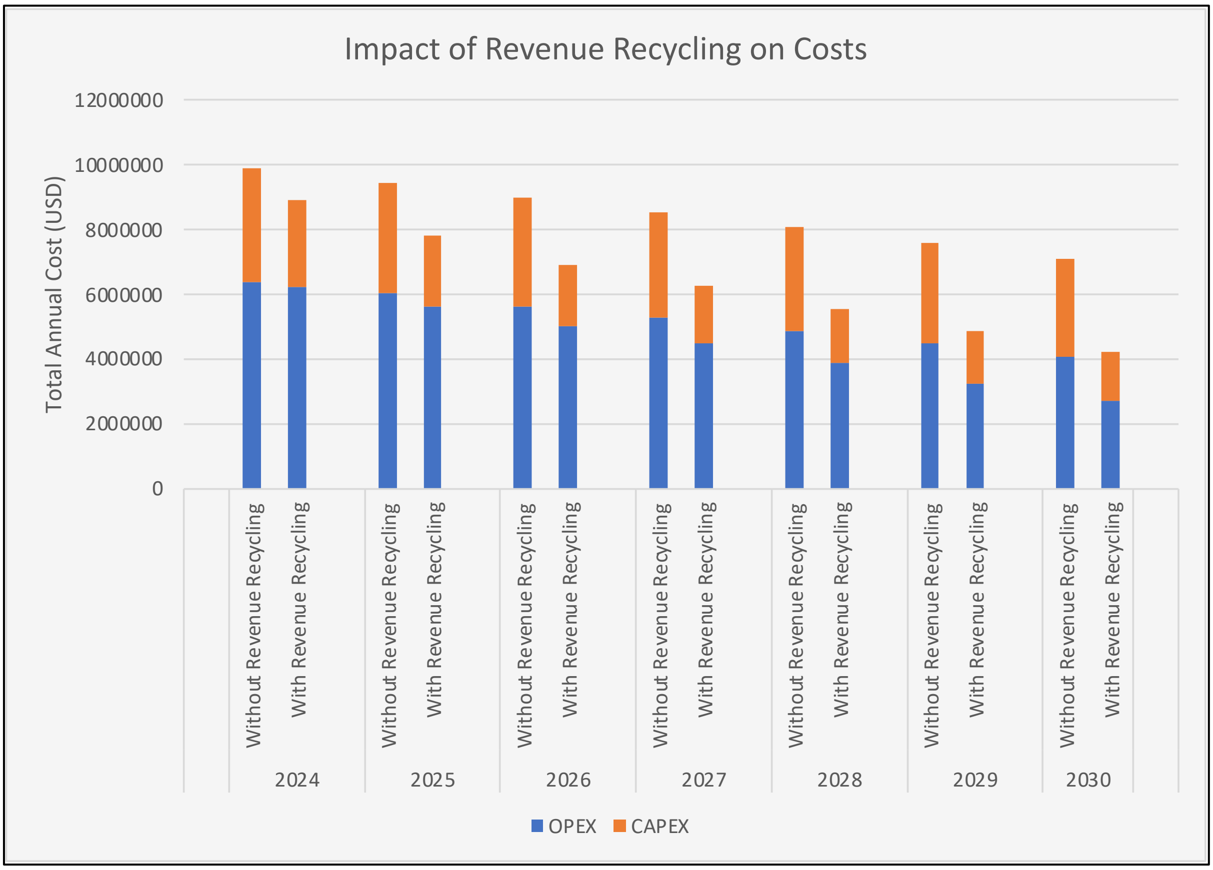


Fig. 4-6: Cost breakdown Analysis for Hydrogen-Powered vessels with and without revenue recycling. *Source: Author*

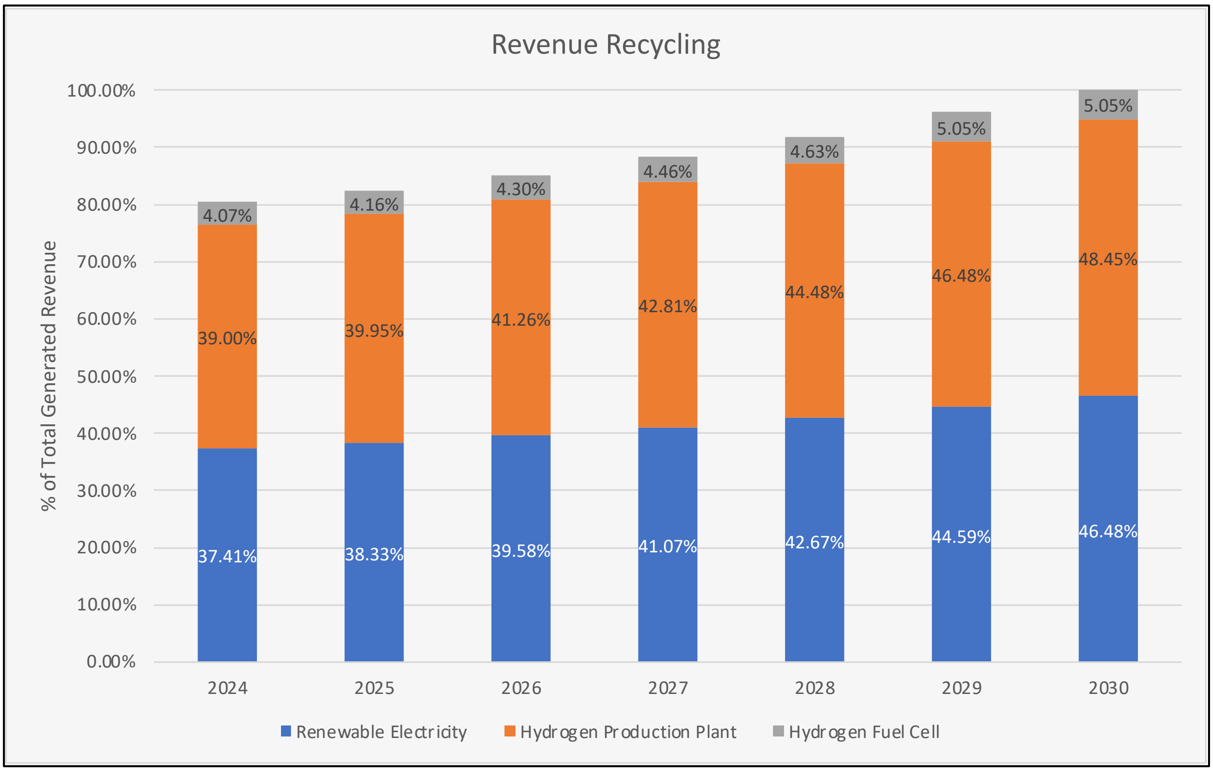


Fig. 4-7: Shares of total revenue invested back for scaling up different technologies. Source: Author

Fig.4-7 above, shows the shares of total revenues required to be invested back for scaling up Hydrogen and related technologies for bringing down the total annual cost of owning and operating hydrogen powered vessels. We found that investing 88% of the total revenues generated only from similar types of vessels can drastically reduce the costs and make hydrogen-powered vessels cost-competitive before 2030.

