Erasmus University Rotterdam

MSc in Maritime Economics and Logistics

THE FEASIBILITY OF GREEN HYDROGEN AS A MARINE FUEL FOR INLAND VESSELS IN EUROPE WITH CASE STUDIES

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BY

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Abstract

The environment is a serious concern to the shipping industry. The shipping industry is a significant contributor to the problems of global warming, leading to the emission of greenhouse gases like carbon dioxide. As Europe is moving towards the zero-emission target a zero-carbon fuel is needed for present and next-generation ships. Green hydrogen is one of the best alternative fuel options available for the propulsion system on the ship. However, this fuel has not yet been fully commercialized in shipping and there are several challenges in its development and deployment. The main objective of this paper is to determine the feasibility of green hydrogen as marine fuel for inland shipping in Europe with the help of a case study. Assessing the feasibility of green hydrogen based on technology, environmental, social, and financial perspectives concerning inland shipping.

The methodology and analysis used in this paper are based on quantitative, analytical, and logical reasoning approaches. The literature review chapter will analyse the technical, environmental, and social aspects of green hydrogen feasibility based on the stated above approaches. The economic feasibility is checked with the help of a case study ship with five types of propulsion options available (LH2-PEMFC, CGH2-PEMFC, LH2-ICE, CGH2-ICE, and LSFO-ICE) and NPV for all these scenarios will be calculated based on the total cash outflow throughout the ships project life. Combining the outcomes of all these different perspectives will give a clear idea of the feasibility of green hydrogen as a marine fuel in inland shipping.

The fundamental conclusion of this paper is that green hydrogen fuel can be successfully implemented in inland shipping provided existing constraints are overcome and bottleneck issues related to hydrogen use on board the ships are efficiently handled. Green hydrogen cost is the major factor in deciding the propulsion system for a ship and hydrogen cost accounts for the major portion of the total cost incurred throughout the project life of the ship. Though a framework related to safety, legal, and technology for hydrogen usage on board the ships exist, but more comprehensive development is required for full adoption in the marine industry. This limitation can be overcome by establishing a hydrogen synergy network around Europe's inland waterways, as well as providing the necessary green hydrogen ecosystem for hydrogen production, fuel cell development, efficient electrolysis, the availability of cheap renewable electricity, effective safety and operational standards, bunkering, storage, distribution, and other parameters.

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Chapter 1. Introduction

1.1Background

Maritime shipping is a required component of trade and economy globally. The market is growing rapidly with the development of sufficiency based on global trade. Shipping lines provide service in the form of transportation and movement of cargo between different ports. That's why maritime transportation is crucial to our daily lives because it carries raw materials and finished products. Our products are exported via sea as finished products or raw materials. Maritime shipping is of most importance to global trade and the economy. Maritime shipping is used in the transportation of goods and commodities to fulfil the present and future needs of a region or any other country. It is one of the most important branches of the world economy. Due to its importance, Maritime shipping has been used as a means of transportation for many centuries. Today it continues to play a significant role in global trade and commerce. Maritime transport has a lot of advantages, this means that it is the most preferred mode of transport for international trade. There are many benefits that different industries can gain from maritime transport. First and foremost, it has a very high capacity. This makes ships very suitable for handling large amounts of goods at one time. This way, there is no need to make long journeys which could prove expensive and inefficient. Furthermore, maritime transport provides quick delivery times because the size of ships usually makes them capable of holding large amounts of cargo under one roof: thus leading to less waiting time for their transfer from one port to another. Finally, since no country can claim ownership over the sea route, this reduces the costs involved in shipping products overseas because there is no need for any infrastructure development between countries or ports before loading larger cargo into vessels.

In contrast to the growing trend of trade in merchandise, transport has been an important contributor to greenhouse gases and other pollutants(Figure1). The shipping-related greenhouse gas emissions had risen by 4.9% in 2021 compared to the years 2020 and 2019 as per the annual industry report of Simpson Spence & Young's. In the year 2021, there were 833 million metric tons of carbon in shipping emissions compared with 2020 and 2019 as that was 794 million metric tons and 800 million metric tons respectively. (Sporrer, 2022). The international shipping emissions are projected for increasing significantly in the next three decades depending on future economic scenarios and developments in the energy sector. The shipping industry is emitting copious amounts of GHG and other pollutants. In the Fourth IMO GHG study (IMO 2020), it was found that the CO_2 of entire shipping emitted was 1,056 million tonnes in 2018, accounting near to 2.89% of the total anthropogenic CO2 emissions in that year globally. As per the types of plausible long-term energy economic business-as-usual scenarios, 90-130% of 2008 emissions by 2050(Imo.org, 2022). Besides the emission of GHG, the shipping industry is responsible for emitting NOx, particulate matter (PM), and Sox. In the pursuit of an environmentally sustainable future, the industry will need to make enduring changes in every aspect of operations. This includes changing the working conditions and improving operational efficiency, as well as reducing emissions and greenhouse gases through technological innovation. If shipping companies adopt sustainability strategies, then they can become more competitive, have a positive impact on the environment and improve their reputation with environmental regulators.

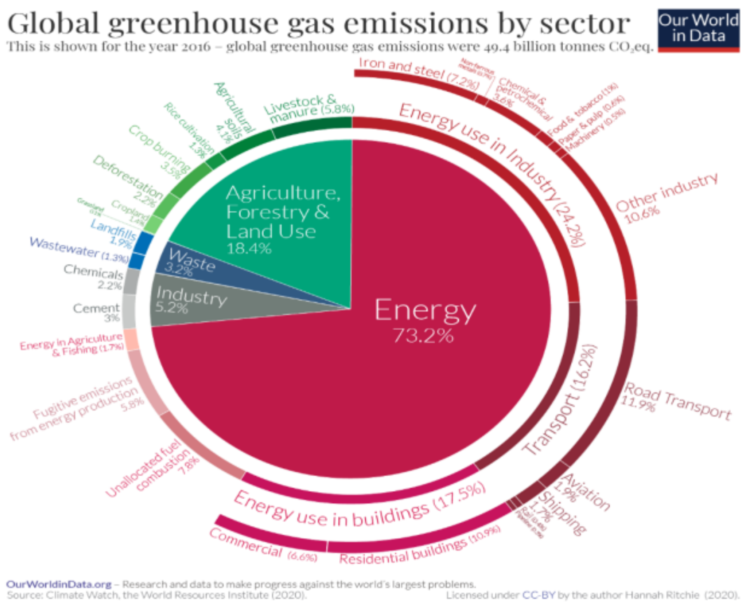

Figure 1: Green House gas emissions by Sector (source- Ritchie and Roser, 2020)

There are several technical possibilities for emission reduction in marine transportation. In 1997, the IMO had taken the International Convention on preventing Pollution from Ships (MARPOL) Annex VI, this needs the owners of the ship for calculating EEDI (Energy Efficiency Design Index), for having a Ship SEEMP (Energy Efficiency Management Plan) in mitigation of CO2, and reduction of discharge of NOx and SOx from ships dramatically in the approaching future. A common option is more efficient ship hull designs, energy-efficient engines, more efficient propulsion, and clean technologies such as fuel cells. Due to increasing environmental responsibilities in the marine industry, various research is launched to find an alternative fuel with less emission of greenhouse gases and air pollutants. Multiple alternatives for LSFO/MGO are available, such as LNG, LPG, methanol, biofuel, and ammonia. These alternative fuels do have some environmental issues and cannot completely reduce co2.

Green Hydrogen can provide potential in marine vessels of carbon-neutral propulsion, as it could be useful via fuel cells or internal combustion engines, additionally, it could be produced by different sources using either conventional or renewable sources. Green Hydrogen can be stated as the alternative to marine fuel and is useful in solving the environmental issues which have been faced with other types of fuels. PEMFCs (Hydrogen with fuel cell) have also been monitored as encouraging technologies that could be supporting energy goals and climate change in different sectors of the energy system. The shipping systems and energy are correlated, if the global energy system is de-carbonized then it can be achieved by using fuels and alternative energy that includes hydrogen, the similar can be experienced by shipping and within the years with a widespread switch for adopting green hydrogen as an alternative fuel (Raucci, 2017). In order to implement a new fuel, it has to comply with a number of requirements. It needs to be available, cost-effective, and compatible with current and/or future technologies and comply with environmental requirements. These requirement form barriers in the way of implementation and are closely connected to each other.

Green Hydrogen is with the potential in becoming a renowned solution for different shipping segments. Manufacturers, ports, and stakeholders have been also rising investment in hydrogen solutions from kinds of foreseen hydrogen that are related to value chains. Additionally, these include transportation of hydrogen applications like maritime heavy trucks and rail transportation. Carbon-free hydrogen could be produced through renewable electricity via electrolysis. This results in non-residual greenhouse gas emissions, and that is increasing system flexibility, selectively from its seasonal storage, to help in integrating bigger shares of wind and solar power. Even though presently expensive, it shall be becoming more competitive from rapidly falling costs for electricity from renewables.

This research paper main objective is to look into the technical, environmental, social, and commercial feasibility of green hydrogen as a marine fuel in an inland commercial vessel in Europe. This paper will also identify and describe hydrogen usage with an internal combustion engine (ICE) and Proton exchange membrane fuel cell (PEMFC) in commercial ships. The other part of the current study revolves around analyzing the major problems regarding the costing of HFCs' and seeking the economic feasibility of the HFCs prevalence on board with a particular case study. The case study involves a brand-new inland container vessel with 5 different options of the propulsion system (LH2-PEMFC, CGH2-PEMFC, LH2-ICE, CGH2-ICE, and VLSFO-ICE) sailing between the port of Rotterdam and the port of Strasbourg. The results of this examination will be useful to argue which investment strategy can be the solution for the ship owner. The case serves as clarification and confirmation of the conclusions taken in the literature study and sheds light on the competitiveness of green hydrogen as a marine fuel.

1.2 Problem statement

The maritime sector is not without its challenges, and this paper examines the possibilities for using hydrogen in a variety of ways in order to shift the maritime industry towards cleaner fuels. While hydrogen seems to be the silver bullet to emissions reductions in the shipping industry, it still has several challenges to overcome with manufacturing, processing, and supply chains, before it is safe for industry adoption to bring about the next shipping revolution. While some of the world's shipping industries have proposed other cleaner fuel types, like methanol and biofuels, green hydrogen is the only fuel technology that we have today that produces zero CO2. Greener hydrogen fuels, although they are not ready yet to replace oil-based or bunker-gas-based fuels across the industry, emit no emissions when used, and could be the best possible solution to the issue. Even staying in liquid form, Hydrogen has less energy-dense than bunker fuels, meaning hydrogen would occupy a larger volume on ships, resulting in efficiency losses and an opportunity cost in lost cargo. On the contrary hydrogen fuel, cells require less space when compared with a conventional engine. Hydrogen may provide a potential for carbon-neutral propulsion in marine vessels, as that could be used either via fuel cells or in internal combustion engines, and, as per the discussion, it could be produced through different sources by using either renewable or conventional energy. Questions remain surrounding the development of this zero-carbon fuel, as well as how it would be produced sustainably, stored securely, and used aboard ships. As a zero-carbon fuel, hydrogen represents a critical solution for ship owners looking to cut emissions. The use of hydrogen as an ocean fuel in ships is being developed, with hydrogen advocates suggesting that it could support a critical component in a path toward decarbonisation. Currently, hydrogen is unfeasible for deep-sea transportation, because the energy density of hydrogen is approximately one-half of other conventional marine fuels, and lower-energy-density fuels present a storage challenge, affecting available operating ranges. Green hydrogen, produced by electrolysis, is free from carbon emissions, and in the future, it may become abundantly available around the world -- either as a ship fuel or a key enabler of synthetic fuels.

As discussed above, there are several challenges with hydrogen available as fuel in shipping. First, the energy density in hydrogen is lower compared with other fuels (e.g., gasoline). Second, storing and transporting large amounts of hydrogen is difficult due to its high compressibility (storage cost and distribution cost). Third, the cost of producing and delivering hydrogen is much higher than for other fuels such as diesel or LNG (production cost and supply cost). Fourth, there are many technical hurdles that must be overcome before using large quantities of hydrogen on ships can become economically viable (technology maturity). Fifth, it will take time for the industry to develop safe and reliable ways to use large volumes of H2 on ships at sea (safety and risk assessment). Hydrogen is a highly flammable gas, so it presents a risk in shipping. The hydrogen is stored at high pressure and temperature in tanks on board the ship. If there's an accident, the hydrogen could explode and cause a fire or explosion. This would be extremely dangerous for the crew members on board as well as for people who are close to where the leak occurs (in this case, people living near ports). Sixth, an efficient legal framework is required for optimal use of hydrogen on the ship (IMO code, rules, and regulation). Seventh, uncertain and unpredictable demand.

Fuel cell technology represents an attractive solution for marine propulsion. However, the use of green hydrogen is not a clear choice for modern shipping as it entails additional investment costs, safety concerns, and supply uncertainty. Thus, from the perspective of a ship owner, choosing green hydrogen as a propulsion fuel would be reasonable only if it engages favourable economic conditions, minimizes technical risks, and make the business sustainable in long term. This paper will only evaluate the technical, commercial, environmental, and social feasibility of green hydrogen as a marine fuel in inland commercial ships in Europe.

To address the technical feasibility, this research will analyse the process of production, storage, distribution, and bunkering of green hydrogen in Europe. The reliability of the hydrogen supply for ever-increasing demands in shipping is to be evaluated and shortcomings if any should be notified. Environmental impact and legal framework requirements will be discussed later in chapter 2.

To understand the economic viability of different investment strategies for green hydrogen as a fuel, different supporting tools are analyzed, and the right capital budgeting method is chosen for further analysis. Economic analysis is done through a case study with five options of the propulsion system (LH2-PEMFC, CGH2-PEMFC, LH2-ICE, CGH2-ICE, and VLSFO-ICE) on a new container vessel sailing between the port of Rotterdam and port of Strasbourg. We will have two scenarios of investment 2022 and 2030 for each propulsion option. Capex, Opex, carbon tax and subsidies are taken into consideration for the final assessment and comparison of investment for the ship owner.

1.3 Aims and Objectives

In this research, the purpose is to clarify the issues mentioned above in detail and seek possible solutions by establishing hypotheses through case studies. To achieve the aim of this research, it would be essential to

- Identify the characteristics of PEMFCs which can be possibly applied to commercial Vessels.
- Summarize and discuss drivers and barriers of hydrogen as a marine fuel.
- Establish the hypotheses and investigate the economic feasibility of commercialization of Intra EU shipping with PEMFCs and ICE through case studies.
- Understand the legal framework and safety standards for use of hydrogen fuel in the marine environment.

1.4 Research questions

This research will mainly discuss and analyse the following research questions:

Main Research Question: How to determine the feasibility of hydrogen as a marine fuel in inland shipping?

Sub Research Question:

- Which are the technical aspects needed to be considered for the successful implementation of hydrogen as a fuel for inland shipping?
- Why and how hydrogen as a marine fuel can be used for inland shipping with the present hydrogen infrastructure and technological development in the EU?
- What will be the environmental impact?
- Is the legal framework ready for using hydrogen as an alternative fuel in shipping?
- How can the results of the economic analysis of presented case studies impact the decision-making power of ship owners?

1.5 Methodology

This paper makes use of an approach that is quantitative as its research methodology helps in providing a detailed analysis of this topic. In addition to this, quantitative data is about the cost of the literature review or hearings to provide real examples by considering case studies.

- Literature review analysis
- Case study scenario (2022 and 2030) based on NPV calculation with inland ships with different propulsion options.

    1. LH2-PEMFC (liquid green hydrogen with PEM fuel cell)
    2. CGH2-PEMFC (compressed gas green hydrogen with PEM fuel cell)
    3. LH2-ICE (liquid green hydrogen with an internal combustion engine)
    4. CGH2-ICE (compressed green hydrogen with an internal combustion engine)
    5. VLSFO-ICE (marine gas oil with internal combustion engine)

- Decision making

1.6 Thesis Structure

Introduction: This chapter introduces the Thesis topic, specifies the research questions sub-question and problem statement, and establishes the flow of the research using the history of the identified problem as a starting point.

Literature review: This chapter includes the literature view and Theoretical for this thesis. The chapter starts with a brief description of climate change, ship emissions and regulations related to it, and European hydrogen economy development. Description About the inland shipping transportation in Europe and then a detailed analysis of the technical, environmental, and social feasibility of green hydrogen fuel. The end of this chapter discusses the system overview and choice of economic analysis measurement.

Method and scenario development: This chapter will give the details about the methodology, data collection, data source, and scenarios details used for the case study to analyse the last part of the research question; economic feasibility. It will also explain the key assumptions and limitations of the model.

Results and Discussion: This chapter will include an analysis of the data, calculations of the scenarios, and a discussion and comparison of the outcome or results of the scenarios.

Conclusion: This chapter will provide the conclusion of the study, key findings, limitations, and suggestions for further research in this field of study.

Chapter 2. Literature review

2.1 Introduction:

Throughout the chapter, this paper will address the main and sub-research questions. To conduct extensive analyses and detailed evaluations of the main research question of the viability of green hydrogen as a fuel in inland transportation, the subject must be divided into four key perspectives: technical, environmental, social, and economic feasibility. This chapter "Literature Review" will address and examine the first three segments: technical, environmental, and social perspectives. In chapters 3 and 4, "Method and scenario development & Result and discussion," the economic feasibility viewpoint will be examined and debated. The literature review chapter will conclude with the selection of a measurement for economic analysis, which will be required for the following chapter's continuation of the methodological element of economic analysis. The part of the literature review is required for the empirical analysis in methodology chapter 3. The literature review chapter aids in understanding the thesis's basic purpose and primary content.

This chapter will first introduce the topic of climate change and decarbonisation. Why there is a need to switch to hydrogen fuel? And what is the EU action toward the hydrogen economy. After an overview of inland waterway transport, we will discuss the main hydrogen properties. After the brief description of the introduction topic, the chapter will then move on to the assessment of the technical, Environmental, and social feasibility. We will also discuss the driver and barrier to the use of green hydrogen in the maritime application.

2.2 Climate change, Emission from ships, and Emission regulation:

The main aim of this part of the literature is to discuss in detail the climate change impact on the shipping industry, emission type, and the globally accepted IMO regulation to tackle the emission.

2.2.1 Climate change:

Climatic change states enduring shifts in the weather patterns and temperatures. These shifts can stand as natural like through changes that happen in the solar cycle. But since the era of the 1800s, the main driver of climate change human activities are, burning fossil fuels like coal, oil, and gas Nations. Climatic change is an enduring process that affects Earth's climate. It occurs when there are changes in the amount of heat energy received by, or radiated into, the Earth system from the sun. These changes can be due to natural processes such as volcanic eruptions and variations in solar output, but they can also be caused by human activities (such as burning fossil fuels) and other factors affecting the atmosphere's ability to transfer energy around the globe. Climate change defines both global warming and cooling trends. The major cause of climatic changes is human activity – specifically greenhouse gas emissions resulting from burning fossil fuels including coal or oil for electricity generation and transportation. Greenhouse gases trap heat within our atmosphere, making it warmer than it would otherwise be without these gases present in our air. This extra heat warms our planet due to warm air holding more water vapour than cold air does (water vapour is what makes up clouds. In the UN reports, there were more than thousands of government reviewers and scientists who agreed for putting a limit on global temperature to not be crossing the1.5°C as that shall help us in avoiding the major climatic impacts while maintaining a lively climate. Even on the basis of current national climatic plans, global warming has been projected for reaching to 3.2°C by the century's end (Nations, 2022). Climatic change has been one of the world's biggest problems. Countries have taken initiatives to address it, but we are not on track to meet the commitments made, agendas, and the UN Framework Convention on Climate Change. Recent research shows that climate action can reduce poverty and improve health, especially in the poorest countries. We need to act at local, national, and global levels while respecting human rights and considering how different groups are impacted differently. There is an urgency in the energy and transportation sector including shipping to shift from fossil fuels to renewable energies such as solar or wind in order to keep the warming below 1.5°C.

