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The environmental and economic assessment of hydrogen fuel for inland shipping industry in Europe

by

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Acknowledgements

I believed I had left my student life behind nine years ago when I graduated from college. Eight years of work made me realise I still had much to learn. This was the beginning of my journey towards reaching where I am today. A long year of learning experiences, growth, discomfort, and joy finally ends. Time flies.

Firstly and most importantly, I would like to thank my family for their constant support and unwavering love throughout this phase of my life. My journey would not have started without their encouragement. Special thanks to my brother, Ankur, for guiding me through this process of student life.

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Finally, to my classmates and friends, I am very glad I met you all and got to work with you this year. I hope we make more memories together and remain in each other's lives for years. Thank you for supporting me and I wish you all the best!

"Earth provides enough to satisfy every man's needs, but not every man's greed" – Mahatma Gandhi

Abstract

Increasing global concern about climate change and a growing demand for clean and sustainable energy solutions have created a market demand for low-carbon or carbon-neutral fuels. The maritime industry can be crucial in limiting GHG emissions by replacing fossil-based fuels with cleaner options. In order to achieve net-zero targets by 2050, shipping companies need to collaborate with governments and research experts to find an economically feasible long-term solution.

Investigating future marine fuels holistically, by recording their carbon footprint in each life cycle stage, is necessary. This study aims to evaluate the environmental and economic impacts of hydrogen fuel. Inland container ships significantly facilitate smooth hinterland trade operations using the Rhine and Danube rivers. The Dutch container barging industry is the baseline in formulating this investigation.

Three different variants of hydrogen fuel – grey, blue and green, were selected to be compared with diesel fuel. A life-cycle assessment methodology is used to analyse the environmental impact of a 188 TEU container ship sailing between Rotterdam and Antwerp. The CO_2 emissions were recorded from each lifecycle stage for this vessel's 30 years of operation. The annual emissions found for diesel, and grey, blue and green hydrogen are 1,233 t-CO_2-eq, 1,563 t-CO_2-eq, 905 t-CO_2-eq and 665 t-CO_2-eq, respectively. The economic analysis is done using the life-cycle cost assessment method. Costs are divided into investment and exploitation costs, with a perspective of minimal modification to the existing power system configuration. A potential carbon allowance factor was also considered under exploitation costs. The total costs came out to be €10.59, €10.57, €9.37, and €26.33 million for diesel, and grey, blue and green hydrogen scenarios, respectively.

The results outline blue hydrogen-powered ship as the most cost-effective and green hydrogen-powered ship as the most eco-friendly among the options considered. Hydrogen energy is still gathering pace regarding technical development, but it is a promising solution for reducing greenhouse gas emissions in the future. In order to achieve mass deployment of this fuel, immediate attention from stakeholders and policymakers is needed.

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List of Abbreviations

CA	Carbon Allowance
CCS	Carbon Capture and Storage
CO_2	Carbon Dioxide
DNV	Det Norske Veritas
ETS	Emission Trading System
EU	European Union
GHG	Greenhouse Gas
GWP	Global Warming Potential
GT	Gross Tonnage
IMO	International Maritime Organisation
IWW	Inland Waterways
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Assessment
LNG	Liquified Natural Gas
MGO	Marine Gas Oil
MRV	Monitoring Reporting and Verification
NO_X	Nitrous Oxides
PEM-FC	Proton Exchange Membrane Fuel Cell
SMR	Steam Methane Reforming
SO_X	Sulphur Oxides
TEN-T	Trans-European Transport Network
TEU	Twenty-foot Equivalent Unit
TkM	Tonne-Kilometres
TtW	Tank-to-Wake
WtT	Well-to-Tank
WtW	Well-to-Wake

1 Introduction

1.1 Background and Relevance

The world is currently transitioning in energy sourcing, exploring alternative sources for generating power domestically and industrially. The socioeconomic debate about emissions caused by burning fossil fuels, which remain the dominant energy source worldwide, has warranted governments and policymakers to regulate emission control systems. It is essential to acknowledge that these resources are limited and irresponsible consumption could result in complete depletion, making them an unsustainable energy source. The shipping industry plays an essential role in facilitating global trade. However, being a slow-moving sector in terms of innovation, a majority of the world fleet still consumes fuels derived from fossil fuels. Despite being an energy-efficient industry, shipping's contribution to global greenhouse gas (GHG) emissions has been rising lately, contributing approximately 3% of the global emissions (European Commission, 2021).

The ratification of the Paris Agreement by member states of the UN in 2015 declared the beginning of the pursuit against climate change on an international level. World leaders are committed to attaining long-term goals of controlling GHG emissions and limiting the temperature increase to 2 degrees Celsius within this century, and making substantial changes to limit this further down to 1.5 degrees Celsius (United Nations, 2017). Transport-related emissions are on the rise and are predicted to grow in the coming decades, specifically in developing economies, the Paris Agreement, therefore, concentrates on financially supporting such countries in combating climate change. The International Maritime Organisation (IMO) sets out targets for international shipping in accordance with the current global ambitions. The initial strategy did not align with the current trends of emissions generated, so it was decided to revise these goals for a better future. The revised strategy strives to improve energy efficiency for new ships, reduce CO_2 emissions per transport work by at least 40% by 2030 (compared to 2008 levels) and eventually comply with net-zero emissions target set for 2050 (IMO, 2023). To achieve these ambitious targets, stakeholders in the shipping industry have started assessing technologies and investing in cleaner fuels that generate minimum or zero emissions. The guidelines adopted by IMO advocate analysing the well-to-wake environmental impact, by carrying out life cycle assessment, of various marine fuels generating power through hydrogen, methanol, biofuels and electricity.

The shift towards a low-carbon economy is influenced by many interconnected factors such as international policies and technological progress. These low-carbon energy systems highly depend on generating electricity as an end product but making them available commercially is a task that comes with multiple stages of emission potential. Building infrastructure for the production phase of an alternative fuel requires a substantial amount of construction work. Then comes the transportation phase of these fuels according to geographical demands, wherein new pipelines are laid, existing pipelines are modified or specific types of cargo ships are used. Following this, a storage phase begins which again requires new constructions or modification of existing tanks. The final stage in the maritime industry is the bunkering of these fuels onto a ship followed by consumption in the propulsion system. Ideally, the GHG emissions generated during combustion are held accountable for damaging the environment. But each stage till this point also generates emissions, which are accounted for only in studies involving life-cycle assessments.

An objective of this paper is to delve deeper into the production, transportation and storage-related carbon emissions of hydrogen as a fuel. Achieving this target for a specific vessel type will add knowledge that could be used for future design modifications in a fleet. Hydrogen has the potential to replace conventional fuel systems because it generates zero carbon dioxide, sulphur oxides and nitrous oxides when used in a Proton Exchange Membrane (PEM) fuel cell. The trade and conversion of each hydrogen stream highly relies on the current level of technology, the type of infrastructure in place, and potential energy losses. Hydrogen must account for 15% of the total global energy mix by the middle of this century to achieve the climate goals set through the Paris Agreement. According to (DNV-Hydrogen Report, 2022), the hydrogen percentage in the global energy mix will reach 0.5% in 2030 and 5% in 2050; and an estimated $7.5 trillion will be spent on hydrogen production and transportation-related activities.

The Netherlands has been a forerunner in providing green maritime solutions by launching various projects in the hydrogen energy sector in the past few years. This year, an inland container barge ‘H2 Barge 1’ was launched to operate between Rotterdam and Antwerp. The vessel got its conventional marine diesel propulsion system replaced by hydrogen fuel technology and this retrofit is predicted to reduce GHG emissions by 2,000 tonnes per year of operations (Maritime, 2023). Drawing inspiration from such a retrofit of greener fuel technology is one reason behind this study. Inland shipping plays a vital role in the multi-modal transportation network in Europe and can potentially replace traffic on roads. Moreover, it is one of the cleanest transport modes when measuring emissions in tonne-kilometre. The contribution that inland shipping can make in achieving ambitious climate goals set by the European Commission is a reason for conducting life-cycle assessment studies. But there is always a trade-off between sustainable solutions and economic benefits, which encourages us to find the right balance between the two. If carbon-free synthetic fuels such as ammonia and hydrogen are produced through renewable energy, they could play a crucial role in inland and short-sea shipping in the future. Still, unfortunately, the present status of infrastructure and fuel prices make them commercially unviable (Xing et al., 2021).

1.2 Objective of the Thesis

The objectives of this research are four-fold: 1) to study and describe hydrogen fuel technology used in the maritime sector and its relevancy in the European inland shipping sector; 2) to conduct a comparative environmental assessment between liquid hydrogen and conventional marine diesel to analyse their global warming potentials using life cycle assessment technique; 3) to conduct an economic analysis between these two fuel types through the life cycle cost assessment method to gauge their feasibility; 4) to provide policy recommendations for various stakeholders involved in facilitating a hydrogen-based maritime economy.

1.3 Main and Sub Research questions

This brings us to formulating the main research question for this paper:

- "What are the environmental and economic impacts of using variants of hydrogen fuel in the European inland shipping sector?"

In order to address the objectives of this paper and answer the main research question, this study will answer the following sub-research questions:

1. Which variants of hydrogen are technically feasible for use in maritime transportation?
2. What is the significance of the inland shipping industry in Europe?
3. Which inputs-outputs are required to assess environmental impact while applying the Life Cycle Assessment (LCA) technique?
4. What is the lifetime economic impact of hydrogen fuel compared to diesel fuel?
5. What are the key considerations for policymakers to adopt a hydrogen-based ecosystem to achieve net-neutral targets timely?

2 Literature Review

2.1 Emission Control Strategies for Europe

The European Union has been at the forefront of implementing comprehensive strategies to fight climate change. They have addressed GHG emissions in the maritime sector as a significant hurdle to overcome to become the first net-neutral continent by 2050. It was reported that 3-4% of the EU's total CO_2 emissions, approximately 144 million tonnes, was generated by maritime transport (Annual Report on CO2 Emissions from Maritime Transport, 2021). Presently, inadequate measures are in place to achieve the necessary net-neutral targets in the maritime industry. At an international level, IMO is putting efforts into promoting decarbonisation but the EU's climate ambitions needed a focused intervention on a continental level. This led to the formulation of some strategies.

The EU Emissions Trading System (EU-ETS) is a market-based mechanism implemented to set overall limits on the amount of GHG emissions released by participating industries such as energy generation, aviation and manufacturing in the European Union. But to achieve proposed emission reduction targets of 61% by 2030, compared to 2005 levels, the EU Commission decided to extend the EU-ETS to maritime activities (climate.ec.europa.eu, n.d.). This further led to the development of EU-MRV, which is discussed later. EU-ETS lays down provisions on maintaining a cap on carbon emissions, so if a company can manage to limit its emissions below the threshold value it will gain carbon credit. If it exceeds the threshold value then an emission debt is created which can lead to financial penalties. The allowance to emit 1 ton of carbon dioxide is referred to as carbon credit cost (Climate Action, 2021). A decision to tax carbon emissions through shipping activities has led shipowners to concentrate on investing in low-carbon fuel technologies. Utilizing hydrogen fuel technologies in newly built vessels can alter ship owners' investment choices especially when carbon-tax rates are set low, therefore if policies soon set these rates high, more owners would commit to a greener shipping industry (Pomaska and Acciaro, 2022).

As a part of EU Commission's 'European Green Deal', a regulatory measure was developed for monitoring, reporting and verification of emission data from vessels. The EU-MRV is applicable to ships over 5,000 gross tonnage and calling ports inside the EU member states (DNV, 2023). An annual database is created after shipowners and operators report the CO_2 emissions generated per transport work and it is a shipowner's responsibility to install designated equipment for monitoring the CO_2 emissions onboard. This study considers inland vessels that are below 5,000 GT and therefore data collected from EU-MRV will be treated as a reference for cross-checking the validity of our results.

Supporting the growth of renewable energy, the EU's hydrogen strategy and REPower EU plans have set a comprehensive framework to deliver future hydrogen demands. Providing renewable energy sources for hydrogen production drastically reduces CO_2 emissions, which has motivated the European Union to set a target for 2030 to produce 10 million tonnes of renewable hydrogen (through installing electrolysers of 40 GW capacity) and import another 10 million tonnes from around the world (Energy, 2022). The EU Hydrogen Strategy, released in July 2020, encompasses various measures to decarbonise hydrogen production methods and promote its market power. The strategy underscores the importance of strengthening the entire hydrogen value chain by investing heavily in research and innovation while transitioning from carbon-intensive production methods to cleaner alternatives (Energy, 2020). For Europe to meet half of its hydrogen demand from outside the continent mandates standardising certification and taxation schemes to foster international collaborations.

Various funding programmes have been created to enhance clean hydrogen applications in the EU. One such public-private funding programme, which succeeded the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH-2-JU) in November 2021, was the Clean Hydrogen Partnership (Clean Hydrogen Partnership, 2023). Research and innovation for this project will receive funding worth €1 billion from the EU tentatively by 2027, and additionally get €1 billion from private investments (Hornby, 2022). CCS-related policies have gained traction in terms of investments for several countries in Europe. Large-scale projects such as the 'Northern Lights' in Norway and 'Porthos' in the Netherlands have become eligible for investments provided by the EU Innovation Fund, taking care of up to 60% of operational costs (DNV-Hydrogen Report, 2022). The CO_2 emissions generated through industrial activities in Port of Rotterdam will be captured, stored and transported to void gas fields below the North Sea, through this project, approximately 2.5 million tonnes of CO_2 will be captured yearly for the next 15 years (Porthos, 2023).

2.1.1 Section Conclusion

In conclusion, the EU is leading in addressing climate change by focusing on the maritime industry. Their extended efforts go beyond the international framework as policies and strategies are being incorporated regionally too. The adoption of low-carbon technologies, notably hydrogen fuel, aligns with the EU's environmental goals and underscores their dedication to achieving sustainable maritime practices.

2.2 Structure of Inland Shipping in the EU

Decarbonising the inland shipping industry is as important as controlling emissions from the main sea-going fleet of the world. Combustion of conventional fuels along the river channels in the EU and elsewhere can have a direct adverse impact on the air quality and gradually create issues for the local population. Two countries play a crucial role in inland waterway (IWW) transport in the EU: Germany and the Netherlands. When their output is measured in tonnes-kilometres (TkM), Germany comes at the top contributing a share of 35.1% while The Netherlands comes in second and contributes 34.6% of the total TkM (Annual Report CCNR, 2022). This report also revealed that the Netherlands operates a maximum number of vessels in the dry and liquid cargo category, 4,209 out of 12,500 vessels in the Rhine fleet; with 53.1 million tonnes of cargo transported through containers. The Rhine and Danube basins are the two main river routes in Europe. As per the Annual Report CCNR (2022), the Rhine handled 57 billion TkM of traffic volume in 2022 with various transport activities stretching across the upper and lower Rhine. In terms of goods carried, mineral oil products are at the top but a lot also depends on the demands of Europe; for example, since the Russo-Ukraine war and the following energy crisis the transport volume of iron ore and coal has drastically increased.

The general trend for container carriage shows loaded containers carried from the Rhine hinterland of Germany, France and Switzerland towards the ARA (Antwerp, Rotterdam, Amsterdam) region for further export out of the continent. These containers are usually returned empty. There is a high incentive for increasing inland container transport-related infrastructure in the Netherlands because Rotterdam is the busiest port in Europe, therefore distributing this traffic and improving inland container shipping is a must. The investments made in recent years for developing IWW are shown below in *Figure 1*. Another technical restriction involving inland shipping is the water level of the rivers. Inadequate levels can cause problems with safe navigation, especially in the innermost parts of the river streams. Goods carried in containers have decreased in the last three years due to limited exports from Europe to other nations during the pandemic and congestion caused in the seaports resulted in a modal shift towards railways. *Figure 2* depicts the container transport volumes in the Rhine.

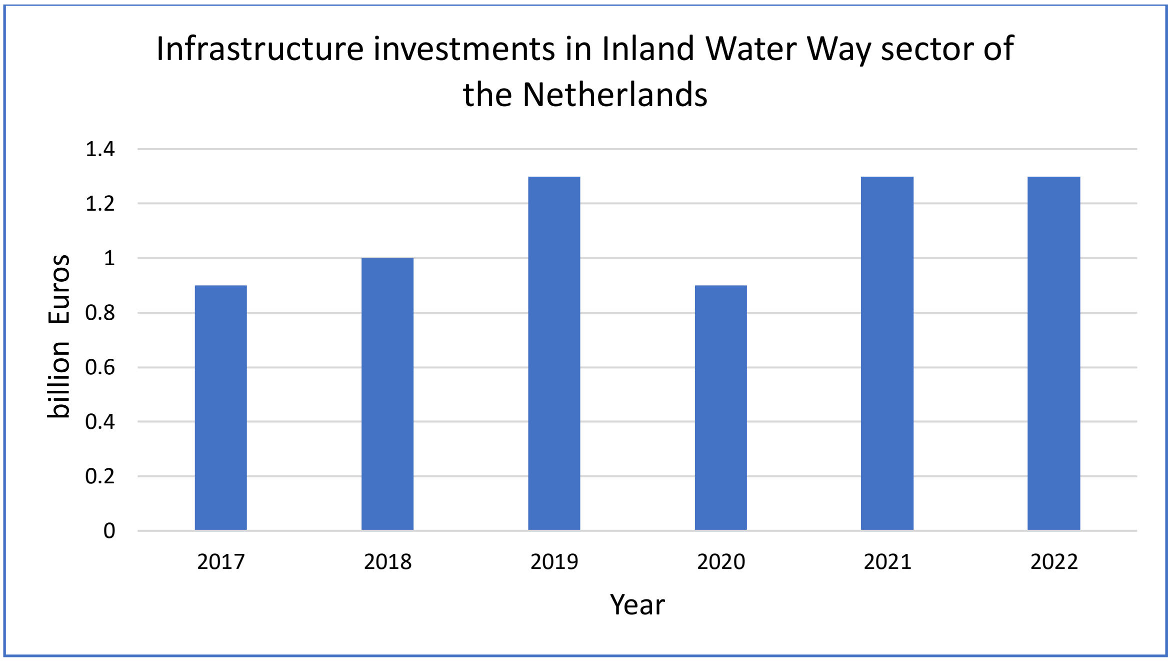

Figure 1: Financial investments in development of inland shipping infrastructure

[Source: Dutch Finance Ministry]

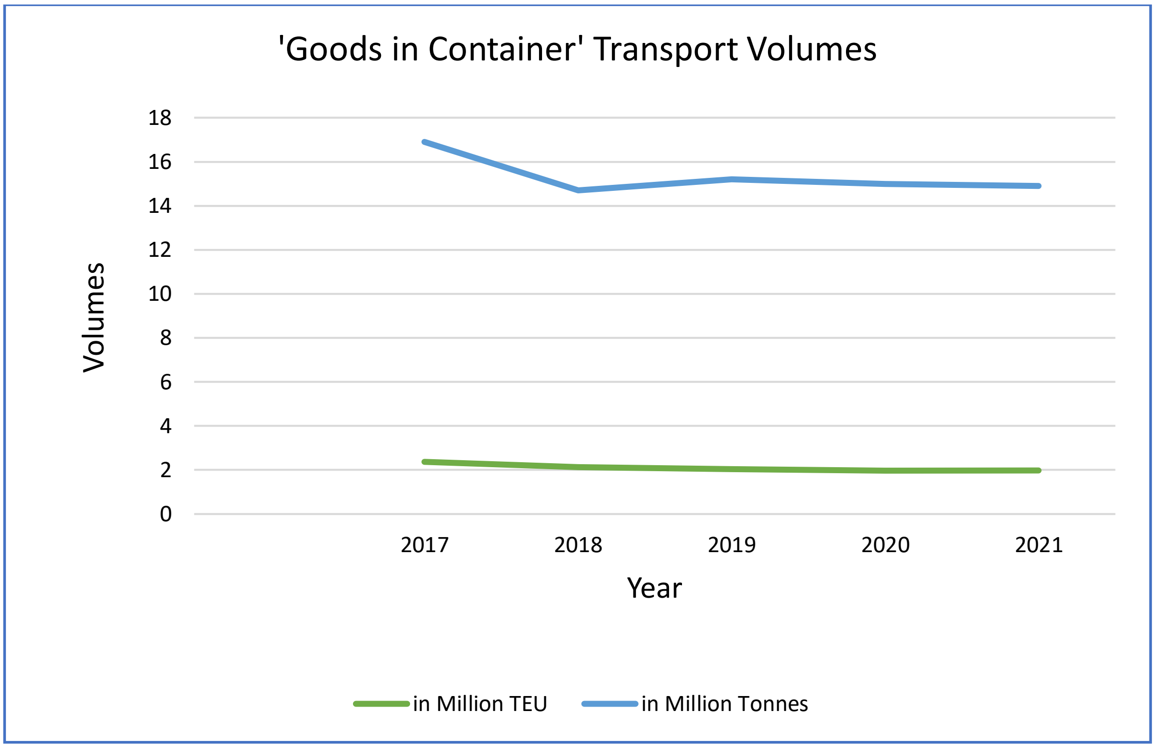

Figure 2: Transport volumes of goods carried in containers in the Rhine fleet

[Source: CCNR Market Observation – Annual Report, 2022]

The success of inland shipping is highly correlated with the enhancement of inland ports. Europe's mission of decarbonising its transport networks gave rise to Trans-European Transport Network (TEN-T) policy, which is a critical measure taken in building sustainable and highly efficient transport networks across the EU. As a part of this policy, 9 core network corridors were created to ease out bottlenecks in inland and hinterland transportation systems (European Commission, 2013). Inland waterways and ports are an integral part of TEN-T as they help improve the connectivity for passengers and cargo. The policy promotes inland waterway activities to avoid congestion on roads and railways while maintaining the status of a 'climate-positive' mode of transport. An assessment of corridor connectivity done by Jansen and Mosmans (n.d.) with seven variables, most importantly green facilities, revealed Duisburg, Vienna, and Strasbourg as the dominant ports of the three corridors Rhine-Danube, Adriatic-Baltic, and Rhine-Alpine respectively. Furthermore, the port in Duisburg offers great connectivity to Dutch, Italian, and Belgian ports and has outperformed its competition in terms of sustainability and energy transition goals.