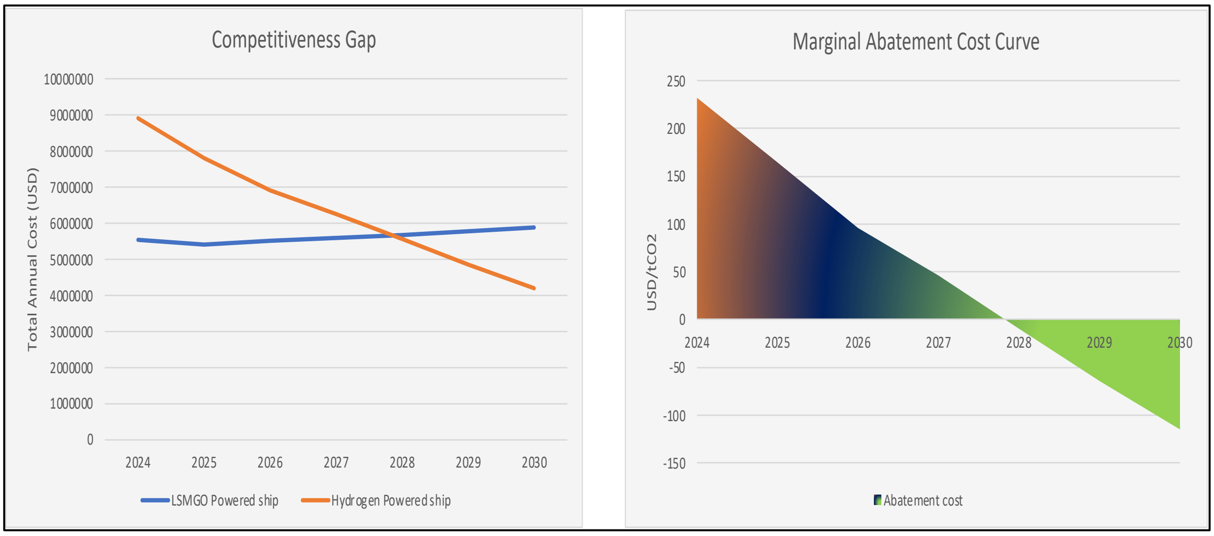


Fig. 4-7: Competitiveness Gap and Marginal abatement cost curve after 88% revenue recycling. *Source: Author*

We found that the competitiveness gap can be narrowed down and eventually closed by 2028 as illustrated in Fig. 4-7. We see that in 2028 and after, the cost of owning and operating Hydrogen-powered vessels will be lesser than that of LSMGO-powered vessels

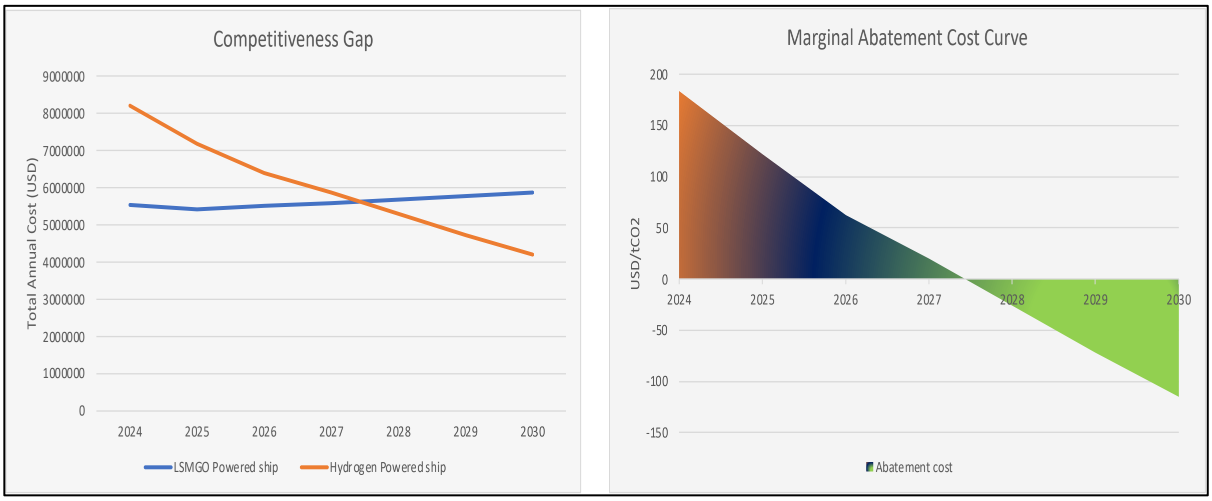


Fig. 4-8: Competitiveness Gap and Marginal abatement cost curve after 100 % revenue recycling. *Source: Author*

Our analysis further suggests that by investing the remaining revenues as CAPEX subsidies to the ship owners, the competitiveness gap can be closed even earlier as illustrated in Fig. 4-8.

4.4.1. Sensitivity to Green Hydrogen Price

Green hydrogen price is one of the main cost drivers for Hydrogen-powered vessels. Hence, it is important to assess the impact of variation in expected green hydrogen prices. We carried out a sensitivity analysis with a +/- 10% change in the expected green hydrogen price. Our analysis shows that hydrogen still remains cost competitive in early 2028 even with a 10% higher expected carbon price. Also, if the green hydrogen price reduces further 10% than the expected price, hydrogen-powered vessels can become cost competitive in late 2027 as illustrated in Fig 4-9 below.

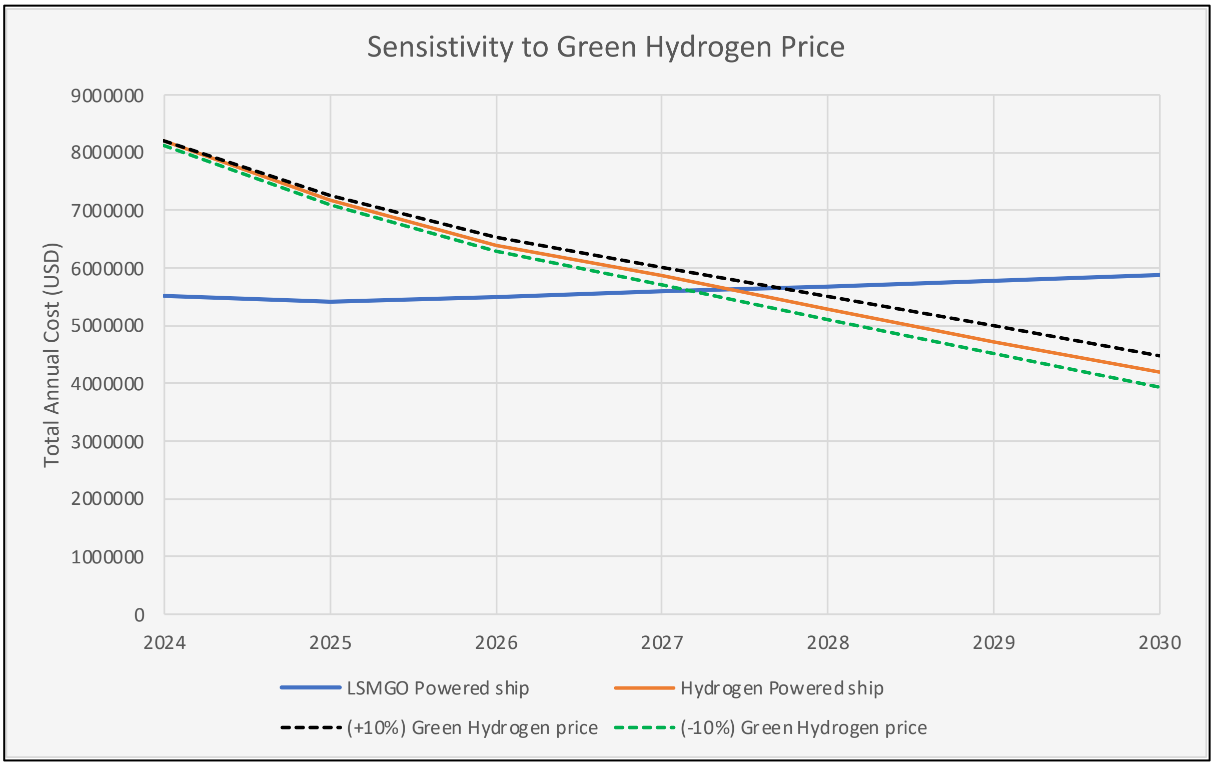


Fig. 4-9: Competitiveness Gap with +/-10% change in green hydrogen price.
Source: Author

4.4.2. Sensitivity to Hydrogen fuel cell price

Hydrogen fuel cell price is the most significant cost driver for hydrogen-powered vessels and is the reason behind the high CAPEX of these types of vessels. We carried out an analysis with a +/-10% variation in expected Hydrogen fuel cell prices.