2.2.2 Emission From shipping:

Emission through the ship is the amount of exhaust gases rescued into the atmosphere. Emission from ships includes both gaseous and particulate matter can cause harm to the ecological system and climate change. Gaseous emissions consisting volatile organic compounds (VOC), nitrogen oxides (NOx), Greenhouse gases (GHG), sulphur oxides (SOx), and Particulate matter including soot, dust, and aerosols.

SOx: It is a collective name for sulphur trioxide (SO3) and sulphur dioxide (SO2). Sulphur is present in fossil fuels. SOx causes acid rain which damages forests causing loss of nutrients needed by plants; it damages crops leading to food shortages; it increases soil erosion reducing agricultural productivity; it contributes significantly to climate change by absorbing heat radiation emitted by the Earth's surface increasing global temperatures; SO2 can cause respiratory problems including bronchitis, emphysema and asthma attacks among others.

Shipping is stated to be responsible for global sulphur oxide (Sox) pollution to be 9% (Vidal, 2009).

NOx: It is formed when nitrogen reacts with oxygen at high combustion temperatures. This occurs almost independently of the fuel type and mainly depends on the high ignition temperature inside the engine during combustion. Nitric oxide and nitrogen oxide are collectively known as NOx. It reacts with other substances in the atmosphere, forming smog, acid rain, ground-level ozone, and fine particles that are associated with pollution. NOx also increases rates of forest destruction and acidifies surface waters, which has a negative impact on crops. The most significant health effects associated with NOx are inflammation of the respiratory system (caused by exposure to PM) as well as increased sensitivity to allergens. Shipping takes the responsibility for the nitrogen oxide (NOx) pollution to be18-30% globally (Vidal, 2009).

Particulate matter (PM): Particulate matter (PM) is an essential pollutant of air and the smallest particles, which are smaller than 2.5 micrometres in diameter, may be harmful to human health. The amount of particulate matter released by ship engines consists of black carbon aerosols, sulphur gases, sulphuric acid droplets, and sea salt and dust particles. These tiny elements are capable of penetrating deep into our lungs and cause human respiratory problems and children such as respiratory infections, asthma episodes, lung cancer, or premature death. Researchers have suggested that long-term exposure can lead to cardiopulmonary disease (better known as a heart-lung disease) and reduce life expectancy. As I mentioned earlier every other industry is contributing equally to air pollution which is slowly increasing the levels of carbon dioxide in the atmosphere annually.

Greenhouse gasses: GHG mainly consists of water vapour (H2O), Methane (CH4), carbon dioxide (CO2), ozone, and nitrogen oxide (NO2). The main component of GHG is CO2 and CH4 caused due to burning of fossil fuel. In contrast to the growing trend of trade in merchandise, transport has been a significant contributor to the greenhouse gases with other pollutants. In 2021, greenhouse gas emissions of shipping had risen by 4.9% comparatively with 2020 as well as the year 2019, as per the annual industry report of Young's Simpson Spence. In 2021 emissions of shipping had been carbon of around 833 million metric tons, compared to the carbon of 794 million metric tons and 800 million metric tons in 2020 and

2019 respectively (Sporrer, 2022). GHG are the main reason for the global warming problem in the world.

The shipping industry presents a promising opportunity to reduce emissions problems. However, as with many other industries, shipping companies are reluctant to invest in clean solutions as they want to remain profitable and increase their market share. The only way shipping companies can be encouraged to invest in clean technologies is by implementing rules and regulations. This thesis will look at the regulation of shipping on the international and local levels.

2.2.3 Emission Regulation by IMO:

IMO (International Maritime Organization) rules related to shipping pollution are presented in the "International Convention on the Prevention of Pollution from Ships". On September 27th of the year1997, the Convention of MARPOL was drafted by the "1997 Protocol", including Annex VI titled "Regulations for the Prevention of Air Pollution from Ships". MARPOL Annex VI has set the limits on the emissions of NOx and SOx from prohibits deliberate emissions of the ozone-depleting substances from ships of 400 gross tonnage ship exhausts unless their engines are equipped with systems designed to reduce harmful emissions.

As of 2008, the revised version of Annex VI was adopted, which significantly strengthened the emission limits. It included a progressive limitation of particulate matter NOx, and SOx, and it introduced the new concept of ECA (emission control areas). There have been currently four ECAs, comprising the North America, North Sea, Baltic Sea, as well as the United States Caribbean Sea areas (Article Bill Kirrane, 2022). In 2011 there had been some changes to MARPOL and Annex VI that launched compulsory energy efficiency measures in reducing emissions of CO2. These included the EEDI (Energy Efficiency Design Index) or SEEMP (Ship Energy Efficiency Management Plan).

NOx emission control:

NOx emission standard is classified into three tiers depending upon the allowed emission allowed. Emission of NOx limits is placed in the diesel engine based upon their size and engine speed as stated in the MARPOL VI as shown in below table and figure. Tier I as well as the Tier II limits are applicable globally, while the Tier III standards consist only in NOx Emission Control Areas (Emissions Standards, 2022).check below figure 2 for details:

Tier	Date	NOx Limit, g/kWh		
		n < 130	130 ≤ n < 2000	n ≥ 2000
Tier I	2000	17.0	$45 \cdot n^{-0.2}$	9.8
Tier II	2011	14.4	$44 \cdot n^{-0.23}$	7.7
Tier III	2016†	3.4	$9 \cdot n^{-0.2}$	1.96
† In NOx Emission Control Areas (Tier II standards apply outside ECAs).				

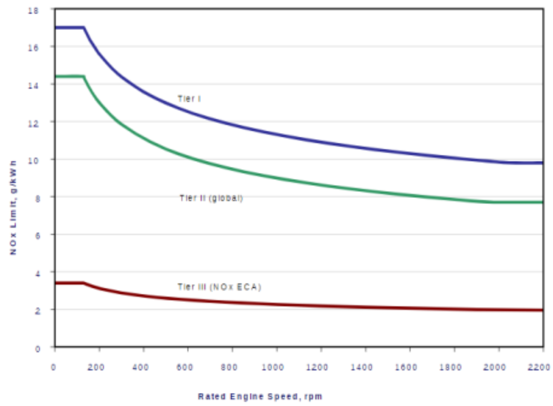

Figure 2: Marpol VI NOx Emission Control Areas

SOx emission control:

Regulations of Annex VI include the caps on the sulphur content from the fuel oil as a measure for controlling emissions of SOx as well as PM emissions (there are no explicit PM emission limits) (Emissions Standards, 2022). The required fuel quality provisions are in existence for the SOx Emission Control Areas (SOx) (Emissions Standards, 2022). From the date, 1 January 2020, the upper limit on the sulphur content of ships' fuel oil globally can be reduced by **0.50%**. Well-known as the "IMO 2020", the requirement of a reduced limit is for all the operating ships outside the designated Emission Control Areas*, where the limit is at 0.10% already (IMO, 2022). The figure 3 below describes the trends in sulphur limits imposed by IMO. (Emission Standard, 2022).

Date	Sulfur Limit in Fuel (% m/m)	
	SOx ECA	Global
2000	1.5%	4.5%
2010.07	1.0%	
2012		3.5%
2015	0.1%	
2020		0.5%

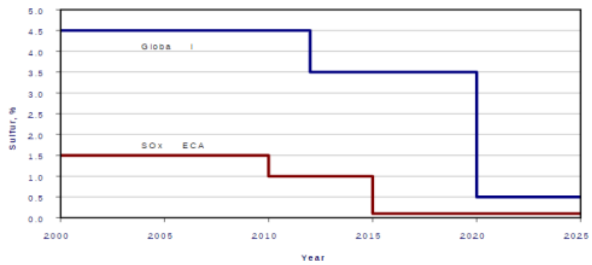

Figure 3: Trends in sulphur limits imposed by IMO

GHG emission control:

MARPOL Annex VI, Chapter 4 has introduced two types of mandatory mechanisms launched for ensuring the energy efficiency standard for the ships: (1) the Energy Efficiency Design Index (EEDI), for new ships, and (2) the Ship Energy Efficiency Management Plan (SEEMP) for all ships (Emissions Standards, 2022).

- The EEDI consists of a mechanism that is performance-based as that needs a particular minimal energy efficiency in the new ships. Additionally, Shipbuilders as well as designers are free for choosing any kind of technology for satisfying the needs of EEDI in the specified ship design.
- The SEEMP has established a mechanism for improving the energy efficiency of ships for the operators.

As discussed IMO strategy for the emission of GHG from ships for reducing the level to at least 50% of the 2008 level by 2050. The strategy says to strengthen the requirements of EEDI and numerous other measures for reducing the emissions, like operational efficiency measures, further speed reductions, taking measures for addressing CH_4 and VOC emissions, substituting low-carbon and zero-carbon fuels, and the market-based measures (MBM) (Emissions Standards, 2022).

2.3 European Union (EU) actions towards decarbonization and the hydrogen economy

2.3.1 European Union (EU) actions towards decarbonization:

Brief introduction of all GHG emission targets for clear understanding:

UN or Paris agreement GHG Emissions target: Presently, the Earth has become 1.1°C warmer than it had been in the era of 1800s, and the emissions are continuing to rise. For keeping global warming to not more than 1.5°C – as stated in the Paris Agreement – the emissions are required to be reduced by approx. 45% by the year 2030 and reach net zero by the year 2050. (Nations, 2022).

IMO GHG emission target: In the year 2018, the IMO acquired the initial strategy in reducing GHG emissions, aiming to cut shipping GHG emissions by around 50 % by 2050, compared to 2008 levels.

European Union (EU) GHG emission target: Through the year 2030 Climate Target Plan, the Commission offers for raising the EU's ambitions to reduce greenhouse gas emissions to be at 55% below the 1990 levels by the year 2030 in accordance with Europe green deal and "fit for 55" agreement. This is a sizeable increase compared to the existing target higher than its previous target of 40% (European Commission, 2022).

European Union (EU) maritime transport GHG emission target: The European Commission's 2011 White Paper (EC, 2011) for transportation endorsed that the EU's CO2 emissions through maritime transportation to be cut by 40 % of 2005 levels by the year 2050, and if possible by 50 % (European Union, 2022).

EU has introduced the following policies, packages, and regulations for accomplishing the net zero climate change target within the desired timeframe:

The 2020 energy and climate packages were introduced in 2009 for securing the EU encountering its energy and climatic targets for the year 2020. The revised 2030 climate and strategy framework covers the time between 2021 and 2030 and the targets are:

1) 55% reduction in GHG emissions relative to 1990 levels

2) 32% of the energy used in the EU should be renewable (currently proposed to be increased to 40 percent)

3) Improvements by 32.5% in energy efficiency. (Currently proposed to be increased to 36–39 percent).

The latest 55% cut in GHG emissions will help the EU to become carbon neutral and reach its goal of the Paris agreement(Table 1). The renewable energy share is increased from the original set point of 27% to 32% share. The energy efficiency factor is increased from the original target of 27% to 32.5%.

Policy	Year	GHG target	Renewable energy share	Improved energy efficiency
2020 climate and energy package	<2020	20%	20%	20%
2030 climate and strategy framework	2021-2030	55%	32%	32.5%
2050 carbon neutral	>2031			

Table 1: Energy efficiency factor

In the year 2013, the commission had to stand out a strategy for reducing the emission of GHG from the shipping industries (European Commission, 2022). The strategy or process is split into three parts:

- **Monitoring, reporting, and verification** (**MRV**) of the CO_2 emissions through the large ships by using EU ports
- **Greenhouse gas reduction targets** are for the maritime transportation sector
- **Further measures**, which includes the MBM (market-based measures), from the medium to long term
- **EU sulphur directive 2020:**

It regulates the sulphur content of fuel used for propulsion of the ship. It states the same IMO Sox Sulphur requirement of not more than 0.1% in SECA and 10.5% outside SECA.

Fuel Quality Directive: The FQD (Fuel Quality Directive) needs fuel suppliers the reduction of the greenhouse gas intensity by 6% by the year 2020 relative to the 2010 energy mix of 94.1 g CO2eq/MJ (commission E, 2022).

Renewable Energy Directive 2009/2018:

The Renewable Energy Directive (RED), with the establishment of the EU, is a step toward lowering greenhouse gas emissions. The RED serves in the EU as a primary regulatory framework for renewable energy.

Emission Trading System:

The ETS (EU Emission Trading System), operates on the cap-and-trade model. The total quantity of GHG emissions that can be emitted is limited for an installation. The cap is gradually decreased in order to minimize overall emissions. Installations purchase or get allowances, which they can swap with other installations if necessary. Heavy penalties are enforced if the installation exceeds the allowed. If an installation has extra allowances, it can sell them or keep them for the following year.

Conclusion of EU rules:

Policy	Target date	Regulation
EU sulphur directive	2015	Sulphur limit 0.5% outside SECA, 0.1% inside SECA
Fuel Quality Directive	2020	Fuel suppliers reduce GHG intensity by 6% relative to the 2010 energy mix, effective since 2017
Renewable energy Directive 2009	2020	20% of energy through renewable sources, including 10% in transport, effective since 2009
Renewable energy Directive 2018	2030	32% of energy through renewable sources, including 14% in transport, effective since 2018
European Commission	2050	Maritime transport should reduce emissions by 40% relative to the 2005 levels, effective since 2011
EU ETS	2030	Increase in the EU's net GHG emission reduction of 55%, effective since 2005

Table 2: Conclusion of EU Rules

We are still lagging behind the emission target, the regulation, and policies are crucial for the green circular economy but without a zero-emission fuel, it is impossible to achieve. That's why green hydrogen is a more sustainable option compared to other alternative fuels in response to carbon-neutral targets and a green economy.

2.3.2 EU approach towards Hydrogen economy:

The EU is speeding up its strategy for a greener hydrogen economy. It is comprehended that hydrogen in the energy sector would revolutionize the climate impact and EU dependence on other carbon-emitting fossil fuel alternatives. In 2020, the European Commission launched its strategy of hydrogen for climatic neutral Europe, as the crucial initiative for the European green deal. The main objective of this strategy is to speed up and support Europe's hydrogen economy development. It has set the target for industrial cluster deployment to bring research to actual practical application. The strategy tries to boost hydrogen production in Europe with three-step pathways:

- By the year 2024 – The approach will help to install at least 6GW of hydrogen electrolysers which are renewable and produce 1 million tonnes of renewable hydrogen.
- 2025-2030 – Renewable hydrogen generation is with 10 million tonnes and at the minimum of 40GW of renewable hydrogen electrolysers, hydrogen will become an integral element of the integrated energy system.
- From 2030– Renewable hydrogen shall be deployed at a larger scale in Europe's hard-to-decarbonize sectors.

Alongside the Hydrogen Strategy, the Commission had set up the European Clean Hydrogen Alliance that focuses on the main issues of production, transmission and distribution, industrial applications, mobility, energy, and domestic applications

2.4 inland waterway transportation in the EU

In this part of the chapter, we will briefly discuss the significance of Europe's inland water transport, its fleet size, transport capacity, corridors involved, and the commodity trade.

Inland waterways are rivers, lakes, and canals that flow into the sea. The network of the inland waterway is formed in Europe. Inland waterway transportation is playing an essential role in the transportation of goods in Europe. Waterways had exceeded 41,000 kilometres in connecting hundred and more cities and industrial regions. 13 Member States are co-connected waterway networks. The prospect to increase a modal share for inland waterway transportation is required. Comparatively, with other transport modes that are frequently faced with congestion and capacity problems, inland waterway transportation has been characterized by its reliability and energy efficiency for increased exploitation.

In the year 2020, the EU of transportation performance of IWT accounted for 131.7 billion tonnes per km. A sector is relying on the market segments like agriculture, steel, chemicals, and food. The modal share of sectors in the EU transportation market had stayed constant at approximately 6 %, standing at the top in the Netherlands (43 %), followed by Romania (28 %) and Bulgaria (31 %). But, the coronavirus crisis delayed around 3 days in freight transportation, with a loss of turnover of €2.2 billion, partly in road transport (European Parliament, 2022).

Inland waterway transportation provides a competitive alternative to road and rail transportation. It has the advantage of enabling the most energy-efficient and environmentally friendly mode of transportation, with per km/ton of energy consumption of transported goods of 50 % of rail transport and 17 % of road transport (European Commission, 2022). As well as, inland waterway transportation is ensuring higher levels of safety when that comes to dangerous goods transportation. This also contributes to decongesting the overloaded road networks in the overly populated regions. The Rhine is the most heavily used inland waterway in the world. It flows through Germany, the Netherlands, and Switzerland. The Ruhr River connects the Rhine from the east. The Rhine is navigable for 700 km south of the Ruhr and connects industrial areas in Germany, France, Netherlands, and Belgium with the North Atlantic Sea Route. Every year more than 20,000 ocean-going ships pass through this stretch of waterway fulfilling their cargoes to Europe or other parts of the world.

Inland waterway network and transportation:

With their geographical environment, Finland had acquired the biggest network of navigable waterways that is closely followed by Germany with around 8000 km. Even after the Netherlands was a smaller area, the length of its waterways amounted to exceeding 6000 km (Interreg Deutschland Nederland, 2018). On the other hand, in Finland, Romania, Poland, Bulgaria, and Hungary, maximum waterways are on the natural water bodies, around $1/4^{th}$ are canals in Germany and Netherlands, France, Italy and Belgium this fraction is even greater than 50 % (Interreg Deutschland Nederland, 2018, Figure 4). The market characteristics presently reflect that for the cross-border traffic in the corridor of Rhine-Alpine, the inland waterways contain the 54% modal share. For the corridor of North-Sea Mediterranean, the IWW traffic amounted to 35%, where 38% for the corridor of North-Sea-Baltic and 14% for the corridor of Rhine-Danube. Rhine countries (Belgium, the Netherlands, Switzerland, Germany, France, Luxembourg) had amounted to about 81.6% in the EU-27of final inland waterway transportation performance, along with Serbia and Switzerland. The Danube countries with a share of about 18.1% and all the countries taken together represented 0.3% (Central Commission for the Navigation of the Rhine, 2020). All types of products related to manufacturing, chemicals, container cargo, food product, and mineral oil products are transported between Rhine countries. As per the Europe inland waterway 2018 data, there are 17000 ships or more including the Rhine fleet, Danube fleet, and other country's fleet (Table 3).The performance of inland water fleet in Europe's different region in Ton kilo meter(Tkm) over the decade has been consistent check Appendix figure 3 and 4 .