Inland ships and recreational boats were held accountable for NO_x and PM released in the air, as concluded by van der Zee et al. (2012) in a study wherein these measurements were taken at five sites in Amsterdam. According to the research conducted by Keuken et al. (2014), 140,000 individuals residing within a 200-metre radius of a heavily trafficked waterway in the Netherlands were exposed to elemental carbon concentrations ranging up to 0.5 μg EC per m^3. Considering the projected growth of water transport, these results call for actions to mitigate CO_2 emissions from inland shipping to minimise the overall carbon footprint (CF).

There is academic research that has explored the usage of various alternative fuels for short-sea and long-distance shipping. A thorough LCA and LCCA for long-distance shipping routes using low sulphur fuels, LNG, variants of hydrogen, and variants of bio-derived fuels was conducted by Gilbert et al. (2018), and concluded that bio-derived fuels had the best potential in minimising emissions and maintaining cost-effectiveness. Perčić et al. (2020) in their study of short-sea shipping in Croatian waters stated that a Lithium-ion battery-powered ship could reduce the CO_2 -equivalent emissions by 50% when compared to a diesel-powered ship. They concluded this technology to be more cost-efficient, costing 56% less than a diesel-powered ship. Gómez Vilchez et al. (2022) analysed market trends and policies to check Europe's readiness for implementing alternative fuel infrastructure in waterborne transport was rather weak compared to road transport. Retrofitting opportunities of net-zero fuel technologies for the inland waterway fleet will be crucial in Europe's battle against climate change.

2.2.1 Section Conclusion

We have inferred that studies related to alternative fuels have widely explored the short-sea and long-distance segments of the maritime industry. In contrast, inland shipping still has limited backing in this aspect. A large volume of trade occurs within Europe through its inland water network. The spread across types of cargo carried revealed the significance of trade via container barges. The European Commission has acknowledged the need for modifications in this segment to accommodate healthier living conditions for the population directly influenced by emissions through inland ships. Inland vessels with gross tonnage over 5,000 tonnes will be evaluated in the EU-MRV database, while those below this tonnage could be left unevaluated.

2.3 Hydrogen

Hydrogen is rarely observed to be freely available as a gas or a liquid in nature. It is mostly found in different chemical forms in hydrocarbon compounds and water, which is why it needs to be produced synthetically (Wang et al., 2021). In its gaseous state, hydrogen exists as a tasteless, colourless, odourless and flammable element. Hydrogen is believed to have a high potential to replace conventional marine fuels in the future (Panić, Cuculić and Ćelić, 2022). There are certain physical and chemical properties of hydrogen that can cause hindrance for its uptake as a common fuel on a large scale. Some properties are shown in *Table 1* below.

Table 1: Physical and Chemical properties of Hydrogen

[Sources: Inchem.org, 2014; Hydrogen: Similar but Different, n.d; Züttel, 2003; Deniz et al., 2016]

Property	*Symbol*	*Value*	*Unit*
Gas Density	$\rho_{H2,gas}$	0.0807	kg/m^3
Liquid Density	$\rho_{H2,liq}$	70.8	kg/m^3
Specific Heat Capacity	C_p	14.199	MJ/kgK
Lower Explosive Limit in air	LEL	4	%
Upper Explosive Limit in air	UEL	77	%
Lower Detonation Limit in air	LDL	18.3	%
Upper Detonation Limit in air	UDL	59	%
Autoignition Temperature	AIT	559.85-585	ºC
Minimum Ignition Energy	MIE	0.19	MJ
Boiling Point	BP	-253	ºC
Net Calorific Value	NCV_H	33.3	kWh/kg
Fuel Carbon Content		0	%
Fuel Oxygen Content		0	%
Fuel Sulphur Content		0	%

As countries and organisations are finding ways to implement low-emission fuels, there is a need to outline the transportation complexities of fuels too. It is one of the limiting factors currently in creating a supply-demand balance for hydrogen as long-distance transportation would require upgrading existing infrastructure or building new facilities. Underwater pipelines may work out well for intra-continent trade but when applying economies of scale, ships will be the best option. Hydrogen can be carried on vessels in the form of ammonia (NH_3) or liquified hydrogen (LH_2) or as a synthetic fuel known as liquid organic hydrogen (LOH) having properties of hydrocarbons. *Figure 3* shows production pathways for hydrogen fuel.

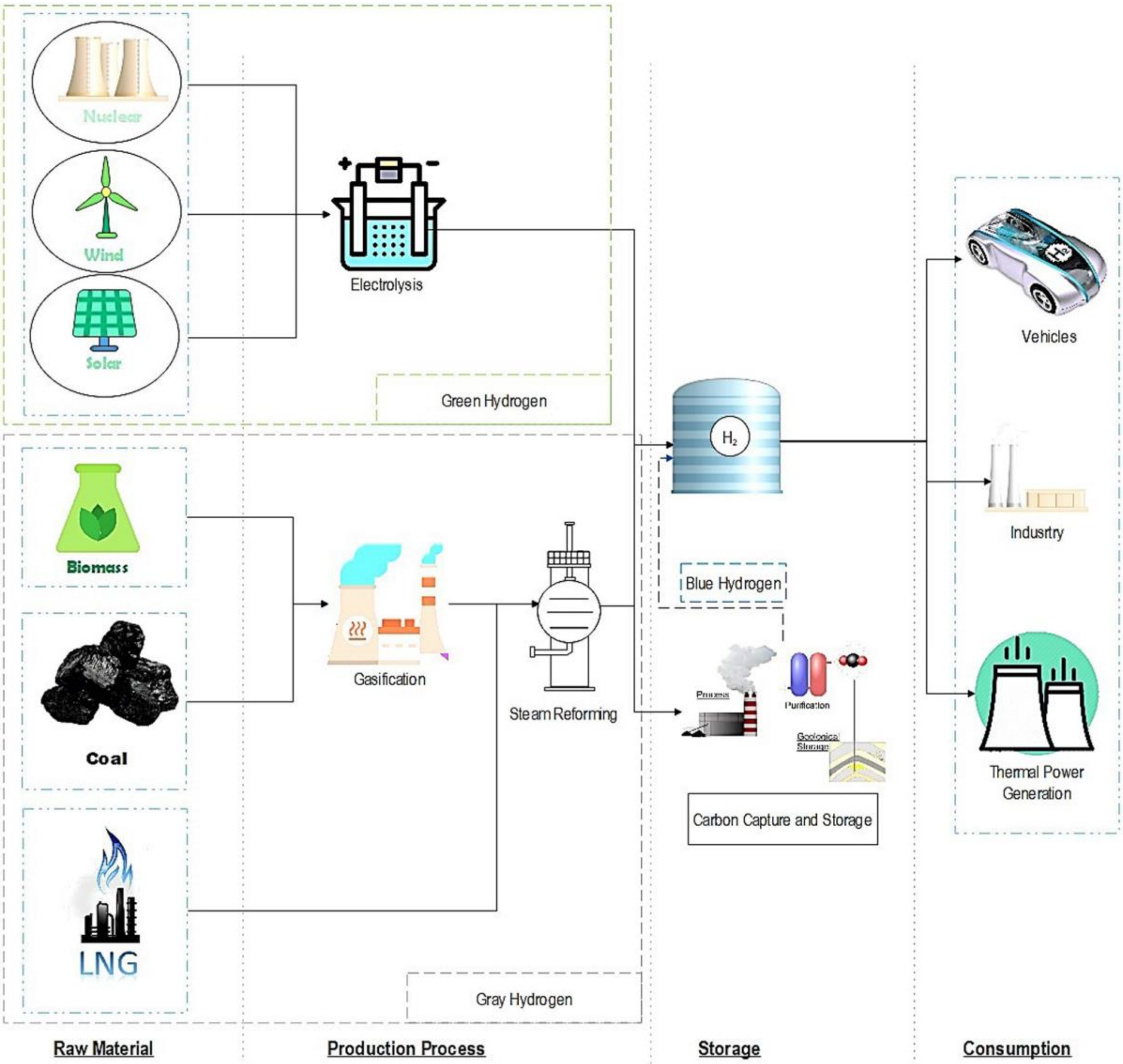

Figure 3: Production routes of Hydrogen via different sources and its applications

[Source: United Nations Environment Program (UNEP), 2006]

Panić et al. (2022) comprehensively analysed different grades of hydrogen and their corresponding production and storage capabilities in the maritime sector. Coded colour-wise, hydrogen is synthesised through different methods and each of these methods is unique, leaving a variable CF. For this study, we have selected three variants of hydrogen; Grey Hydrogen, Blue Hydrogen and Green Hydrogen. The production pathways depicted in *Figure 3* will be used as a reference for deducing environmental impacts later in this study.

2.3.1 Grey Hydrogen

The most commonly produced form of hydrogen presently, it is derived from natural gas or methane (CH_4). The process of Steam Methane Reforming (SMR) is used for this which causes the generation of GHG in the form of CO_2. As Carbon Capture, Utilization and Storage (CCUS) methods are not used here, this commonly available source of producing hydrogen is not very environmentally friendly.

A heat-absorbing reaction between methane and steam at 900 °C is triggered under controlled pressures ranging from 1.5-3.5 MPa resulting in the formation of carbon monoxide and hydrogen as shown in *Equation 1*. To make even more hydrogen, another step is introduced in this process wherein steam or condensate at 370 °C is added to the exhaust to make it react with carbon monoxide, the result shown in *Equation 2*. The net resultant of SMR is shown in *Equation 3* (Hacker and Mitsushima, 2018).

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (1)$$
$$CO + H_2O \rightarrow CO_2 + H_2 \quad (2)$$
$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 \quad (3)$$

The final step involves the separation of hydrogen from the resultant reaction while making sure it is free from carbon dioxide and other impurities. The heat required for the combustion of methane to sustain this chemical reaction is responsible for 41% of the CO_2 emissions released in this process. This is why researchers are trying out alternative sources of providing the heat required such as electrification for limiting the carbon footprint in SMR (Hoecke et al., 2021).

2.3.2 Blue Hydrogen

The fact that the production of hydrogen using conventional methods inherently produces GHG emissions defeats the purpose of transitioning to cleaner fuel sources. CO_2 produced as the by-product as described earlier can be captured, stored and utilised in different ways. The captured carbon can be transported through pipelines or ships or permanently stored underground. It is described as 'low-carbon' hydrogen too as the steam heating process does not avoid GHG production but depending on the efficiency of the CCS method used, we can count blue hydrogen as a cleaner alternative fuel.

Oni et al. (2022) in their investigation of Blue Hydrogen production methods, highlighted the carbon capture efficiency of SMR with CCS methods was between 50-90% whereas when auto thermal reforming (ATR) and natural gas decomposition methods were used, the efficiency ranged between 53-85%. They also observed that Blue Hydrogen produced via the ATR method generated the lowest GHG emissions of 3.91 $kgCO_2eq/kgH_2$. The costs of producing 1kg of H_2 vary depending on the production method used and were observed at \$1.69-\$2.55, as per this study. The development of these CCUS technologies is capital intensive and hence to promote decarbonisation, the Dutch government in 2021 offered €2 billion in subsidies over a period of the next 15 years (Reuters, 2021).

2.3.3 Green Hydrogen

The separation of hydrogen from water molecules through an electrochemical process is powered by renewable energy sources such as wind or solar energy, producing Green Hydrogen. Although this is a more environmentally friendly version, it only makes up for a small portion of all hydrogen produced as the process is costly. The availability of renewable energy will evaluate the cost efficiency of Green Hydrogen in the coming future.

When a high-intensity current is passed through water, it results in the splitting of hydrogen and oxygen molecules, *Equation 4* depicts this reaction.

$$H_2O + Current \rightarrow H_2 + \frac{1}{2}O_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (4)$$

There are multiple methods by which this process of electrolysis can be carried out, Hoecke et al. (2021) pointed out the three most common processes: Alkaline Water Electrolysis (AEL), Proton Exchange Membrane Electrolysis (PEMEL), and Solid Oxide Electrolysis (SOEL). Studies focusing on employing AEL in challenging marine environments for off-shore purposes have demonstrated that these alkaline electrolysers remain unchanged in their structure and composition when exposed to salt sprays (Amores et al., 2021). Amongst the three methods, alkaline electrolysis tops in terms of being compatible with the maritime industry. The maturity of this technology is at a 'state of the art' level, cell temperature needs to be maintained at 60-80 °C, the cell area needed is less than $4m^2$, the average lifetime of a system is 20-30 years, and it produces hydrogen of 99.8% purity (Bhandari et al., 2014).

2.3.4 Storage

Hydrogen in its elemental state exists as a gas. It can be stored for long-term use by either compressing or liquifying it. Being a highly combustible gas, hydrogen storage calls for implementing high safety standards. Over the past few years, research has been conducted to outline the safest and most feasible storage methods in the maritime environment. Although these studies have only been restricted to smaller short-sea ships, there are hybrid methods that can be utilised for long-route vessels.

Storing compressed hydrogen on ships requires careful planning as high-pressure systems need to be installed; tanks, pipelines, compressors etc. This can be difficult due to space constraints on the main deck and potential fire and explosion risks involved due to a high-pressure system. The corrosive effect of the marine environment must also be accounted for. Hydrogen can be stored in its liquid state which it attains at a temperature of -253° C and is typically stored at a pressure of 0.6 MPa (Züttel, 2004). The process of liquification is complex and incurs considerable costs but the ease of distribution is a reason why this storage method has gained importance in recent research.

2.3.5 Hydrogen in Marine Systems

Both liquid and compressed hydrogen can power ships using either fuel cells or internal combustion engines. Fuel cells convert hydrogen energy into electricity and heat, producing water as a by-product. They can be seamlessly incorporated into the existing power grid of a ship and can also be used in hybrid arrangements with diesel engines onboard. Their design simplicity comes as an advantage and makes fuel cell technology for ships such as ferries, cargo-passenger vessels and smaller coastal vessels. The successful integration of fuel cell technology in recent years has confirmed the feasibility of hydrogen as an alternative fuel. Some of these projects are listed in *Table 2* below.

Table 2: Hydrogen fuel-related projects in the maritime industry

[Source: Author's compilation]

Name	***Description***	***Reference***
Condor H_2	It is a part of the Rhine zero-emission project. The purpose is to provide modular containers which can be loaded-unloaded from inland/short-sea vessels. These containers will have stored hydrogen which can be replaced when older containers run-out of power, thereby increasing the ease of covering longer distances for a vessel.	*(Port of Rotterdam, 2023)*
Energy Observer	This former racing catamaran was retrofitted with hydrogen propulsion technology and derives its energy requirements through a mixture of solar, wind and hydro-power. It serves as a floating laboratory for testing hydrogen technologies at sea.	*(Energy Observer, 2019)*
FreeCO_2ast	A collaboration of commercial and research based companies in Norway to develop large zero-emission vessels. A prototype of their hydrogen system has been deployed in a 120-metre-long passenger ship that can sail for 20 hours in Norway's coast.	*(Havhydrogen.no, 2023)*
Hydrogenesis	The first hydrogen-powered passenger ferry operating in the United Kingdom. Daily operation is of 6 hours. Four fuel cells generating 12kW of power are used to propel this ferry.	*(Ship Technology, 2022)*
MF Hydra	A Ro-Pax ferry with a capacity of carrying up to 300 passengers and 80 vehicles operating in Norway. Liquid hydrogen propulsion system deployed here has the ability to reduce annual CO_2 emissions by 95%.	*(Baba Tamim, 2023)*
Nemo H_2	A tour boat operating in canals of Amsterdam with a capacity of 87 passengers. Propulsion system is powered by fuel cells with 24 kg of H_2 stored in cylinders to complete a sailing time of 9 hours.	*(Dekker, 2010)*

SF Breeze	Designed as a high-speed commuter ferry to overcome road congestion in the San Francisco Bay Area. Uses 400kg of liquid hydrogen for a 50 nautical miles trip, cruising at 35 knots. It has a capacity of 150 passengers.	*(Pratt and Escher, 2016)*
Sea Change	A 22-metre aluminium catamaran with capacity of carrying 75 passengers at a top-speed of 15 knots. Three independent fuel cells of 120kW power each are used but hydrogen is stored in compressed state.	*(Ca.gov, 2018)*
Suiso Frontier	This tanker is the first liquid hydrogen carrier in the world. It has a cargo-carrying capacity of approximately 1,250 m^3 . This project, developed in Japan, targets at creating a supply chain for hydrogen fuel. It will be used to transport liquid hydrogen from Australia to Japan.	*(Kawasaki Heavy Industries, Ltd., 2019)*
Topeka	A Norwegian project under which two sister vessels powered by liquid hydrogen and hydrogen fuel cells. It is regarded as gateway to building liquid hydrogen related bunkering infrastructure for coastal shipping activities in Norway.	*(Wilhelmsen, 2021)*
ZEMship	A joint project by nine partners have developed a Proton Motor technology which was put to use in passenger vessel carrying 100 persons in Alster lake, Hamburg. 50kg of hydrogen storage capacity on-board requires refuelling only once in three days.	*(Schneider and This, 2010)*

2.3.6 Section Conclusion

The uptake of hydrogen fuel technology has been explored globally but mostly on research basis. Extensive studies have been conducted on production methods of hydrogen and their long-term feasibility in industrial as well as domestic applications. Hydrogen can be extracted by reforming fossil fuel products or through renewable energy sources. The transportation and storage infrastructure for both liquid and gaseous hydrogen is limited and expensive. Fuel cell technology has proven beneficial in the deployment of hydrogen projects in marine environments. The concept of a replaceable hydrogen fuel container can be explored for inland container barge fleet.

2.4 Life-Cycle Assessment

The Life-Cycle Assessment (LCA) methodology is a systematic approach that is used to evaluate the environmental impacts of a product or a service throughout its complete life cycle. The cycle begins with production or extraction, distribution, consumption and disposal of the said product. Each of these processes generates certain costs and emissions, which are analysed by researchers or companies to assess the overall feasibility of the product. The primary objective of an LCA is to provide a holistic view of the environmental implications to better understand the negative natural footprint it generates. There are numerous factors in conducting an LCA study which can make it a very complicated process, to tackle this it is important to define the scope and boundaries of such a study. LCA is a powerful tool that helps in developing sustainable product designs, formulating science-based business strategies and making environmentally focused policies. Quist (2019) has defined four phases of an LCA study described below:

- Defining Goal and Scope: Selecting the product for analysis, describing how to analyse it and explaining to what extent we will analyse it.
- Life-Cycle Inventory: a collection of data for defined variables of the study and running them in the chosen model.
- Impact Assessment: Select the categories in which we want to check the impact, for example - global warming potential, acidification, eutrophication etc. Then measuring the impact in metric units to quantify the impact.
- Interpretation: Which stage has the most or least environmental damage, and how does it compare to other products? This is what gradually helps in developing policies and strategies.

In the maritime industry, the LCA has been widely used in the past to determine which grade of combustion fuel should be used to minimise emissions. Life cycle emissions are categorised into two main phases: Well-to-Tank (WtT) and Tank-to-Wake (TtW). The cumulative emissions generated in the two phases are the Well-to-Wake (WtW) emissions.

Well-to-Tank: The initial stages of a product's lifecycle, encompassing the extraction, production, processing, and transportation of raw materials, as well as the manufacturing and distribution process that leads to creating a specific energy source (Diogo Kramel et al., 2021). This phase includes both upstream and downstream processes.