Our analysis shows that a Hydrogen-powered vessel retains its position of being a cost-competitive zero-emission alternative in 2028 even with 10% higher than anticipated hydrogen fuel cell prices. Our analysis further suggests that if the hydrogen fuel cell price can be reduced a further 10%, the Hydrogen-powered vessels can become cost competitive before the end of 2027.

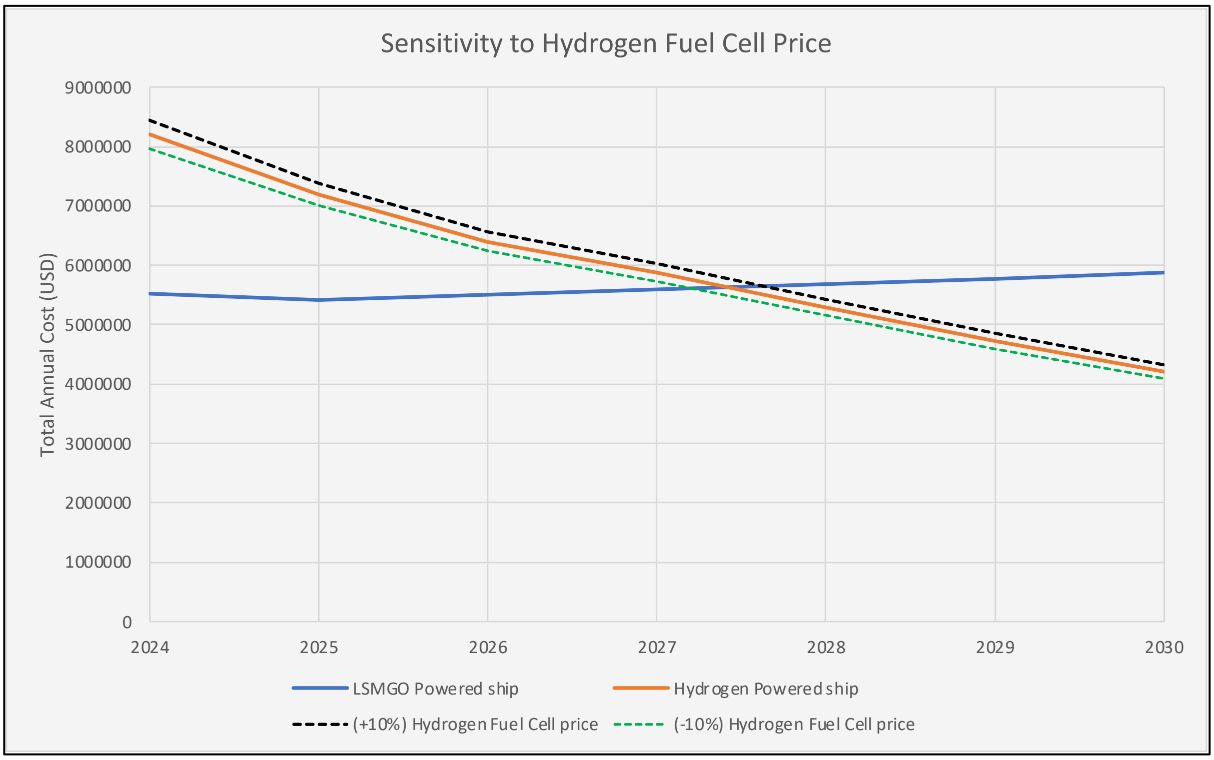


Fig. 4-10: Competitiveness Gap with +/-10% change in green hydrogen price.
Source: Author

5. Conclusion and Recommendations

To accomplish the ambitious goals of the IMO's initial strategy for the reduction of GHG emissions from ships, the industry needs to transition to zero-carbon fuel alternatives, and hydrogen is one of the potential alternatives under consideration for a clean energy mix of the decarbonised shipping industry. Studies suggest that zero-emission vessels must need to be entering into service by 2030 and should constitute a significant part of new builds if shipping has to meet its ambitious GHG reduction strategy in line with the Paris agreement (Lloyd's Register and UMAS, 2019). Although hydrogen has all the potential to be an ideal alternative marine fuel, a few obstacles need to be overcome, such as complex storage requirements and fire risk reduction. However, the experience from the LNG shipping industry of handling high-pressure and cryogenic liquids can be used for further developments in technology and regulations. Its low volumetric density requires a larger fuel volume to be stored onboard which may require a trade-off between some cargo spaces. Also, hydrogen can only be considered carbon neutral if it is green, which means it has been produced using renewable sources. In order to become a competitive alternative, hydrogen faces challenges in terms of availability and high cost. There is a significant competitiveness gap between hydrogen and conventional fossil fuels which requires additional R&D, innovative technologies, production scale-up, a reduced cost of renewable electricity and hence, additional Investments (Baresic et al., 2022). As a result, effective policy measures are required to close this competitiveness gap to support a cost-effective and efficient transition.

Our analysis suggests that, at the current rate of technological development and with the existing policy measures, the abatement cost per ton of CO_2 emissions using Hydrogen in 2030 is still more than USD 200 which translates to an additional USD 640/MT on the price of conventional fuel oil. The analysis further suggests that by implementing a carbon price, this gap can be lowered but not completely closed by 2030. By including the shipping industry in the EU ETS, as proposed by the European Commission, the competitiveness gap significantly reduces but the abatement cost per MT of CO_2 emissions in 2030 is still USD 85 which translates into an additional USD 272/MT on the price of conventional fossil fuel. However, carbon pricing does generate a significant amount of revenue which can be recycled back into the maritime industry to mitigate its economic burden for an effective and efficient transition. These potential revenues can be invested into R&D and innovation for scaling up Hydrogen and related technologies.

Our analysis suggests that combining the Market-Based measures with revenue recycling policies can lead to hydrogen-powered vessels becoming cost competitive even before 2030. We found that recycling 88% of the total revenues generated from only similar types of vessels can make hydrogen cost-competitive by 2028. Also, by recycling 100% of the revenues, this goal can be achieved even before the end of 2027. We also carried out a sensitivity analysis to assess a +/- 10% change in expected green Hydrogen and Hydrogen Fuel Cell prices over time and the results remained the same.

Our study shows that by designing and effectively implementing the right policy measures, zero-emission vessels such as hydrogen-powered vessels can become a reality even before 2030. However, to fully realise their potential, green hydrogen production and fuel cell manufacturing must be scaled up, and the necessary regulatory framework developed which requires joint efforts from various stakeholders. The scaling up of technology combined with effective policy measures will boost both the supply and demand side of hydrogen as an alternative fuel. Also, the existing fossil fuel companies, with their extensive capabilities, resources, and project management expertise, will play a crucial role in developing hydrogen as an alternative fuel. We must not forget that even the conventional bunker fuel and the so-called efficient marine diesel engines were not gifted to us naturally. They were developed over time to the form in which they exist now and are widely used for our benefit. Hence, instead of finding a 'perfect' alternative, the stakeholders must come together and develop them to the required specification, especially now, when it is almost certain that we are going to have a clean energy mix and not just one fuel for the maritime industry unlike conventional marine fuel.