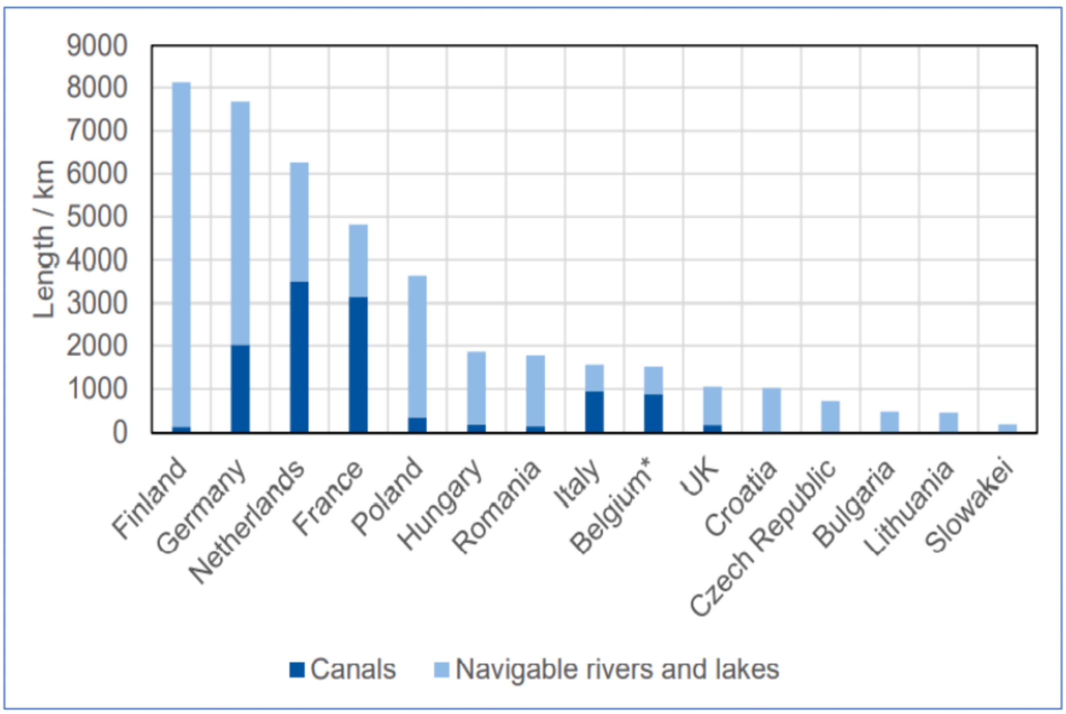

Figure 4:Inland waterways in Europe in 2015

European inland waterway fleet							
Country	**Dry cargo vessel**	**Tanker vessels**	**Push Boats**	**Tug boats**	**Cargo Boats**	**Tanker Barges**	**Total**
Belgium	806	216	94	10	230	8	1364
Germany	916	419	285	140	789	44	2593
France	860	44	93	0	383	47	1427
Luxembourg	8	16	11	0	0	2	37
Netherlands	3993	1240	649	479	1135	51	7547
Switzerland	17	55	0	2	4	3	81
Rhine countries	**6600**	**1990**	**1132**	**631**	**2541**	**155**	**13049**
Bulgaria	26	4	38	13	161	5	247
Croatia	8	5	10	32	98	21	174
Hungary	78	2	26	53	300	4	463
Moldova	8	5	1	10	26	0	50
Austria	6	5	10	0	54	15	90
Poland	109	2	0	0	431	0	542
Romania	75	4	183	69	984	97	1412
Serbia	62	5	40	82	245	37	571
Slovakia	26	4	41	1	119	32	223
Czech Republic	44	0	0	0	145	0	189
Ukrain	44	3	73	15	472	22	629
Central and Eastern Europe	**0**	**39**	**422**	**275**	**3135**	**233**	**4590**
Toatal	**7086**	**2029**	**1554**	**906**	**5676**	**388**	**17639**

Table 3: European Inland Waterway Fleet

2.5 Hydrogen properties

This part of the paper will discuss the chemical properties of hydrogen and then compare it with different fuels.

Hydrogen Properties:

Under typical Earthly circumstances, hydrogen is a colourless, tasteless, odourless, and non-poisonous gas. Because it normally exists as a diatomic molecule, which has two hydrogen atoms in each molecule, pure hydrogen is often written as "H2”. As the most prevalent element in the cosmos, hydrogen makes up 90% of the universe's total weight. Since it easily mixes with other elements, it is seldom encountered in its pure state. Moreover, it is the lightest element.

It contains a large energy content per weight (around three times that of gasoline), but at typical temperature and pressure, the energy density per volume is rather low. The hydrogen can be kept under higher pressure or kept as a liquid at low temperatures to boost the volumetric energy density. Metal hydrides are capable of adsorbing hydrogen as well. Due to its tremendous flammability, hydrogen may be ignited and burned with a very tiny amount of energy. It may also burn when it makes up 4 to 74% of the air volume, which indicates that it has a broad flammability range. Hydrogen fires are challenging to spot because hydrogen burns with a pale blue, nearly undetectable flame. Carbon dioxide is not produced when hydrogen is burned.

Chemical property	HYDROGEN
Boiling Temperature (° C)	-253
Liquid Density (kg/m3)	70.8
Gas Density (kg/m3) (Air: 1.198)	0.084
Dynamic Viscosity (g/cm•s x 10-6) gas	8.8
Dynamic Viscosity (g/cm•s x 10-6) liquid	13.49
Flame Temperature in Air (° C)	2396
Maximum Burning Velocity (m/s)	3.15
The heat of Vaporization (J/g)	448.7
Lower Flammability Limit (% vol. fraction)	4.0
Upper Flammability Limit (% vol. fraction)	75.0
Minimum Ignition Energy (MJ)	0.017
Auto-ignition Temperature (° C)	585
The temperature at Critical Point (K)	33.19
Pressure at Critical Point (kPaA)	1297

Table 4: Chemical properties of Hydrogen

By having the highest energy content, the Hydrogen fuel is identified per mass including all the chemical fuels at around 120.2 MJ/kg. The mass energy exceeds MGO by about 2.8 times, and the alcohols by five to six times. Hence, hydrogen fuel could be increasing the appropriate efficiency of the engine and be helpful in reducing particular fuel consumption. But, on a volumetric basis, because of the lower volumetric energy density, the liquid hydrogen might demand an extra four times more space than MGO or about two times extra space than liquefied natural gas (LNG) for an equivalent amount of carried energy. Additionally, it is necessary for comparing fuel energy and its required volumes then energy efficiencies of the consumer, or electrical energy losses in fuel cells are required. Appropriate for entire marine fuels, excess volumes of fuel might be needed for accounting for the efficiency losses between the tank to the output shaft power (The American Bureau of Shipping, 2021). Hydrogen needs temperatures to be low around 253 ° C (-423.4° F) to liquefy. This results in low temperature, and the essential volume for storing liquid hydrogen can be even more when all necessary layers of materials or vacuum insulation are considered in the cryogenic storage and various structural arrangements (The American Bureau of Shipping, 2021). For reference of Comparison of hydrogen fuel with different alternative marine fuel is given below(Table 5).

	UNIT	HYDROGEN	MGO	HEAVY FUEL OIL (HFO)	METHANE (LNG)	ETHANE	PROPANE	BUTANE	DIMETHYL-ETHER (DME)	METHANOL	ETHANOL	AMMONIA
Boiling Point	° C	-253	180-360	180-360	-161	-89	-43	-1	-25	65	78	-33
Density	kg/m³	70.8	900	991	430	570	500	600	670	790	790	696
Lower Heating Value	MJ/kg	120.2	42.7	40.2	48	47.8	46.3	45.7	28.7	19.9	26.8	22.5
Auto Ignition Temp	° C	585	250	250	537	515	470	365	350	450	420	630
Flashpoint	° C	-	> 60	> 60	-188	-135	-104	-60	-41	11	16	132
Energy Density Liquid (H_2 Gas at 700 bar)	MJ/L	8.51 (4.8)	38.4	39.8	20.6	27.2	23.2	27.4	19.2	15.7	21.2	15.7
Compared Volume to MGO (H_2 Gas at 700 bar)		4.51 (7.98)	1.00	0.96	1.86	1.41	1.66	1.40	2.00	2.45	1.81	2.45

Table 5: Properties of Hydrogen compared to other Marine Fuels

2.6 Technical feasibility

This part of the literature review will test the technical feasibility of hydrogen as a marine fuel in Europe's inland waterways. Details about the infrastructure available and the reliability of hydrogen as a fuel will be discussed. For comprehensive technical analysis, compatibility of hydrogen with existing infrastructure, the current amount of storage, distribution, bunker facilities available, raw material available, production capacity, and supply potential needs to be evaluated.

2.6.1 Green Hydrogen production

This part of the paper will discuss the methods of production for green hydrogen, the present infrastructure for green hydrogen production, and the availability of green hydrogen for inland shipping in Europe.

Types of hydrogen and Method of green hydrogen production:

There're numerous kinds of hydrogen based on the manner of creation, and different colors are used to distinguish them. There are four kinds of hydrogen: grey, blue, brown, and green. Brown hydrogen is made as a by-product of the processing of coal. Grey hydrogen is created through the processing of natural gas and other fossil fuels. Blue hydrogen is created through the processing of fossil fuels in conjunction with emission control technology like storage (CCUS) techniques and carbon capture, and utilization. Green hydrogen is formed from sustainable energy resources, often by electrolysis through the use of water. Solar or wind power might be used for generating carbon hydrogen to be net zero. The grey hydrogen formed by natural gas is the predominant hydrogen production technique of hydrogen, estimating around 75% of worldwide hydrogen production. The second major source is brown hydrogen, particularly in China. Green hydrogen generation accounts for just 2% of worldwide hydrogen supply, whereas blue hydrogen production is not yet ubiquitous. The two most popular ways to produce hydrogen are steam-methane reforming (SMR) and electrolysis (splitting water with electricity). The topic of this study is confined to green hydrogen and the electrolysis process.

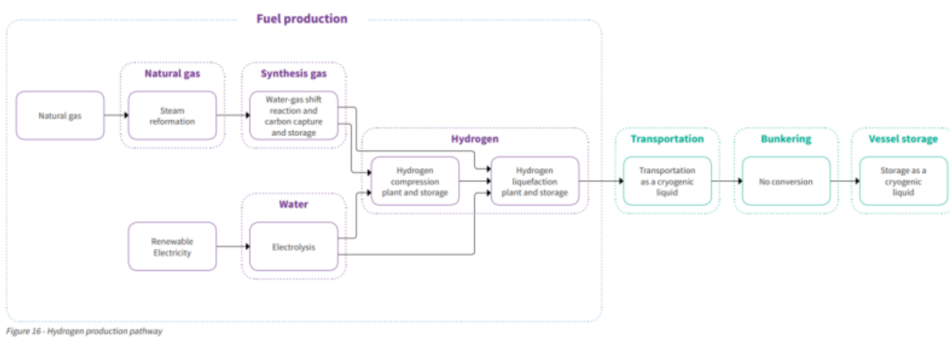

Figure 5: Hydrogen Production Pathway(source-Lloyd's list,2022)

Green hydrogen: It is explained as hydrogen produced by splitting water into hydrogen and oxygen (electrolysis) to use renewable electricity(figure 7).

Electrolysis process: To produce carbon-free hydrogen from nuclear and renewable sources, electrolysis is a potential alternative. The method of separating the water in the hydrogen and oxygen from high current is known as electrolysis. A reaction takes place in a device known as an electrolyser. An electrolyte acts as a medium between the anode and cathode in an electrolyser. Different electrolysers operate differently, mostly because of the various electrolyte materials used and the ionic species they conduct. Alkaline electrolysers, solid oxide electrolysers, anion exchange membrane (AEM), and polymer electrolyte membrane (PEM) electrolysers are the four primary categories of electrolysers. The scope of this paper is limited to PEM electrolyser or PEM Fuel cell and it will be discussed in detail in later chapters.

A water electrolysis cell's fundamental design consists of two electrodes that are separated by an electrolyte. The electrolyte is in charge of moving anions (-) or cautions (+) produced chemical charges from one electrode to the other. In the alkaline type, a highly concentrated potassium hydroxide solution serves as the electrolyte that transports the OH anions. A porous inorganic diaphragm, also known as a separator and permeable to the KOH solution, physically separates the electrodes from the generated gases. An electron-insulating solid electrolyte separates the electrodes in PEM, AEM, and solid oxide electrolyzers. This solid electrolyte is in charge of moving ions between the electrodes while also physically separating the generated gases. Ion transit belongs within the PEM, AEM, or solid oxide component in these cases, eliminating the requirement for a liquid electrolyte solution (IRENA, 2020). The chemical reaction at anode and cathode for different type of electrolyzer is shown in below figure 8 and table 6 gives explains the basic characteristics for all four electrolyzers.

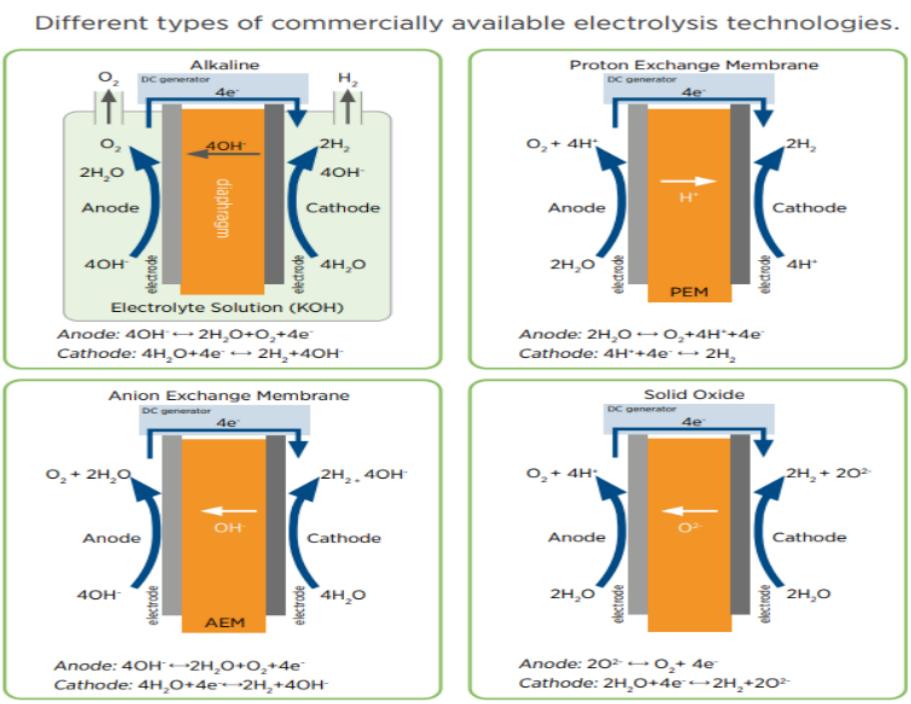

Figure 6: Different Types of Commercial available electrolysis technologies

	Alkaline	PEM	AEM	Solid Oxide
Operating temperature	70-90 °C	50-80 °C	40-60 °C	700-850 °C
Operating pressure	1-30 bar	< 70 bar	< 35 bar	1 bar
Electrolyte	Potassium hydroxide (KOH) 5-7 $molL^{-1}$	PFSA membranes	DVB polymer support with KOH or NaHCO3 1$molL^{-1}$	Yttria-stabilized Zirconia (YSZ)
Separator	ZrO_2 stabilized with PPS mesh	Solid electrolyte (above)	Solid electrolyte (above)	Solid electrolyte (above)
Electrode / catalyst (oxygen side)	Nickel coated perforated stainless steel	Iridium oxide	High surface area Nickel or NiFeCo alloys	Perovskite-type (*e.g.* LSCF, LSM)
Electrode / catalyst (hydrogen side)	Nickel coated perforated stainless steel	Platinum nanoparticles on carbon black	High surface area nickel	Ni/YSZ
Porous transport layer anode	Nickel mesh (not always present)	Platinum coated sintered porous titanium	Nickel foam	Coarse Nickel-mesh or foam
Porous transport layer cathode	Nickel mesh	Sintered porous titanium or carbon cloth	Nickel foam or carbon Cloth	None
Bipolar plate anode	Nickel-coated stainless steel	Platinum-coated titanium	Nickel-coated stainless steel	None
Bipolar plate cathode	Nickel-coated stainless steel	Gold-coated titanium	Nickel-coated Stainless steel	Cobalt-coated stainless steel
Frames and sealing	PSU, PTFE, EPDM	PTFE, PSU, ETFE	PTFE, Silicon	Ceramic glass

Table 6: Characterisation of the four types of water electrolysers

Infrastructure and Reliability of green hydrogen in inland waterway shipping:

In 2019, the total estimated volume of the goods transported through inland waterways by the 27 European Union countries had been around 523 million tonnes (EUROSTAT); it had been transported by 17000 vessels which included cargo vessels, tugs, and push boats used for the safe logistics and cost-effective solutions by Europe inland transport corridors. The Green Deal has the recent targets and the Fit of the 55 packages open with new perspectives to accelerate the growth of inland water transportation by renewable hydrogen. Eliminating its emissions through those vessels, while forming a tough commercial proposition, would uplift the European waterborne transportation sector and also have a major and positive impact on the air pollution and emissions of GHG.

For successful implementation of green hydrogen as a marine fuel on the inland vessel we need to elaborate in detail on the total available energy in the EU (including Primary production + Recovered & Recycled products + energy Imports – energy Export + Stock changes), what is the Renewable energy sources (RES) share in it? How much is the energy consumption in the transportation sector? How much is the energy consumption share related to inland shipping? Can RES apply to fulfil the green hydrogen demand for propulsion in inland shipping?

Gross available energy in the EU in 2020= 57 767 Petajoule (PJ), the available gross energy is with structural split in the EU through the essential categories for energy balance. In the EU for the year 2020, the biggest share of energy was useful in the energy transformation (24.2 %), also, followed by the transportation sector (18.8 %), non-energy use (6.7 %), the households (18.5 %), industry sector (17.2 %), the services (9.1 %) and other sectors (5.5 %) (Eurostat, 2022).

The available gross energy share in Renewable energy sources (RES) for 2020 ≈10000 PJ(*for the scope of the paper we not considering the contribution of biofuels) (Eurostat, 2022,figure 9).

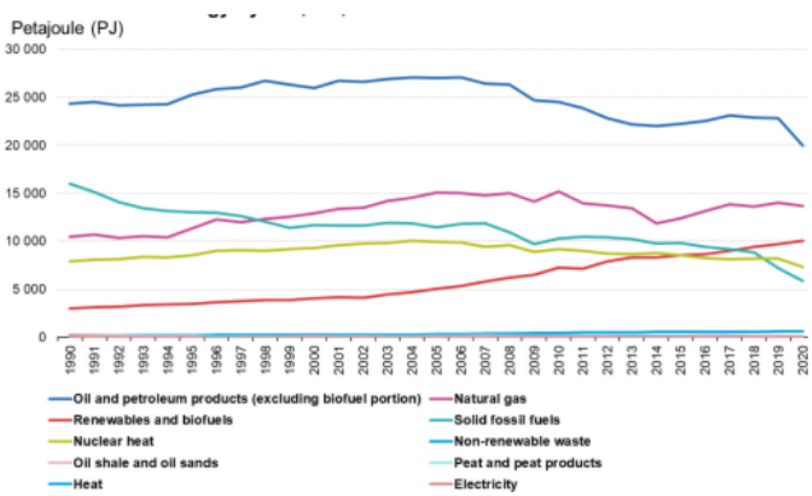

Figure 7: Gross Available energy by Fuel, 1990-2020

Ending energy consumption in the EU in 2020 =37 086 PJ.

Energy consumption by the transport sector is 28.4% of total energy consumption=28.4$ of 37086 PJ=10532.23 PJ. Inland waterways account for 1.6 -2 % of the final energy consumption in transportation units as per European commission data .so the **energy consumption by inland ships in Europe=2% of 10532.23=210.6 PJ.**

As per the other source (EEA, 2022), **domestic navigation final energy consumption in 2017=0.2 million terajoules=200PJ**(figure 10)

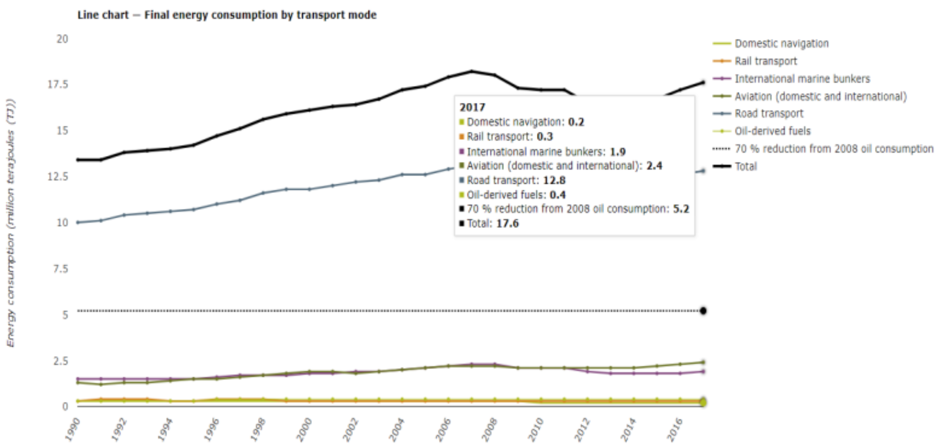

Figure 8: Final Energy Consumption by Transport Mode

As per the available 2020 data, the EU's gross available RES (**10000 PJ**) can easily match the energy requirement of inland shipping in Europe (**210.6 PJ**) if there is no or less requirement in other sectors. This available RES can be used for a hydrogen electrolyser to produce sufficient green hydrogen to run a complete fleet of inland waterways. But yes, the growing demand for green hydrogen in the different sector could influence the complete implementation of hydrogen as marine fuel unless the green hydrogen production is further improved and upscale to match the demand. At the EU level, renewable energy consumption climbed gradually from 9.6 percent in 2004 to 22.1 percent in 2020, exceeding the EU objective of 20% renewables by 2020. The higher percentage of renewables in 2020 was spurred in part by the decline in fossil fuel usage caused by the COVID-19 epidemic. The new EU objective for 2030 is 32%. (The target is under revision). Europe has a plethora of renewable energy sources, and its governments have emerged as leaders in promoting the implementation of renewable technology in recent years. Efforts to strengthen the sustainability of Europe's energy systems are ongoing, with renewable energy targets established for all European nations and the European Union's aim (EU). According to the study, Europe can presently create 56 MW or around 4,700 tons of green hydrogen per year. The transportation industry consumes half of this production, and about one-third is utilized to reduce carbon emissions in industrial applications such as petrochemical refining. In terms of hydrogen, Germany is the market leader. The country is responsible for about half of European output, with no other country producing more than 10 MW. However, the industry is thriving, with major projects set to begin this year in Spain, the Netherlands, and Denmark, where 10 MW of green hydrogen will be generated by 2020 and 100 MW by 2025 (David, 2021).