Tank-to-Wake: This phase specifically focuses on fuel consumption on a ship. When fuel is loaded on a ship and used in its propulsion system, it generates direct ship emissions that adversely impact air and water quality (Diogo Kramel et al., 2021).

Well-to-Wake: The journey of fuel from the first stage of its lifecycle to the last stage of its lifecycle. This perspective is specifically assumed while assessing lifecycle emissions in the maritime industry (Xing et al., 2021).

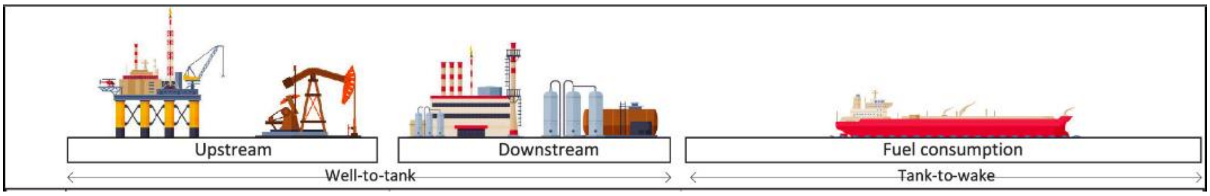

Figure 4: Pictorial representation of emission phases for a marine fuel

[Source: Environmental Science & Technology, 2021]

When we talk about the impact of any fuel, we measure this in different types of emission categories such as CO_2, CH_4, NMVOC (non-methane volatile organic compounds), SO_x, NO_x, CO, EC (elemental carbon), BC (black carbon), PM (particulate matter). Evaluating a fuel's emission based on all these categories is out of scope for our study. Hence, we have selected the most detrimental greenhouse gas emitted by ships, carbon dioxide. The weight of CO_2 released in the atmosphere during any phase of the product's life cycle is quantified in terms of global warming potential (GWP).

The concept of WtW analysis was used when the maritime industry was transitioning to using low-sulphur fuels from conventional Heavy Fuel Oil (HFO). Diogo Kramel et al. (2021) created a modelling framework which factored in emissions during the fuel production stage, and emissions during the fuel combustion stage. They calculated the annual consumption of the fuel mix of Heavy Fuel Oil (HFO), Marine Gas Oil (MGO), and Liquified Natural Gas (LNG) to further subcategorise the amount of pollutants generated by each during the WtT and TtW phases. Then they derived emissions through the combustion of each fuel on a ship taking into account technical details of the vessel such as engine design and resistance offered by sea. Final results suggested that introducing low-carbon or zero-carbon fuels on ships would drastically reduce the ratio of upstream emissions to operational emissions.

Life cycle studies are complex and hence require specialised tools/software to derive the environmental impact of processes. *Table 3* lists out some of these tools which have been used in past research work. In order to assess which tool to use, we need to understand the specific requirements of the study, the industry in focus, and user's familiarity with the tool. Recent trends in LCA applications show a strong international presence, some of the activities listed globally are – International Civil Aviation Organisation's CORSIA program, IMO's discussion on potential net-zero fuel standards, EU's Renewable Fuel Directive, Canadian Clean Fuel Standard, and Brazilian RenovoBio program (Wang, 2022).

Table 3: LCA studies performed for various fuels in the maritime industry

[Source: Author's compilation]

Study	***Fuel Type***	***Vessel Type***	***Contribution***	***Tool(s) Used***
(Florinnicolae, Cătălin Popa and Haralambie Beizadea, 2014)	Not applicable	Ultra Large Container Ship	- Emissions generated throughout the life cycle of a model ship, from construction to operation along a fixed route for 20 years, and subsequent dismantling/recycling was calculated.	Solid Works
(Hua, Wu and Chen, 2017)	LNG and HFO	Container Feeder Vessel and Passenger-Cargo Catamaran	- Emissions differ notably between the two vessels, with feeder emitting 48% more while using HFO - Using LNG reduces overall GHG and CO_2 emissions but slightly increase methane and N_2O gases. - Switching from HFO to LNG reduces NO_x, CO, SO_2 and PM emissions by 38, 42, 99.8 and 97.5 percent respectively. - Cross strait shipping can achieve significant emission reduction, promoting liner services to adapt alternative fuel technologies. - Policymakers should be proactive in bridging the gap between conventional fuels and alternative fuel options for shipping fleet.	SimaPro 7.24 GREET 2016
(Ren and Liang, 2017)	Hydrogen, Methanol and LNG	Not applicable	- An assessment of level of sustainability based on environmental, economic, technological and social factors for each of these alternative marine fuels was done.	Multi Criteria Fuzzy TOPSIS (Technique for Order Performance by

			- Criterion for analysing used were, CO_2 emission reduction, effect on NO_x, SO_x, and PM reduction, capital cost, operational cost, maturity, reliability, capacity and social acceptance. - It was observed that opinions and demands of different stakeholders can be included in making final decisions. - The impact of alternative marine fuels can be quantified even if stakeholders cannot gather complete data for any particular criteria.	Similarity to Ideal Solution) Method
(Bicer and Dincer, 2018a)	Hydrogen and Ammonia	Transoceanic Tanker and Freight Ship	- For this study, complete life cycle of ship, fuels and corresponding port infrastructure were analysed in a cradle-to-cradle perspective. - Ammonia and hydrogen are carbon-free fuels and therefore have considerably lower global warming impact. - Using ammonia and hydrogen as dual fuel technology with HFO can reduce life cycle emissions by 27% and 40% respectively.	GREET 2016
(Yusuf Bicer and Ibrahim Dincer, 2018)	Hydrogen and Ammonia	Transoceanic Tanker and Transoceanic Freight Ship	- Both hydrogen and ammonia are carbon-neutral fuels and have strong potential of reducing GHG emissions. - Operational stage of both vessels generate a lower global warming impact when compared to HFO. - Using hydrogen and ammonia as a duel fuel technology releases much lower CO_2 emission (33.5% reduction) than HFO fuelled tanker ship. - For transoceanic tankers, HFO releases 5.33g/TkM CO_2 eq. whereas ammonia and hydrogen propulsion release 0.98g/TkM and 1.65 g/TkM CO_2 eq. respectively.	GREET 2016 SimaPro 7.3
(Kesieme et al., 2019)	SVO (Straight Vegetable	Slow speed Diesel engine Ship	- Study based on attributional LCA factoring in substitute geographical locations and cultivation methods.	SimaPro 8.0.5

	Oil) and Biodiesel		- Economic allocation had the highest environmental impacts whereas mass allocation had the lowest impact. - Fuel production pathways are most eco-friendly when done in the same country, reiterating that distance between export-import countries is a critical parameter in assessing emissions over the life-cycle. - Biofuel production demands changes in land use, clearing land and cultivating bio-products, this can have an adverse impact on the GWP. - Ignoring the impact of this factor showed GWP emission reduction of 70% when soybean based biofuel system was used.	
(Hwang et al., 2019)	MGO and LNG	Bulk Carrier (50,000 GT)	- Using LNG as a fuel proved to emit lesser marine pollutants than using MGO. - The distance between exporting and importing regions which in this case were USA-South Korea and Middle East-South Korea, was an important parameter that suggested need for optimal production and transportation plans. - Leakage of methane while handling LNG can be critical as it increases the GWP highly. - LCA methodology is a comprehensive and robust tool for maritime industry in terms of analysing environmental impacts of different fuel technologies and forming future regulations.	CML 2001 GaBi Software
(Hwang et al., 2020)	Hydrogen, MGO and LNG	Coastal Ferry (12,000 GT)	- MGO and LNG generated similar levels of GWP, much lower than the levels generated by hydrogen derived from hard coal. - LNG produces lower GWP emissions during the well-to-tank phase when compared to hydrogen and MGO.	CML 2001 Environmental Footprint 2.0 TRACI 2.1

			- The energy source used in producing hydrogen mainly determines the WtT emissions, particularly SMR process, which create substantially higher emissions than MGO and LNG. - Gray hydrogen produced via SMR process is less eco-friendly than natural gas due to high well-to-tank emissions so, in future, hydrogen produced via renewable energy would help achieving IMO's GHG emission targets.	
(Al-Enazi et al., 2021)	Hydrogen, Ammonia, Biofuels, and LNG	Not applicable	- Comprehensive investigation of alternative marine fuels against heavy fuel oil. - Hydrogen has a higher energy per unit mass output and lowest GHG emissions but cost of production and storage is high. - Keeping long term future in mind, LNG acts as a transition fuel whereas investments in hydrogen and ammonia are predicted to grow. - The rise in demand for cleaner fuels will reap commercial benefits for early adopters if they invest in port modification strategies.	Not applicable
(Lee et al., 2022)	Hydrogen MGO and LNG	Nearshore Ferry (170 GT)	- Hydrogen shows highest level of GWP, AP, POCP, EP and PM emissions during the well-to-tank phase. - MGO and LNG can drastically reduce NO_x and SO_x emissions during the tank-to-wake phase while hydrogen only produces water and zero gases when used through fuel cells. - Total GWP from well-to-wake phase had similar values for MGO and LNG while Hydrogen generated 10% higher value. - Hydrogen's life cycle emit substantially lower amounts of other environmental pollutants as compared to LNG and MGO, and hence these must be taken into	GaBi Software

			account to paint a holistic picture for future scenarios.	
(Fernández-Ríos et al., 2022)	Hydrogen as PEMFC and Dual Fuel with Diesel in Internal Combustion Engine (ICE)	Tourist Boat and Windfarm Support Vessel	- Hydrogen based ICE is a more sustainable option than PEMFC technology in this study. - H_2 ICE can be used as a medium to long-term solution for decarbonisation in shipping as it recorded 45-72% emission reduction in 10 out of 11 pollutant categories.	GaBi Software OpenLCA 1.10.3 CML 2001

2.4.1 Section Conclusion

LCA is a resourceful technique that is used in formulating policies and strategies on an industrial level. It encompasses environmental impacts from each stage of a product. Many studies have used this tool to compare cleaner alternatives with conventional fuels but our focus was on alternative fuels in the maritime industry. Although emission categories vary, CO_2 concentrations are highly toxic amongst all GHGs, and hence they are always considered essential to assess. There are many commercially available software with a considerable size of database for conducting these studies. Fuel technologies such as HFO, MGO, LNG, methanol, biofuels, ammonia and hydrogen are compared with each other for sea-going vessels of various types.

2.5 Economic Assessment

Introducing new technologies on a large scale requires a strong collaboration between different industry stakeholders. The shipping industry is capital intensive, meaning high initial investments are needed to build a ship and its equipment. There are two options for introducing hydrogen systems on board: either retrofit the technology on an old ship or build a new one from scratch. There are studies that have predicted future prices of alternative fuels based on certain assumptions and available factual knowledge. Essentially, the lack of presence of alternative fuel infrastructure around the world has limited these cost analysis studies in deriving consistent conclusions.

Expenses incurred over the life-cycle of a ship can be divided into – capital expenses (capex) which are the initial investments for ship-building, operational expenses (opex) which are maintenance costs, consumable costs which are through spare parts, lubricating oil and other additional system needs, and Fuel costs (Deniz and Zincir, 2016). When we consider a new fuel such as hydrogen, we also need to account for costs subjected to the manufacturing of infrastructure such as production and storage facilities, bunkering stations, and pipeline network systems. The level of modification needed on an existing layout of a ship will directly increase the costs of retrofit. According to Deniz and Zincir (2016), hydrogen fuel technology is more adaptable for retrofitting on an old ship than other alternative fuels, because it has fewer stationary and moving parts, a less complex system, minimal lateral space requirements, and it does not need any storage tanks.

Horvath et al. (2018) created a cost modelling framework, levelized cost of mobility, to predict the cost-effectiveness of alternative fuels by the years 2030 and 2040. In their study, they considered capex, opex, fuel costs, cargo space lost costs and CO_2 costs to conclude that hydrogen fuel cells would be the best option to replace conventional internal combustion engines if the fuel cell technology follows its projected development journey in the next two decades. Their research indicates a substantial global capability to manufacture the necessary synthetic fuel, Argentina's solar and wind energy alone could produce enough hydrogen to match the demands of the shipping industry at a reasonable price range of 38-49 €/MWh. An improvement in the efficiency of PEM-FC, recorded at 40-45% in this study, along with enhanced production technologies will reduce the overall fuel costs making hydrogen a competitive energy source of the future.

Taljegard et al. (2014) conducted a study wherein they refined a global energy model to incorporate the maritime sector and assess the potential economic effectiveness of alternative fuel and propulsion technologies by the year 2050 while limiting the CO_2 emissions to 400-500 ppm by the year 2100. The results of this study were verified statistically using the Monte Carlo method. The authors suggest phasing out fossilised fuels on ships must begin by the year 2024 in order to achieve cost benefits in the given timeframe of the study. Natural gas-based fuels will have a high probability of supplying the bunker demands in shipping but this choice will strongly depend on the availability of carbon capture technologies, climate goals, and storage and production feasibility of other cleaner alternatives. Hydrogen fuel technology was predicted to play no role in sourcing energy for ships regardless of carbon capture and storage techniques till 2050.

Energy efficient solutions are vital for short-sea and inland shipping as the resultant pollution through exhaust systems directly affects the local population living around the water body. A study on Croatian inland waterway done by Perčić et al. (2021), revealed that the use of hydrogen for inland shipping is not suitable even though tank-to-wake emissions are zero because the amount of carbon footprint left during the well-to-tank phase is larger than other options' total life-cycle emissions. The capital costs for a hydrogen-propelled vessel depend on the power needed from the PEM-FC; the cost of the fuel cell was taken as 368 €/kW. The authors calculated the storage costs of hydrogen based on the quantity needed depending on the vessel's route, this was taken as 5 €/kWh. A general range of price for hydrogen was taken as 5.35 – 9 €/kg, to calculate future maintenance costs during the vessel's life cycle. This paper also studied the implications of carbon credit rules (discussed in Section 2.1) even though these rules are not valid for the inland shipping sector as yet. In another similar study by the same authors Perčić et al. (2020), considered two options for hydrogen-powered ships, a non-renewable and a renewable energy source derived from hydrogen fuel. This division depicts the production pathway of hydrogen, renewable hydrogen – made from renewable energy sources, and fossilised hydrogen – produced from liquified natural gas. The electrolyser was estimated at 92 €/kW and the PEM fuel cell at 368 €/kW. The battery price, which is required to store the hydrogen energy, depends on the battery capacity, investment cost factor (45%), and battery price (assumed to be 200 €/kWh). Both of these studies generated results that show hydrogen fuel technologies (renewable and fossilised) to be less cost-effective when compared with energy sources such as methanol, electricity, and dimethyl ether (DME) which is obtained from natural gas.

Cruise ships require a relatively larger share of auxiliary power when compared to merchant vessels. In practice, cruise ships have adopted methods to partially generate this load through a renewable source such as solar energy. Ghenai et al. (2019) investigated the possibility of integrating renewable energy systems with diesel generators for small and large cruise ships between Stockholm (Sweden) and Mariehamn (the Aland Islands). The power requirements to serve main and auxiliary loads were distributed amongst photovoltaic solar panels, a combination of PEM fuel cells and electrolyser units, and diesel generators. Results of this study show that a hybrid energy system can offer optimisation of renewable resources in the maritime industry, the fraction of total power, generated by renewable energy, stood at 13.83%. Photovoltaic solar panels contributed 9.44% while PEM fuel cells contributed 4.39% to this total. The authors suggest that this integration can be very useful for coastal vessels or ferries in regions with high average solar irradiance, such as cities in Middle-East countries (an average of three times greater than of cities in Scandinavian countries). A substantial amount of electricity can be produced through solar panels to operate electrolysers which in turn would feed the hydrogen fuel cells, if the average availability of sunlight is greater throughout the year, hence increasing the renewable percentage of the energy system. The cost of hydrogen fuel for this study was assumed $1/kg. *Table 4* below details other relevant costs.

Table 4: Estimated price of hybrid energy mix for a cruise ship

[Source: Ghenai et al., 2019]

System Component	Cost Structure
Solar Panels (Photovoltaic)	- Capital cost: $1200/kW - Renewal cost: $1200/kW - Operation and Maintenance cost: $3/year/kW
Generic Diesel Generator	- Capital cost: $300/kW - Renewal cost: $300/kW - Operation and Maintenance cost: $0.01/hour
PEM Fuel Cell	- Capital cost: $400/kW - Renewal cost: $400/kW - Operation and Maintenance cost: $0.01/hour
Electrolyser unit	- Capital cost: $100/kW - Renewal cost: $100/kW - Operation and Maintenance cost: $8/year/kW
AC-DC Converter	- Capital cost: $40/kW - Renewal cost: $40/kW - Operation and Maintenance cost: $10/year/kW

The cost of producing a commodity gradually reduces as the production volume increases. This may not be true in all cases but DNV's Hydrogen Report – 2050, forecasts this scenario in the coming three decades. The global average cost of hydrogen will greatly depend on the production pathway used but in every case, will drop as the year 2050 approaches. *Table 5* shows the levelized cost of hydrogen as forecasted considering the weighted world average. The cost of repurposing natural gas pipelines is expected to be 10-35% of the cost of newly constructed hydrogen pipelines, therefore it is predicted that more than 50% of existing natural gas lines around the globe will be repurposed to minimise costs (DNV-Hydrogen Report, 2022).

Table 5: Cost forecast of hydrogen for the years 2020, 2030 and 2050

[Source: Figure 3 – Levelized Cost of Hydrogen, DNV – Hydrogen Report – 2022]

Production Pathway	**2020**	**2030**	**2050**
Grid-based Electrolysis	\$3.2/kgH_2	\$3.2/kgH_2	\$1.5/kgH_2
Methane Reforming with CCS (Blue Hydrogen)	\$3/kgH_2	\$2.5/kgH_2	\$2.2/kgH_2
Dedicated Renewable Electrolysis (Green Hydrogen)	\$5/kgH_2	\$2.4/kgH_2	\$2/kgH_2

A cost-effectiveness study for four alternative fuels – LNG, methanol, green ammonia, and green hydrogen for the twenty most frequently visiting vessels in ports of Ireland was conducted by Gore, Rigot-Müller and Coughlan (2022). They included costs saved due to external factors, carbon tax and conventional fuel prices and calculated the Net Present Value (NPV) for a period of 25 years. LNG and green hydrogen had NPVs of €6,166 million and €319 million respectively. They concluded that a reduction of 60% in the current price of green hydrogen and an increase of 275% in carbon-tax rate, could improve hydrogen's cost-competitiveness over LNG and methanol. A comparative study between hydrogen and ammonia as shipping fuels revealed that ammonia had an upper hand in terms of cost for production and storage on board vessels (Inal, Zincir and Deniz, 2022). This study assumed total costs as a function of fuels costs, €153/kWh for hydrogen and €120/kWh for ammonia, and onboard storage costs, €1.29 – €1.71/kWh for hydrogen and €0.23 – €0.29/kWh for ammonia. Hydrogen has the potential to become the most favoured alternative fuel in the coming decades only if stakeholders in the maritime industry refrain from deferring initial investments needed to promote and accelerate net-neutral fuel technologies to decarbonise the shipping industry by 2050 (Pomaska and Acciaro, 2022).

2.5.1 Section Conclusion

Introducing hydrogen as a maritime fuel could be capital-intensive and hinges on multiple factors. Large-scale retrofitting may not be feasible in the main sea-going fleet but could benefit inland shipping. The prospect of reduced fuel costs and advancement in fuel cell technology will bolster hydrogen's adoption in future maritime activities. Compared with other alternative fuels, the cost competitiveness of hydrogen will remain low for a few decades. Carbon emission penalties will encourage stakeholders to expedite the uptake of hydrogen fuel technologies by making crucial initial investments.

2.6 Synthesis of literature studied

Through this comprehensive exploration, we arrived at formulating the base of our research. The EU's climate agenda focuses on implementing regional strategies for the maritime sector. This idea is relevant in the context of the inland shipping sector, which is the backbone of hinterland connectivity in Europe, with container barges playing a significant role in facilitating import-export trade. The potential of hydrogen fuel technology has been studied in comparison with other alternative fuels, but exploration of different grades of hydrogen has a limited knowledge base. The concept of portable liquid hydrogen containers can be extended to the inland container barge segment, as the TEU capacity of these vessels is optimal for practical research. The utilisation of LCA tools can be complex unless logical system boundaries are defined. Therefore, our study will focus on comparing three grades of hydrogen power system with conventional diesel power system for an inland container barge deployed in Europe, and assess their environmental and economic impacts with each other.