5.1. Limitations of the study

Although our study proves the potential of hydrogen to become a cost-effective alternative fuel by 2030, we must acknowledge that this study is also based on certain assumptions which can significantly affect the findings of our research. The LSMGO price and the Carbon price are based on historical trends as well as future outlooks, which can change significantly depending on the economic and environmental policies as well as the ongoing changes in geopolitical scenarios.

Also, the analysis does not take into account the elasticity of the shipping industry and its reaction to certain policies like carbon pricing and fuel mandate. Moreover, we have taken only certain MBMs and regulatory approaches into account for closing the gap which is again questionable as the economists and political stalwarts point to the necessity and benefits of implementing a much more diverse policy mix.

Further, to estimate the investments required to scale up the production of green hydrogen, our study is based on an onsite production facility which does not take into account the associated costs for transportation and storage. However, this may not always be possible, and transportation and storage facilities combined with the bunkering infrastructure will also remain important factors in facilitating the uptake of hydrogen as an alternative zero-emission fuel.

5.2. Scope for Further Research

More research is needed to identify and assess how multiple policy alternatives, both supply and demand-side, could be implemented in the maritime sector to enable not only an effective but also an equitable transition to zero-emission fuels within the required timeframe as decarbonisation should not become a process that exacerbates existing inequalities when, with good planning, decarbonisation policy may be used to reduce current inequalities.

Bibliography:

Abraham, N. (2021). *Benchmarking the Performance of Alternative Fuels on Container Vessels*.

ABS. (2021). *HYDROGEN AS MARINE FUEL*. https://maritimecyprus.com/wp-content/uploads/2021/06/ABS-hydrogen-as-marine-fuel.pdf

Acciaro, M. (2014). A real option application to investment in low-sulphur maritime transport. *International Journal of Shipping and Transport Logistics*, *6*(2), 189–212. https://doi.org/10.1504/IJSTL.2014.059570

APCUK. (2022). *Reducing the cost of fuel cells: how can it be done? Conclusions on cost reduction potential of a light duty hydrogen fuel cell system*. https://www.apcuk.co.uk/app/uploads/2022/07/Reducing-the-cost-of-fuel-cells-how-can-it-be-done-report.pdf

Appunn, K. (2021). *Understanding the European Union's Emissions Trading System (EU ETS) | Clean Energy Wire*. https://www.cleanenergywire.org/factsheets/understanding-european-unions-emissions-trading-system

Aronietis, R., Sys, C., van Hassel, E., & Vanelslander, T. (2016). Forecasting port-level demand for LNG as a ship fuel: the case of the port of Antwerp. *Journal of Shipping and Trade*, *1*(1). https://doi.org/10.1186/S41072-016-0007-1

Bahtic, F. (2021). *World's first hydrogen-powered ships one step closer to reality - Offshore Energy*. https://www.offshore-energy.biz/worlds-first-hydrogen-powered-ships-one-step-closer-to-reality/

Ban Ki-moon. (2016). *Maritime Transport Is 'Backbone of Global Trade and the Global Economy', Says Secretary-General in Message for International Day | UN Press*. https://press.un.org/en/2016/sgsm18129.doc.htm

Baresic, Rojon, Shaw, & Rehmatullah. (2022). *Closing the Gap: An Overview of the Policy Options to Close the Competitiveness Gap and Enable an Equitable Zero-Emission Fuel Transition in Shipping Closing the Gap: An Overview of the Policy Options to Close the Competitiveness Gap and Enable an Equitable Zero-Emission Fuel Transition in Shipping*. www.u-mas.co.uk

Blanco, H., & Maigret, J. (2022). *Global map of the future cost of clean Hydrogen production in 2030 and 2050 - Energy Post*. https://energypost.eu/global-map-of-the-future-cost-of-clean-hydrogen-production-in-2030-and-2050/

Bloomberg. (2021). *Europe CO2 Prices May Rise More Than 50% by 2030, EU Draft Shows - Bloomberg*. https://www.bloomberg.com/news/articles/2021-06-29/europe-co2-prices-may-rise-more-than-50-by-2030-eu-draft-shows#xj4y7vzkg

Bob, I., Albrecht, J., & Behaeghel, W. (2021). *ASSESSMENT OF THE FUTURE POTENTIAL OF HYDROGEN WITH A FOCUS ON ITS ROLE IN THE DECARBONISATION OF SHIPPING*.

Bradley Beth, & Hoyland Rachel. (2022). *Decarbonisation and shipping: EU Emissions Trading Scheme – Update (June 2022) | Hill Dickinson*. https://www.hilldickinson.com/insights/articles/decarbonisation-and-shipping-eu-emissions-trading-scheme-%E2%80%93-update-june-2022

Burgess, J. (2022). *European Hydrogen Backbone sees enough supply to surpass EU 2030 targets | S&P Global Commodity Insights*. https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/electric-power/060122-european-hydrogen-backbone-sees-enough-supply-to-surpass-eu-2030-targets

Castigliego Joshua. (2021). *The "Colors" of Hydrogen — Applied Economics Clinic*. https://aeclinic.org/aec-blog/2021/6/24/the-colors-of-hydrogen

de Groot, T. (2022). *Five drivers of cost reduction in green hydrogen production*. https://hydrogentechworld.com/five-drivers-of-cost-reduction-in-green-hydrogen-production

Deloitte. (2020). *Decarbonizing Shipping: All Hands on Deck | Deloitte global*. https://www2.deloitte.com/global/en/pages/energy-and-resources/articles/decarbonising-shipping.html

Deloitte. (2022). *Oil and gas price forecast Strategic transitioning: The future of oil and gas in a decarbonized world*.

Deniz, C., & Zincir, B. (2016a). Environmental and economical assessment of alternative marine fuels. *Journal of Cleaner Production*, *113*, 438–449. https://doi.org/10.1016/J.JCLEPRO.2015.11.089

Deniz, C., & Zincir, B. (2016b). Environmental and economical assessment of alternative marine fuels. *Journal of Cleaner Production*, *113*, 438–449. https://doi.org/10.1016/J.JCLEPRO.2015.11.089

De-Troya, J. J., Álvarez, C., Fernández-Garrido, C., & Carral, L. (2016). Analysing the possibilities of using fuel cells in ships. *International Journal of Hydrogen Energy*, *41*(4), 2853–2866. https://doi.org/10.1016/J.IJHYDENE.2015.11.145

Diermann, R. (2022). *Green hydrogen, blue hydrogen to reach cost parity in Europe by 2030 – pv magazine International*. https://www.pv-magazine.com/2022/02/28/green-hydrogen-blue-hydrogen-to-reach-cost-parity-in-europe-by-2030/

DNV. (2018). *Alternative fuels: the options - DNV*. https://www.dnv.com/expert-story/maritime-impact/alternative-fuels.html

DNV-GL. (2017). *Study on the use of fuel cells in shipping DNV GL 1 MARITIME STUDY ON THE USE OF FUEL CELLS IN SHIPPING*. https://www.emsa.europa.eu/sustainable-shipping/new-technologies/download/4545/4507/23.html

EERE. (2021). *Hydrogen Production: Electrolysis | Department of Energy*. https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis

EERE. (2022). *Types of Fuel Cells | Department of Energy*. https://www.energy.gov/eere/fuelcells/types-fuel-cells

Enapter. (2022). *What is the energy content of hydrogen? - Enapter*. https://www.enapter.com/newsroom/kb_post/what-is-the-energy-content-of-hydrogen

European Commission. (2020a). *Full-length report Accompanying the document Report from the Commission 2019 Annual Report on CO2 Emissions from Maritime Transport 2019 Annual Report from the European Commission on CO 2 Emissions from Maritime Transport*. https://ec.europa.eu/clima/system/files/2020-05/swd_2020_82_en.pdf

European Commission. (2020b). *Hydrogen generation in Europe - Publications Office of the EU*. https://op.europa.eu/en/publication-detail/-/publication/7e4afa7d-d077-11ea-adf7-01aa75ed71a1/language-en

European Commission. (2021a). *2020 Annual Report on CO2 Emissions from Maritime Transport {C(2021) 6022 final}*.