Future EU policies and strategies are aligned to fulfil the future green hydrogen demand from all sectors including inland shipping. As per the hydrogen policy of the EU, about 6 GW

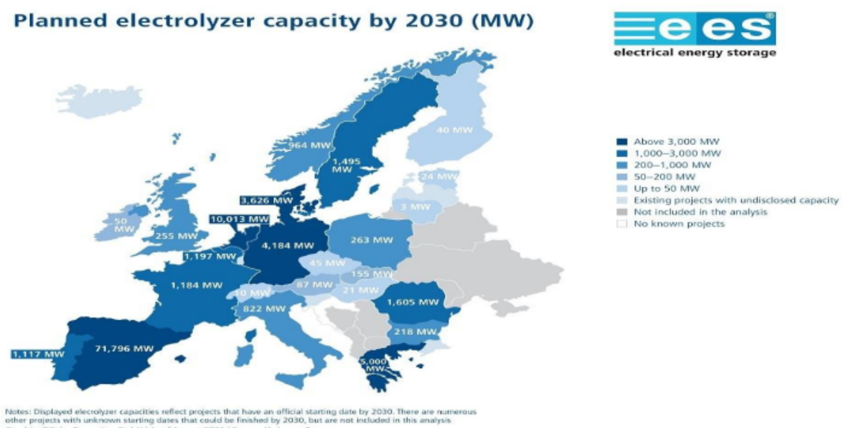

Figure 9: Planned electrolyser capacity by 2030(MW)(hydrogen Europe)

(renewable energy-powered electrolysers) required are installed between the years 2020 and 2024. Determining the use, such capacity can create about 0.8 Mt of clean hydrogen per year. Such a figure is expected to rise to 40 GW by 2030. Figure 11 shows the planned electrolyser capacity by 2030 for different part of Europe .In accordance with 2019 ambitious scenario of Hydrogen Roadmap Europe, the hydrogen demand in the EU+UK will reach 665 TWh or 16.9 Mt by that time. Additionally to support this argument, G.kakoulaki's research paper named "Green hydrogen in Europe regional assessment : Substituting existing production cycle with electrolysis powered by renewables" details the promising future of green hydrogen in Europe. The land use and environmental constraints, and different techno-economic parameters are accounted as the study evaluates the specialized potential of RES on a regional as well as national scale. The paper evaluates the viability of RES-based water electrolysis for replacing carbon intensive hydrogen hubs and provides estimates for localized clean hydrogen production. The paper concluded that for all the countries in Europe ,the available RES electricity potential was found to be more than the final electricity demand and the share of production of hydrogen via electrolysis(Table 7).

Country ID	Technical potential (green electricity)					Hydrogen Electrolysis Require-ment [TWh]	Current electricity Consumption [TWh]	Electricity Balance Supply-Demand
	Ground PV [TWh]	Rooftop PV [TWh]	Onshore Wind [TWh]	Offshore Wind [TWh]	Hydro Power [TWh]			
AT	34.9	12.9	59.5	0.0	31.8	5.8	63.6	69.7
BE	19.0	12.5	0.9	7.6	0.2	15.9	87.2	−62.8
BG	111.3	17.5	58.5	1.3	3.5	8.9	38.8	144.4
CH	15.5	10.2	0.0	0.0	0.0	0.0	59.6	−33.9
CY	11.0	5.7	2.4	0.0	0.0	0.0	4.5	14.7
CZ	70.1	13.7	23.4	0.0	1.1	4.7	66.1	37.5
DE	333.0	104.6	134.5	106.5	14.9	69.7	493.2	130.5
DK	41.2	6.2	40.1	112.6	0.0	0.8	32.3	167.0
EE	14.1	1.3	54.3	5.1	0.0	1.4	8.1	65.3
EL	38.6	19.2	365.4	0.1	4.2	4.0	50.9	372.5
ES	376.2	69.3	1172.4	2.1	20.7	11.2	252.7	1376.7
FI	23.7	5.2	61.1	84.6	8.2	5.3	83.2	94.4
FR	550.5	129.5	613.4	57.2	42.9	16.9	476.4	900.3
HR	20.8	9.0	23.6	11.7	5.5	3.8	17.4	49.3
HU	133.9	18.0	86.4	0.0	0.2	5.6	43.0	189.9
IE	62.5	3.0	277.3	4.6	0.7	0.0	27.7	320.4
IT	246.8	93.7	282.2	12.6	34.3	22.6	291.1	356.0
LT	40.3	3.0	144.2	11.8	0.4	6.4	11.7	181.6
LU	1.3	0.7	0.1	0.0	0.0	0.0	4.3	−2.2
LV	26.1	1.5	123.5	60.9	1.2	0.0	7.2	206.0
ME	0.7	1.2	0.0	0.0	0.9	0.0	3.4	−0.6
MK	13.1	2.3	0.0	0.0	0.7	0.0	7.0	9.0
MT	0.03	0.9	0	0	0	0	2	−1.1
NL	31.4	17.9	10.6	196.0	0.0	39.8	113.7	102.4
NO	7.8	2.6	0.0	0.0	104.0	0.0	127.6	−13.1
PL	272.4	31.0	270.5	48.7	1.3	25.4	168.3	430.2
PT	29.3	25.7	48.2	0.0	5.4	2.8	49.5	56.3
RO	274.5	35.9	201.1	27.4	14.5	13.3	60.0	480.0
RS	70.7	12.5	0.0	0.0	5.4	0.0	39.8	48.7
SE	46.5	7.9	343.2	119.7	47.4	3.0	136.9	424.8
SI	3.8	2.7	1.9	0.0	3.1	0.0	13.2	−1.6
SK	35.5	9.1	21.3	0.0	4.1	4.5	29.7	35.7
UK	207.1	45.3	526.8	441.2	4.2	18.4	306.3	899.9

Table 7: RES electricity potential in various countries (source-G.kakaolaki, 2020)

2.6.2 Green Hydrogen storage and bunkering

This part of the paper will discuss about the storage methods, on board implement of liquid hydrogen (LH2) and compressed gas hydrogen (CGH2) and their bunkering arrangement.

Hydrogen's competitiveness will be largely determined by the evolution of storage and transport techniques, and the costs tagged with doing so. Hydrogen's energy density per kilogram is higher than that of fossil fuels, LPG, and gasoline. When compared to other fossil fuels, hydrogen has an extremely low volumetric density per kilogram. It will necessitate much more room on board, which may affect the owner's final choice. Consequently, a wide variety of storage options are created to negate the necessity for such massive vessels. High-pressure and/or low-temperature physical approaches can be differentiated from material-based storage methods in which hydrogen is bonded chemically or physically. Compressed gas, liquid, and cryo-compressed hydrogen comes under physical-based category whereas Liquid organic hydrogen carrier (LOHC) and metal hydrides with material-based storage category(Figure 12). In Europe, salt caverns, aquifers, and depleted fields may all be used to store hydrogen on a massive scale for cyclical and seasonal use, ensuring a steady supply, allowing for more adaptability in the operation of electrolysers, and helping to meet energy demand during times of peak usage. The minimal cushion gas demand, capacity of high sealing rock salt, and inert nature of salt structures for making salt caverns an ideal location for storing pure hydrogen. In

Europe for automobile sector infrastructure has already been developed, inlands ships can Bunker either by a fixed installation near the port or by truck or by newly developed hydrogen bunker ships

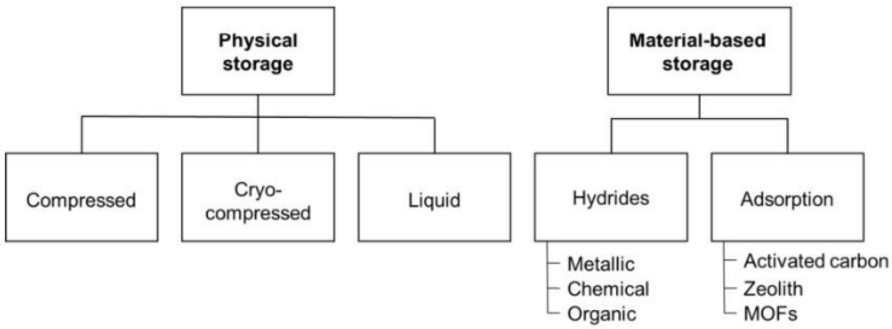

Figure 10: Hydrogen Feasibility Inland Shipping

Compressed gas hydrogen (CGH2) storage on board and bunkering:

Compressing hydrogen in a storage tank is the most popular technique of hydrogen storage. Compression of hydrogen gas work by 1 bar to 700 bar / 1000 bar requires the amount of energy approximately of 10 or 15 % lower heating value of hydrogen [Mar15]. Hydrogen is reserved under varying pressures. Gas providers often supply 200 or 300-bar steel cylinders and bundles. The majority of storage tanks are lined with carbon fibre-wrapped metal or polyethylene.

The below figure 13 describes the outline of a compressed hydrogen storage system on ships below deck with a fuel cell propulsion. In order for the tank hold area on the ship to be suitable for the storage of compressed hydrogen, the following components must be present as described by the hand out for hydrogen-fuelled vessel 2021:

• CH2 tank bundle(s), normally at a pressure of 250 bar (depending on the present level of maritime certification; larger pressures are anticipated for the future).

• Fuel lines, Pressure regulating unit, H2 detecting system, a mechanism to guard against fire, Fire protection for the structure itself

• Ventilation system (by using artificial ventilation method to supply the tank hold space with continual air changes)

• Safety systems (including a fire detection system, a fire fighting system, and an emergency shutdown system).

We are going to assume that the principal lines of fuel supply aboard the ships are for the pipe-in-pipe, and they will run from the pipe leading through the CH2 bunkering station to the pipe leading to the ship's fuel storage system.

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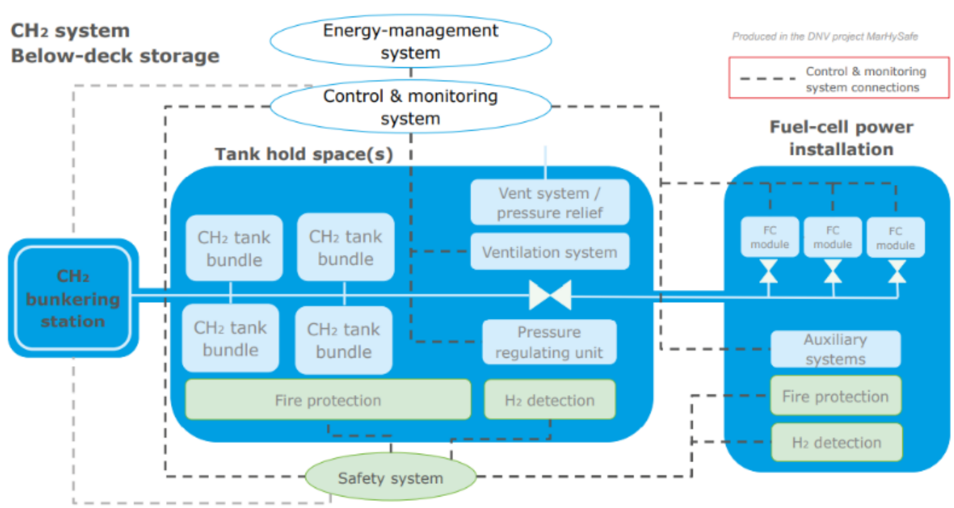

Figure 11: Generic block diagram for compresses gas hydrogen (CH2) with below deck storage(source-DNV, 2021)

To move hydrogen from the bunkering station to the ship, either direct compression of the hydrogen gas is used or pressure balancing. For pressure balancing, the bunkering station's hydrogen storage pressure(s) must be greater than what the ship needs. This is often accomplished through a process known as cascade filling, in which hydrogen is pumped from land-based tanks that store the gas at various pressures, starting with the tanks with the lowest pressure. Hydrogen at 250 bar is needed in the typical ship situation. The bunkering station must thus have a higher storage pressure. An alternate method of bunkering involves using an uplifted compressor for raising its pressure and also bunkering the hydrogen in the ship.

Liquid hydrogen (LH2) storage on board and bunkering:

Liquefaction of hydrogen occurs when the element is kept at a temperature lower than the boiling point, which is about 20 degrees Kelvin (K) as standard atmospheric pressure. The energy that is consumed for this is somewhere around 20 to 35% of the total energy content of hydrogen in proportion to its lower calorific value [Mar15]. This percentage varies depending on the system. Containers made of double walls and vacuum insulation are used to hold the liquid hydrogen. When compared to compressed hydrogen storage at 700 bar, liquid hydrogen storage has a significant advantage in that its energy density is twice as high as regular hydrogen storage.

The below figure 14 outlines the ship's system arrangement for below-deck storage of cryogenic hydrogen in liquid form (LH2) as described by the hand out for hydrogen-fuelled vessel 2021.

The following characteristics must be present.

Tank capacity:

• Tank for liquid hydrogen (LH2) (cryogenic), Hydrogen vent system, TCS (tank connection space), Gasoline queues, LH2-specific vaporizer Pressure regulating unit (PRU), which might be a pressure build-up device, and a conditioning tank.

• A conditioned tank might be required for reducing the risk of sloshing caused by inadequately raising power provided through LH2 conditions. The FC system typically requires an intake pressure of roughly 3.5 bar.

A conditioning tank will normally operate on an intermittent basis, warming up the liquid at the equilibrium temperature for the 5 bars.

• Hydrogen vent system (a pressure relief system for the hydrogen fuel-transfer system).

• A structural fire prevention (the insulation needed against adjacent areas).

• Ventilation system (artificial ventilation given for the TCS with continual air changes).

• H2 detection system (for example, audible).

• A safety system (suppression, fire detection, and emergency shutdown).

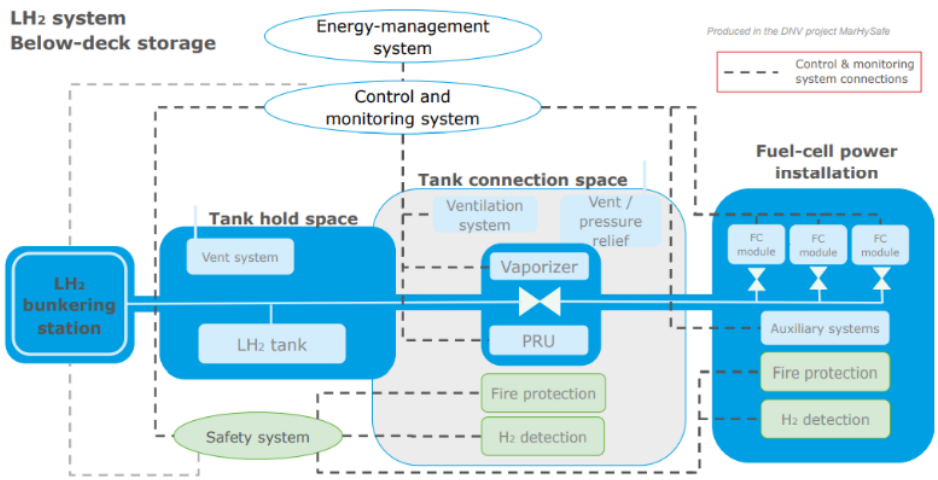

Figure 12: Generic Block diagram for a system with liquid hydrogen (LH2) storage below deck (source-DNV, 2021)

Pressure fill (a differential pressure flow between the 2 tanks) and cryogenic pumps are two methods for bunkering ships with liquid hydrogen. Whatever the case may be, the LH2 bunkering station is comprised of the inert gas supply, a flexible bunkering hose assembly, and an LH2 source tank. There should be 2 hose connections: first for the inert gas or liquefied hydrogen, and the second one for the cooled hydrogen gas return. To maintain a clean fuel supply for bunkering, inert gas is utilized to drive out moisture and air. The bunkering line can be pre-cooled using liquid helium because it is an inert gas with a low boiling point. Due to helium scarcity, alternatives like nitrogen or hydrogen pre-cooling may be explored.

Cryo-compressed hydrogen: When it comes to hydrogen storage, cryo-compressed systems combine the advantages of both compressed and cryogenic systems. Hydrogen is stored in an insulated tank that can endure cryogenic temperatures and high pressures. If you want to increase the safety and storage capacity of hydrogen, this is a good alternative to using compressed hydrogen or cryogenic LH2. This improves the volumetric capacity for storing hydrogen. Further, compared to compressed hydrogen storage (usually 700 bar), the pressures used in cryo-compressed hydrogen storage (about 300 bar) may lessen the need for more expensive carbon fibre composites.

LOHC: Hydrogen is stored and released from a liquid organic hydrogen carrier by hydrogenating and dehydrogenating it. Since there is none of the molecular hydrogen's in the storage of LOHCs, attaching the hydrogen to the carrier material is crucial.

2.6.3 Green Hydrogen transport and distribution

Hydrogen may be carried in a variety of ways and is easy to move across great distances. Today, compressed gaseous or liquid hydrogen is transported by lorry. Pipelines are used for compressed gas hydrogen transport to the selected location in Europe. The primary modes of transportation employed are pipelines carrying hydrogen to specific destinations. The most used method of transporting hydrogen, accommodating various hydrogen markets include(figure 15):

- Cryogenic liquid tankers or compressed gas cylinders
- Hydrogen pipelines
- blending with natural gas

Compressed gas cylinder Transport by truck:

Trucks may transport compressed gas hydrogen in small to medium volumes in all the compressed gas containers. Various pressurized gas cylinders or tubes are stacked together with CGH2 tube trailers to transfer bigger amounts. Inside a protective frame, the huge tubes are grouped together (hydrogeneurope.eu, 2021). Steel tubes with high net weight are commonly used. This may result in mass transportation constraints. For truck transport, the recent pressurized storage system is employed with lighter composite storage containers. Because hydrogen has a low density, a tube trailer couldn't hold compressed gas as a tanker for liquid fuels (petrol or diesel) (hydrogeneurope.eu, 2021).

Cryogenic liquid hydrogen tankers:

Hydrogen can be carried in liquid form in trucks or other vehicles. Since the liquid hydrogen density is more than the gaseous hydrogen, an LH2 trailer can transport more hydrogen than a pressurized gas tank. The hydrogen is stored in cryogenic tanks for delivery in liquid form. LH2 trailers can go up to 4,000 kilometres without refuelling. As the cryogenic hydrogen within the container warms up throughout the trip, the internal pressure increases.

Pipelines:

If hydrogen were to be used extensively and on a big scale as an energy source, a pipeline network would be the ideal solution. However, pipelines need substantial up-front investment, which may be worthwhile, but only if substantial quantities of hydrogen are transported. Still, one possibility for developing the pipeline networks for hydrogen distribution is the local or regional networks, called as micro-networks. These could be combined in the process of Trans regional networks (hydrogeneurope.eu, 2021). As per hyARC 2017, Belgium =613 km, Germany=373 km, France=303 km and Netherlands=237 km of hydrogen pipelines. A hydrogen distribution system with 875 kilometres of pipeline connecting 25 chemical and petrochemical industries in the Rhine-Ruhr region already exists (Isting, 2012).