3 Research Methodology

The literature review found that the CML-2001 method Guinee (2002), which comprises maximum characterisation factors (eleven) compared to other methods, was the most common in studies related to life cycle impact assessment involving hydrogen systems. The selection of software depended on its availability as an open-source tool and implementation in the maritime industry. The choice between OpenLCA and GREET was made based on the scope of this study. OpenLCA is a more general LCA tool which offers flexibility for a broader range of applications. It also provides an option of integration with various other databases, facilitating customisations with different industries. On the other hand, GREET is a transportation-focused LCA tool that models different fuel technologies. As a part of our study aims to evaluate environmental impacts in the context of energy use and emissions in maritime transportation, using the GREET tool was decided to be more appropriate. LCCA will be conducted by estimating investment, fuel, maintenance, and carbon costs over the time horizon of the ship's lifetime. Secondary data gathered from the literature study will be used.

3.1 The Greenhouse Gases, Regulated Emissions, and Energy use in Technologies Model (GREET)

Argonne National Laboratory, sponsored by the U.S. Department of Energy laboratory, has developed this life cycle assessment tool for evaluating the environmental impacts of different transportation fuels, vehicles and technologies. Every process leading up to the combustion of a fuel onboard can emit toxic gases. GREET has a detailed and regularly updated database which covers a broad spectrum of fuel technologies. Its widespread use and recognition by U.S. government agencies and other leading international transport companies lend credibility to studies conducted using GREET. Attributional LCA is the primary approach incorporated in this tool, with some consequential effects recorded in the final results. The availability of this software was free of cost, and its intuitive interface helped in modelling our required scenarios. The inbuilt well-to-tank module present for analysing simulations in the maritime industry was relied upon for the study. Diesel energy is applicable as the baseline, as it is the most common fuel used in inland shipping presently, and out of the other energy systems available, we focused on hydrogen and its varying production pathways (Energy.gov, 2018; GREET, n.d.).

3.2 Ship Selection

The scope of this research directs us to select the closest representative vessel based on our focus group. As we intend to find an inland container vessel of gross tonnage ranging from 3,000 – 4,000 tonnes, operating between two major inland ports of Europe (discussed in section 3.3), we looked at the websites of various barge service companies around the Rhine area. Some players in this sector are CCT Barge Services, Danser Containerline, Rederij de Jong, Nedcargo BV, and Contargo Trimodal Network. With limitations of data availability and the study's focus on the Rotterdam-Antwerp route, we chose Contargo Trimodal Network. Their core activities include high-frequency barge services between Rotterdam-Antwerp under the 'Transbox Services' feature shown in *Figure 5* below. Collection of secondary data through sources such as Fleetmon, Marine Traffic, De Binnenvaart, and the company website helped us gather vessel details as shown in *Table 6*.


CONTARGO
trimodal network

Transbox Rotterdam-Antwerp Service

Rotterdam-Antwerp

Import	Antwerp	Rotterdam	Rotterdam	Antwerp	Antwerp	Rotterdam
	Tues / morning	Wed / midday	Thurs / evening	Fri / morning	Sat / evening	Sun / morning

Export	Rotterdam	Antwerp	Antwerp	Rotterdam	Rotterdam	Antwerp
	Tues/ evening	Wed / morning	Thurs / evening	Fri / morning	Sun / evening	Mon / morning

www.contargo.net

Figure 5: Contargo's regular barge services between Rotterdam and Antwerp

[Source: Company's official website]

Table 6: Vessel Particulars

[Source: Author's compilation through different sources]

Name of the Ship	**Aqua-Myra**
EU Number	2319046
MMSI	244630035
Vessel Type	Inland Container Barge
Call Sign	PC5373
Flag	The Netherlands
Deadweight (tonnes)	3168
TEU Capacity	188
Length (m)	110
Breadth (m)	11.40
Draft (m)	3.75
Design/Average Speed (knots)	9/7.6
Main Engine Make	Caterpillar 2028 hp
Main Engine Model	3516 (B) DI-TA Electronic
Main Engine Power, P_{ME} (kW)	1512
Bow Thruster	Scania-Veth-Jet 571 hp
Auxiliary Power, P_{AE} (kW)	425
Year Built	1989
Home Port	Rotterdam

Figure 6: Representative vessel for the study

[Source: De Binnenvaart]

3.3 Route Selection

There are multiple major ports in Europe which accommodate inland shipping activities. We have selected Rotterdam and Antwerp as the base ports for this research. Rotterdam stands as the largest seaport in Europe regarding the volume of cargo loaded and unloaded (Port of Rotterdam Authority, 2022). To maintain its market position, Rotterdam has been implementing sustainable solutions in the transport sector by using modal shift techniques. This is where inland shipping makes a big difference in achieving minimum carbon emissions. Meanwhile, Antwerp sits in the heart of Europe and provides an effective connection with the hinterland. A division modal split shows a majority of the share, 48 per cent, is dedicated to the inland navigation sector (Port of Antwerp – Facts and Figures, 2023). This report also indicates the operation of 49,000 inland vessels per year in Antwerp with around 200 shore power connection points across all terminals to minimise emissions during the docking period of a vessel. Considering the absolute volume of inland cargo loaded and unloaded at these two ports, we draw a comparison with other major ports on the Rhine River as shown in *Figure 7*.

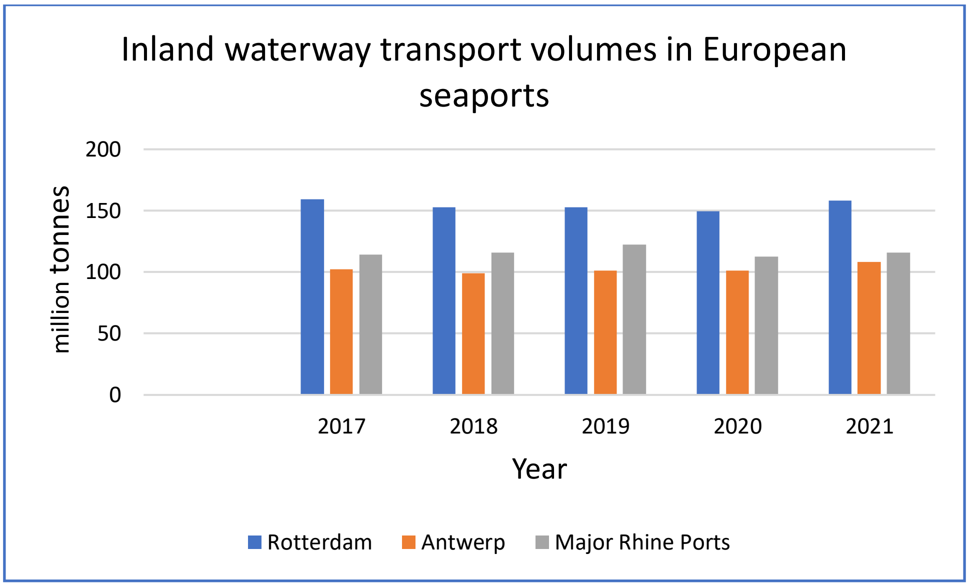

Figure 7: Cargo shipping volumes handled by major European inland ports

[Source: CCNR Market Observation – Annual Report 2022]

Figure 8: Inland water route from Rotterdam to Antwerp

[Source: RouteScanner – Plan your door-to-door container route, 2023]

Contargo's barge services provide high-frequency connections between ports in western Europe (Contargo.net, 2023). We have assumed that the container barge 'Aqua-Myra' is a part of Contargo's trans-box service between Rotterdam-Antwerp. This assumption was verified by tracking the vessel's ports of call through 'Marine Traffic'. The vessel's schedule as per *Figure 5* shows 2 round-trips per week. A visual depiction of the selected route from Rotterdam to Antwerp is shown in *Figure 8*. The distance between the two inland terminals is 112 km ≅ 60 nautical miles. Therefore, in a single week, the container barge will cover this distance 4 times, computing a total sailing distance of 240 nautical miles per week. Assuming the average speed of the vessel is 7.6 knots, both upstream and downstream, the total sailing time per week can be calculated. Furthermore, the total number of annual trips was calculated by assuming 52 weeks in a calendar year.

$$Annual\ Number\ of\ Trips\ (N_A) = 52 * 4 = 208$$

3.4 Deriving Input Variables

We determined input variables for this study by exploring available literature and conducting independent research work. An important parameter for any LCA study is the average lifetime of a vessel. Due to operation within relatively steady waters, an inland ship is known to have an average lifetime of over 40 years (CORDIS, 2016). But in most of the academic papers reviewed, the average age of a vessel was assumed to be 20-25 years. Acknowledging these facts, we have assumed the average age of an inland ship as 30 years, for this study. Furthermore, to calculate CO_2 emissions and total costs over the lifetime of a vessel, we need to calculate the total energy consumption.

The average speed (v_{avg}) of this inland barge was observed to be 14.07 km/h. The main engine was, on average, assumed to operate at a 75% maximum continuous rating (Essen, Faber and Wit, 2004). The main engine load varies according to the average speed, and to calculate this, Perčić, Vladimir and Fan (2021) used relation between design speed (v_{des}) and average speed (v_{avg}) according to *Equation 5.*

$$P_{ave.ME} \quad = \quad (P_{ME} * 0.75) * (\frac{v_{avg}}{v_{des}})^3 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

The auxiliary engines onboard which supply energy to utilities such as bow thrusters and other supplementary types of machinery also produce energy. This portion of energy on average is assumed to be 50% of the maximum continuous rating (Perčić, Vladimir and Fan, 2021). This gives us $P_{avg.AE} = 0.5*P_{AE}$

Summation of these two average powers when divided by the average speed of the vessel, will give us the energy consumption (EC) per distance travelled (Perčić, Vladimir and Fan, 2020). This gives us $P_{avg} = P_{avg.ME} + P_{avg.AE}$. The general formula for calculating EC is shown by *Equation 6.*

$$EC\left(\frac{kWh}{km}\right) \quad = \quad \frac{P_{avg}}{v_{avg}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Through this equation, we will calculate the fuel consumption (FC) by multiplying energy consumption with specific fuel consumption (SFC). The value of SFC will vary according to the chemical properties of the fuel in consideration (Perčić, Vladimir and Fan, 2021). This gives us *Equation 7.*

$$FC\ \left(\frac{kg}{km}\right) \qquad = \qquad EC * SFC \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

As the route for this vessel is fixed and we have assumed 4 one-way trips per week, we can calculate the total number of annual trips (N_A). We also know the distance *(l)* between the two inland terminals. Using these parameters and assuming the lifetime of the vessel as 30 years, we will derive the Lifetime Mileage (LM). Perčić, Vladimir and Fan (2021) performed these calculations as shown in *Equation 8.*

$$LM\ (km) \qquad = \qquad 30 * N_A * 2 * l \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

It was assumed that an inland barge uses high/medium speed marine diesel engines as a baseline case, the specific fuel consumption (SFC_{Diesel}) was taken as 0.215 kg/kWh (Ivica Ančić, Nikola Vladimir and Cho, 2018). Subsequently, all the required baseline parameters were calculated and are shown in *Table 7.*

Table 7: Calculated values for a fixed-route inland barge

[Source: Author's compilation]

Parameter	**Value**
Average power of the ship, P_{avg} (kW)	895
Average speed of the ship, v_{avg} (km/h)	14.07
Average energy consumption, EC (kWh/km)	63.64
Average fuel consumption, FC (kg/km)	13.68
Lifetime Mileage, LM (km)	698,880

The raw materials used in manufacturing the main propulsion system vary in quantity and produce an environmental impact. Jeong et al. (2018) conducted a study to assess the emissions generated in the production stage of a generic marine diesel engine. They calculated the total mass *(m)* of the engine and multiplied it by the corresponding fraction of raw material used. The total mass *(m)* takes average power (P_{avg}) into account and will be assumed to be equal for any combination of power systems considered in this study, and will be calculated through *Equation 9* (Jeong et al., 2018).

$$m = \frac{2 * P_{avg}}{450} \dots\dots\dots\dots\dots\dots\dots\dots\dots (9)$$

When fuel is ignited inside the combustion chamber of the main engine, it releases exhaust gas which accounts for the tailpipe emissions (TE). This emission can be quantified by multiplying fuel consumption with emission factor (EF), according to *Equation 10* (Perčić, Vladimir and Fan, 2021)

$$TE = EF * FC \dots\dots\dots\dots\dots\dots\dots\dots\dots (10)$$

A benefit of using hydrogen as an alternative fuel is its high energy value per mass unit, the net calorific value for hydrogen (NCV_H) is 33.3 kWh/kg. In literature studies conducted on hydrogen, most systems assumed power generation for auxiliary purposes but to maintain consistency, we have assumed that the energy consumption in all configurations will be for the total average power of the ship. The efficiency of a PEM fuel cell is predicted to improve in the coming decades but in the current scenario, it ranges between 32-49% (Horvath, Fasihi and Breyer, 2018). Our study assumes the efficiency (η_{FC}) as 50%. The hydrogen consumption (FC_H) per unit distance is then calculated through *Equation 11* (Perčić, Vladimir and Fan, 2021).

$$FC_H = \frac{EC}{\eta_{FC} * NCV_H} \dots\dots\dots\dots\dots\dots\dots\dots\dots (11)$$

In order to determine the cost-effectiveness and economic feasibility of each fuel type considered, we need to perform a life-cycle cost assessment study. The total costs for the system will include investment costs and exploitation costs. Investment costs are incurred in manufacturing base components required for the system such as engine, electrolyser, and fuel cells. Exploitation costs are divided into fuel costs, maintenance costs and carbon emission costs. Carbon emission cost is a futuristic idea but will be included in our analysis. This cost is only valid for tailpipe emissions, hence all three scenarios of hydrogen fuel will be exempted from carbon costs. The life-cycle fuel costs of diesel ($LCFC_D$), maintenance costs of diesel-powered ship ($LCMC_D$), and life-cycle carbon emission costs for tailpipe emissions (LCCEC) are calculated by *Equations 12,13,14* respectively (Perčić, Vladimir and Fan, 2021).

$$LCFC_D \quad = \quad LM * FC_D * PR_D \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

$$LCMC_D \quad = \quad LM * EC * MF_D \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

$$LCCEC \quad = \quad TtW_C * CA \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

The fuel costs for liquid hydrogen directly rely on the production pathway, ranging from three to five times more than the cost of diesel. The average price of grey hydrogen ranges from €1.65 to €3.2 per kilogram while that of green hydrogen is €3.04-€9.1 per kilogram (Pomaska and Acciaro, 2022). The lifecycle fuel costs can then be calculated as per *Equation 15*, where the price of hydrogen (PR_H) will be assumed accordingly (Perčić, Vladimir and Fan, 2021).

$$LCFC_H \quad = \quad LM * FC_H * PR_H \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (15)$$

4 Analysis

4.1 The life cycle assessment of a diesel-powered ship

The present fleet of inland ships mostly uses diesel-powered engines, a system configuration that will be used as a baseline for our analysis. Although diesel is categorised as low-sulphur fuel, its extraction from crude oil and combustion in engines generates a carbon footprint. Prior to analysing any alternative energy source, we need to determine the environmental impact of our base fuel system. We will divide the analysis into three parts to estimate the lifetime CO_2 emissions from a diesel-powered ship.

4.1.1 Manufacturing phase:

As discussed in Section 3.4, manufacturing a diesel engine comes with certain environmental consequences. The total mass *(m)* obtained for our representative engine size through *Equation 8,* will be used to determine the fractional weight of each raw material used in manufacturing the diesel engine as per *Table 8*.

Table 8: Raw material weight ratios for a generic diesel engine

[Source: Jeong et al., 2018]

Engine Material	Ratio (%)
Cast Iron	46.0
Steel	40.0
Aluminium	8.0
Oil and Grease	3.0
Paint	0.9
Plastic	0.9
Rubber	0.9
Zinc and Copper	0.2
Lead	0.1

The emissions released through the production stage of these engine materials were gathered by inputting the relevant weight required for each raw material in the GREET 2022 software. The outputs were obtained as CO_2 equivalent in kilograms, the sum total of these is the CO_2 released during the manufacturing of a diesel engine, and are shown in *Appendix A*.

4.1.2 Well-to-Tank phase:

Diesel is produced through the fractional distillation process of crude oil in refineries (Valero, 2023). The final product is then dispatched to importing nations through a combination of modes of transport such as ships, trucks, and pipelines. To assess the emissions generated in this phase, we must establish a pathway from crude oil in factories to diesel on ships.

We have assumed that Rotterdam will be the bunkering port for our study and hence investigated data for the Netherlands' crude oil imports. The top three exporters of crude oil to the Netherlands are Russia, the United Kingdom and the United States of America; accounting for approximately 65% of total crude oil imports (OEC - The Observatory of Economic Complexity, 2021).

Recent geopolitical complexities such as the Russian invasion of Ukraine and BREXIT resulted in significantly high crude oil exports from the USA to the Netherlands, recorded at 698,000 barrels per day in March 2023 (Eia.gov, 2015). The states of Texas and New Mexico are the largest crude oil producers in the USA. These states are also home to the largest oil field, the Permian Basin, from where all major exports occur (Eia.gov, 2023). Crude oil is transported from the Permian Basin to Corpus Christi via pipelines (1,126 km) and then loaded onto VLCCs which transport the cargo to Rotterdam, covering a distance of 11,378 km (WSJ, 2023; Ports.com, 2023). The port of Rotterdam comprises refineries operated by Shell Nederland, Exxon Mobil, Vitol, and BP, which are responsible for converting crude oil to conventional diesel and finally making it available to be bunkered on ships (Port of Rotterdam, 2021). The combined pipeline distance of this process is assumed to be 15 km.

Simulation of this phase was carried out by selecting 'conventional diesel' as the input resource for GREET 2022 software. The extraction, transportation and storage stages are included in the modelling to obtain the cumulative CO_2 emissions over the lifecycle of diesel. A visual description of the described details is presented in *Figure 9*. The complete results of total emissions are shown in *Appendix B*.

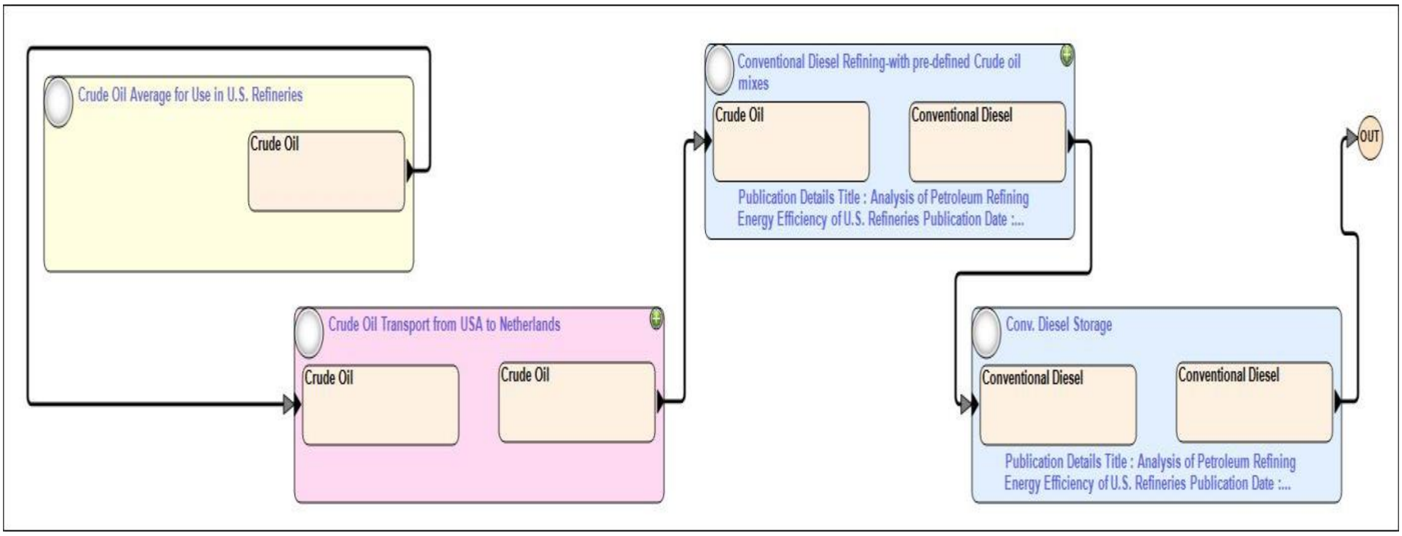

Figure 9: Conventional Diesel production pathway simulated through the model

[Source: Author]

4.1.3 Tank-to-Wake phase:

Once the optimal amount of diesel is bunkered, the engine burns it to propel the ship. The tailpipe emission generated leaves a carbon footprint which depends on the emission factor for diesel. The emission factor of diesel is assumed to be 3.206 kg-CO_2.eq per kg of fuel (Perčić, Vladimir and Fan, 2021). The CO_2 emissions generated in this phase are then calculated using *Equation 9*, wherein we take the fuel consumption over the complete 30 years of the ship's operational lifetime. The final results from each stage are depicted in *Table 9* below. Total emission is the sum of CO_2 equivalent from each phase and is recorded at 36,993 tons.