European Commission. (2021b). *Emissions Trading – Putting a Price on carbon*. https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_3542

European Commission. (2021c). *EUR-Lex - 52021PC0559 - EN - EUR-Lex*. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2021:559:FIN

European Commission. (2021d). *EUR-Lex - 52021PC0562 - EN - EUR-Lex*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021PC0562

European Commission. (2021e). *EUR-Lex - 52021PC0563 - EN - EUR-Lex*. https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:52021PC0563

European Commission. (2021f). *Reducing emissions from the shipping sector*. https://ec.europa.eu/clima/eu-action/transport-emissions/reducing-emissions-shipping-sector_en#modal

European Commission. (2021g). *Revision of the Energy Taxation Directive (ETD)*. https://ec.europa.eu/commission/presscorner/detail/en/qanda_21_3662

European Environment Agency. (2022). *The role of environmental taxation in support of sustainability transitions*. *22/2021*.

Faber, J., Lee, D. s, & Becken, S. (2020). *Bridging the gap-the role of international shipping and aviation Lead authors*.

Faber, J., van den Berg, R., & Leestemaker, L. (2021). *The impacts of the ETD proposals on shipping and bunkering*. www.cedelft.eu

Faber, Zhang, Hanayama, & Pereda. (2020). *Fourth IMO GHG study*. https://greenvoyage2050.imo.org/wp-content/uploads/2021/07/Fourth-IMO-GHG-Study-2020-Full-report-and-annexes_compressed.pdf

FuelCellWorks. (2021). *World's First Liquid Hydrogen-Powered Vessel Wins Ship Of The Year Award*. https://fuelcellsworks.com/news/worlds-first-liquid-hydrogen-powered-vessel-wins-ship-of-the-year-award/

Goodwin, A., & Hildre, K. S. (2015). *Hydrogen in the Maritime Sector A feasibility study on hydrogen as fuel in Norwegian ferries NORWEGIAN SCHOOL OF ECONOMICS*.

Gore, K., Rigot-Müller, P., & Coughlan, J. (2022). Cost assessment of alternative fuels for maritime transportation in Ireland. *Transportation Research Part D: Transport and Environment*, *110*, 103416. https://doi.org/10.1016/J.TRD.2022.103416

Hagberg, H. (2022). *Update on the extension of EU ETS to include maritime transportation | Advokatfirmaet Thommessen*. https://www.thommessen.no/en/news/extension-of-eu-ets-to-include-maritime-transportation

Hellenic Shipping News. (2021). *New milestone for TECO 2030: Has been granted up to NOK 5.4 million in tax relief for the development of a production process for hydrogen fuel cells | Hellenic Shipping News Worldwide*. https://www.hellenicshippingnews.com/new-milestone-for-teco-2030-has-been-granted-up-to-nok-5-4-million-in-tax-relief-for-the-development-of-a-production-process-for-hydrogen-fuel-cells/

Hersher, R. (2019). *Global Shipping Is About To Get Greener : NPR*. https://www.npr.org/2019/07/16/716693006/the-dawn-of-low-carbon-shipping?t=1661094986197

Hoenders, R. (2020). *Achieving the goals of the Initial IMO Strategy on reduction of GHG emissions from ships IMO policy context Roel Hoenders Acting Head of Air Pollution and Energy Efficiency International Maritime Organization*.

Horvath, S., Fasihi, M., & Breyer, C. (2018). Techno-economic analysis of a decarbonized shipping sector: Technology suggestions for a fleet in 2030 and 2040. *Energy Conversion and Management*, *164*, 230–241. https://doi.org/10.1016/J.ENCONMAN.2018.02.098

Howarth, R. W., & Jacobson, M. Z. (2021). How green is blue hydrogen? *Energy Science & Engineering*, *9*(10), 1676–1687. https://doi.org/10.1002/ESE3.956

Hydrogen Council. (2020a). *Path to hydrogen competitiveness A cost perspective*. https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf

Hydrogen Council. (2020b). *Path to Hydrogen Competitiveness: A Cost Perspective - Hydrogen Council*. https://hydrogencouncil.com/en/path-to-hydrogen-competitiveness-a-cost-perspective/

Hydrogen Hub. (2022). *Home - Hydrogen Hub*. https://www.hydrogenhub.org/

IEA. (2019). *The Future of Hydrogen*.

IEA. (2020). *IEA G20 Hydrogen report: Assumptions*. https://iea.blob.core.windows.net/assets/a02a0c80-77b2-462e-a9d5-1099e0e572ce/IEA-The-Future-of-Hydrogen-Assumptions-Annex.pdf

IHS Markit. (2020). *News Release | IHS Markit Online Newsroom*. https://news.ihsmarkit.com/prviewer/release_only/slug/bizwire-2020-7-15-ihs-markit-production-of-carbon-free-green-hydrogen-could-be-cost-competitive-by-2030

IMO. (2018a). *Initial IMO GHG Strategy*. https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx

IMO. (2018b). *Initial IMO GHG Strategy*. https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx

IMO. (2019). *Market-Based Measures*. https://www.imo.org/en/OurWork/Environment/Pages/Market-Based-Measures.aspx

IMO. (2020). *Fourth Greenhouse Gas Study 2020*. https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx

IMO. (2021). *Further shipping GHG emission reduction measures adopted*. https://www.imo.org/en/MediaCentre/PressBriefings/pages/MEPC76.aspx

Inal, O. B., & Deniz, C. (2020). Assessment of fuel cell types for ships: Based on multi-criteria decision analysis. *Journal of Cleaner Production*, *265*, 121734. https://doi.org/10.1016/J.JCLEPRO.2020.121734

IRENA. (2019). *FUTURE OF WIND Deployment, investment, technology, grid integration and socio-economic aspects A Global Energy Transformation paper Citation About IRENA*. www.irena.org/publications.