Hydrogen blending with natural gas:

With hydrogen blending, a portion of hydrogen is added to the total volume of gaseous energy carriers injected into the existing gas infrastructure. It's possible that the capacity of the gas infrastructure won't be significantly impacted by the different hydrogen blending levels, with the exception of the injected shares and the regions of application.

Hydrogen deblending form is the reversal of the hydrogen blending process, and it permits the separation of hydrogen for specific applications (such as hydrogen fuel cells or feedstock) and a relatively hydrogen-free natural gas. Multiple membrane plant configurations and hybrid approaches are employed for hydrogen deblending.

Apart from pipeline and blending transport options, hydrogen may also be carried via:

Marine terminals: Hydrogen may be imported/exported using sea-side terminals, which include LNG terminals that are specially designed for the purpose. Those terminals could be multifunctional, multi-energy carrier entry gateways for the EU by offering marine logistics, transport links, storage, pipeline connections, conversion, multimodal, and quality monitoring.

Hydrogen shipping is the delivery of hydrogen over long distances by ship in either liquid or gaseous form, or through liquid or gaseous hydrogen carriers.

Transporting hydrogen by rail: hydrogen can be transported:

- in gaseous form, the carriers employ compressed gas cylinders by tube trailers.
- for liquid hydrogen, a liquid is specialized in containers via liquid hydrogen carriers.

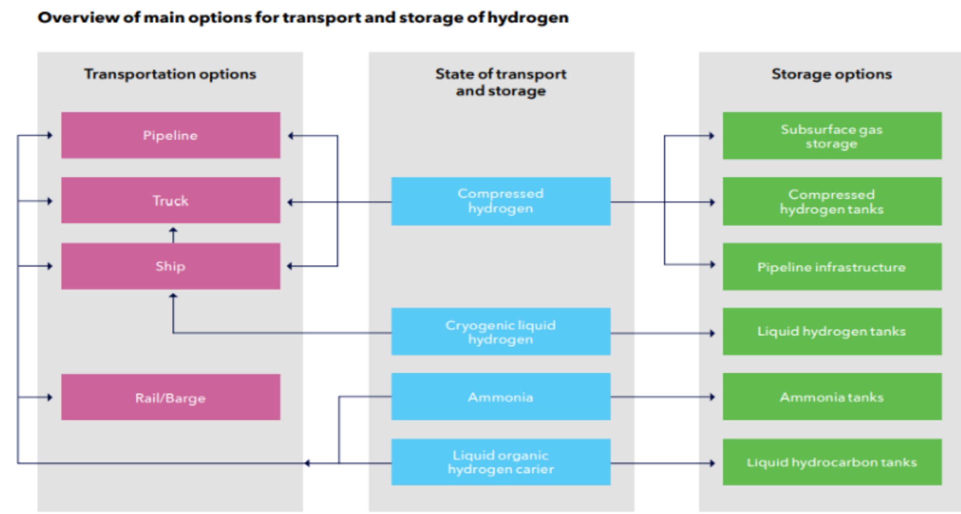

Figure 13: Overview of main options for transport and storage of hydrogen

2.6.4 Green Hydrogen propulsion technology

This part of the paper will discuss the maturity and application of energy conversion technology on inland ships, new projects in place, and, an overview of fuel cell and internal combustion systems for hydrogen fuel.

Both a fuel cell (with a motor drive) can be utilized to power a ship's propulsion with green hydrogen or the internal combustion engine (with a combination with a Genset or electrical motor). Both of these technologies have been developed and tested in inland transportation, and now, a large number of ferries and tugboats are employing them as their primary means of propulsion. When analyzing ICEs and FCs side by side, it is important to differentiate between mechanical and electrical energy. In contrast to fuel cells, which directly create electricity, internal combustion engines supply mechanical energy. The power that is utilized for propulsion is mechanical power, but the majority of auxiliary consumers require energy that is electrical in nature. When converting between these energy types, there are usually certain losses. Both liquid hydrogen and compressed gas hydrogen can be used in both technology ICE and FC. The below table 8 gives the details of projects which are using hydrogen as a fuel.

Project Name	Vessel type	Hydrogen method	Estimated date of completion	Company	Location	Source
ABB and CFT River Vessel	Cargo transport	LH_2 + fuel cells	2021	ABB, CFT, VTT, and Ballard Power Systems	Europe – France	Flagships (2021)
FreeCO2ast	Pax ferry	LH_2 + fuel cells	2022	Norwegian Electrical Systems, Havyard Design, Havila	Europe – Norway	Osnes (2021)
HydroBingo	Pax ferry	CH_2 + MGO in ICE	2021	CMB and TFC	Japan – Inland Sea	CMB Tech (2021)
Hydrocat	Crew transfer vessel	CH_2 + MGO in ICE	2022	CMB and Windcat Workboats	Europe – Netherlands	CMB Tech (2021)
Hydrogen-fueled demonstration ship	Inland river self-unloading ship	CH_2 + fuel cells	2021	The 605th Research Institute of Chinese State Shipbuilding Corporation	China – Guangdong Province	Fahnestock & Bingham (2021)
Hydrotug	Tugboat	CH_2 + MGO in ICE	2021	ABC and CMB	Europe – Port of Antwerp	CMB Tech (2021)
Hydroville	Passenger shuttle	CH_2 + MGO in ICE	2017	ABC and CMB	Europe – Port of Antwerp	CMB Tech (2021)
HySeas III	Ferry	CH_2 + fuel cells	2021	Ferguson Marine, Government of Scotland	Europe – Scotland	HySeas III Project (2019)
Norled Hydrogen Ferry	Passenger ferry	LH_2 + Fuel cells	2021	Norled, Westcon, Norwegian Public Roads Administration	Europe – Norway	FuelCellsWorks (2020)
NYK Hydrogen-Powered Ferry	Tour boat	H_2 + fuel cells	2024	NYK Line	Japan – Yokohama	Maritime Executive (2020)
NYK Super Eco Ship 2050	Vehicle carrier	LH_2 + fuel cells	Concept study	NYK Line	Japan	NYK Line (2016)
Topeka	Ro-Ro	LH_2 + fuel cells	2024	Wilhelmsen	Europe – Norway	Jiang (2020)
Ulstein SX190 Zero Emission DP2	Offshore support vessel	CH_2 + fuel cells	2022	Ulstein Design & Solutions BV and Nedstack	Europe – Norway	Ulstein (2021)
Water-Go-Round	Passenger ferry	CH_2 + fuel cells	2021	Golden Gate Zero Emission Marine, CARB, SWITCH Maritime	United States – California	Water-Go-Round (2021)
Yanmar EX38A	Fishing vessel	CH_2 + fuel cells	2021	Yanmar and Toyota	Japan – Kunisaki	Butler (2021)
ZeFF	Fast ferry	CH_2 + fuel cells	2020	Selfa Arctic, Norled, Hyon	Europe – Norway	Hyon (2019)

Table 8: Hydrogen-powered vessel projects

Hydrogen with fuel cell:

It is possible to incorporate fuel cell technology into the majority of existing ship designs. Hydrogen needs to be fed into fuel cells in order for ships to be powered. During this process, the energy contained inside the hydrogen is turned into electricity and heat energy, which in turn drives the ship's propulsion system. This technique, which is the inverse of electrolysis, has the potential to produce a constant flow of energy so long as the cell continues to be supplied with fuel. This is an advantage over batteries, which have to be recharged on a regular basis. Due to the fact that fuel cells don't provide enough mechanical energy for propulsion, they must be joint with a battery-powered motor. An efficiency of more than 60 percent has been established for fuel cells, and it is conceivable to achieve an efficiency of more than 80 percent under specific conditions. NOx emissions are reduced since high-temperature combustion is not required. Fuel cells produce little to no noise, contain no moving components, and can be stacked in any configuration, making them an excellent choice for powering bigger vessels. Fuel cell systems are highly scalable due to their modular design and consistent electrochemical performance. Fuel cells might be installed in the majority of ships in use today. There're various types of fuel cells available in the market, for shipping low and high-temperature fuel cells can be used. In case of low temperature, a proton exchange membrane fuel cell (PEMFC) seems to be the best choice to ship in wide uses. For high temperatures, PAFC, MFFC, and, SOFC are used. The technical aspect of all fuel cells is not covered in this paper and it is given in below table 9. The efficiency of a typical combustion-based power plant is around 33% to 35%, whereas fuel cell systems may achieve efficiencies of up to 60% or higher (U.S. Department of Energy, 2022).

Comparison of Fuel Cell Technologies

Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Electrical Efficiency (LHV)	Applications	Advantages	Challenges
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	<120°C	<1 kW - 100 kW	60% direct H_2;[i] 40% reformed fuel[ii]	• Backup power • Portable power • Distributed generation • Transportation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up and load following	• Expensive catalysts • Sensitive to fuel impurities
Alkaline (AFC)	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	<100°C	1 - 100 kW	60%[iii]	• Military • Space • Backup power • Transportation	• Wider range of stable materials allows lower cost components • Low temperature • Quick start-up	• Sensitive to CO_2 in fuel and air • Electrolyte management (aqueous) • Electrolyte conductivity (polymer)
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a porous matrix or imbibed in a polymer membrane	150 - 200°C	5 - 400 kW, 100 kW module (liquid PAFC); <10 kW (polymer membrane)	40%[iv]	• Distributed generation	• Suitable for CHP • Increased tolerance to fuel impurities	• Expensive catalysts • Long start-up time • Sulfur sensitivity
Molten Carbonate (MCFC)	Molten lithium, sodium, and/ or potassium carbonates, soaked in a porous matrix	600 - 700°C	300 kW - 3 MW, 300 kW module	50%[v]	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	500 - 1000°C	1 kW - 2 MW	60%[vi]	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Solid electrolyte • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Limited number of shutdowns

Table 9: Comparison of Fuel Cell Technologies

Hydrogen with Internal combustion engine:

Hydrogen is substituted for traditional fuel in the internal combustion engine's combustor. The engine is worked by injecting hydrogen into the cylinders, where it is burned to provide mechanical power that is sent to the shaft. Compressed hydrogen or liquid hydrogen can be utilized in this process. Internal combustion engines that run on hydrogen are larger in size because of the many adjustments necessary to operate them safely and efficiently. For the same reason, they are more expensive to produce than ICE vehicles that run on gasoline. Altering gasoline engines to function on hydrogen is another option. This makes them "hybrids" or "dual fuel," and they may take benefit of the existing gasoline infrastructure in addition to the hydrogen infrastructure (for fuelling) until the latter is firmly established. Most ships used on inland waterways nowadays are propelled by combustion engines. In addition to the novel design of engines specialized for hydrogen as fuel, numerous adjustments to the configuration of a combustion engine are necessary for hydrogen use.

2.7 Environmental feasibility

This section of the thesis will go into detail on the environmental acceptability or negative environmental impact of green hydrogen use as a maritime fuel in Europe, as well as the health risks associated with it.

2.7.1 Environmental assessment

This part of the paper is divided into two parts for clear analysis

1. Emissions or climate change assessment
2. Freshwater assessment for electrolysis

1. Emissions or climate change assessment

The positive impact of using green hydrogen for the zero-emission target is well understood but for future and long-run use of hydrogen, its negative impact needs to be comprehended. For that, a detailed study of the complete process of the production, distribution of fuel, and using the fuel is always required for a completely ecological and environmental assessment. For an accurate assessment of emissions, the whole well-to-wheel (WTW) process must be studied(figure 16). Well-to-wheel (WTW) of total green hydrogen utilization on the ship is separated into two parts: well-to-tank (WTT) process from fuel generation to ship and tank to wheel (TTW) process including fuel installation on ships. Because comprehensive wheel-to-ship data is unavailable, we will analyse the emission in three segments 1. Co2 emission from renewable energy resources, 2. Co2 emission from electrolysis, 3. Emission due to usage of green hydrogen as fuel on the ship. Emission during storage, transport, distribution, and bunkering is not considered due to the unavailability of data and multiple selection criteria are involved. As said earlier, for accurate prediction of environmental impact due to green hydrogen usage on the ship a detailed LCA approach is required and which is out of the scope of this paper.

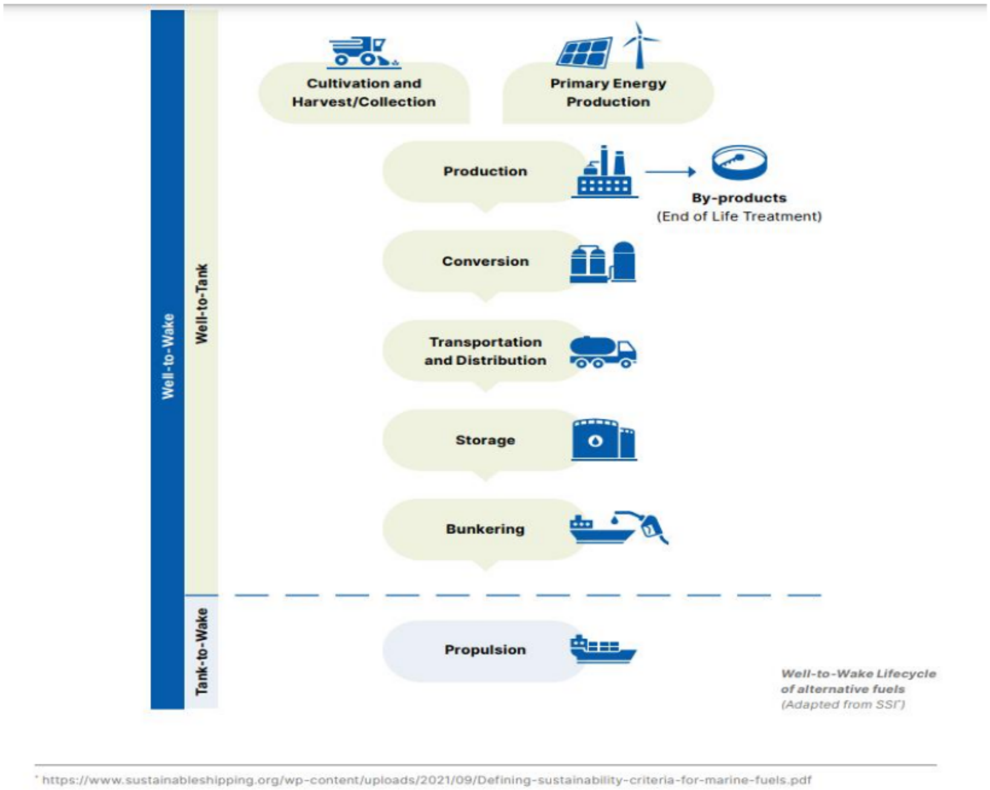

Figure 14: Well to wake Lifecycle of Alternative Fuels

Co2 emission from Renewable energy sources-

Renewable energy generates electricity sources ranging from 90-99% fewer greenhouse gases (GHGs) comparatively with the coal-fired plants and this produces 70-90% less pollution (Scandrett, 2017). As all the sources of electricity result in emissions of GHG over their lifetime, renewable energy sources contain fewer emissions than fossil fuel-fired power plants. Renewable energy sources work with emissions of about 50g or less of emissions of CO2 per kWh in their lifetime, comparatively with coal of 1000 g CO2/kWh and natural gas of 475 g CO2/kWh. Maximum of the entire emissions by the fossil generators occurs from the fuel combustion, and also come from the raw materials extraction, plant operation fuel processing, construction, and decommissioning of facilities.

Co2 emission from electrolysis-

Electrolysis fuelled by renewable energy or nuclear power can generate extremely low emissions. The CAPEX emissions are higher embedded for solar panels causing solar power to attain 1.0 kg CO2eq/kg H2 in 2030, whereas wind power only achieves 0.5 kg CO2eq/kg H2 (because of the global grid mix taken for the panel manufacture) (Brown, 2021). In fact, it is possible to reduce emissions even further to 0.3 kg CO2eq/kg H2 by electrolysis using run-of-river hydropower (Brown, 2021).

Emission due to green hydrogen from the ship*-*

The use of hydrogen in fuel cells produces no carbon emissions, just power, water, and heat. When hydrogen is burned in an internal combustion engine, no carbon emissions are produced, but NOx emissions are around six times higher than those produced by methane combustion. NOx could have major health consequences, such as asthma and a high risk of respiratory infections, all of that is harmful to the respiratory system. While there are solutions for reducing NOx emissions in gas power plants, those technologies are only effective at reducing NOx at a hydrogen mix of 30% or less.

Based on these three segments it is clear that the use of hydrogen as fuel in shipping on a larger scale will not have a negative emission impact on the environment other than improving the present emission condition.

Freshwater assessment for the green hydrogen production:

For an undisrupted supply of green hydrogen, it is crucial to assess the reliability or availability of raw materials required for green hydrogen and its impact on the environment. The raw material available for green hydrogen production is pure fresh water. The main question is, “are we going to harm the ecological surrounding with the green hydrogen approach in Europe?” Europe including the inland waterway region does have an ample amount of freshwater reserve for future green economy conversion.1 kilogram of hydrogen takes 8.92 litres of water based on the atomic characteristics of water. If the EU's Hydrogen Strategy's aim of 10 million tons (MT) of hydrogen production is met by 2030, electrolysis will need 89 million tons of water. This equates to 0.00478% of the EU's total yearly freshwater resources (Hydrogen Europe, 2020). When comparing water usage for electrolysis to other energy sources, many fossil-based methods have a higher water footprint than hydrogen. Per unit of energy, crude oil recovery and diesel refining utilize around 40% more water than green hydrogen synthesis (Hydrogen Europe, 2020). Water for large-scale electrolysis may be obtained from any water resource (seawater, wastewater, etc.) once it has been demineralized using reverse osmosis (RO) plants. Continuous development of adjacent water desalination facilities, various ways of low-grade and saline surface water electrolysis, and water distribution through wastewater treatment plants demonstrate their practicality and cost-effectiveness (Hydrogen Europe, 2020).

2.7.2 Health Impact

NO fuel is 100 % safe, and with limited contact, hydrogen doesn't possess any major threats to health. Hydrogen is the universe's most plentiful element. On Earth, it's usually found in water (H2O). Hydrogen gas is flammable due to its basic chemical structure. It's also non-toxic, odourless, tasteless, and light. For proper health impact assessment Hydrogen's safety must be compared to gasoline, propane, and diesel. Green hydrogen is safer than traditional fuels in many ways. Unlike traditional fuels, hydrogen is nontoxic. Many traditional fuels are hazardous or contain carcinogens. Hydrogen-powered ships with fuel cells create just water, while traditional fuels cause air pollution. Hydrogen leaks or spills won't poison the environment or harm humans or wildlife, but fossil fuels may.

Despite not being hazardous, hydrogen is a flammable gas because of its fast flame velocity, wide ignition range, and low ignition energy. This is partially offset by the fact that it dissipates fast due to its high buoyancy and diffusivity. It is tougher for people to notice fires and leaks since it has a flame that cannot be seen with the unaided eye and is colourless and odourless. Hydrogen has been used in industry for many years, notably in massive, specialized distribution pipes. Similar locations already have safe handling procedures in place, and site-specific hydrogen refuelling infrastructure also has these procedures. Utilization on a large scale in the energy system would present additional obstacles. They would require additional development and the alleviation of any public worries.

2.8 Social feasibility

This portion of the study will explore how technological advancements in hydrogen safety have enabled its global adoption. Furthermore, the section will go into depth on the legal structure that exists in shipping for the work of hydrogen as fuel.

2.8.1 Hydrogen safety

Creating a reliable hydrogen system is the primary technological obstacle. Hydrogen is generally safer for the environment than other fuels, but it still presents safety concerns when being used in a system due to its flammability, buoyancy, and ability to embitter metals, all of which must be managed via engineering (Gexcon.com, 2022). These difficulties are confronted not only by facilities managing hydrogen operations but also by vendors of equipment utilized in a safe hydrogen system (Gexcon.com, 2022). Rapid innovation in new technology, spurred by the launch of several new hydrogen projects throughout the world, can bring its own set of challenges (Gexcon.com, 2022). It is required that the hydrogen-powered ship crew is guided on maintaining a hydrogen system on the wheel to manage fire safety.