Table 9: Carbon dioxide released over the vessel's lifetime when operating on diesel.

[Source: Author]

Lifecycle Phase	*CO_2 emission generated (tons)*
Manufacturing Engine	7.2
Well-to-Tank	6,331
Tank-to-Wake	30,655
Well-to-Wake	36,993

Note: All values from each phase are rounded up to the nearest whole number.

4.2 The life cycle assessment of Grey Hydrogen-powered ship

There are several new components required to be built for successfully deploying a hydrogen-based propulsion technology. A combination of an electric engine and a fuel cell is assumed to propel the ship in this case. Hydrogen extracted from natural gas in refineries on land is supplied to the fuel cells onboard. This section will estimate the emissions from each process under the manufacturing, recovery, transportation and storage phases for fossil-based hydrogen fuel.

4.2.1 Manufacturing phase:

A fuel cell is manufactured by assembling various components made up of different raw materials. An exploratory study on assessing the environmental impact of materials used in the production and processing stages of a PEM fuel cell was done by Garraín and Lechón (2014). By using the life cycle inventory data presented in their research, we calculated the corresponding weights of materials needed to make the fuel cell. Material data is shown in *Table 10.*

Table 10: Lifecycle inventory of parts included in manufacturing PEM-FC of 1kW rating

[Source: Garraín and Lechón, 2014]

Fuel Cell Stack Part	Materials	Quantity (kg)
Electrode	Porous carbon paper	0.03
Seal	EPDM rubber	0.02
Circuit Board	Pertinax, tin	2.75
Cable	PVC, copper	2.5
Catalyst	Platinum dispersed, carbon powder and PTFE	0.0025
Screws	Steel	1.5
Pipe connectors	Plastic (HDPE)	0.75
Pipes	Plastic (PU)	1
Membrane	Nafion	0.0025
Heat Sink	Aluminium	2
Valves	Steel, plastic (HDPE), copper	2.5
Flow Field Plate	Graphite	3
Pump	PEEK (polyetheretherketone) Aluminium, copper	6
Box Metal	Steel Sheet	5
Ventilators	Plastic (HDPE), copper	3

The input values needed to manufacture a PEM-FC (895 kW) were extrapolated using *Table 10* and entered in GREET 2022 to obtain final CO_2 emissions. Results are presented in *Appendix C.* The fuel cells are assumed to be replaced every 10 years. The manufacturing of electric engine is assumed to generate an equal amount of CO_2 emissions as calculated for diesel engine in the previous section.

4.2.2 Well-to-Tank phase:

The production methods for hydrogen majorly rely on fossil fuels such as coal and natural gas. In 2022, about 84% of the total energy produced via hydrogen was sourced through fossil fuels, out of which 70% share was from natural gas reforming (IEA, 2021). Hydrogen is recovered in a gaseous state from natural gas plants, which is then sent to a liquefaction facility and further stored and distributed as needed. Air Liquide and Air Products have developed a comprehensive production and distribution infrastructure for 'merchant hydrogen' – they have approximately 1,000 km of pipelines stretching across western European countries such as France, Germany, the Netherlands and Belgium (Weeda and Segers, 2020). Air Liquide operates a plant, with a daily capacity of 280 tons, in the Rotterdam-Botlek region to produce pure hydrogen via the SMR process (H2tools.org, 2023). The distance from Botlek to Rotterdam is considered to be 16 km, and the liquified hydrogen is assumed to be carried via pipelines. We simulated the production, transportation and storage scenarios of liquid hydrogen from natural gas using GREET 2022 – the pathway is depicted in *Figure 10*. The emissions are calculated as per the required mass of hydrogen that we calculated as FC_H. An expanded view of the first block in Figure 10, shown in *Figure 11*, depicts our modelling of the grey hydrogen scenario. In this figure, natural gas recovered is sectioned off into two process blocks – one with CCS technology and the other without CCS technology. These converge back into a single process block with adjustable input ratios. As grey hydrogen production excludes carbon capture and storage methods, we input 100% from the 'without CCS' process block and obtain the final CO_2 emissions. We also simulated emission output from the steam methane reforming process by clicking on the first box in the block diagram. This software feature allows us to read parameters from a particular process in the pathway selectively. The SMR process produces 9.30 kg-CO_2/kg-H_2. A detailed result of this phase is reproduced in *Appendix D*.

4.2.3 Tank-to-Wake phase:

Vessel operation under this category of fuel will not generate any tailpipe emissions. Hence, this phase does not have an adverse environmental impact.

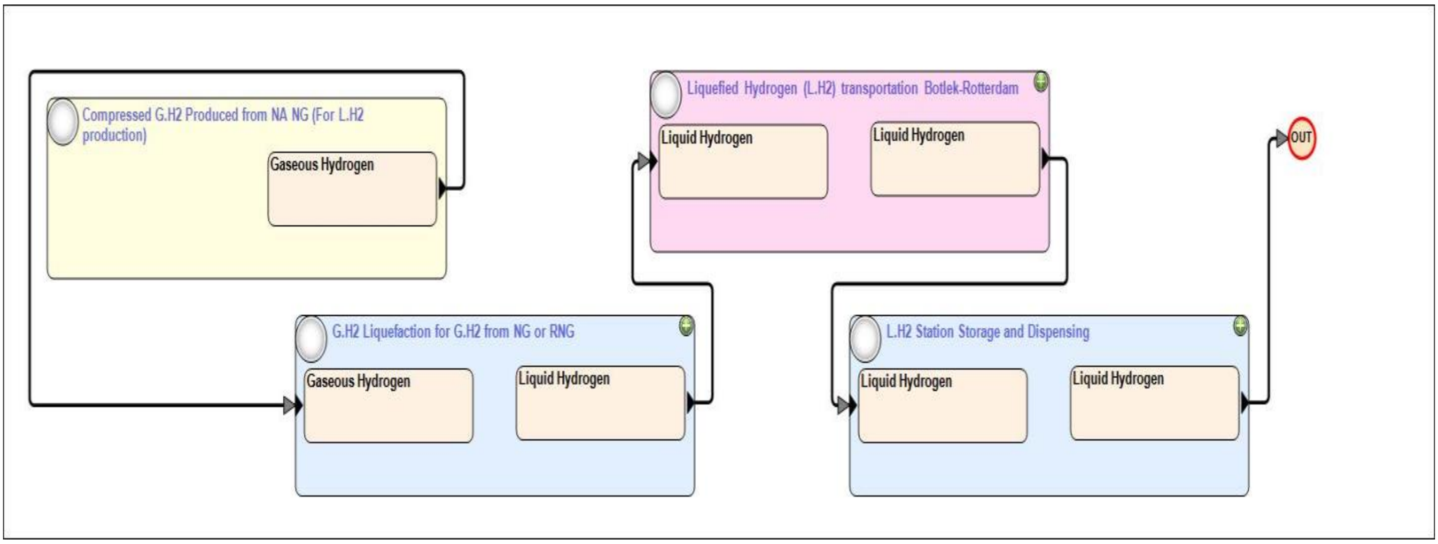

Figure 10: Production pathway of liquid hydrogen through SMR process

[Source: Author]

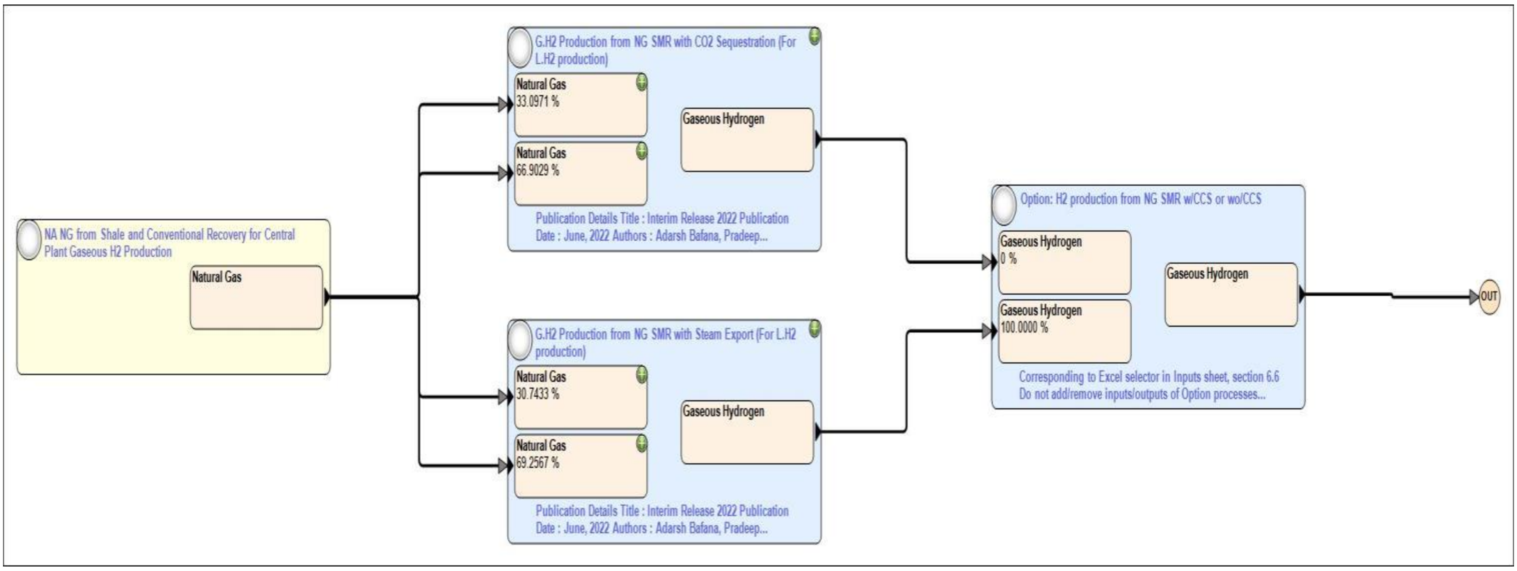

Figure 11: Production pathway of Grey Hydrogen via SMR without CCS technology

[Source: Author]

An overview of the results from this section is presented in *Table 11*. We have accounted for emissions generated during the production phase of the fuel cell thrice because it will be replaced in 10 years. WtT emissions are significant as the process of reforming methane, liquefaction of gaseous hydrogen, and storage and distribution of liquid hydrogen come with high indirect carbon emissions.

Table 11: Carbon dioxide released over the vessel's lifetime when operating on grey hydrogen. [Source: Author]

Lifecycle Phase	*CO_2 emission generated (tons)*
Manufacturing Engine and PEM-FC	437
Well-to-Tank	46,456
Tank-to-Wake	0
Well-to-Wake	46,893

Note: All values from each phase are rounded up to the nearest whole number.

4.3 The life cycle assessment of Blue Hydrogen-powered ship

The current infrastructure for extracting hydrogen from hydrocarbon compounds via steam methane reforming and auto-thermal reforming is considered carbon-intensive activities. To minimise CO_2 emissions released during the reforming process, carbon capture, utilisation and storage methods are deployed in these industrial procedures. Focusing on this, we simulated a pathway for producing hydrogen via SMR with CCS techniques.

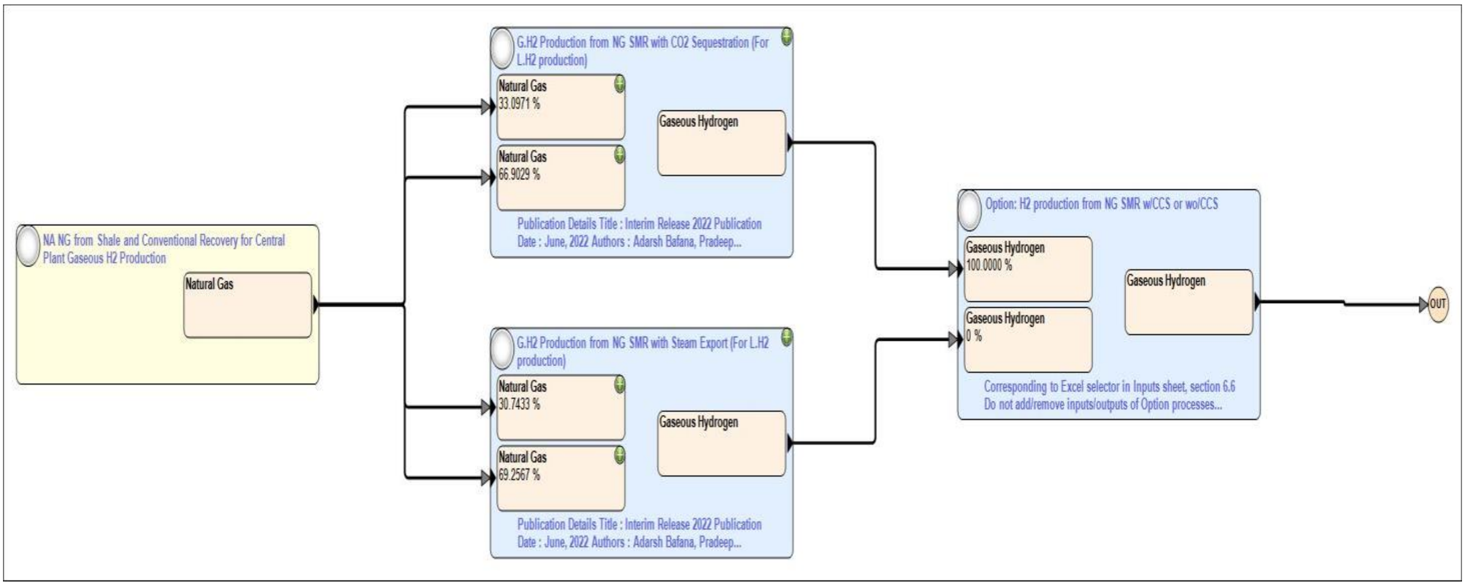

Figure 12: Production pathway of Blue Hydrogen via SMR with CCS technology

[Source: Author]

We modified the pathway to input 100% of the gaseous hydrogen from the ‘SMR w/CCS’ route to investigate the emissions generated. The impact of electrical engine and fuel cell manufacturing is assumed to be same as that calculated in the previous section. Well-to-Tank phase-related emissions were calculated, by simulating the scenario in Figure 12, on the GREET 2022 software. *Appendix E* displays detailed information on these findings. SMR with CCS technology produced 2.46 kg-CO_2/kg-H_2 during the process stage. Final results from each phase are shown in *Table 12*.

Table 12: Carbon dioxide released over the vessel's lifetime when operating on blue hydrogen

[Source: Author]

Lifecycle Phase	*CO_2 emission generated (tons)*
Manufacturing Engine and PEM-FC	437
Well-to-Tank	26,719
Tank-to-Wake	0
Well-to-Wake	27,156

Note: All values from each phase are rounded up to the nearest whole number.

4.4 The life cycle assessment of Green Hydrogen-powered ship

Green hydrogen is produced by utilizing renewable energy sources generated through solar panels, wind farms, geothermal energy, and hydropower. This scenario incorporates a complex system which will be broken down into parts for overall assessment. Literature studied earlier in the paper described the process of electrolysis, a simple chemical reaction in which hydrogen and oxygen are produced when electricity is passed through water. The electricity used must come from a renewable resource to limit the carbon footprint of this process. A study of the Dutch electricity mix revealed that approximately 43% of the output in 2022 was produced through renewable energy sources (Ritchie, Roser and Rosado, 2022). It is evident from *Figure 13* that wind energy is widely utilised in the energy mix of the Netherlands. Future plans of harnessing this resource to produce green hydrogen have encouraged Shell to construct a 200 MW offshore wind power plant in Rotterdam (Reuters, 2023). Based on the favourability of wind energy as a power source in the Netherlands, we will conduct further analysis by assuming that the electrolysers will use electricity from windmills.

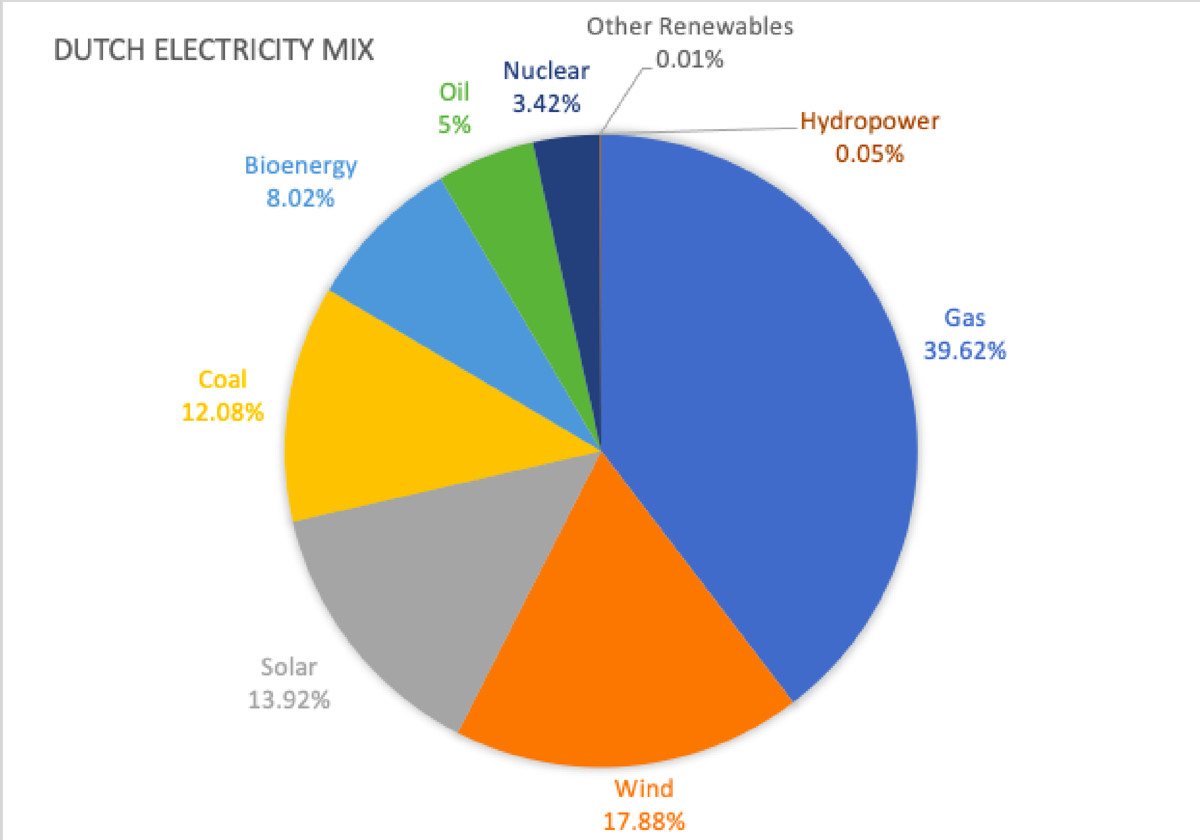

Figure 13: The Dutch electricity mix categorised by energy sources used for the year 2022

[Source: Compiled by Author]

4.4.1 Manufacturing phase:

The study maintains consistency with results from previous sections on the manufacturing of base components. The hybrid system in use for this case will include an electric engine and a PEM fuel cell. The fuel cell onboard will be fed with liquid hydrogen produced via electrolyser units offshore. The fuel cell will convert this input into electrical energy which will be fed to the electric engine. Fuel cell replacement is accounted for once in 10 years.

4.4.2 Well-to-Tank phase:

In order to achieve the closest simulation as per our targets, we modified the pre-existing pathway in GREET. The first process block in *Figure 14* was edited to include wind power as the primary energy parameter for the electrolysis process. This phase also includes emissions from liquefaction, transportation, storage and dispensation as depicted in the figure. The final results obtained for every emission category are listed in *Appendix F*.