IRENA. (2020). *GREEN HYDROGEN COST REDUCTION SCALING UP ELECTROLYSERS TO MEET THE 1.5°C CLIMATE GOAL H 2 O 2*. www.irena.org/publications

ISPT. (2022). *Hydrohub Innovation Program Public report A One-GigaWatt Green-Hydrogen Plant Advanced Design and Total Installed-Capital Costs*. https://ispt.eu/media/Public-report-gigawatt-advanced-green-electrolyser-design.pdf

Kenton, W. (2020). *Equivalent Annual Cost – EAC Definition*. https://www.investopedia.com/terms/e/eac.asp

KPMG. (2021). *The hydrogen trajectory - KPMG Global*. https://home.kpmg/xx/en/home/insights/2020/11/the-hydrogen-trajectory.html

Lamas, M. I., Professor A Rodríguez, A., & Professor B Rodríguez, J. A. (2015). *NUMERICAL ANALYSIS OF EMISSIONS FROM MARINE ENGINES USING ALTERNATIVE FUELS*. *22*(4), 48–52. https://doi.org/10.1515/pomr-2015-0070

Leibreich Michael. (2020). *Liebreich: Separating Hype from Hydrogen – Part One: The Supply Side | BloombergNEF*. https://about.bnef.com/blog/liebreich-separating-hype-from-hydrogen-part-one-the-supply-side/

Lin, M. T. (2022). *Record-high prices forecast across global carbon markets, and still room for more | IHS Markit*. https://cleanenergynews.ihsmarkit.com/research-analysis/recordhigh-price-forecasts-across-global-carbon-markets-and-st.html

Lloyd's Register and UMAS. (2019). *Zero-Emission Vessels 2030. How do we get there?* https://www.lrs.or.jp/news/pdf/LR_Zero_Emission_Vessels_2030.pdf

macrotrends. (2022). *Brent Crude Oil Prices - 10 Year Daily Chart | MacroTrends*. https://www.macrotrends.net/2480/brent-crude-oil-prices-10-year-daily-chart

Maersk. (2022). *47O Gbf Feeder 1 | Europe | Maersk*. https://www.maersk.com/local-information/europe-feeder-shipping-routes/47o-gbf-feeder-1

MAN B&W Diesel A/S. (2019). *Propulsion trends in container vessels Modern two-stroke engine technology for one of the workhorses of global trade MAN Energy Solutions Propulsion trends in container vessels Future in the making*.

MAN Energy solution. (2022). *Hydrogen*. https://www.man-es.com/marine/strategic-expertise/future-fuels/hydrogen

MTU. (2021). *Fuel Cells*. https://www.mtu-solutions.com/eu/en/about-us/innovation-and-technology/fuel-cells.html

NAPA. (2022). *How the Fit For 55 legislation will affect the shipping industry - and how you can prepare – NAPA*. https://www.napa.fi/eu-fit-for-55-for-shipping/

Open access Government. (2022). *What is the FuelEU Maritime Regulation?* https://www.openaccessgovernment.org/eesc-fueleu-maritime-regulation-carbon-emissions/133459/

Osorio, S., Tietjen, O., Pahle, M., Pietzcker, R. C., & Edenhofer, O. (2021). Reviewing the Market Stability Reserve in light of more ambitious EU ETS emission targets. *Energy Policy*, *158*. https://doi.org/10.1016/J.ENPOL.2021.112530

Papadias, D., Ahluwalia, R. K., Connelly, E., & Devlin, P. (2019). *Total Cost of Ownership (TCO) Analysis for Hydrogen Fuel Cells in Maritime Applications-Preliminary Results*. https://shipandbunker.com

Parker, S., Shaw, A., Rojon, I., & Smith, T. (2021). *Harnessing the EU ETS to reduce international shipping emissions Assessing the effectiveness of the proposed policy inclusion of shipping in the EU ETS to reduce international shipping emissions*. www.u-mas.co.uk

Pierre-Louis Ragon, Eamonn Mulholland, Hussein Basma, & Felipe Rodríguez. (2022). *A review of the AFIR proposal: Public infrastructure needs to support the transition to a zero-emission truck fleet in the European Union - International Council on Clean Transportation*. https://theicct.org/publication/afir-eu-hdv-infrastructure-mar22/

Pocard Nicolas. (2022). *Fuel Cell Price to Drop 70-80% as Production Volume Scales*. https://blog.ballard.com/fuel-cell-price-drop

Pollet, B. G., Franco, A. A., Su, H., Liang, H., & Pasupathi, S. (2016). Proton exchange membrane fuel cells. *Compendium of Hydrogen Energy*, 3–56. https://doi.org/10.1016/B978-1-78242-363-8.00001-3

Pomaska, L., & Acciaro, M. (2022). Bridging the Maritime-Hydrogen Cost-Gap: Real options analysis of policy alternatives. *Transportation Research Part D: Transport and Environment*, *107*, 103283. https://doi.org/10.1016/J.TRD.2022.103283

Reinsch, W. A. (2021). *Hydrogen: The Key to Decarbonizing the Global Shipping Industry? | Center for Strategic and International Studies*. https://www.csis.org/analysis/hydrogen-key-decarbonizing-global-shipping-industry

Requate, T. (2013). Prices versus Quantities. *Encyclopedia of Energy, Natural Resource, and Environmental Economics*, *3–3*, 193–203. https://doi.org/10.1016/B978-0-12-375067-9.00027-9

REUTERS. (2022). *EU launches 5.4-billion-euro hydrogen project with Alstom, Daimler, others | Reuters*. https://www.reuters.com/business/energy/eu-launches-54-bln-euro-hydrogen-project-with-alstom-daimler-others-2022-07-15/

Rogelj, joeri, & Shindell, D. (2019). *Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development*. https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf

Shell. (2021). *Hydrogen - What Is It? | Hydrogen Fuel & Projects | Shell Global*. https://www.shell.com/energy-and-innovation/new-energies/hydrogen.html

Ship & Bunker. (2022). *Rotterdam Bunker Prices - Ship & Bunker*. https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam#_LSMGO

Sills, E. O., & Jones, K. (2018). Selection and design of environmental policy instruments. *Handbook of Environmental Economics*, *4*, 395–437. https://doi.org/10.1016/bs.hesenv.2018.09.001

Simon, F. (2021). *Analyst: EU carbon price on track to reach €90 by 2030 – EURACTIV.com*. https://www.euractiv.com/section/emissions-trading-scheme/interview/analyst-eu-carbon-price-on-track-to-reach-e90-by-2030/

SmartPort. (2020). *Power-2-Fuel Cost Analysis smartport.nl*. www.smartport.nl

Smith, T., Raucci, C., & Faber, J. (2019). *REDUCING THE MARITIME SECTOR'S CONTRIBUTION TO CLIMATE CHANGE AND AIR POLLUTION Scenario Analysis: Take-up of Emissions Reduction Options and their Impacts on Emissions and Costs A Report for the Department for Transport Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution Reducing the Maritime Sector's Contribution to Climate Change and Air Pollution*.

Smith, T., Raucci, C., Sabio, N., & Argyros, D. (2014). *Global Marine Fuel Trends 2030*.

Sohani, A., Naderi, S., Torabi, F., Sayyaadi, H., Golizadeh Akhlaghi, Y., Zhao, X., Talukdar, K., & Said, Z. (2020). Application based multi-objective performance optimization of a proton exchange membrane fuel cell. *Journal of Cleaner Production*, *252*, 119567. https://doi.org/10.1016/J.JCLEPRO.2019.119567

Somanathan, E., Sterner, T., & Sugiyama, T. (2014). *5 National and Sub-national Policies and Institutions Coordinating Lead Authors: Lead Authors*.