As per the DNV hydrogen report 2022, investor's and developer's safety concerns pose a serious threat to their bottom line. Despite the rapid development of technology in this industry, few accidents have occurred on ships and hydrogen plants. For decades, the industry has relied on tried and tested methods for regulating the safety of flammable gases, and those approaches come with hard-earned lessons. Firstly, understanding how the specific properties of hydrogen and hydrogen derivatives influence potential hazards is critical for guaranteeing safety. Second, it is significantly more beneficial (in terms of both safety and cost) to incorporate suitable risk-reduction strategies early in the design stage. Finally, the design goal must be maintained over the whole life cycle: safety measures must not deteriorate. All of this requires an understanding of the key properties of hydrogen (and its derivatives) that define the hazards. Because hydrogen and its derivatives are essentially distinct, we must consider them separately.

Based on the properties of green hydrogen, Safety standards must be thoroughly addressed throughout the design and construction of hydrogen systems for inland ships. The below tables shows a few natural tendencies (propensity) of green hydrogen in addition to caustic embrittlement.

Propensity to leak	Propensity to ignite	A consequence of fire/explosion
Low viscosity	High flammable range	Invisible flame
Extremely high diffusivity	The very low ignition point	Rapid burning rate
High buoyancy	Spontaneous ignition	Possibility of detonation

Table 10: Few natural tendencies (propensity) of green hydrogen

On board the ship the following consideration is to be made while using a hydrogen system:

- Highly flammable range & Invisible flame-At concentrations ranging from 4% to 75%, hydrogen is extremely flammable. This indicates that a little spark is all that is required to ignite a small quantity of hydrogen in the air. Hydrogen fires just like hydrogen gas leaks are difficult to detect (Webster, 2021). The flame is essentially invisible, creates little smoke, and releases minimal radiant heat, so unless you are extremely close to it, you may not see or even feel the heat from a hydrogen fire (Webster, 2021). As a result, sensors like thermal imaging cameras are critical for fire monitoring (Webster, 2021).
- Low viscosity-Due to hydrogen gas consisting of low viscosity, it becomes extremely hard for keeping the hydrogen systems to be leaked. To reduce potential leak spots, pipe and tubing systems should have as few joints as feasible, and all components must be rated for hydrogen service and the process's unique operating conditions (Webster, 2021).
- Extremely high diffusivity and high bouncy-As the lightest molecule in the universe, hydrogen rises swiftly when it leaks. Outdoors, dissipate quickly, reducing the risk of fire. However, when hydrogen leaks indoors, it rises to the ceiling and tends to collect in small pockets (Webster, 2021). The combustible gas won't be exposed to workers on the ground, but this might still result in fires or explosions, and again, it's easy to overlook these pockets of invisible gas. To avoid this risk, proper ventilation system design is essential on board (Webster, 2021).
- Low ignition point-The gas system must be separated from areas where a hazardous atmosphere can occur. On gas detection, the installed auto ignition control system shuts down potential ignition sources. This is often done on electrical and other systems that do not need to be operational during an emergency.
- Arrangement for the safe venting of gas
- Protection of high-pressure hydrogen vessel -The storage vessel should be installed with safety valves and molten plugs in order to avoid its rupture during the excess pressure build-up.
- Gas detection and alarms system
- Approved Fire detection and extinguishing system should be installed on the ships

So, in terms of hydrogen system safety, technical growth in the sector has prepared it for future problems.

2.8.2 Legal framework

This chapter focuses on the legal framework for fuel cell installation and hydrogen tanks on ships. This chapter starts with a brief overview of IWT emission requirements, followed by restrictions for the requirement of fuel cells in ships and then the standards for hydrogen storage are listed.

The legal framework is the backbone for the safety of ships, it provides standards for construction, equipment type, operational guidelines, and everything related to safety. The legal framework required for the successful implementation of green hydrogen as fuel in inland waterways is already developed, monitored, and continuously evaluated by the national and international regulatory bodies in Europe. Regulatory bodies Such as the EU Commission, classification societies, the central commission for navigating in the Rhine (CCNR), CESN, European Standard downing with the requirements of technicalities for the Inland Navigation vessels (ES-TRIN - 2019/1), EU directive 2006/87 EC, ISO, International Electro technical Commission IEC, and EMSA (IVR, 2022). The European Committee does not undertake installation of fuel cells for the Development of Common Standards in the Field of Inland Navigation (CESNI) in their present regulations of European Standard setting downwards with the Technical Requirements for Inland Navigation Vessels (ES-TRIN - 2019/1) (IVR, 2022). Green Hydrogen as a maritime fuel appears feasible with such regulatory and standard specifications.

Regulation on emission from inland ship's engine:

The IWT emission standards come in stages I and II of CCNR(table 11,12) also, as per recently issued EU Regulation 2016/1628 on "'Requirements pertaining for the particulate pollutant and gaseous emission limitations. The different certifications for its internal combustion engines and the non-road mobile machinery (IVR, 2022). The following engines have been designed and delivered in inland navigation over the years that satisfied the various emission requirements:

• Pre-CCR engines from before 2002.

• CCR1 engines, installed between 2002 and 2007.

• CCRII engines were deployed, between 2007 and 2020.

• Stage-V engines, delivered after January 1, 2020.

CCNR Stage I (Directive 97/68/EC)					
Emission stage	**Power range**	**CO**	**HC**	**NOX**	**PM mass**
	KW	g/kWh	g/kWh	g/kWh	g/kWh
Stage I	37 ≤ P < 75	6.5	1.3	9.2	0.85
Stage I	75 ≤ P < 130	5	1.3	9.2	0.7
Stage I	P > 130 and 500 1/min < n < 2800 1/min	5	1.3	$45 \bullet n^{(-0.2)}$	0.54
Stage I	P > 130 and n > 2800 1/min	5	1.3	9.2	0.54

Table 11: CCNR stage 1

CCNR Stage II (Directive 2004/26/EG)					
Emission stage	**Power range**	**CO**	**HC**	**NOX**	**PM mass**
	KW	g/kWh	g/kWh	g/kWh	g/kWh
Stage II	18 ≤ P < 37	5.5	1.3	9.2	0.85
Stage II	37 ≤ P < 75	5	1.3	9.2	0.7
Stage II	75 ≤ P < 130	5	1.3	$45 \bullet n^{(-0.2)}$	0.54
Stage II	130 ≤ P < 560	3.5	1.3	9.2	0.54
Stage II	P > 560 and n < 3430 1/min	3.5	1.3	$45 \bullet n^{(-0.2)}$	0.54
Stage II	P > 560 and 343 ≤ n < 3150 1/min	3.5	1.3	$45 \bullet n^{(-0.2)}$	0.54
Stage II	P > 560 and n ≥ 3150 1/min	3.5	1.3	$45 \bullet n^{(-0.2)}$	0.54

Table 12: CCNR stage 2

Rules for fuel cells in shipping:

Major classification societies have already published their class rules on fuel cell technology implementation on board the ship. Below are a few documents related to it?

Classification society	Title of document
Det Norske Veritas (DNV)	Guidelines for the Use of Fuel Cell Systems on Board of Ships and Boats
Indian registrar of shipping (IRS)	Vessels with Fuel Cell Power Installations
Lloyds Register (LR)	LR Technical Papers: Development of requirements for Fuel cells in the marine environment – Performance and prescription

Bureau Veritas (BV)	(BV) Guidelines for Fuel cell Systems On-board Commercial Ships
ABS	Fuel Cell Power Systems for Marine and Offshore Applications
China classification society	Guidelines for the application of fuel cell power system

Table 13: Class Rules on Fuel Technology

General international standards in the fuel cells and hydrogen storage: The report of EMSA provides a summary of global FC standards like those employed by the IEC and the International Organization of Standardization ISO. EMSA research also provides a synopsis of the storage of hydrogen. The most crucial are as follows

Standards
IEC 62282-1:2012 Terminology
IEC 62282-2:2012 Fuel cell modules
IEC 62282-3-100:2012 Stationary fuel cell power systems – Safety
IEC 62282-3-200:2015 Stationary fuel cell power systems - Performance test methods
IEC 62282-3-300:2012 Stationary fuel cell power systems – Installations
IEC 62282-7-1:2010 Single cell test methods for polymer electrolyte fuel cell (PEFC)
IEC 62282-7-2:2014 Single cell and stack performance tests for solid oxide fuel cells (SOFC)
ISO 14687-3:2014 Proton exchange membrane (PEM) fuel cell applications for stationary appliance
ISO 16110-1:2007 Hydrogen generators using fuel processing technologies – Safety
ISOTR15916 Basis considerations for the safety of hydrogen systems
Compressed gas hydrogen storage
ISO 15399 Gaseous Hydrogen - Cylinders and tubes for stationary storage.
Liquid hydrogen storage IGF Code/IGC Code
ISO/TC 220
ISO 26142:2010 for leak detection
ISO 15649:2001 Hydrogen piping network

Table 14: Standards in the Fuel cells and Hydrogen Storage

2.9 driver or barrier in using green hydrogen in maritime application

In the past, there were various waves of collective interest in hydrogen. These were due to shocks in oil price, fears for the peak oil demand, and the study into alternate fuels (IRENA, 2021). Hydrogen can contribute to energy security by offering an additional energy carrier and distinct supply chains, so diversifying the energy mix and enhancing the resilience of the system. Hydrogen can lessen air pollution when utilized in fuel cells, which emit only water (IRENA, 2021). With the huge investment required for generating hydrogen as the energy carrier from the industrial feedstocks, its adoption is conducive to economic growth and employment creation (IRENA, 2021). As a result, green hydrogen is gaining prominence in an increasing number of energy scenarios, but at drastically varying penetration rates (IRENA, 2021). The current wave of interest focuses on providing solutions for low-carbon and extra advantages which only can be supplied by green hydrogen.

2.9.1 The drivers for green hydrogen include:

1. Low solar and wind electricity costs. The price of electricity is the biggest factor in the entire cost of producing green hydrogen. During the past decade, the cost of power generated by renewable sources like solar photovoltaic panels and onshore wind turbines has dropped dramatically (IRENA, 2021). In the year 2018, the average price for solar energy globally contracts was USD 56/MWh, lower than USD 250/MWh in the year 2018 (IRENA, 2021). During that time, the price of onshore wind energy decreased from $75/MWh in the year 2010 to $48/MWh in the year 2018(IRENA, 2019).

2. Technologies ready for scale-up. Maximum parts of the hydrogen value chain are tested at low volumes and are now ready for commercialization; all that is needed is capital to bring them to market on a larger scale. Since 2010 (Hydrogen Council, 2020), the capital cost of the electrolysis was decreased by 60%, bringing prices of hydrogen down from USD 10-15/kg to USD 4-6/kg. There are a variety of approaches that may be taken to further reduce costs and encourage the widespread adoption of hydrogen (IRENA, 2020d). In-vehicle fuel cell prices have dropped by at least 70% since 2006 (IRENA, 2021).

3. Benefits for the power system: The power system will require more adaptability as a percentage of wind and solar power, also known as VRE (variable renewable energy), quickly grows in different markets of the world (IRENA, 2021). Long-term storage of green hydrogen allows for its usage in the generation of power using hydrogen-ready gas turbines or stationary fuel cells at times when VRE is not accessible. Hydrogen, in conjunction with pumped-storage hydropower facilities, may now be used for seasonal, long-term energy storage (IRENA, 2021). Because of this, green hydrogen allows for a greater proportion of VRE to be included in the grid, which improves the efficacy and efficiency of the system overall (IRENA, 2021).

4. Government aims to create a net zero energy system. By mid of 2020, there were 7 nations enacted legislation setting NetZero GHG emission objectives, while 15 more had submitted comparable legislation or policy statements (IRENA,2021). 120 nations or more have declared net-zero emission targets (WEF, 2020).

5. Broader use of hydrogen. Earlier waves of interest in hydrogen were working on increasing its usage in fuel-cell electric cars (FCEVs) (IRENA, 2021). The current interest encompasses a wide range of potential green hydrogen applications globally, including the conversion of hydrogen into other energy carriers and products such as ammonia, synthetic liquids, and methanol (IRENA, 2021). Those applications can boost upcoming hydrogen demand by the use of potential synergies for reducing the costs in the green hydrogen value chain.

6. Interest of multiple stakeholders. Resulting of the above points, the interest of both public and private entities in hydrogen has grown (IRENA, 2021). These consist of steel manufacturers, chemical firms, energy utilities, port authorities, vehicle and airlines, aircraft manufacturers, ship-owners, as well as different jurisdictions and nations looking to export renewable energy or utilize hydrogen to better their own energy security (IRENA, 2021).

2.9.2 The barriers to green hydrogen include:

Certain barriers are applicable to all hydrogen colors. One is a scarcity of specialized infrastructure (e.g., storage facilities and transport) (IRENA, 2021). Others are mostly related with the electrolysis stage of the green hydrogen generation (for example. a lack of value recognition, energy losses, issues assuring sustainability, and high production costs) (IRENA, 2021).

1. High production cost. Green hydrogen is generated in the year 2019 with energy from a usual VRE plant to be two to three times more expensive than grey hydrogen (IRENA, 2021). Furthermore, for end users deploying the green hydrogen technology was costly. The ships equipped with fuel cells and hydrogen tanks are very expensive than their counterparts in fossil fuel.

2. Lack of dedicated infrastructure. Too far, hydrogen had been generated closer to where it is utilized, and minimal dedicated transportation infrastructure. Around 5000 km of hydrogen transmission pipes exist globally (Hydrogen Analysis Resource Centre, 2016). Natural gas infrastructure might be converted to hydrogen infrastructure (RENA, 2020). Synthetic fuels created from green hydrogen, on the other hand, may be able to utilize current infrastructure, though it may need to be extended (IRENA, 2021).

3. Energy loss. At each level of the value chain, green hydrogen incurs severe energy losses. Approximately 30- of the energy utilized 35% for making hydrogen via electrolysis is lost (IRENA, 2020). Furthermore, conversion of hydrogen to other carriers (like ammonia) can be resulted loss of 13-25% energy, and transporting hydrogen necessitates a surplus of energy inputs that are equivalent to 10-12% of the hydrogen energy itself (IRENA, 2021). Using hydrogen in fuel cells might result in an energy loss of 40-50% (IRENA, 2021). The entire energy loss shall be determined by the ultimate application of hydrogen. The greater the energy losses, the greater the demand for renewable power generation to make green hydrogen (IRENA, 2021).

4. Lack of value recognition. There are no green steels, no green hydrogen markets, and no way for valuing the reduced GHG emissions that green hydrogen could provide (IRENA, 2021). Hydrogen is not included in energy statistics of official final energy consumption, and no globally recognized methods for distinguishing between green and grey hydrogen (IRENA, 2021). Also, the absence of objectives or incentives for encouraging the use of green goods precludes maximum the potential downstream applications for green hydrogen (IRENA, 2021). This reduces the need for green hydrogen.

5. Need to ensure sustainability. A renewable energy plant can provide electricity, from the grid, or from a combination of those two. A renewable energy plant use power to assure that the hydrogen is always "green". Grid-connected electrolysers can generate for longer periods of time, lowering hydrogen costs (IRENA, 2021). However, grid power may contain electricity generated by fossil fuel facilities, thus any CO2 emissions related to that electricity must be considered when assessing the sustainability of hydrogen (IRENA, 2021). Resulting in the electrolysis of hydrogen generators, for amounting the fossil fuel-generated energy in becoming a hurdle, especially if the relative carbon emissions are calculated by using national emission factors (IRENA, 2021).

2.10 Interim conclusion of Literature review

In the preceding literature study, a full analysis and discussion of the diverse perspectives on the viability of using green hydrogen as a marine fuel in European inland commerce are provided. The above literature review has answered part of the main research question and few sub research questions. The result indicates that the structure, technology, and Regulation for the deployment of green hydrogen as ship propulsion fuel are now in place. For greater efficiency and fewer incidents/accidents on board the ship, however, further development, monitoring, and ongoing system upgrades are necessary. It will take the appropriate amount of time for hydrogen fuel to be completely acknowledged as a universal marine fuel aboard ships. For Europe's emission and hydrogen economy goals, the expansion of the green hydrogen industry must be accelerated. With future improvements related to green hydrogen fuel in Fuel cell and Electrolyzer technologies; storage, bunkering and pipeline system; safety standards and regulation; and onboard personnel training, the scale-up of green hydrogen as a marine fuel and attainment of the emission target appear feasible. The financial element of the propulsion system is another key consideration for the effective adoption of any alternative fuel in the maritime industry. Unless the system is commercially feasible, ship owners/organizations/government will be hesitant to include it into their supply chain. The next chapter will consist of a detailed financial analysis and evaluation of various propulsion systems associated with the selected case study vessel. Therefore, the literature review will conclude with Section 2.11, "Choice of Measurements for Economic Feasibility," and the results of this section will be used in chapter 3 for complete assessment of the case study ship propulsion system and can used to answer the main research question

2.11 Choice of measurement for economic feasibility

The preceding section of the literature study has gone into great length about the technical, environmental, and social viability of using green hydrogen fuel in inland transport in Europe. All elements of green hydrogen fuel systems are still being explored; it will take time and improvement in green hydrogen technology for global acceptability in shipping. However, for a green hydrogen propulsion system on a ship, it is crucial to assess it from a financial perspective. This part of the paper discusses the last part of the research question which is the economic feasibility of hydrogen fuel in inland shipping. For that the choice of the measurement for the economic analysis is important. Assessment and applicability of the two financial measurements—Net present value model (NPV) and the Real option are (ROA)—used for determining the proposed financial viability of new ship investment. The chosen measurement will be used in the later chapter for further analysis.

Brief detail about the case study: In a commercial ship without a propulsion system, there are five propulsion options available (LH2-PEMFC, CGH2-PEMFC, LH2-ICE, CGH2-ICE, and LSFO-ICE) with two different scenarios of investment in 2022 and 2030. The chosen model will be used for financial analysis by comparing the result of each scenario based on the Capex of the propulsion system, carbon tax, subsidies, fuel price, cost of the fuel cell, and replacement of PEM cost and fuel cell after-life cycle and other cash outflows. **There are a few assumptions for this analysis such as:**

- Total cash inflow is the same for all cases, Same cash inflow for each case at different years (inland transport performance is same for each case at different years)
- No additional risks involved or low uncertainty investment (no War, no financial crisis, no unexpected loss or gain in revenue, limited volatility in freight rates, no accidents or major incidents, no takeover of the company, change of ownership of the vessel, Project will commence immediately and proceed until it finishes, resources for fuel is available, growing economy, the same number of member state involved till the complete project life, a full corporation in the usage of inland waters and etc.)
- No deferral or cancelling option (Based on the business model of the company, the Ship's owner is certain to buy a commercial ship. There is no option of backing out from the investment).
- No opportunities to exploit in between the scenario date (Investment is either in 2022 or 2030)
- The hydrogen economy in Europe is realistic and hydrogen technology including renewable energy source (RES) and electrolyser are fully developed or evolving
- Less flexibility
- Mandatory Enforcement of carbon tax on the shipping company
- Once a decision is made about the type of propulsion, the ship-owner cannot change it
- No additional cost involved

Statement: For this case study, an assumption is necessary to limit the boundaries or scope of the investigation. In reality, there are several uncertainties with the project investment, and it is hard to account for all of them in a single study; therefore, the conclusion is never completely correct. On contrary, True analysis can only be performed by including as many variables or uncertainties as feasible, however, this would be considered an extensive and specific research topic that is beyond the scope of this study. The author is attempting to analyse the base condition for hydrogen investment by restricting the range of the study by assumptions. The objective of this study is not to maximize ship-owner profit by accounting for all sorts of uncertainty, or to provide maximum flexibility options for managers/ship-owners, or to provide alternatives for reacting to future possibilities accessible over the course of the project. The goal of the analysis is to determine the economic feasibility of using hydrogen as fuel in inland shipping through the propulsion options and scenario presented.

Net present value (NPV): NPV is the variation in current cash inflows value and cash outflows value over a duration of time. NPV is required in capital budgeting and for investment planning to analyse the profitability of the projected investment (Fernando, 2022).