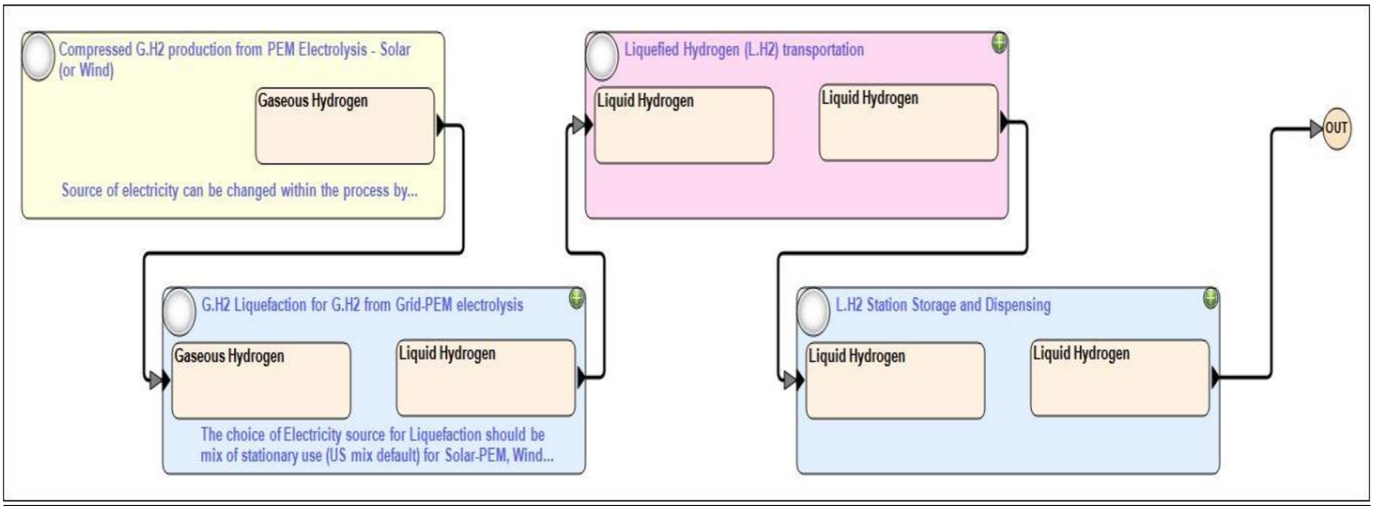

Figure 14: Production pathway of Green Hydrogen via wind-powered electrolysis method

[Source: Author]

4.4.3 Tank-to-Wake phase:

No tailpipe emissions are generated in this case. The total emissions from each phase are shown in *Table 13*.

Table 13: Carbon dioxide released over the vessel's lifetime when operating on green hydrogen

[Source: Author]

Lifecycle Phase	*CO_2 emission generated (tons)*
Manufacturing Engine and PEM-FC	437
Well-to-Tank	19,508
Tank-to-Wake	0
Well-to-Wake	19,945

Note: All values from each phase are rounded up to the nearest whole number.

4.5 Life cycle cost assessment of Diesel-powered ship

The average power of the inland barge is multiplied by a conversion factor, assumed as €250/kW, to calculate the capital cost of manufacturing a diesel engine (Perčić, Vladimir and Fan, 2021). Research on price trends of diesel in the Dutch market gave us the average price of diesel (PR_D) as €0.7/kg. Therefore, we calculate fuel costs over the lifetime using *Equation 12* while assuming a fixed price of diesel. Maintaining the engine incurs a cost that is determined using *Equation 13,* the maintenance factor (MF_D) is assumed as €0.014/kWh (Iannaccone et al., 2020). In order to include future costs through the carbon tax system, we referred to reports that have estimated price levels in the range of €23-87 per ton of CO_2 by 2030, and €64-124 per ton of CO_2 by 2050 (DNV-Hydrogen Report, 2022). In section 4.1, we calculated the tailpipe emission (TtW_C) for the lifetime operation of the ship, assuming the carbon allowance (CA) as €100/t-CO_2, we will calculate the carbon costs as per *Equation 14.* The final cost assessment is displayed in *Table 14*, totalling to €10.59 million.

Table 14: Lifetime costs for diesel powered system configuration.

[Source: Author]

Cost Category	*Amount (in million Euros)*
Investment Cost	0.22
Fuel Cost	6.69
Maintenance Cost	0.62
Carbon Emission Cost	3.06
Total	10.59

4.6 Life cycle cost assessment of Grey Hydrogen-powered ship

The capital cost of an electric engine is assumed to be same as that of a diesel engine. In addition to this, we will calculate the capital needed for manufacturing a PEM fuel cell. The cost for fuel cell is calculated at a rate of €368/kW (refer to Section 2.5). In order to account for additional parts required, such as a hydrogen storage tank and other ancillary equipment, in deploying liquid hydrogen energy on a ship, we assumed the rate as 50% higher than the original (Perčić, Vladimir and Fan, 2020). The fuel costs are calculated by taking an average of cost estimates from the literature studied. The grid-based electrolysis system (refer to Table 5) along with research done by Pomaska and Acciaro (2022) are used to derive a representative cost for grey hydrogen, and the cost is then assumed at €3.2/kg.H_2. The maintenance cost includes the cost of electrical engine's operation and the replacement cost of fuel cell every 10 years. Maintenance cost factor for an electrical engine is taken as €0.015/kWh (Iannaccone et al., 2020). The replacement of fuel cell incurs same costs as that of production of the fuel cell excluding ancillary parts. The carbon emission costs are nil as no tailpipe emissions are observed using this technology.

Table 15: Lifetime costs for grey hydrogen-powered system configuration

[Source: Author]

Cost Category	*Amount (in million Euros)*
Investment Cost	0.71
Fuel Cost	8.54
Maintenance Cost	1.32
Carbon Emission Cost	0
Total	10.57

4.7 Life cycle cost assessment of Blue Hydrogen-powered ship

Investment costs will remain consistent with results found for grey hydrogen. The fuel costs include implementing carbon capture and storage techniques which are accounted for in the data available in *Table 5*. The higher range of these estimated prices over the next three decades gives us the cost of blue hydrogen as €2.75/kg.H_2. The maintenance and carbon emission costs will remain the same as those calculated in the grey hydrogen scenario.

Table 16: Lifetime costs for blue hydrogen-powered system configuration

[Source: Author]

Cost Category	*Amount (in million Euros)*
Investment Cost	0.71
Fuel Cost	7.34
Maintenance Cost	1.32
Carbon Emission Cost	0
Total	9.37

4.8 Life cycle cost assessment of Green Hydrogen-powered ship

The production of green hydrogen is presently very expensive, but it is estimated to level down in the coming decades. Most of the research done on green hydrogen had a wide range of pricing, this was claimed to be a result of future policies and mandates related to taxation of carbon emissions. Whether strict regulations are implemented or not is out of the scope of our study and hence we have assumed the price as €9.1/kg.H_2. All other categories incur the same costs as in the previous section.

Table 17: Lifetime costs for blue hydrogen-powered system configuration.

[Source: Author]

Cost Category	*Amount (in million Euros)*
Investment Cost	0.71
Fuel Cost	24.3
Maintenance Cost	1.32
Carbon Emission Cost	0
Total	26.33

5 Results

The environmental and economic impact of an inland container barge sailing on a fixed route between Rotterdam and Antwerp, was assessed using pre-existing database and forecasted parameters. To simulate each scenario, we used the GREET software and modified fuel pathways as per our research parameters. A comparison of CO_2 emissions from each phase for each fuel technology is shown in *Figure 15*. The summation of outputs from each phase is the well-to-wake emission – carbon dioxide released from extraction till the combustion of a fuel. The total carbon footprint of green hydrogen was around 54% of that generated by diesel. Grey hydrogen produced 26% more CO_2 emissions than diesel, even though no part came from tailpipe emissions. The total lifecycle carbon footprint left by grey, blue, and green hydrogen was found at 46,893 t-CO_2-eq, 27,156 t-CO_2-eq, and 19,945 t-CO_2-eq, respectively.

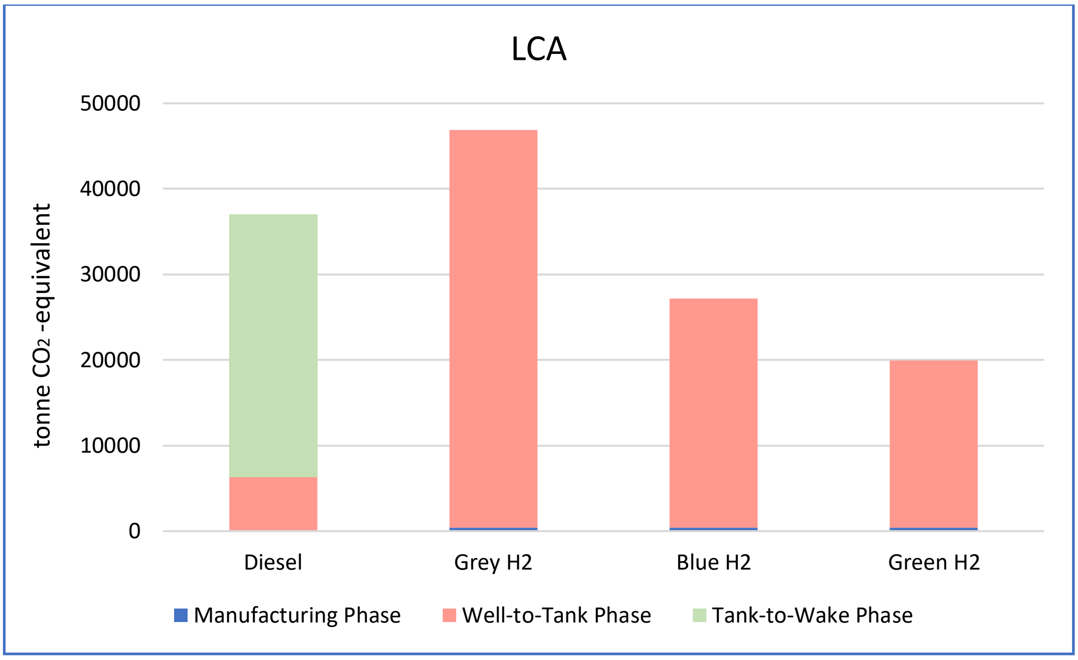

Figure 15: Life-Cycle Assessment results comparison

[Source: Author]

The cost structure for a ship can be a complex mix of different categories. Two base categories – investment and exploitation costs, were explored and applied specifically to the power system configuration. The capital required for building main parts of the system varies as per the fuel technology used. Exploitation costs include fuel costs and maintenance costs. They also account for future GHG-limiting strategies by including carbon emission costs. The final comparison of results is presented in *Figure 16*. The total costs for diesel and grey hydrogen were almost equal at €10.59 million and €10.57 million respectively. The fraction shared by each category of these costs was different for the two. Burning diesel incurs a carbon cost of €3.06 million. Implementing blue hydrogen results in the lowest overall costs at €9.37 million. Green hydrogen has an exceptionally high fuel cost, resulting in the highest total costs at €26.33 million. The investment costs for all hydrogen types were equal at €0.7 million.

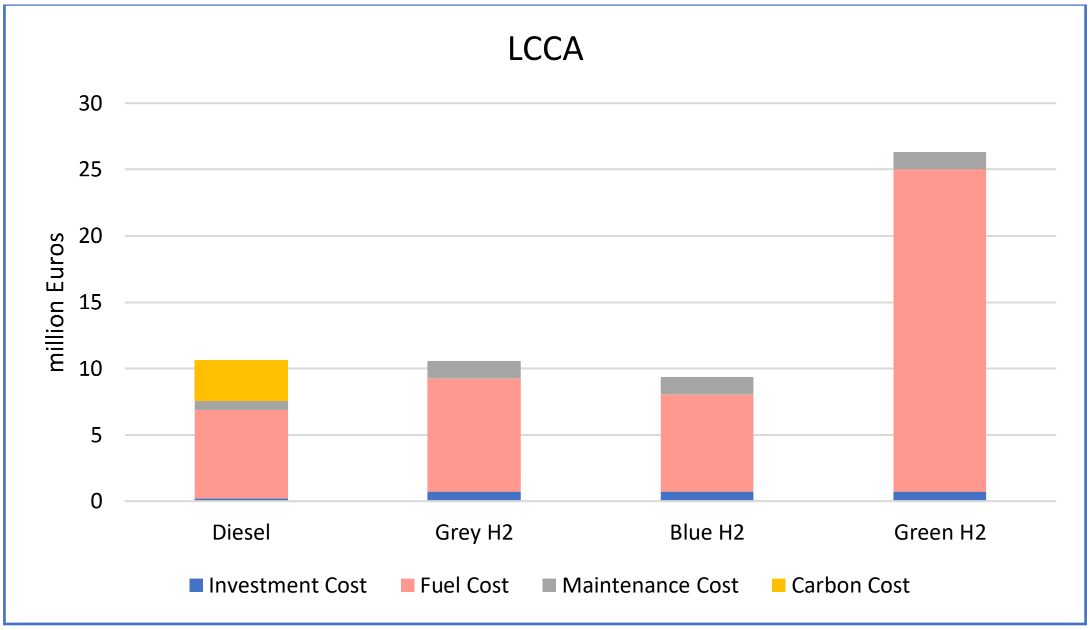

Figure 16: Life-Cycle Cost Assessment results comparison

[Source: Author]

6 Discussions

6.1 General

The maritime industry comprises vast opportunities to combat climate crises, and utilising LCA and LCCA tools for optimal decision-making can add value to the present literature. Inspired by the flexibility of these techniques, we narrowed down the scope of our research to obtain findings for an inland container barge deploying hydrogen fuel technology. The dependence on fossil fuels for producing energy has resulted in increased concentrations of GHGs in Earth's atmosphere. CO_2 is considered one of the most harmful gases due to its current abundance in the atmosphere and its ability to persist for centuries once released into the air. Hence, we selected CO_2 emissions and its global warming potential as the focal point for our environmental assessment and investigated CO_2 concentrations released from each lifecycle phase. As per the system boundaries of our study, these phases were divided into: 1) manufacturing phase – only the power system components such as engine and fuel cell were considered; 2) well-to-tank phase – refining, reforming, transporting, and storage-related activities were incorporated, and 3) tank-to-wake phase – combustion of fuel in the main propulsion system onboard. The three most commonly studied and applicable variants of hydrogen – grey, blue and green, were selected to be compared with diesel.

This study found that hydrogen production emits considerable CO_2 unless CCS techniques or renewable electricity are used. Grey hydrogen production generates more tonnes of CO_2 in its well-to-tank phase than conventional diesel does in its complete lifecycle. This is because the SMR method uses raw materials such as coal, crude oil, iron ore and limestone, all of which release carbon dioxide into the air (Suleman, Dincer and Agelin-Chaab, 2016). Therefore, grey hydrogen will not be a feasible clean fuel in the future as its direct CO_2 emissions do not comply with international regulations. Perčić et al. (2020) found a similar pattern between diesel and fossilised hydrogen in their study. In the same study, the authors found contradictory results between diesel and renewable hydrogen when compared to our results. The only difference between grey and blue hydrogen was a simulation of CCS technology. Implementing this in our model resulted in a 73.5% reduction of CO_2 emissions. This could be considered as the efficiency of the CCS plant. However, in some of the research, the efficiency of a CCS plant was recorded at 90% (Fernández-Ríos et al., 2022). Green hydrogen is clearly the cleanest fuel technology in our assessment. But its feasibility is highly dependent on the nature and availability of renewable energy sources such as solar, wind, nuclear, and geothermal energy. Liquefaction, transportation and storage-related activities contributed 98% to the total carbon footprint for green hydrogen. It is possible that the electrolysis process in a hybrid power system using fuel cells and solar panels, studied by Ghenai et al. (2019), can theoretically achieve zero emissions by omitting the logistics of supplying hydrogen on board. The geographical location of the production facility for green hydrogen would play a key role because the availability of infrastructure for utilising renewable energy is scattered across the world.

There is a direct link between LCA and LCCA results through tailpipe emissions generated in the tank-to-wake phase. In this study, this connection was only relevant for the diesel-propulsion scenario and resulted in a carbon cost of €3.06 million. Although we chose a carbon tax of €100/t-CO_2, research indicates that to substantially improve the cost-effectiveness of renewable fuels over fossil fuels, a carbon tax of over €278/t-CO_2 is needed (Hansson et al., 2019). Suppose a high tax rate is introduced soon. In that case, it will push shipowners to uptake hydrogen technology with urgency because policymakers' decision to implement a low tax rate and gradually increase it can result in deferred initial investments by shipowners (Pomaska and Acciaro, 2022). Hydrogen has a lower investment cost than other alternative fuels such as LNG, ethanol and methanol. It has shown better adaptability to existing ship systems due to a simple configuration, minimal space requirements, and on-demand production capability (Deniz and Zincir, 2016). The average price of fuel cells was increased by a factor of 1.5 for this study. However, timely investments in this technology would lead to mass production of fuel cells and gradually reduce prices.

There are financially encouraging signs of adopting cleaner alternatives in Europe, as the continent has saved €163 billion in the electricity sector by replacing fossil fuel with renewable energy output since 2010 (IRENA, 2023). The regulatory body of the inland shipping sector could incentivise small and medium-sized companies to adopt greener maritime practices by providing low-cost refuelling opportunities for ships using renewable fuels. This would encourage barge owners to renew their diesel fleet with hydrogen fuel cells and other options such as battery power. Policy action and stakeholder involvement tied together could advance inland shipping's commitment to bring about a positive climate outlook and set standards for short-long sea shipping. The inland waterway department must advocate for a framework similar to EU-MRV and collect emission data from inland ships of all sizes and types.

6.2 Limitations

The research methods of LCA and LCCA, for assessing environmental and economic impacts respectively, are highly reliable investigation techniques that have been widely used in existing literature. Our intended scope and boundary for this study were chosen to simulate the most realistic conditions possible. However, we did encounter certain obstacles on our path to achieving precise results.

The selection of a representative vessel was done based on limited data availability. We contacted the Managing Director of Contargo Waterway Logistics BV to gather information on their container barge services on the Rotterdam-Antwerp route. Unfortunately, we could not gain the needed insight, which led us to gather data from other credible sources. Although the vessel's current age is 35 years, the lifetime for our study was assumed to be 30 years, keeping a time horizon of IMO-2050 in mind. The fixed route of Rotterdam-Antwerp was selected on the basis of cargo volume handled by inland terminals of these ports and not on the basis of cargo carried between the two ports. Space constraints for installing a fuel cell and hydrogen storage tanks were not considered, and design modifications in the main engine system were minimal. While modelling the blue hydrogen scenario in the LCA software, it was unclear whether the carbon footprint from constructing a CCS plant was included in the results. Similarly, the electricity generation stage of the green hydrogen pathway was kept at the default of 'U.S. Electricity Mix' because the design of the LCA software cannot be altered for some processes.

The cost assessment criteria for hydrogen had to rely on available data, which could be better organised. The market maturity for this fuel type is currently low, and information on infrastructure costs in the public domain is limited. The concept of a carbon tax is yet to be applied in real-world scenarios for the maritime industry. Hence, the cost assumptions are solely based on forecasted values which could alter the results in future. The results of this study can only be applied to newly built ships, as replacing a mechanical engine with an electric engine may not be a viable option for most companies.

7 Conclusion

The shipping industry is being pushed to adopt innovative solutions to limit its global carbon footprint. There is an urgent need to replace fossil-based fuels with alternative fuels. This study investigated the environmental and economic impact of deploying hydrogen as an alternative marine fuel. The barging industry of Europe plays an important role in mobilising containers to generate trade revenues. But these inland vessels majorly operate on diesel fuel, releasing toxic gases around populated areas. Replacing diesel with hydrogen technology aligns with the EU's climate goals and can help Europe transition to sustainable maritime practices. Thus, this research was designed to analyse hydrogen's benefits and drawbacks for the inland shipping segment in Europe.

The main question of this study was answered using the LCA and LCCA approach. These methods have been substantiated in various transport-related studies. The LCA was done to compare the GWP of diesel with grey, blue, and green hydrogen. Similarly, the LCCA was done by analysing investment, fuel, maintenance and carbon emission costs. A representative inland container barge with 188 TEU capacity operating on the Rotterdam-Antwerp route was selected. The obtained results showed that implementing grey hydrogen generates more CO_2 emissions than presently used diesel fuel. The carbon capture process reduces emissions in the WtT phase by 73.5%, and the resultant product is known as blue hydrogen. Green hydrogen was found to be the most eco-friendly option in this analysis. However, the total cost of using green hydrogen technology was 61% higher than the average total costs of the other options. The blue hydrogen scenario is the most cost-effective in this study. This is because implementing CCS technology removes the risk of carbon pricing schemes for producers and allows them to maintain a competitive price with other fuels. As the production and use of blue hydrogen increase, economies of scale may lead to cost reductions for CCS technologies and further reduce the price, making it a viable option for future.

According to current regulations, a carbon emission tax is only valid during a ship's sea-going operations. If these taxes are extended to emissions generated during land-based production methods, penalties for even the cleanest fuels could be involved. In this regard, LCA and LCCA studies could contribute critical information for policymakers in regulating the transition to alternative fuels. The assessment of GWP is important, but other pollutants could adversely impact populations living near river channels. Thus, the environmental impact of releasing other greenhouse gases such as methane, sulphur oxides, and nitrous oxides can be incorporated into future studies related to hydrogen use in inland shipping.