Sonnichsen, N. (2022). • *Europe: green hydrogen costs 2030 | Statista*. https://www.statista.com/statistics/1312286/europe-green-hydrogen-production-and-import-costs-2030/

S&P Global. (2022). *INTERVIEW: Sustained high European gas prices making green hydrogen competitive -- ETC | S&P Global Commodity Insights*. https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/electric-power/052722-interview-sustained-high-european-gas-prices-making-green-hydrogen-competitive-etc

Stępień, Z. (2021). A comprehensive overview of hydrogen-fueled internal combustion engines: Achievements and future challenges. In *Energies* (Vol. 14, Issue 20). MDPI. https://doi.org/10.3390/en14206504

TECO 2030. (2022). *EUROPE'S FIRST GIGA PRODUCTION OF HYDROGEN PEM FUEL CELLS, NARVIK, NORWAY COMPANY PRESENTATION.*

Terun, K. (2020). *Assessing Alternative Fuel Types for ULCVs in Face of Uncertainty*. https://repository.tudelft.nl/islandora/object/uuid%3A84f29960-87fd-427b-bc9d-96b46f4bfe3c

The Maritime Executive. (2019). *Hydrogen Fuel Cell Vessels Destined for France and Norway*. https://www.maritime-executive.com/article/hydrogen-fuel-cell-vessels-destined-for-france-and-norway

Tjalve Svendsen. (2022). *Fuel cell technology for the shipping industry*. https://nor-shipping.com/fuel-cell-technology/

UNEP. (2020). *Emissions Gap Report 2020*. https://www.unep.org/emissions-gap-report-2020

van Biert, L., Godjevac, M., Visser, K., & Aravind, P. v. (2016). A review of fuel cell systems for maritime applications. *Journal of Power Sources*, *327*, 345–364. https://doi.org/10.1016/J.JPOWSOUR.2016.07.007

van Hoecke, L., Laffineur, L., Campe, R., Perreault, P., Verbruggen, S. W., & Lenaerts, S. (2021). Challenges in the use of hydrogen for maritime applications. *Energy & Environmental Science*, *14*(2), 815–843. https://doi.org/10.1039/D0EE01545H

Wang, Y., Wright, L. A., & Bergman, M. (2021). A Comparative Review of Alternative Fuels for the Maritime Sector: Economic, Technology, and Policy Challenges for Clean Energy Implementation. *World 2021, Vol. 2, Pages 456-481*, *2*(4), 456–481. https://doi.org/10.3390/WORLD2040029

Wärtsilä. (2022). *Improving ship efficiency - Copenhagen Centre on Energy Efficiency*. https://c2e2.unepccc.org/kms_object/improving-ship-efficiency/

WORLD ECONOMIC FORUM. (2018). *If shipping were a country, it would be the world's sixth-biggest greenhouse gas emitter | World Economic Forum*. https://www.weforum.org/agenda/2018/04/if-shipping-were-a-country-it-would-be-the-world-s-sixth-biggest-greenhouse-gas-emitter

WORLD ECONOMIC FORUM. (2021). *What is green hydrogen? An expert explains its benefits | World Economic Forum*. https://www.weforum.org/agenda/2021/12/what-is-green-hydrogen-expert-explains-benefits/

Appendix

Appendix -1: Average main engine and auxiliary engine power

	2018			2019		
Vessel size	Average propulsion power (kW)	Average Aux Engine (kW)	No. of ships	Average propulsion power (kW)	Average Aux Engine (kW)	No. of ships
DWT: 000 000 - 009 999	7 520	453	108	7 302	423	104
DWT: 010 000 - 014 999	9 463	751	199	9 397	754	215
DWT: 015 000 - 039 999	17 888	1 355	404	17 841	1 349	392
DWT: 040 000 - 079 999	40 437	2 009	439	39 978	1 991	408
DWT: 080 000 - 119 999	56 947	2 918	312	56 704	2 867	305
DWT: 120 000 - 199 999	60 653	3 823	310	59 570	3 855	350
DWT: 200 000 - 999 999	59 504	4 179	20	63 970	4 236	27

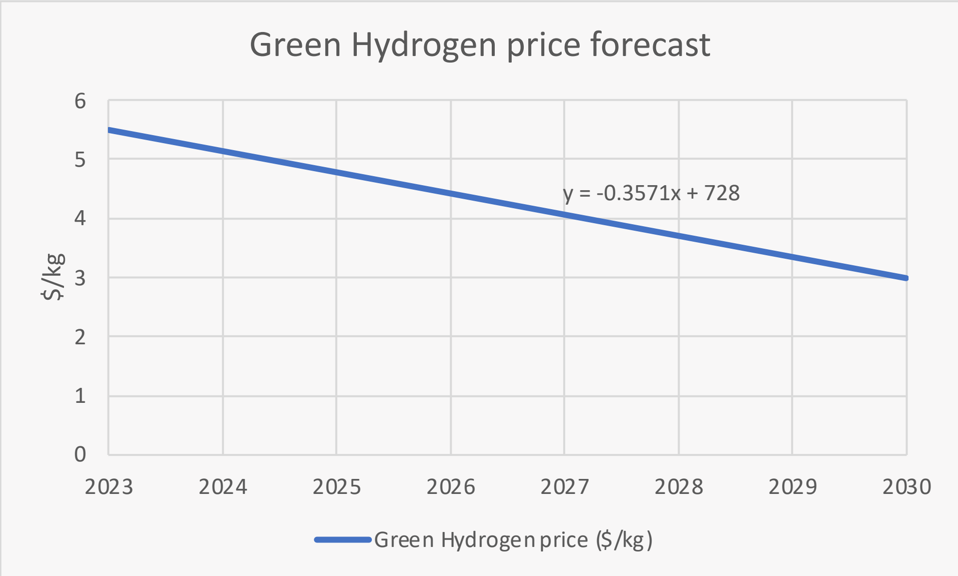
Source: Adapted from (European Commission, 2021a)

Appendix - 2: Crude oil price forecast

Year	Average wri Spot	Alaskan North Slope	Brent Spot	Sour Crude Index ASCI	Average OPEC Basket	Venezuelan Merey	Arabia UAE Dubai Feteh	Russia Urals	Indonesia Minas
	US$/bbl Current	US$/bbl Current	US$/bbl Current	US$/bbl Current	US$/bbl Current	US$/bbl Current	US$/bbl Current	US$/bbl Current	US$/bbl Current
2022	$92.50	$87.00	$95.50	$90.50	$94.50	$76.50	$94.00	$70.50	$93.25
2023	$81 .60	$76.00	$84.65	$79.55	$83.65	$65.30	$83.15	$69.35	$82.35
2024	$72.85	$67.10	$75.95	$70.75	$74.90	$56.20	$74.40	$68.65	$73.60
2025	$69.00	$63.15	$72.15	$66.85	$71.10	$52.00	$70.55	$69.00	$69.75
2026	$70.35	$64.40	$73.60	$68.20	$72.50	$53.05	$72.00	$70.35	$71 .15
2027	$71.75	$65.70	$75.10	$69.55	$73.95	$54.10	$73.40	$71.75	$72.60
2028	$73.20	$67.00	$76.60	$70.95	$75.45	$55.20	$74.90	$73.20	$74.05
2029	$74.65	$68.35	$78.10	$72.35	$76.95	$56.30	$76.40	$74.65	$75.55
2030	$76.15	$69.70	$79.65	$73.80	$78.50	$57.40	$77.90	$76.15	$77.05
2031	$77.70	$71.10	$81.25	$75.30	$80.05	$58.55	$79.45	$77.70	$78.60
2032	$79.25	$72.55	$82.90	$76.80	$81.65	$59.75	$81.05	$79.25	$80.15
2033	$80.80	$74.00	$84.55	$78.35	$83.30	$60.95	$82.70	$80.80	$81 .75
2034	$82.45	$75.45	$86.25	$79.90	$84.95	$62.15	$84.35	$82.45	$83.40
2035	$84.10	$76.95	$87.95	$81 .50	$86.65	$63.40	$86.00	$84.10	$85.05
2036	$85.75	$78.50	$89.70	$83.15	$88.40	$64.65	$87.75	$85.75	$86.75
2037	$87.50	$80.10	$91.50	$84.80	$90.15	$65.95	$89.50	$87.50	$88.50
2038	$89.25	$81.70	$93.35	$86.50	$92.00	$67.25	$91.30	$89.25	$90.25
2039	$91 .00	$83.30	$95.20	$88.20	$93.80	$68.60	$93.10	$91.00	$92.05
2040	$92.85	$85.00	$97.10	$90.00	$95.70	$70.00	$95.00	$92.85	$93.90
2041	$94.70	$86.70	$99.05	$91 .80	$97.60	$71.40	$96.90	$94.70	$95.80
2041+	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%	2.00%