For a project that requires a long duration with various cash flows, the NPV formula of a project is as follows (Fernando, 2022):

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t}$$

Where:

Rt=net cash inflow-outflows during a single period

ti=discount rate or return that could be earned in alternative investments

t=number of times periods

Because of its ability to consider the passage of time, net present value (NPV) is a useful tool for comparing the returns on various projects or for determining if a proposed return rate is sufficient to clear a certain investment threshold. The discount rate in the NPV calculation represents the time value of money and might serve as a project hurdle rate depending on the capital cost of the company. A negative NPV indicates that the predicted rate of return will be lower than the discount rate, and hence the project will not generate value.

The technique of traditional NPV stated that a project starts immediately and until completed, it keeps going as expected. It implies as a result that the decision is taken now or never and that once made, no alteration can be done. Failure in recognizing the maximum investment evaluation is flexible and can serve the managers with an option of actions to pursue.

How valuable an investment, project, or set of cash flows may be calculated with the use of NPV analysis? It's a comprehensive measure since it considers the investment's FCF with its income, expenditures, and capital costs (FCF).

Real options analysis (ROA): An ROA is an economically valuable right for making or for abandoning the managers of a company, often concerned with business projects or investment opportunities (HAYES, 2022). The company's actual options provide itself the option for providing to change, expand or curtail the projects which are based on changing economic, or market conditions or technology (HAYES, 2022)

A value estimated by the real options is for choices and flexibility with managers for deciding and undertaking the project. NPV with real options provides situations of uncertainty that exist like 1. Decisions don't be taken immediately or never basis and can be delayed, 2. Decisions can be changed when required. 3. Future contingent opportunities can be undertaken in the project (ACCA, 2022). Hence, the organization with flexibility in the decisions made or future decisions comes with the options for altering the decision in the firm value (ACCA, 2022).

The traditional NPV accounts come with risks and uncertainties in the projects as they consist of capital cost through assigning profitability in discrete and their outcomes and considering sensitivity analysis. There's a risk and opportunities structure viewed as the opportunities with an organization that come with negative consequences to be overlooked. The real options approaches are considered with the amount of available time until the choice can be taken and the risks and uncertainties of projects can be analyzed. This shall help its parameters for calculating its incremental value in the project.

Today's world is full of unpredictability and competitiveness which provides a complex and strategic investment decision-making environment for growing in that environment. The cash flow analysis has a dominant discounted structure about the cash inflows. But in the uncertainty of the traditional DCF approaches, it has been proven less applicable in providing strategic decision support. This situation consists of the new methods for the evaluation of investment. The ROA has shown the potential valuation of the strategic corporate investment decisions and its managerial flexibility for high uncertainty situations. Under the ROA framework, the projects are open and there are options for the frequent use of financial options by the pricing techniques. This framework is useful for the owners in keeping the investment options available and benefiting the upside potential by providing an opportunity for controlling the downside risk.

So, NPV models work best when there is less investment risk and uncertainties. ROA model is best suited for thorough analysis including alternatives, uncertainty, risks, and investment flexibility. According to our thesis statement requirement and assumption above, NPV analysis is highly suitable.

Chapter3.METHOD AND SCENARIO DEVELOPMENT

3.1Introduction

This section of the article will go through the methodology for properly assessing the financial viability of green hydrogen in inland shipping. **A real-world case study is presented in which liquid green hydrogen is employed as a ship fuel, but it is important to note that the case study ship (energy observer 2) is still in the shipyard, it will be delivered and put to use by next year 2023**. We will test hypotheses of alternative propulsion options for the given case study ship with the same power need. The net present value will be the financial evaluation tool used to analyse the overall investment cost for two alternative scenarios, 2022 and 2030, for different propulsion options. As Europe strives for zero-carbon emissions in the transportation sector, we have emphasized in previous chapters the need to select a zero-carbon fuel such as green hydrogen as one of the feasible possibilities. Other choices, such as carbon taxes, subsidies, government support programs, and government funding for renewable energy, will also be crucial in meeting the 2050 objective. In this financial study, we will look at carbon taxes and subsidies for different hydrogen energy carriers. Although shipping and aviation have always been exempt from carbon tax restrictions, the European Commission made it clear in July 2021 that this would likely change, and a carbon price would be adopted. The European Union has made efforts to reduce carbon emissions from ships. The European Union (EU) unveiled its "Fit for 55" package in July 2021, which details a strategy to cut emissions throughout the union beginning in 2023. A carbon tax on emissions from ships is one of the measures proposed by the Fit for 55 plans. After the package's implementation, all ships flying any flag will need to buy carbon permits to cover their whole emissions output during EU journeys and for 50% of their worldwide emissions output if their journey begins or ends in an EU port (Loftis et al., 2022).

The comparison of the potential cost of building and operating a green hydrogen-powered (liquid hydrogen (LH2) or compressed hydrogen gas (CGH2)) commercial ship with a PEM fuel cell or internal combustion propulsion option as opposed to a traditional VLSFO-powered commercial ship is estimated to demonstrate the economic limitations and viability. Also, the prospects of green hydrogen in this inland waterway transport sector are being broadly evaluated. Net present value is determined for two scenarios: 2022 and 2030. Starting conditions are the same in each scenario: a brand-new commercial ship is without its propulsion equipment. In each scenario, the five-propulsion option for the given ship is considered, and the total cost incurred throughout the project life is calculated and compared. We have already discussed in the literature review how these different propulsion options are feasible and complimented by current technological advancements in the shipping industry. The five scenarios are as follows:

- LH2-PEMFC (liquid green hydrogen with a PEM fuel cell)
- CGH2-PEMFC (compressed gas green hydrogen with a PEM fuel cell)
- LH2-ICE (liquid green hydrogen with an internal combustion engine)
- CGH2-ICE (compressed green hydrogen with an internal combustion engine)
- LSFO-ICE (marine gas oil with an internal combustion engine)

For detailed illustration, a French commercial demonstrator ship is chosen that travels between the ports of Rotterdam (Netherlands) and Strasbourg (France). Since the paper is based on inland shipping in Europe, this particular route has been selected with frequent port calls throughout the project life. Europe has been a hub for hydrogen production. France and the Netherlands are the leading countries in contributing the share of green hydrogen production towards different sectors. This opens the door to the use of alternative fuels for specialized energy convertors such as PEM fuel cells and internal combustion engines, and it also makes it possible to concentrate fuel production at a single port.

The purpose of this thesis is to examine and contrast these investments in order to draw a conclusion on the present and future competitive viability of hydrogen with different energy convertors for inland ships in Europe. Furthermore, for investment calculation estimation for each scenario, subsidies for the installation of PEM fuel cells and CO2 taxation on fossil fuels are considered.

Different variables and estimations from the literature will be used to create a pessimistic, optimistic, and baseline scenario. Through this medium, a picture will be painted of this technology's potential to compete with traditional solutions in the not-too-distant future. Also, it could be decided if the current level of government help in the form of taxes and subsidies is enough to use this technology as a possible way to make inland shipping free of carbon emissions.

3.2 Ship technical specification

Ships dimension

As a case study, this thesis will examine the commercial ship that operates between the ports of Rotterdam (the Netherlands) and Strasbourg (France). The two primary justifications for this decision are:

1. The EU's hydrogen plan from last July has specific goals: 6GW electrolysers by 2024, and 40GW by 2030. Netherlands and France are green hydrogen hubs besides Germany. Hydrogen is abundant and cheap in these countries.

France-Till 2028, France aims to produce 0.4 Mt/year of low-carbon hydrogen. The government also plans to construct 6.5 GW of renewable hydrogen electrolysis by 2030. (RVO, 2022). Between 2020 and 2023, € 650 million are committed to a method to stimulate the production of carbon-free hydrogen through enhanced remuneration. The French government plans to bring 8.75 GW of the offshore wind online by 2028, up from 4.7 GW-5.2 GW (RVO, 2022). France will be Europe's fourth-largest offshore wind power generator by 2030, with 7.4 GW of capacity (RVO, 2022). Total and Engine will design, develop, build, and manage the Masshylia project in Châteauneuf-les-Martigues, Provence-Alpes-Côte d'Azur South (Buljan, 2022). The 40 MW electrolyser will create 5 tonnes of green hydrogen per day to suit the demands of Total's La Mède biorefinery, eliminating 15,000 tonnes of CO2 emissions per year. Lhyfe and Chantiers de l'Atlantique signed a MoU on offshore hydrogen production platforms (Buljan, 2022).

Netherlands- Europe's second-largest hydrogen production is the Netherlands (after Germany) (Nicholls-Lee, 2022). The government has vowed to increase the country's wind energy capacity, while the EU has subsidized Heavenn, a network of hydrogen projects in the north slated to be completed in 2026 (Nicholls-Lee, 2022). The Dutch Hydrogen Strategy (2020) calls for electrolyser capacity to expand from 0.5 to 3-4 gigawatts by 2030 (Nicholls-Lee, 2022). Network Services is building a "hydrogen backbone" to connect industrial clusters in five key locations: Chemelot in Limburg, the North Sea Port in Zeeland, the North Sea Canal, the Hydrogen Hub in Rotterdam, and the northern Netherlands, where Hydrogen Valley is being constructed (Nicholls-Lee, 2022). Dutch North Sea may install 11 GW of offshore wind capacity by 2030, with room for 20-40 GW more.

2.The French firm Energy Observer has introduced plans for a hydrogen-powered, multipurpose cargo ship (Energy Observer 2). Recent generations of commercially available fuel cells, global deployment of liquefiers and the mastery of liquid hydrogen storage mark the technological maturity of these systems. The corporation collaborates with a number of other entities to bring about the new ship design. Air Liquid is participating due to its expertise in the field of liquid hydrogen production, storage, distribution, and safety. Energy Observers collaborates with the CMA CGM Group to assess the economic and operational factors of this next-generation cargo ship. The Energy Observer 2 will have a range of up to 4,000 nautical miles owing to its commercial speed of 12kts, 2.5MW Fuel cell system (PEMFC) with an additional electric propulsion system of 4MW and 1,000m3 liquid hydrogen tanks (Prevljak, 2022). The Energy Observer 2 will have a cutting-edge sailing system designed by Ayro in addition to its electric propulsion and hydrogen fuel cell technology. The Table 15 below provides technical information on the vessel utilized for the calculations, and the Figure17 provides an idea of the vessel.

The main features of Energy Observer 2 are:
Length: 120 meters
Width: 22 meters
Draft: 5,5 meters
The surface of the wings: 1450 m^2
Deadweight: 5,000 tons
Containers: 240 TEU
RoRo bridge: 480 linear meters (trucks, vehicles, and containers)
Tween deck height: 6.5 meters
Access ramp: 15 meters wide
Commercial speed: 12 knots
Electric propulsion: 4 MW
Fuel cell power (RexH2 EODev): 2.5 MW
Liquid hydrogen tanks (LH2): 70 tons (1000 m3)
Range: up to 4,000 nautical miles.

Table 15: Features of Energy Observer 2

Figure 15:Energy observer 2

Sailing route

Distance between Rotterdam (the Netherlands) and Strasbourg (France) is 298 nautical miles (551.89 kilometres) as per ports.com, 2022. When traveling at a cruising speed of 12 knots (22.22 km/h), the multipurpose cargo ship completes the round journey in 60 hours with a total distance of 1103.78 km. This led to the conclusion that a round journey requires 48.00 hours of sailing time and 12.00 hours of rest time (including loading and unloading). Total number of round trips in a year is assumed to be 120 due to breakdown, uncertainties and dry-dock. The one way route of the energy observer 2 is given below (Ports.com, 2022,figure 18):

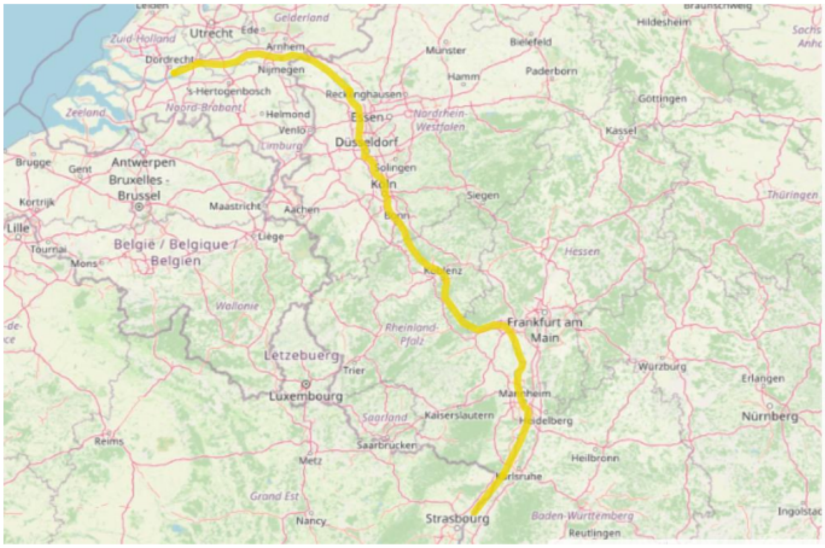

Figure 16:Inland waterway route from rotterdam to strasbourg

3.3 Net present value calculations

The cash flows are assumed to be accurate for a period of 18 years because research revealed that this is the typical lifespan of a commercial ship before significant upgrades are required (Dinu & Ilie, 2015). As a result, the assumption was made that the ship's components all have a minimum lifespan of 18 years. A PEM fuel cell, on the other hand, has a lifespan of around 40,000 working hours, which is equivalent to six years for an inland vessel operating for 6000 hrs per year (NEDSTACK 2022, n.d.).

The discount rate that is being utilized is 10%, which falls within a range that is comparable to the values that can be discovered in the publications of internationally famous institutes (between 7% and 10%) (IEA, 2020; IRENA, 2020). In both scenarios, the initial investment is subtracted from subsidies (where applicable). This initial investment, denoted by "C0," comes from the CAPEX costs. The outgoing cash flow (Ct) for every subsequent year is comprised of:

1. The costs of using VLSFO and paying (estimated) carbon taxes

2. The costs of consuming hydrogen and replacing the PEM fuel cell every 6 year

Each cash flow is shown in terms of a dollar. We'll assume a one-year construction period for a given vessel.

$$NPV = Co + \sum_{t=1}^{18} \frac{Ct}{(1+r)^{\wedge}t}$$

Where,

NPV = Net present value [$].

C0 = Year 0 initial investment [$]

Ct = Year t Outgoing Cash Flow [$]

r = [%] Discount rate

It's worth noting that just the difference outflows values between all cases for each scenario are considered. Cash inflows are considered to be the same individual cases in each scenario, the net present value is calculated without its inclusion. Furthermore, the financial expenditures associated with maintenance are ignored since they are presumed to be equivalent across the two scenarios, except for the replacement of fuel cell stacks. It should be noted that the results do not represent the investment's net cash flow. Nonetheless, the results may be used to compare the net cash flow originating from all investments in each scenario.

Each computation is performed using a variety of alternative assumptions. This was done so that the most important cost drivers under alternative scenarios could be determined. As a result, we may make conclusions regarding the most crucial factors that affect the commercial feasibility of green hydrogen as a fuel for inland shipping transport in Europe. The following cases are included in the NPV analyses for scenarios (2022=case A & 2030=case B):

3.4 Data collection

The NPV cost structure of cash outflow for installation and running of different propulsion systems throughout the project life of the case study ship is stated below in the table. This part of the paper will discuss in detail the value prediction of each cost component for both scenarios, assumptions, and paper references.

Below table 17 shows the basic cost structure for the NPV outflow cashflow which includes Capex, Opex, stack replacement, fuel cost and subsidy for both the case A and case B. Capex is further divided into subcategory depending upon the type of propulsion system.

	COST ANALYSIS FOR SCENERIO CASE A (2022) & CASE B (2030)				
	LH2-PEMFC	**CGH2-PEMFC**	**LH2-ICE**	**CGH2-ICE**	**VLSFO-ICE**
C A P E X	CAPEX of PEMFC	CAPEX of PEMFC	CAPEX OF ICE	CAPEX OF ICE	CAPEX OF ICE
	ELECTROMOTOR COST	ELECTROMOTOR COST	N/A	N/A	N/A
	INVERTOR,CONVERTOR ,BATTERY	INVERTOR,CONVERTOR ,BATTERY	N/A	N/A	N/A
	EVAPORATOR AND COMPRESSOR COST	N/A	EVAPORATOR AND COMPRESSOR COST	N/A	N/A
	STORAGE COST	STORAGE COST	STORAGE COST	STORAGE COST	STORAGE COST
OPEX	OPEX of LH2-PEMFC	OPEX of CGH2-PEMFC	OPEX of LH2- ICE	OPEX of CGH2- ICE	OPEX of VLSFO- ICE
	STACK REPLACEMENT COST(every 6 year)	STACK REPLACEMENT COST(every 6 year)	N/A	N/A	N/A
FUEL	H2 FUEL COST	H2 FUEL COST	H2 FUEL COST	H2 FUEL COST	VLSFO FUEL COST
POLICY	SUBSIDY FOR PEMFC	SUBSIDY FOR PEMFC	N/A	N/A	CARBON TAX

Table 16: Cost Analysis for Scenario Case A (2022) & Case B (2030)

For data, assumption, and methodology, this paper will mainly refer to the following published paper as stated below:

- “Comparative report on alternative fuels for ship propulsion” by Interreg H2ships (Interreg,2020)
- “Assessment of the future potential of hydrogen with a focus on its role in the decarbonisation of shipping” by Bob Fosco & Seppe van neer (Seppe,Bob ,2021)
- “Power-2-fuel cost analysis” by smart port(smart port,2020)

CAPEX

Internal combustion engine (ICE): As per (smartport.nl, 2020) cost of ICE is 625 €/Kw in 2022; 625 $/Kw in 2022 and it is projected to increase in 2030, so due to unavailability of the data it can be assumed to be 800 $/kW. The requirement of power for our case study ship is around 2500 KW. The cost of an ICE engine for all three-propulsion systems (LH2-ICE.CGH2-ICE, VLSFO-ICE) is assumed to be the same consequently the final cost for the engine will be 1,562,500 $ and 2,000,000 $ in 2022 and 2030 respectively.

VLSFO storage tank cost: Capex for the VLSFO storage tank is 27 €/GJ ; 27 $/GJ (smartport.nl, 2020) . The fuel storage requirement for the case study ship is 70 tons of hydrogen tanks. So, the energy requirement is 70000 h2 kg * 125 MJ/h2kg =8750 GJ. Consequently, **the total cost of a VLSFO storage tank cost for the same energy requirement is 27 * 8750= 236250 $.**

PEM Fuel cell: The cost of PEMFC in 2022 is 2000 $/kW (smart port, 2020) and in 2030 is 250 $/kW (Interreg, 2020).so, the as per our case study the propulsion need is 2.5 GW (2500kw), the total cost of PEMFC is 5000,000 $ and 625000$ in 2022 and 2030 respectively. Additionally, the NPV is also determined for a subsidy-based scenario**.** Recently Dutch Transport Minister Cora Van Nieuwenhuizen awarded 4 million euros to Lenten Scheepvaart, a member of the inland shipping cooperative NPRC, for the first hydrogen-powered cargo ship (NPRC, 2022). Assuming the same value of subsidy will give to our case study ship energy observer 2 for the 2022 and 2030 scenarios. In this paper, the PEM fuel cell has a lifetime of around 40 000 operating hours or 6 years. PEMFC system the stack cost ranges from 9.2 to 14.7% of the total system cost (MDPI energies, 2021). The stack replacement cost is 850 $/kW for the PEM Fuel cell (MDPI energies, 2021).

Electromotor: According to the International Energy Agency (IEA, 2020), the price of an electromotor will be 70 $/kW in 2020 and $90 in 2030. Thus, between 2022 and 2030, the electro motor's CAPEX total is $175000.

Converter, Inverter, and Battery: We assumed that the upfront costs (CAPEX) of the converter, inverter, and battery would be the same between 2022and 2030. The estimated initial investment for the converter is 270 000 $, the inverter is 135 000 $, and the battery was 527 850 $ (Seppe,Bob 2021).

Evaporator and Compressor: As described in the literature review earlier Liquid hydrogen needs to be pumped, heated, and compressed before feeding to ICE. The cost of the compressor together with other components is 39.3 $/kW in 2022 and 2030 (Baxter, 2022). Consequently, the total cost of the evaporator and compressor for the case study is 98250 $ in 2022 and 2030.