An important system component for analysing hydrogen-related scenarios was the PEM fuel cell. The speed of technological development of fuel cells and their operational abilities will dictate hydrogen's uptake in ship operations. Carbon pricing mechanisms and the competitiveness of other alternative fuels will determine hydrogen's growth in the maritime sector. The construction of bunker terminals for hydrogen, specifically in the ports considered in this study, should be investigated for potential environmental and economic impacts. Future studies that choose hydrogen fuel as a focal point could gain better insights into its economic viability if costs incurred in setting up components for liquid hydrogen in each life cycle stage are considered. Inland ships, on average, have a longer lifespan than other sea-going vessels. An idea for future study could include assessing the economic consequences of retrofitting fuel cells while losing out on cargo space – a gradual reduction in price could compensate for revenue lost in cargo space.

Although we are a long way from a hydrogen-based maritime economy, it is important to start addressing the numerous challenges on this path. The regulatory landscape of adopting hydrogen as a marine fuel is at an early stage of development. Significant stakeholders should be encouraged to make financial investments so that small and medium-sized enterprises can focus on rebuilding a greener fleet. The development of hydrogen industry needs international organisations to formulate strategies and make informed decisions using support from financial, technological, and legal advisories.

8 References

Al-Enazi, A., Okonkwo, E.C., Bicer, Y. and Al-Ansari, T. (2021). A review of cleaner alternative fuels for maritime transportation. *Energy Reports*, 7, pp.1962–1985. https://doi.org/10.1016/j.egyr.2021.03.036.

Alkhaledi, A.NFNR., Sampath, S. and Pilidis, P. (2022). Economic analysis of a zero-carbon liquefied hydrogen tanker ship. *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2022.06.168.

Amores, E., Sánchez-Molina, M. and Sánchez, M. (2021). Effects of the marine atmosphere on the components of an alkaline water electrolysis cell for hydrogen production. *Results in Engineering*, [online] 10, p.100235. https://doi.org/10.1016/j.rineng.2021.100235.

Annual Report CCNR. (2022). [online] Central Commission for the Navigation of the Rhine. Available at: https://www.ccr-zkr.org/files/documents/om/om22_II_en.pdf [Accessed 18 Jul. 2023]. Inland Navigation in Europe Market Observation.

Annual Report on CO2 Emissions from Maritime Transport . (2021). Available at: https://climate.ec.europa.eu/system/files/2021-08/swd_2021_228_en.pdf [Accessed 22 Jul. 2023].

Baba Tamim (2023). *'MF Hydra': World's first liquid hydrogen-powered ferry gets operational*. [online] Interestingengineering.com. Available at: https://interestingengineering.com/transportation/mf-hydra-worlds-first-liquid-hydrogen-powered-ferry [Accessed 24 Aug. 2023].

Bhandari, R., Trudewind, C.A. and Zapp, P. (2014). Life cycle assessment of hydrogen production via electrolysis – a review. *Journal of Cleaner Production*, [online] 85, pp.151–163. https://doi.org/10.1016/j.jclepro.2013.07.048.

Bicer, Y. and Dincer, I. (2018a). Clean fuel options with hydrogen for sea transportation: A life cycle approach. *International Journal of Hydrogen Energy*, 43(2), pp.1179–1193. https://doi.org/10.1016/j.ijhydene.2017.10.157.

Ca.gov. (2018). *LCTI: Zero-Emission Hydrogen Ferry Demonstration Project | California Air Resources Board*. [online] Available at: https://ww2.arb.ca.gov/lcti-zero-emission-hydrogen-ferry-demonstration- [Accessed 24 Aug. 2023].

Clean Hydrogen Partnership. (2023). *Homepage*. [online] Available at: https://www.clean-hydrogen.europa.eu/index_en [Accessed 19 Aug. 2023].

Climate Action. (2021). *EU Emissions Trading System (EU ETS)*. [online] Available at: https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en [Accessed 18 Aug. 2023].

climate.ec.europa.eu. (n.d.). *Increasing the Ambition of EU Emissions Trading*. [online] Available at: https://climate.ec.europa.eu/eu-action/european-green-deal/delivering-european-green-deal/increasing-ambition-eu-emissions-trading_en [Accessed 24 Jul. 2023].

Contargo.net. (2023). *CONTARGO - Inland Barge*. [online] Available at: https://www.contargo.net/en/transport/inlandbarge/ [Accessed 9 Aug. 2023].

CORDIS, cordis.europa.eu (2016). *Modernisation of Vessels for Inland waterway freight Transport*. [online] CORDIS | European Commission. Available at: https://cordis.europa.eu/project/id/285405/reporting#:~:text=The%20average%20age%20of%20inland,of%20improving%20existing%20inland%20ships. [Accessed 21 Aug. 2023].

Dekker, M. (2010). *Rondvaartboot Nemo H2 betekent waterstofdoorbraak*. [online] Binnenvaartkrant. Available at: https://binnenvaartkrant.nl/rondvaartboot-nemo-h2-betekent-waterstofdoorbraak [Accessed 16 Aug. 2023].

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

Diogo Kramel, Muri, H., Kim, Y.-R., Radek Lonka, Jørgen Bremnes Nielsen, Anna Ljønes Ringvold, Bouman, E.A., Steen, S. and Anders Hammer Strømman (2021). Global Shipping Emissions from a Well-to-Wake Perspective: The MariTEAM Model. *Environmental Science & Technology*, [online] 55(22), pp.15040–15050. https://doi.org/10.1021/acs.est.1c03937.

DNV. (2022). *DNV - Hydrogen Forecast to 2050*. [online] Available at: https://www.dnv.com/news/hydrogen-at-risk-of-being-the-great-missed-opportunity-of-the-energy-transition-226628 [Accessed 19 Aug. 2023]. Energy Transition Outlook 2022.

DNV. (2023). *FAQs - EU MRV - DNV*. [online] Available at: https://www.dnv.com/maritime/insights/topics/mrv/FAQs-EU-MRV.html [Accessed 22 Jul. 2023].

Eia.gov. (2015). *U.S. Exports to Netherlands of Crude Oil (Thousand Barrels per Day)*. [online] Available at: https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MCREX_NUS-NNL_2&f=M [Accessed 23 Aug. 2023].

Eia.gov. (2023). *Where our oil comes from - U.S. Energy Information Administration (EIA)*. [online] Available at: https://www.eia.gov/energyexplained/oil-and-petroleum-products/where-our-oil-comes-from.php [Accessed 23 Aug. 2023].

Energy Observer. (2019). *Our vessel*. [online] Available at: https://www.energy-observer.org/about/vessel [Accessed 16 Aug. 2023].

Energy. (2020). *Key actions of the EU Hydrogen Strategy*. [online] Available at: https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen/key-actions-eu-hydrogen-strategy_en [Accessed 19 Aug. 2023].

Energy. (2022). *Hydrogen*. [online] Available at: https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en [Accessed 19 Aug. 2023].

Energy.gov. (2018). *GREET: The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model*. [online] Available at: https://www.energy.gov/eere/bioenergy/articles/greet-greenhouse-gases-regulated-emissions-and-energy-use-transportation.

Environmental Science & Technology. (2021). *Global Shipping Emissions from a Well-to-Wake Perspective: The MariTEAM Model*. [online] Available at: https://pubs.acs.org/doi/full/10.1021/acs.est.1c03937 [Accessed 10 Aug. 2023].

Essen, V., Faber, J. and Wit, R. (2004). *Charges for barges? Preliminary study of economics incentives to reduce engine emissions from inland shipping in Europe*. [online] Osti.gov. Available at: https://www.osti.gov/etdeweb/biblio/20670924 [Accessed 21 Aug. 2023].

Europa.eu. (2023). *Eurostat*. [online] Available at: https://ec.europa.eu/eurostat/data/database [Accessed 10 Aug. 2023].

European Commission (2013). *Trans-European Transport Network (TEN-T)*. [online] transport.ec.europa.eu. Available at: https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t_en [Accessed 7 Aug. 2023].

European Commission (2021). *Reducing emissions from the shipping sector*. [online] climate.ec.europa.eu. Available at: https://climate.ec.europa.eu/eu-action/transport-emissions/reducing-emissions-shipping-sector_en [Accessed 17 Jul. 2023].

Fan, A., Wang, J., He, Y., Perčić, M., Vladimir, N. and Yang, L. (2021). Decarbonising inland ship power system: Alternative solution and assessment method. *Energy*, 226, p.120266. https://doi.org/10.1016/j.energy.2021.120266.

Fernández-Ríos, A., Santos, G., Pinedo, J., Santos, E., Ruiz-Salmón, I., Laso, J., Lyne, A., Ortiz, A., Ortiz, I., Irabien, Á., Aldaco, R. and Margallo, M. (2022). Environmental sustainability of alternative marine propulsion technologies powered by hydrogen - a life cycle assessment approach. *Science of The Total Environment*, 820, p.153189. https://doi.org/10.1016/j.scitotenv.2022.153189.

Florinnicolae, E., Cătălin Popa and Haralambie Beizadea, E. (2014). Application of Life Cycle Assessment (LCA) in Shipping Industry . *Air Pollution and Climate Change*. https://doi.org/10.5593/SGEM2014/B42/S19.038.

Garraín, D. and Lechón, Y. (2014). Exploratory environmental impact assessment of the manufacturing and disposal stages of a new PEM fuel cell. *International Journal of Hydrogen Energy*, 39(4), pp.1769–1774. https://doi.org/10.1016/j.ijhydene.2013.11.095.

Ghenai, C., Bettayeb, M., Brdjanin, B. and Hamid, A.K. (2019). Hybrid solar PV/PEM fuel Cell/Diesel Generator power system for cruise ship: A case study in Stockholm, Sweden. *Case Studies in Thermal Engineering*, 14, p.100497. https://doi.org/10.1016/j.csite.2019.100497.

Gilbert, P., Walsh, C., Traut, M., Kesieme, U., Pazouki, K. and Murphy, A. (2018). Assessment of full life-cycle air emissions of alternative shipping fuels. *Journal of Cleaner Production*, 172, pp.855–866. https://doi.org/10.1016/j.jclepro.2017.10.165.

GlobalPetrolPrices.com. (2023). *Diesel prices in Rotterdam, the Netherlands - 21-Aug-2023 | GlobalPetrolPrices.com*. [online] Available at: https://www.globalpetrolprices.com/Netherlands/Rotterdam/diesel_prices/#:~:text=Rotterdam%20Diesel%20prices%2C%20litre%2C%2014%2DAug%2D2023&text=The%20average%20value%20for%20Rotterdam,this%20period%20is%201.50%20Euro. [Accessed 30 Aug. 2023].

Gómez Vilchez, J.J., Julea, A., Lodi, C. and Marotta, A. (2022). An Analysis of Trends and Policies Promoting Alternative Fuel Vessels and Their Refueling Infrastructure in Europe. *Frontiers in Energy Research*, 10. https://doi.org/10.3389/fenrg.2022.904500.

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

GREET: THE GREENHOUSE GASES, REGULATED EMISSIONS, AND ENERGY USE IN TECHNOLOGIES MODEL. (n.d.).

Guinee, J.B. (2002). Handbook on life cycle assessment operational guide to the ISO standards. *The International Journal of Life Cycle Assessment*, [online] 7(5), pp.311–313. https://doi.org/10.1007/bf02978897.

H2tools.org. (2023). *Merchant Hydrogen Plant Capacities in Europe | Hydrogen Tools*. [online] Available at: https://h2tools.org/hyarc/hydrogen-data/merchant-hydrogen-plant-capacities-europe [Accessed 27 Aug. 2023].

Hacker, V. and Mitsushima, S. (2018). *Fuel Cells and Hydrogen: From Fundamentals to Applied Research*. [online] *Google Books*. Elsevier. Available at: https://books.google.nl/books?hl=en&lr=&id=njVHDgAAQBAJ&oi=fnd&pg=PP1&dq=fuel+cells+and+hydrogen&ots=y9SDqxtEqA&sig=Hse0cY4AZoeaXfzcD801NqjWWZU&redir_esc=y#v=onepage&q=fuel%20cells%20and%20hydrogen&f=false [Accessed 19 Jul. 2023].

Hansson, J., Stina Månsson, Brynolf, S. and Grahn, M. (2019). Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders. *Biomass & Bioenergy*, [online] 126, pp.159–173. https://doi.org/10.1016/j.biombioe.2019.05.008.

Havhydrogen.no. (2023). *A Solution for the Future - FreeCO2ast | HAV Hydrogen - HAV*. [online] Available at: https://www.havhydrogen.no/hav-hydrogen/freeco2ast/ [Accessed 16 Aug. 2023].

Highlights annual report 2022 -Port of Rotterdam Authority. (n.d.). Available at: https://reporting.portofrotterdam.com/FbContent.ashx/pub_1011/downloads/v230308134647/Highlights-annual-report-2022-Port-of-Rotterdam-Authority.pdf.

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

Hornby, G. (2022). *EU's Clean Hydrogen Partnership launches €195m research call*. [online] ICIS Explore. Available at: https://www.icis.com/explore/resources/news/2023/01/17/10845721/eu-s-clean-hydrogen-partnership-launches-195m-research-call/ [Accessed 19 Aug. 2023].

Horvath, S., Fasihi, M. and 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, pp.230–241. https://doi.org/10.1016/j.enconman.2018.02.098.

Hua, J., Wu, Y. and Chen, H. (2017). Alternative fuel for sustainable shipping across the Taiwan Strait. *Transportation Research Part D: Transport and Environment*, 52, pp.254–276. https://doi.org/10.1016/j.trd.2017.03.015.

Hwang, S., Jeong, B., Jung, K., Kim, M. and Zhou, P. (2019). Life Cycle Assessment of LNG Fuelled Vessel in Domestic Services . *Journal of Marine Science and Engineering*, 7, pp.359–384. https://doi.org/10.3390/jmse7100359.

Hwang, S.S., Gil, S.J., Lee, G.N., Lee, J.W., Park, H., Jung, K.H. and Suh, S.B. (2020). Life Cycle Assessment of Alternative Ship Fuels for Coastal Ferry Operating in Republic of Korea. *Journal of Marine Science and Engineering*, 8(9), p.660. https://doi.org/10.3390/jmse8090660.

Hydrogen generation in Europe. (2020). [online] European Commission. Available at: https://www.apren.pt/contents/publicationsothers/hydrogen-generation-in-europe.pdf [Accessed 27 Aug. 2023].

Hydrogen: Similar but Different. (n.d.). Available at: https://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/h2_safety_fsheet.pdf.

Iannaccone, T., Landucci, G., Alessandro Tugnoli, Salzano, E. and Valerio Cozzani (2020). Sustainability of cruise ship fuel systems: Comparison among LNG and diesel technologies. *Journal of Cleaner Production*, [online] 260, pp.121069–121069. https://doi.org/10.1016/j.jclepro.2020.121069.

IEA, H. (2021). *Hydrogen - IEA*. [online] IEA. Available at: https://www.iea.org/energy-system/low-emission-fuels/hydrogen [Accessed 27 Aug. 2023].

IEA. (2020). *A new era for CCUS – CCUS in Clean Energy Transitions – Analysis*. [online] Available at: https://www.iea.org/reports/ccus-in-clean-energy-transitions/a-new-era-for-ccus [Accessed 19 Jul. 2023].

Imo.org. (2023). *Revised GHG reduction strategy for global shipping adopted*. [online] Available at: https://www.imo.org/en/MediaCentre/PressBriefings/pages/Revised-GHG-reduction-strategy-for-global-shipping-adopted-.aspx#:~:text=The%20revised%20IMO%20GHG%20Strategy [Accessed 17 Jul. 2023].

Inal, O.B., Zincir, B. and Deniz, C. (2022). Investigation on the decarbonization of shipping: An approach to hydrogen and ammonia. *International Journal of Hydrogen Energy*, 47(45), pp.19888–19900. https://doi.org/10.1016/j.ijhydene.2022.01.189.

Inchem.org. (2014). *ICSC 0001 - HYDROGEN*. [online] Available at: https://inchem.org/documents/icsc/icsc/eics0001.htm [Accessed 22 Aug. 2023].

Ivica Ančić, Nikola Vladimir and Cho, D.-S. (2018). Determining environmental pollution from ships using Index of Energy Efficiency and Environmental Eligibility (I4E). *Marine Policy*, [online] 95, pp.1–7. https://doi.org/10.1016/j.marpol.2018.06.019.

Jansen, M. and Mosmans, H. (n.d.). *Corridor connectivity index: a methodology to assess dynamics of trade routes and impact on existing TEN-T corridors*. Conference paper.

Jeong, B., Wang, H., Oguz, E. and Zhou, P. (2018). An effective framework for life cycle and cost assessment for marine vessels aiming to select optimal propulsion systems. *Journal of Cleaner Production*, [online] 187, pp.111–130. https://doi.org/10.1016/j.jclepro.2018.03.184.

Kawasaki Heavy Industries, Ltd. (2019). *News & Events | Kawasaki Heavy Industries, Ltd.* [online] Available at: https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20191211_3487 [Accessed 24 Aug. 2023].

Kesieme, U., Pazouki, K., Murphy, A. and Chrysanthou, A. (2019). Attributional life cycle assessment of biofuels for shipping: Addressing alternative geographical locations and cultivation systems. *Journal of Environmental Management*, 235, pp.96–104. https://doi.org/10.1016/j.jenvman.2019.01.036.

Keuken, M.P., Moerman, M., Jonkers, J., Hulskotte, J., Denier van der Gon, H.A.C., Hoek, G. and Sokhi, R.S. (2014). Impact of inland shipping emissions on elemental carbon concentrations near waterways in The Netherlands. *Atmospheric Environment*, 95, pp.1–9. https://doi.org/10.1016/j.atmosenv.2014.06.008.

Leiden University. (2016). *CML-IA Characterisation Factors*. [online] Available at: https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors#features [Accessed 15 Aug. 2023].

Maritime, B. (2023). *VESSEL REFIT | H2 Barge 1 – Dutch operator adds hydrogen-powered boxship to inland fleet*. [online] Baird Maritime. Available at: https://www.bairdmaritime.com/ship-world/boxship-world/vessel-refit-h2-barge-1-dutch-operator-adds-hydrogen-powered-boxship-to-inland-fleet/ [Accessed 30 Jul. 2023].

OEC - The Observatory of Economic Complexity. (2021). *Crude Petroleum in Netherlands | OEC*. [online] Available at: https://oec.world/en/profile/bilateral-product/crude-petroleum/reporter/nld#:~:text=Netherlands%20imports%20Crude%20Petroleum%20primarily,United%20States%20(%242.34B). [Accessed 23 Aug. 2023].

Oni, A.O., Anaya, K., Giwa, T., Di Lullo, G. and Kumar, A. (2022). Comparative assessment of blue hydrogen from steam methane reforming, autothermal reforming, and natural gas decomposition technologies for natural gas-producing regions. *Energy Conversion and Management*, 254, p.115245. https://doi.org/10.1016/j.enconman.2022.115245.

Overview of Hydrogen Projects in the Netherlands. (2020). Available at: https://topsectorenergie.nl/documents/81/TKI_Nieuw_Gas-Overview_Hydrogen_projects_in_the_Netherlands_versie_21_-_200801.pdf [Accessed 27 Aug. 2023].

Panić, I., Cuculić, A. and Ćelić, J. (2022). Color-Coded Hydrogen: Production and Storage in Maritime Sector. *Journal of Marine Science and Engineering*, 10(12), p.1995. https://doi.org/10.3390/jmse10121995.

Perčić, M., Vladimir, N. and Fan, A. (2020). Life-cycle cost assessment of alternative marine fuels to reduce the carbon footprint in short-sea shipping: A case study of Croatia. *Applied Energy*, 279, p.115848. https://doi.org/10.1016/j.apenergy.2020.115848.

Perčić, M., Vladimir, N. and Fan, A. (2021). Techno-economic assessment of alternative marine fuels for inland shipping in Croatia. *Renewable and Sustainable Energy Reviews*, 148, p.111363. https://doi.org/10.1016/j.rser.2021.111363.

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

Port of Rotterdam. (2021). *Oil refineries | Port of Rotterdam*. [online] Available at: https://www.portofrotterdam.com/en/setting/industry-port/refining-and-chemicals/oil-refineries [Accessed 23 Aug. 2023].

Port of Rotterdam. (2023). *Condor H2 | Port of Rotterdam*. [online] Available at: https://www.portofrotterdam.com/en/port-future/energy-transition/making-logistics-chains-more-sustainable/condor-h2 [Accessed 16 Aug. 2023].

Porthos. (2023). *Project - Porthos*. [online] Available at: https://www.porthosco2.nl/en/project/ [Accessed 20 Aug. 2023].

Ports.com. (2023). *Port of Houston, United States to Port of Rotterdam, Netherlands sea route and distance*. [online] Available at: http://ports.com/sea-route/port-of-houston,united-states/port-of-rotterdam,netherlands/#/?a=1812&b=0&c=Port%20of%20Corpus%20Christi,%20United%20States&d=Port%20of%20Rotterdam [Accessed 23 Aug. 2023].