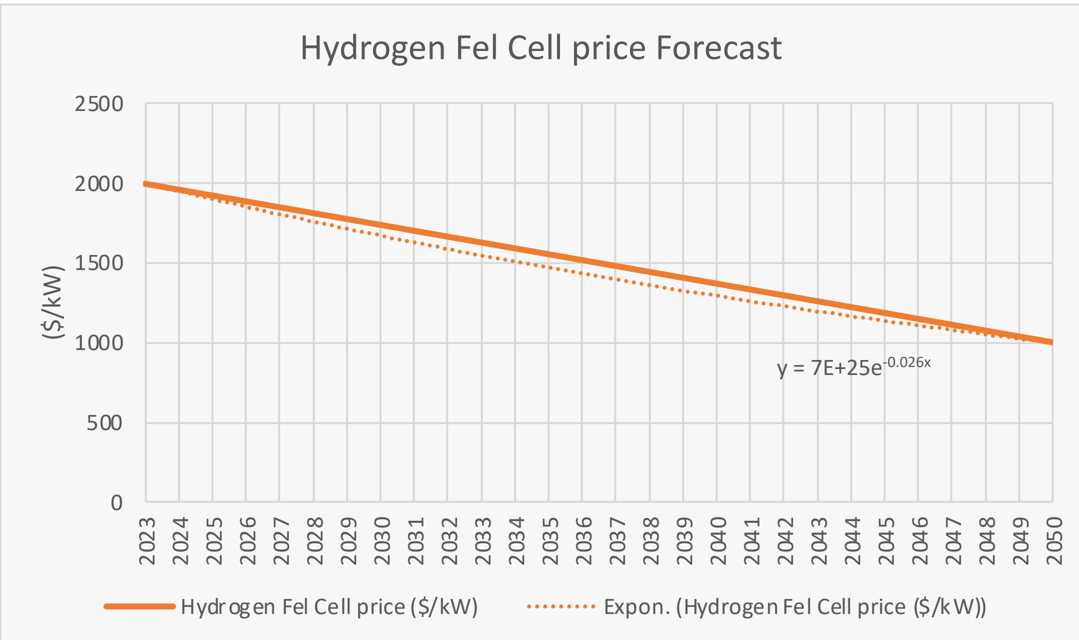
Source: Adapted from (Deloitte, 2022)

Appendix - 3: Green Hydrogen Price Forecast



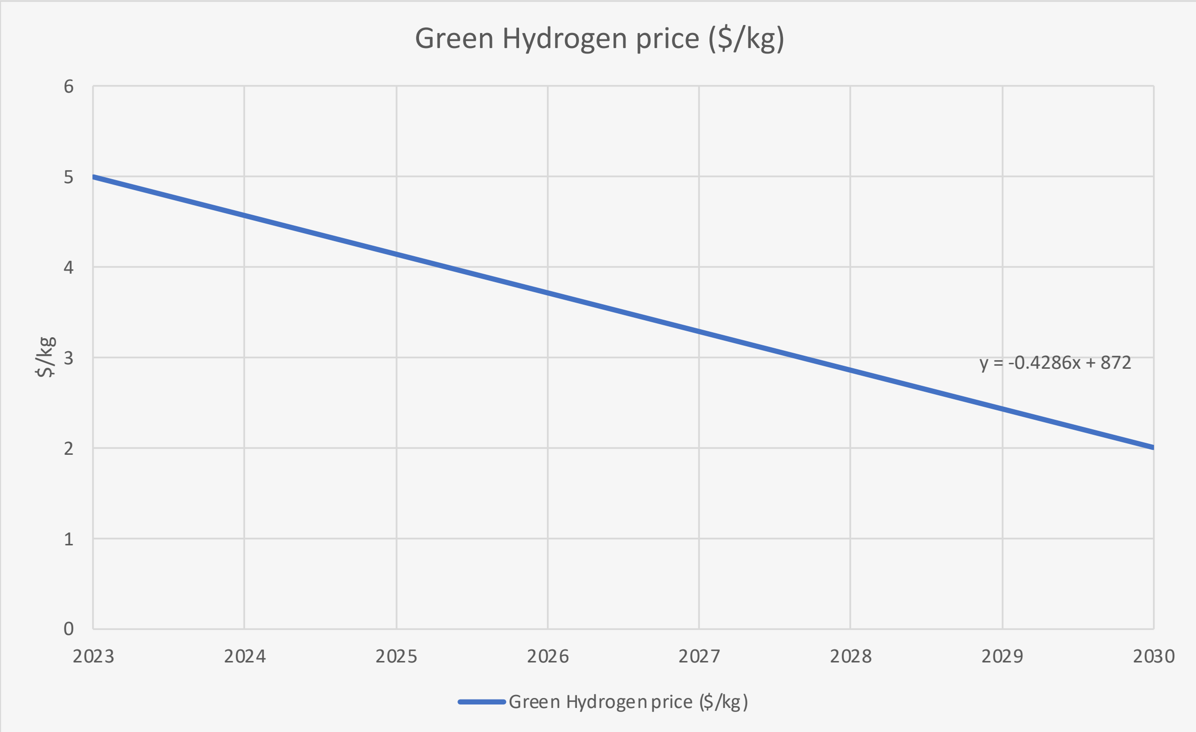
Source: Adapted from (Diermann, 2022; S&P Global, 2022)

Appendix - 4: Hydrogen Fuel cell Price forecast



Source: Adapted from (IEA, 2020)

Appendix - 5: Hydrogen Price forecast under developed scenario



Source: Author

Appendix - 6: Total cost of ownership under the existing scenario

year	LSMGO Powered ship	Hydrogen Powered ship	Abatement cost
2023	4338742	10363056	414
2024	3996850	9874672	404
2025	3847542	9454099	387
2026	3904487	8965715	348
2027	3963974	8545142	315
2028	4022371	8073062	278
2029	4081359	7592831	241
2030	4142253	7112600	204

Source: Author

Appendix - 7: Total annual costs after EU ETS and Revised ETD

year	LSMGO Powered ship	Hydrogen Powered ship	Abatement cost
2023	4534005	10363056	401
2024	5528983	9874672	299
2025	5416003	9454099	277
2026	5502010	8965715	238
2027	5594919	8545142	203
2028	5685285	8073062	164
2029	5773335	7592831	125
2030	5877823	7112600	85

Source: Author

Appendix - 8: Total annual costs after 88% Revenue recycling

year	LSMGO Powered ship	Hydrogen Powered ship	Abatement cost
2024	5528983	8907539	232
2025	5416003	7808120	165
2026	5502010	6904351	96
2027	5594919	6264042	46
2028	5685285	5555922	-9
2029	5773335	4847803	-64
2030	5877823	4207494	-115

Source: Author

Appendix - 9: Total annual cost after 100% Revenue recycling

year	LSMGO Powered ship	Hydrogen Powered ship	Abatement cost
2024	5528983	8203496	184
2025	5416003	7190538	122
2026	5502010	6398070	62
2027	5594919	5881141	20
2028	5685285	5296538	-26
2029	5773335	4724287	-72
2030	5877823	4207494	-115

Source: Author