Pratt, J.W. and Escher, T.C. (2016). *The SF-BREEZE: Can a Zero Emission Hydrogen Ferry Really Work in the San Francisco Bay?*. [online] www.osti.gov. Available at: https://www.osti.gov/servlets/purl/1428166 [Accessed 24 Aug. 2023].

Quist, Z. (2019a). *Life Cycle Assessment (LCA) - Complete Beginner's Guide*. [online] Ecochain - LCA software company. Available at: https://ecochain.com/knowledge/life-cycle-assessment-lca-guide/ [Accessed 10 Aug. 2023].

Quist, Z. (2019b). *Life Cycle Assessment (LCA) - Complete Beginner's Guide*. [online] Ecochain - LCA software company. Available at: https://ecochain.com/knowledge/life-cycle-assessment-lca-guide/ [Accessed 10 Aug. 2023].

Ren, J. and Liang, H. (2017). Measuring the sustainability of marine fuels: A fuzzy group multi-criteria decision making approach. *Transportation Research Part D: Transport and Environment*, 54, pp.12–29. https://doi.org/10.1016/j.trd.2017.05.004.

Renewable Power Generation Costs In 2022. (2023). [online] International Renewable Energy Agency. Available at: https://mc-cd8320d4-36a1-40ac-83cc-3389-cdn-endpoint.azureedge.net//media/Files/IRENA/Agency/Publication/2023/Aug/IRENA_Renewable_power_generation_costs_in_2022.pdf?rev=3b8966ac0f0544e89d7110d90c9656a0 [Accessed 2 Sep. 2023].

Reuters (2023). *Shell-led Dutch wind farm delivers first electricity*. [online] Reuters. Available at: https://www.reuters.com/business/energy/shell-led-dutch-wind-farm-delivers-first-electricity-2023-06-19/ [Accessed 29 Aug. 2023].

Reuters. (2021). *Dutch govt grants $2.4 bln in subsidies to huge carbon storage project*. [online] Available at: https://www.reuters.com/business/sustainable-business/dutch-govt-grants-24-bln-subsidies-huge-carbon-storage-project-2021-05-09/ [Accessed 20 Jul. 2023].

Ritchie, H., Roser, M. and Rosado, P. (2022). *Energy*. [online] Our World in Data. Available at: https://ourworldindata.org/energy/country/netherlands#what-sources-does-the-country-get-its-energy-from [Accessed 29 Aug. 2023].

"Routescanner – Plan your door-to-door container route. (2023). *Routescanner - worldwide container shipping platform*. [online] Available at: https://www.routescanner.com/app/voyages/detail?departure=2023-08-09&sort=emission_co2&fromType=locode&from=NLRTM&fromLabel=Port+of+Rotterdam&toType=locode&to=BEANR&toLabel=Port+of+Antwerp&limit=3&originsNearby=1&destinationsNearby=1&modalities=barge&voyageIndex=0 [Accessed 9 Aug. 2023].

Schneider, J. and This, S. (2010). ZEMShip. *Essen Schriften des Forschungszentrums Jülich / Energy & Environment*, [online] 78(6). Available at: https://juser.fz-juelich.de/record/135721/files/TA1_pp_Schn_Schneider.pdf [Accessed 16 Aug. 2023].

Ship Technology. (2022). *Hydrogenesis Passenger Ferry*. [online] Available at: https://www.ship-technology.com/projects/hydrogenesis-passenger-ferry/ [Accessed 16 Aug. 2023].

Sphera. (2020). *How Does Life Cycle Assessment (LCA) Work?* [online] Available at: https://sphera.com/infographic/how-does-life-cycle-assessment-lca-work/.

Suleman, F., Dincer, I. and Agelin-Chaab, M. (2016). Comparative impact assessment study of various hydrogen production methods in terms of emissions. *International Journal of Hydrogen Energy*, 41(19), pp.8364–8375. https://doi.org/10.1016/j.ijhydene.2015.12.225.

Sys, C., Van de Voorde, E., Vanelslander, T. and van Hassel, E. (2020a). Pathways for a sustainable future inland water transport: A case study for the European inland navigation sector. *Case Studies on Transport Policy*, 8(3), pp.686–699. https://doi.org/10.1016/j.cstp.2020.07.013.

Sys, C., Van, E., Thierry Vanelslander and Edwin van Hassel (2020b). Pathways for a sustainable future inland water transport: A case study for the European inland navigation sector. [online] 8(3), pp.686–699. https://doi.org/10.1016/j.cstp.2020.07.013.

Taljegard, M., Brynolf, S., Grahn, M., Andersson, K. and Johnson, H. (2014). Cost-Effective Choices of Marine Fuels in a Carbon-Constrained World: Results from a Global Energy Model. *Environmental Science & Technology*, 48(21), pp.12986–12993. https://doi.org/10.1021/es5018575.

United Nations (2017). *The Paris Agreement*. [online] United Nations. Available at: https://www.un.org/en/climatechange/paris-agreement [Accessed 17 Jul. 2023].

Valero. (2023). *Refining Science & Process*. [online] Available at: https://www.valero.com/refining/oil-refining/refining-science-process#:~:text=The%20crude%20is%20heated%20by,products%20like%20asphalt%20and%20solvents. [Accessed 23 Aug. 2023].

van der Zee, S.C., Dijkema, M.B.A., van der Laan, J. and Hoek, G. (2012). The impact of inland ships and recreational boats on measured NOx and ultrafine particle concentrations along the waterways. *Atmospheric Environment*, 55, pp.368–376. https://doi.org/10.1016/j.atmosenv.2012.03.055.

Wang, M. (2022). *Overview of the GREET Life-Cycle Analysis Model NOVEMBER 7 2022 GREET TRAINING WORKSHOP*.

Wang, Y., Muhammad Zaki Memon, Majid Ali Seelro, Fu, W., Gao, Y., Dong, Y. and Ji, G. (2021). A review of CO2 sorbents for promoting hydrogen production in the sorption-enhanced steam reforming process. *International Journal of Hydrogen Energy*, [online] 46(45), pp.23358–23379. https://doi.org/10.1016/j.ijhydene.2021.01.206.

Weeda, M. and Segers, R. (2020). *The Dutch hydrogen balance, and the current and future representation of hydrogen in the energy statistics*. TNO Publiek.

Wilhelmsen (2021). *Topeka's hydrogen vessels one step closer to reality*. [online] Wilhelmsen. Available at: https://www.wilhelmsen.com/media-news-and-events/press-releases/2021/topekas-hydrogen-vessels-one-step-closer-to-reality/ [Accessed 16 Aug. 2023].

WSJ (2023). *America's Rise as an Energy Export Powerhouse Hinges on One Town | Mint*. [online] mint. Available at: https://www.livemint.com/economy/americas-rise-as-an-energy-export-powerhouse-hinges-on-one-town-11689968830425.html [Accessed 23 Aug. 2023].

www.maersk.com. (n.d.). *A.P. Moller – Maersk welcomes landmark green methanol vessel in Copenhagen this fall*. [online] Available at: https://www.maersk.com/news/articles/2023/04/26/maersk-welcomes-landmark-green-methanol-vessel-in-copenhagen-this-fall [Accessed 5 Jun. 2023].

www.maersk.com. (n.d.). *Europe feeder shipping routes*. [online] Available at: https://www.maersk.com/local-information/europe-feeder-shipping-routes [Accessed 5 Jun. 2023].

www.rijksfinancien.nl. (n.d.). *Visuals | Ministerie van Financiën - Rijksoverheid*. [online] Available at: https://www.rijksfinancien.nl/visuals/2022/begroting/uitgaven/A?graph=pie [Accessed 6 Aug. 2023]. Dutch Finance Ministry's report on budget allocation.

Xing, H., Stuart, C., Spence, S. and Chen, H. (2021). Alternative fuel options for low carbon maritime transportation: Pathways to 2050. *Journal of Cleaner Production*, 297, p.126651. https://doi.org/10.1016/j.jclepro.2021.126651.

Yusuf Bicer and Ibrahim Dincer (2018b). Environmental impact categories of hydrogen and ammonia driven transoceanic maritime vehicles: A comparative evaluation. *International Journal of Hydrogen Energy*, [online] 43(9), pp.4583–4596. https://doi.org/10.1016/j.ijhydene.2017.07.110.

Züttel, A. (2003). Materials for hydrogen storage. *Materials Today*, [online] 6(9), pp.24–33. https://doi.org/10.1016/s1369-7021(03)00922-2.

Züttel, A. (2004). Hydrogen storage methods. *Naturwissenschaften*, 91(4), pp.157–172. https://doi.org/10.1007/s00114-004-0516-x.

9 Appendices

9.1 Appendix A: Diesel Engine manufacturing stage and related CO_2 emissions

Material	Ratios (%)	Weight (tons)	Emissions (kgs)
Cast Iron	46	1.84	826.34
Steel	40	1.60	4311.04
Aluminium	8	0.32	1897.89
Oil and Grease	3	0.12	0.00
Paint	0.9	0.04	0.00
Plastic	0.9	0.04	97.77
Rubber	0.9	0.04	118.29
Zinc and Copper	0.2	0.01	18.49
Lead	0.1	0.00	1.91
Total	100	4	7271.74

9.2 Appendix B: Detailed emission outputs during the Well-to-Tank phase of Diesel-powered vessel over a period of 30 years

Category	Value	Unit
CO2 Total	4532	t
CO2	4540	t
CO2_Biogenic	-7.085	t
VOC	2232.440	kg
CO	4195.209	kg
NOx	6.251	t
PM10	456.272	kg
PM2.5	384.111	kg
SOx	1759.914	kg
CH4	39.157	t
N2O	84.074	kg
BC	58.349	kg
POC	102.530	kg
Groups		
GHG-100	5736	t
GHG-20	7800	t
Flow properties		
Biogenic carbon mass ratio	0.000	%
Resources Used		
Resources	438794108.940	MJ
Water Total	30674.731	m^3
Water_Mining	23417.922	m^3
Water_Process	4403.266	m^3
Water_Reservoir Evaporation	1539.097	m^3
Water_Cooling	1314.446	m^3
Crude Oil	299237191.036	MJ
Natural Gas	45744609.726	MJ
Coal Average	3473975.251	MJ
Forest Residue	77237.157	MJ
Pet Coke	413127.080	MJ
Renewable, Other	23058.256	MJ
Uranium Ore	9.679	kg
Hydroelectric Power	331996.882	MJ
Nuclear Energy	1022107.231	MJ
GeoThermal Power	20844.638	MJ

Solar	140221.583	MJ
Wind Power	495177.776	MJ
Bitumen	34082148.558	MJ
Shale Oil (Bakken)	29135913.265	MJ
Shale Oil (Eagle Ford)	24596499.451	MJ
Groups		
Fossil Fuel	436683464.893	MJ
Petroleum Fuel	387464879.915	MJ
Natural Gas Fuel	45744609.726	MJ
Coal Fuel	3473975.251	MJ
Non Fossil Fuel	2110644.047	MJ
Renewable	1088536.817	MJ
Nuclear	1022107.231	MJ
Biomass	77237.157	MJ
Water	30674.731	m^3
Urban Emissions		
CO2 Total	1798	t
CO2	1798	t
CO2_Biogenic	-92.100	kg
VOC	712.841	kg
CO	612.045	kg
NOx	953.798	kg
PM10	172.494	kg
PM2.5	149.065	kg
SOx	374.842	kg
CH4	1090.300	kg
N2O	20.700	kg
BC	18.811	kg
POC	26.052	kg
Groups		
GHG-100	1840	t
GHG-20	1897	t
Total CO2 emissions	6331	tonnes

9.3 Appendix C: CO_2 emissions generated during the production of input parts for a PEM fuel cell of rating 895kW

Fuel Cell Stack Part	Materials	Quantity for 1kW (kgs)	Quantity for 895kW (kgs)	CO2 Emissions (tons)
Electrode	Porous carbon paper	0.03	27.05	1.71
Seal	EPDM rubber	0.02	18.03	0.03
Circuit Board	Pertinax, tin	2.75	2479.21	24.93
Cable	PVC, copper	2.5	2253.83	4.87
Catalyst	Platinum dispersed, carbon powder and PTFE	0.0025	2.25	0.02
Screws	Steel	1.5	1352.30	3.64
Pipe connectors	Plastic (HDPE)	0.75	676.15	0.72
Pipes	Plastic (PU)	1	901.53	0.04
Membrane	Nafion	0.0025	2.25	0.00
Heat Sink	Aluminium	2	1803.06	7.90
Valves	Steel, plastic (HDPE), copper	2.5	2253.83	7.55
Flow Field Plate	Graphite	3	2704.59	9.50
Pump	PEEK (polyetheretherketone) Aluminium, copper	6	5409.18	57.61
Box Metal	Steel Sheet	5	4507.65	12.14
Ventilators	Plastic (HDPE), copper	3	2704.59	12.49
Total CO2 emissions				143.15

9.4 Appendix D: Detailed emission outputs during the Well-to-Tank phase of a grey hydrogen-powered vessel over a period of 30 years

Category	Value	Unit
CO2 Total	39149	t
CO2	39325	t
CO2_Biogenic	-176.0634548	t
VOC	6.25286504	t
CO	17.96851356	t
NOx	25.36229174	t
PM10	2385.896158	kg
PM2.5	1587.478269	kg
SOx	14.19310051	t
CH4	113.6987995	t
N2O	863.0122668	kg
H2	214.5657734	t
BC	109.0683594	kg
POC	379.1590986	kg
Groups		
GHG-100	42820	t
GHG-20	48812	t
Flow properties		
Biogenic carbon mass ratio	0	%
Resources Used		
Resources	686328078	MJ
Water Total	126451.5551	m^3
Water_Process	49570.29116	m^3
Water_Reservoir Evaporation	39359.03583	m^3
Water_Cooling	33205.40033	m^3
Water_Mining	4316.827702	m^3
Crude Oil	2213054.659	MJ
Natural Gas	541117557.6	MJ
Coal Average	89652951.38	MJ
Forest Residue	1919458.73	MJ
Pet Coke	3055.1715	MJ
Renewable, Other	573033.8611	MJ
Uranium Ore	240.5356258	kg
Hydroelectric Power	8490090.027	MJ
Nuclear Energy	25400835.85	MJ

GeoThermal Power	518023.4062	MJ
Solar	3484710.192	MJ
Wind Power	12305876.6	MJ
Bitumen	252053.4908	MJ
Shale Oil (Bakken)	215474.0619	MJ
Shale Oil (Eagle Ford)	181902.9638	MJ
Groups		
Fossil Fuel	633636049.3	MJ
Natural Gas Fuel	541117557.6	MJ
Coal Fuel	89652951.38	MJ
Non Fossil Fuel	52692028.67	MJ
Renewable	27291192.82	MJ
Nuclear	25400835.85	MJ
Petroleum Fuel	2865540.347	MJ
Biomass	1919458.73	MJ
Water	126451.5551	m^3
Urban Emissions		
CO2 Total	7307	t
CO2	7309	t
CO2_Biogenic	-2.28882607	t
VOC	377.0264257	kg
CO	2357.705267	kg
NOx	4135.919498	kg
PM10	393.1750991	kg
PM2.5	333.7890913	kg
SOx	3164.277279	kg
CH4	6.12544781	t
N2O	167.0944081	kg
H2	136.0077091	t
BC	16.54850353	kg
POC	79.56187623	kg
Groups		
GHG-100	7539.7738	t
GHG-20	7862.922	t
Total CO2 emissions	46456	tonnes

9.5 Appendix E: Detailed emission outputs during the Well-to-Tank phase of a blue hydrogen-powered vessel over a period of 30 years

Category	Value	Unit
CO2 Total	20868	t
CO2	21065	t
CO2_Biogenic	-196.7785702	t
VOC	8.01965414	t
CO	24.77278311	t
NOx	34.88911119	t
PM10	3003.242058	kg
PM2.5	2111.580545	kg
SOx	16.70086738	t
CH4	143.4862742	t
N2O	1144.280723	kg
H2	214.5657734	t
BC	186.4783002	kg
POC	588.030727	kg
Groups		
GHG-100	25521	t
GHG-20	33082	t
Flow properties		
Biogenic carbon mass ratio	0	%
Resources Used		
Resources	852789009.8	MJ
Water Total	161229.995	m^3
Water_Process	74931.97239	m^3
Water_Reservoir Evaporation	43989.90421	m^3
Water_Cooling	37112.25139	m^3
Water_Mining	5195.867014	m^3
Crude Oil	2497757.17	MJ
Natural Gas	690461953.4	MJ
Coal Average	100201251.2	MJ
Forest Residue	2145296.692	MJ
Pet Coke	3448.3176	MJ
Renewable, Other	640455.5226	MJ
Uranium Ore	268.8364084	kg
Hydroelectric Power	9489009.005	MJ
Nuclear Energy	28389425.66	MJ

GeoThermal Power	578972.6303	MJ
Solar	3894711.576	MJ
Wind Power	13753751.06	MJ
Bitumen	284479.8864	MJ
Shale Oil (Bakken)	243194.2829	MJ
Shale Oil (Eagle Ford)	205304.367	MJ
Groups		
Fossil Fuel	793897387.6	MJ
Natural Gas Fuel	690461953.4	MJ
Coal Fuel	100201251.2	MJ
Non Fossil Fuel	58891621.62	MJ
Renewable	30502195.96	MJ
Nuclear	28389425.66	MJ
Petroleum Fuel	3234182.972	MJ
Biomass	2145296.692	MJ
Water	161229.995	m^3
Urban Emissions		
CO2 Total	5851	t
CO2	5853.5	t
CO2_Biogenic	-2.55813378	t
VOC	486.7066089	kg
CO	3060.205138	kg
NOx	5225.969111	kg
PM10	470.8675578	kg
PM2.5	404.6523864	kg
SOx	3547.349629	kg
CH4	7.81271298	t
N2O	208.602426	kg
H2	136.0077091	t
BC	24.5013702	kg
POC	104.4384457	kg
Groups		
GHG-100	6147	t
GHG-20	6559	t
Total CO2 Emissions	26719	tonnes

9.6 Appendix F: Detailed emission outputs during the Well-to-Tank phase of a green hydrogen-powered vessel over a period of 30 years

Category	Value	Unit
CO2 Total	14591	t
CO2	14843	t
CO2_Biogenic	-252.3075	t
VOC	1728.0728	kg
CO	6249.0334	kg
NOx	11.2569	t
PM10	1696.8974	kg
PM2.5	931.3842	kg
SOx	9951.734	kg
CH4	30.9051	t
N2O	299.9032	kg
H2	214.605	t
BC	49.338	kg
POC	237.0816	kg
Groups		
GHG-100	15609	t
GHG-20	17237	t
Emissions		
H2	54.5149	t
Flow properties		
Biogenic carbon mass ratio	0	%
Resources Used		
Resources	857461505	MJ
Water Total	183925.6826	m^3
Water_Cooling	109257.8697	m^3
Water_Reservoir Evaporation	39189.8826	m^3
Water_Process	33067.4615	m^3
Water_Mining	2410.4688	m^3
Crude Oil	2050914	MJ
Natural Gas	107090162	MJ
Coal Average	88082561	MJ
Forest Residue	2750679	MJ
Pet Coke	2831	MJ
Renewable, Other	550598	MJ
Uranium Ore	238.9643	kg

Hydroelectric Power	8453602	MJ
Nuclear Energy	25234899	MJ
GeoThermal Power	497741	MJ
Solar	609838784	MJ
Wind Power	12306885	MJ
Bitumen	233586	MJ
Shale Oil (Bakken)	199687	MJ
Shale Oil (Eagle Ford)	168575	MJ
Groups	...	
Non Fossil Fuel	659633188	MJ
Renewable	634398289	MJ
Fossil Fuel	197828317	MJ
Natural Gas Fuel	107090162	MJ
Coal Fuel	88082561	MJ
Nuclear	25234899	MJ
Biomass	2750679	MJ
Petroleum Fuel	2655594	MJ
Water	183925.6826	m^3
OnSite		
Resources	330199189	MJ
Liquid Hydrogen	327284822	MJ
Electricity	2914367	MJ
Groups	...	
Urban Emissions		
CO2 Total	4917	t
CO2	4920	t
CO2_Biogenic	-3.28	t
VOC	115.8405	kg
CO	1386.659	kg
NOx	2943.9119	kg
PM10	331.8086	kg
PM2.5	274.9504	kg
SOx	3068.4546	kg
CH4	1280.3697	kg
N2O	89.8781	kg
H2	134.3855	t
BC	12.6366	kg
POC	68.7348	kg
Groups		
GHG-100	4982	t
GHG-20	5050	t
OnSite Emissions		

H2	38.1604	t
Total CO2 emissions	19508	tonnes