Compressed hydrogen storage cost: Compressed hydrogen can be stored in four types of vessels depending upon their material quality and pressure range. The cost for the vessel ranges from 83 -700 $/kg and the pressure range is from 200 to 700 bar**.** For calculation purposes, we will use a Type 1 metal construction 300 bar vessel and the cost of that vessel is 83 $/kg. **The required storage capacity in the presented case study is 70 tons of hydrogen, so the total associated cost with the compressed hydrogen storage system is 83 * 70000 =5,810,000 $**

Liquid hydrogen storage cost:

As per (Derking, 2022), the specific cost of a cryogenic tank system of 4300kg capacity is 167 $/kg (petitpas, Simon, 2017). We are assuming the same cost for our case study requirement of 70 tons. **Consequently, the total cost associated with the Liquid hydrogen storage system is 70000*167=11690000 $**

OPEX

As per the Interreg h2ships report, the OPEX for each system is as follows (Table 18):

As per INTERREG H2SHIPS REPORT				
LH2-PEMFC	**CGH2-PEMFC**	**LH2-ICE**	**CGH2-ICE**	**VLSFO-ICE**
2 % of CAPEX	2 % of CAPEX	1 % of CAPEX	1 % of CAPEX	1 % of CAPEX

Table 17: OPEX for each system

FUEL COST

VLSFO fuel consumption: As the case study ship is still under construction so the exact fuel consumption is unknown. For this reason, from the data available for already existing ships we can calculate the value of fuel consumption for the case study ship (energy observer 2). 1200 kW engine of 4670 deadweight cargo ships consume 5 tons/day of fuel (Deltamarine.com.tr, 2022). And 1600kw engine of 5000 deadweight cargo ships consumes 5.2 tons/day of fuel while sailing (Briese.de, 2022). Consequently, for 2500 kW engine the fuel consumption will vary in the range of 9-14 tons/day depending upon the engine speed, dimension of the ship, weather condition, and loading condition. For the calculation purpose we will assume the fuel consumption to be 10 tons/day; **416.67 kg/hr.** in case of sailing.

Fuel consumption for one compete round trip=sailing time on a round trip x hourly average fuel consumption=48h x 416.67 kg/hr.=**20000.16 kg**

Hydrogen consumption:

The roundtrip average hourly VLSFO consumption was determined to be 416.67 kg/h. VLSFO has an average energy value of 42 MJ/kg, thus that 17500.14 MJ of VLSFO is used each hour. Assuming the same ICE and PEMFC efficiency, the hourly average energy consumption of hydrogen is **140.00 kg H2/h** when the energy content of hydrogen (= 125 MJ/kg) is considered.

Total hydrogen consumption for propulsion during one complete round trip from the port of Rotterdam to the port of Strasbourg of 60 hours is calculated as follows:

Fuel consumption in one round trip with hydrogen

= Sailing time on a round trip x hourly average fuel consumption

= 48 h x 140 kg/h = **6720 kg of hydrogen**

Compressed hydrogen requirement summary: In addition to the hydrogen consumed for ship propulsion, hydrogen is also consumed to keep the storage tank at a constant pressure as stated earlier in the literature review. According to the literature, compressing the gas requires 10-15% of the stored hydrogen energy (Mar15).so calculation purposes we will use 12.5 % of stored energy is used to keep the gas in compression plus the same as LSFO we will keep 20 % reserve.

Hydrogen energy needed for storage = 12.5% of total hydrogen energy stored

= 12.5 % (hydrogen energy required for propulsion + hydrogen energy reserve)

= 0.125 x (6270 kg *125 MJ/Kg + 0.2 *6270 kg * 125 MJ/Kg)

= 117562.5 MJ or 940.5 kg h2

Compressed hydrogen summary	
Amount consumed for propulsion	**6720 Kg**
Reserve	**1344 Kg**
Amount consumed for storage	**940.5 Kg**
Total amount of compressed hydrogen in storage	**9004.5 Kg**

Table 18: Compressed Hydrogen Summary

So, the total hydrogen consumption per round trip =Amount consumed for propulsion + Amount consumed for storage (*Reserve will not be consumed) =7660.5 kg

Liquid hydrogen requirement summary: In addition to the hydrogen consumed for ship propulsion, hydrogen is also consumed to keep the storage tank at a constant pressure as stated earlier in the literature review. According to the literature, Large cryogenic liquid hydrogen tanks require 20-35% of the stored hydrogen energy (Mar15).so calculation purposes we will use 27.5 % of stored energy is used to keep the Liquid hydrogen tank operational plus the same as LSFO we will keep 20 % reserve.

Hydrogen energy needed for storage = 27.5% of total hydrogen energy stored

= 27.5 % (hydrogen energy required for propulsion + hydrogen energy reserve)

= 0.275 x (6270 kg *125 MJ/Kg + 0.2 *6270 kg * 125 MJ/Kg)

= 258637.5 MJ or 2069.1 kg h2

Liquid hydrogen summary	
Amount consumed for propulsion	**6720 Kg**
Reserve	**1344 Kg**
Amount consumed for storage	**2069.1 Kg**
Total amount of compressed hydrogen in storage	**10133.1 Kg**

Table 19: Liquid Hydrogen Summary

So, the total hydrogen consumption per round trip =Amount consumed for propulsion + Amount consumed for storage (*Reserve will not be consumed) =8789.1 kg

Hydrogen fuel cost per year =number of round trips in a year x hydrogen fuel price for that year

Total Hydrogen fuel cost throughout the project life of 18 years = Addition of all year fuel cost throughout the project life

VLSFO price prediction:

VLSFO price projection is based on the highest, lowest, and average crude oil price predictions available in the literature (The World Bank, 2020; Ulysses Petroleum Management, 2020; Seppe, Bob 2021). As per the Seppe, Bob paper it is assumed that the relative changes in future VLSFO prices will be the same as the changes in the price of crude oil, and more specifically the average price of Brent, which is used as a benchmark for crude oil pricing. Ulysses Petroleum Management and Total, Shell, BP, ENI, Occidental, and Equinor (The World Bank, 2020; Ulysses Petroleum Management, 2020) were considered for their crude oil forecasts. We will be using the result of the analysis of Seppe, bob, 2021 for the VLSFO price prediction in this paper because the prediction and assumptions for the calculation are more realistic and logical. These data will be used for VLSFO Fuel cost calculation throughout the project life of 18 years for scenarios A51, A52, 53, B51, B52, and B53 for investment in 2022 and 2030.

CASE	CASE A=2022			CASE B=2030		
	VLSFO price			VLSFO price		
	Low	Avg	High	Low	Avg	High
LSFO-ICE	A.51	A.52	A.53	B.51	B.52	B.53

Table 22: VLSFO price for Case A & Case B

VLSFO price prediction based on the highest, lowest and an average price prediction of crude oil found in literature (Seppe,Bob ,2021,The World Bank, 2020; Ulysses PetroleumManagement, 2020)			
Year	**Lowest($/mt)**	**Average($/mt)**	**Higest ($/mt)**
2020	524	524	524
2021	568.73	618.73	598.86
2022	613.46	643.9	823.43
2023	658.2	669.06	853.37
2024	702.93	695.71	898.29
2025	702.93	723.83	898.29
2026	702.93	728.86	898.29
2027	702.93	735.15	898.29
2028	702.93	741.45	898.29
2029	702.93	747.74	898.29
2030	702.93	748.99	898.29
2031	702.93	748.99	898.29
2032	702.93	748.99	898.29
2033	702.93	748.99	898.29
2034	702.93	748.99	898.29
2035	702.93	748.99	898.29
2036	702.93	748.99	898.29
2037	702.93	748.99	898.29
2038	702.93	748.99	898.29
2039	702.93	748.99	898.29
2040	702.93	748.99	898.29
2041	702.93	748.99	898.29
2042	702.93	748.99	898.29
2043	702.93	748.99	898.29
2044	702.93	748.99	898.29
2045	702.93	748.99	898.29
2046	702.93	748.99	898.29
2047	702.93	748.99	898.29
2048	702.93	748.99	898.29
2049	702.93	748.99	898.29
2050	702.93	748.99	898.29

Table 20: VLSFO Price prediction Case A and Case B

Carbon Tax scenario Prediction:

There are projections that show that by 2050, shipping might be responsible for as much as 20% of world emissions if nothing is done to reduce the industry's existing impact. With this situation in mind, the idea of imposing a charge on emissions from ships has received attention. The European Commission has recently recommended the implementation of a carbon tax for industries that are not yet a part of the trading system. These industries include shipping and aviation. As a result, it was recommended to incorporate potential prices associated with carbon taxes into the NPV calculation for scenarios A51, A52, A53, B51, B52, and B53. For carbon tax prediction we will use the analysis and data results predicted by Seppe, Bob in 2021.On the basis of the forecasts provided by OECD (2021) and ICCT(2021), three distinct scenarios will be taken into consideration(Seppe, Bob 2021).

(1) The first possible outcome is a pessimistic one in which there are no carbon fees added, similar to the one that exists right now.

(2) A low-end, average benchmark of EUR 30 (USD 35.45) per tonne by 2025 is being studied as a second scenario. This benchmark is projected to rise to EUR 60 (USD 70.9) per tonne by 2030 and to 100 USD per tonne by 2050.

(3) There is a third potential outcome that takes into account an optimistic high-end benchmark price of EUR 120 (USD 141.8) per tonne in 2030, which increases to USD 160 in 2050. Utilizing linear interpolation, we were able to determine the carbon tax price forecasts for the years that fall in between these values. Burning 1 tonne of very low-sulfur fuel oil (VLSFO) emits about 3.15 tonnes of CO_2 (Lloyd's List, 2022).

Carbon tax price prediction based on the pessimistic, optimistic and an average price predictions found in literature (Seppe,Bob,2021 ,OECD, 2021; ICCT, 2021)			
Year	Pessimistic ($/mT)	Average ($/mt)	Optimistic($/mt)
2020	0	0	0
2021	0	7.09	7.09
2022	0	14.18	14.18
2023	0	21.27	21.27
2024	0	28.36	28.36
2025	0	35.45	35.45
2026	0	42.54	56.72
2027	0	49.63	77.99
2028	0	56.72	99.26
2029	0	63.81	120.53
2030	0	70.90	141.80
2031	0	72.36	142.71
2032	0	73.81	143.62
2033	0	75.27	144.53
2034	0	76.72	145.44
2035	0	78.18	146.35
2036	0	79.63	147.26
2037	0	81.09	148.17
2038	0	82.54	149.08
2039	0	84.00	149.99
2040	0	85.45	150.90
2041	0	86.91	151.81
2042	0	88.36	152.72
2043	0	89.82	153.63
2044	0	91.27	154.54
2045	0	92.73	155.45
2046	0	94.18	156.36
2047	0	95.64	157.27
2048	0	97.09	158.18
2049	0	98.55	159.09
2050	0	100	160

Table 21: Carbon Tax Price Prediction

Hydrogen price prediction:

Given the considerable variation in published projections for hydrogen prices, three scenarios are chosen: those with the most optimistic (Lowest price), median (Average price), and most pessimistic (The highest price) estimates for hydrogen prices. Specifically, in these three types of hydrogen pricing, the NPV will be calculated for both cases A (2022) and case B (2030). In these three types of pricing, the NPV will be calculated using anticipated hydrogen price projections for 2020 and 2030, and then extended exponentially to 2050. Below stated Scenarios describe a hydrogen price that is either low, medium, or high (in the case of a PEM fuel cell and ICE for propulsion), respectively. For the hydrogen price prediction, I will be using the methodology of Seppe, Bob, 2021.

CASE	CASE A=2022			CASE B=2030		
	Hydrogen price			hydrogen price		
	Low	Avg	High	Low	Avg	High
LH2-PEMFC	A.11	A.12	A.13	B.11	B.12	B.13
CGH2-PEMFC	A.21	A.22	A.23	B.21	B.22	B.23
LH2-ICE	A.31	A.32	A.33	B.31	B.32	B.33
CGH2-ICE	A.41	A.42	A.43	B.41	B.42	B.43

Table 22: Hydrogen Price for Case A & Case B

The industrialization of electrolyser manufacturing, improvements in efficiency and operational and maintenance, and the use of low-cost renewable power are significant drivers of hydrogen cost reduction. For the latter, the availability of renewable resources (sun and wind) will be critical across geographies (Hydrogen council, 2020). According to the hydrogen council, the price of hydrogen will fall as technology advances. As a result, the price of green hydrogen in 2050 will be lower than the price in 2030, and the price in 2030 will be lower than the price today. We will use the exponential extradition approach to obtain data for all years between 2022 and 2050 for this declining hydrogen price in all three pricing scenarios (Low, average, high)

Low hydrogen price prediction:

An info graphic from the Hydrogen Council (2020) study, shown in the figure below, is used to determine the lowest hydrogen pricing scenario. Hydrogen production costs in Europe may be approximated using this approach, provided that the power price, load or capacity factor of the electricity producing facility, and electrolyzing system CAPEX were known. Hydrogen prices for 2022 and 2030 were extrapolated from the figure using the given assumptions, and the resulting values were used to calculate the low hydrogen price projection for all years between 2022-2050.

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

SOURCE: McKinsey

Table 23: LCOE and Capex electrolyzer

As per NEA (Nuclear energy agency) at present LCOE (Levelized cost of energy) in Europe is between 50-90 $/MWh for wind and solar. For Netherlands and France, capacity-specific wind LCOE are 56.06 $/MWh and 41.17 $/MWh respectively and for solar PV 86.93 $/MWh and 73.29 respectively as per NEA**.** For hydrogen cost estimation purposes we will take $50 /MWh as a reference with the Capex cost of PEM electrolyser in Europe still around 700-1800 $/kW (Agora-energiewende.de, 2022). So we will choose the 750 $/kW scenario for price prediction. We are assuming the load factor to be 40 % looking at the hydrogen council info graph above we can say that the cost of hydrogen is **3.7 $/kg in 2022**.

The procedure is then repeated to predict the cost of hydrogen in 2030. The CAPEX of electrolyzing technology is predicted to decrease by around 66% by 2020 (Hydrogen Council, 2020). As a result, the CAPEX in 2030 is projected to be USD 308.8 /kW, which is consistent with the earlier forecast of USD 750 /kW for 2020. Thus, a CAPEX of USD 250/kW will be employed for this forecast. The International Renewable Energy Agency (IRENA) predicted that by 2022, the price of energy generated by offshore wind will fall to 54.25 U.S. dollars per megawatt-hour (MWh) (2019). So, the low hydrogen price prediction for **2030 is 3 $/kg.**Low hydrogen prediction exponential graph is displayed below (figure-19):

Figure 17: Low Hydrogen Price Prediction

Average and high hydrogen pricing:

The average and high price predictions were inspired by data found in a report by ICCT (2020). For the purposes of this study, the ICCT (2020) minimal hydrogen price case is regarded to be the average hydrogen price case, while the ICCT (2020) average case is considered to be the highest hydrogen price projection. ICCT (2020) considered plausible (or pessimistic) power price estimates, electrolyser learning curves, and distribution scenarios, resulting in significantly more expensive hydrogen than reported in the studies (Seppe, bob,2021). The International Council on Clean Transportation (ICCT) (2020) claims that the study by IRENA (2020) and the Hydrogen Council (HCT) significantly understates the expenses associated with distributing, compressing, and transporting hydrogen, all of which contribute to the relatively higher price 2020 (Seppe, bob,2021).

	2020($/kg)	2030 ($/kg)	Reference
Average H2 price	6.62	5.4	ICCT(2020)
High H2 price	14.19	7.18	ICCT(2020)

Table 24: Average and high hydrogen pricing

For exponential graph of Average and high hydrogen pricing check Appendix figure 3 and 4 in appendix section. The table 26 shows the yearly price prediction of hydrogen from 2020 to 2050 for three type of ranges lowest, average and highest hydrogen price based on extrapolation of hydrogen data discussed above and figure 19 and appendix figure 3,4.For all the cases the hydrogen price is decreasing over the years in future and condition is becoming more favourable for green hydrogen usage.

Hydrogen price prediction			
Year	Lowest	Average	Highest
2020	3.72	6.62	14.19
2021	3.64	6.51	13.45
2022	3.56	6.38	12.56
2023	3.49	6.25	11.73
2024	3.42	6.13	10.96
2025	3.35	6.00	10.24
2026	3.28	5.88	9.56
2027	3.21	5.76	8.94
2028	3.14	5.65	8.35
2029	3.08	5.53	7.80
2030	3.01	5.42	7.18
2031	2.95	5.31	6.80
2032	2.89	5.21	6.36
2033	2.83	5.10	5.94
2034	2.77	5.00	5.55
2035	2.71	4.90	5.18
2036	2.66	4.80	4.84
2037	2.60	4.70	4.52
2038	2.55	4.61	4.22
2039	2.50	4.51	3.95
2040	2.44	4.42	3.69
2041	2.39	4.33	3.44
2042	2.34	4.25	3.22
2043	2.29	4.16	3.00
2044	2.25	4.08	2.81
2045	2.20	4.00	2.62
2046	2.15	3.91	2.45
2047	2.11	3.84	2.29
2048	2.07	3.76	2.14
2049	2.02	3.68	2.00
2050	1.98	3.61	1.87

Table 25: Hydrogen Price Prediction

3.5 Data analysis

In the next chapter (Chapter 4:Results and discussion) we will use the data collected in previous section 3.4 to calculate the NPV for different scenario and cases throughout the project life of 18 years (Table 16). NPV calculation formula and terms are discussed in detail in the section 3.3. As discussed, before we will be using only the outflow of the project and inflows are assumed to be same for all scenarios. The following cases are included in the NPV analyses for scenarios (2022=case A & 2030=case B):

CASE	CASE A=2022			CASE B=2030		
	VLSFO/H2 price			VLSFO/H2 price		
	Low	Avg	High	Low	Avg	High
LH2-PEMFC	A.11	A.12	A.13	B.11	B.12	B.13
CGH2-PEMFC	A.21	A.22	A.23	B.21	B.22	B.23
LH2-ICE	A.31	A.32	A.33	B.31	B.32	B.33
CGH2-ICE	A.41	A.42	A.43	B.41	B.42	B.43
LSFO-ICE	A.51	A.52	A.53	B.51	B.52	B.53

Table 26: NPV analyses for scenarios

- Low, Average, and high values of VLSFO scenario for Case A=2022 (A51.A52.A53) and Case B=2030 (B51, B52, B53)
- Low, Average and high hydrogen fuel price scenario for Case A =2022(A11, A12, A13, A21, A22, A23, A31, A32, A33, A41, A42, A43) and Case B=2030(B11, B12, B13, B21, B22, B23, B31, B32, B33, B41, B42, B43)
- Low, Average, and high values for carbon taxes will be taken into consideration for a case involving VLSFO-ICE For 2022 and 2030 (A51, A52, A53, B51, B52, B53)
- Each scenario will be calculated in two timeframes, one where the initial investment (year 0) is in 2022 and a scenario where the initial investment is in 2030

Chapter 4. RESULTS AND DISCUSSION

In this section of the chapter, we will first review briefly the case study terminology and situations again before interpreting and analyzing the findings of each case scenario (CASE A& case B). Which scenario choice is optimal, and why, shall be discussed. We shall attempt to determine the economic feasibility of hydrogen as a fuel for inland ships.

The "energy observer 2" case study vessel has a propulsion energy demand of 2.5 GW (2500 KW). We have five propulsion choices available (LH2-PEMFC, CGH2-PEMFC, LH2-ICE, CGH2-ICE, and LSFO-ICE) available. There are two instances in, we will calculate the NPV of the project's total cash outflow (CAPEX, OPEX, STACK REPLACEMENT, FUEL COST, and CARBON TAX) depending on the time of investment (2022 & 2030). The cash inflow is assumed to be the same for each case and scenario and is thus excluded from NPV calculations. NPV is calculated for the project life of the ship which is assumed to be 18 years. CARBON TAX and SUBSIDY are applied to the scenario wherever appropriate. The outcome will be used to evaluate all propulsion alternatives and aid in determining the viability of hydrogen as a transportation fuel.

- Each propulsion system will have three scenarios of low, average, and high fuel prices (Hydrogen or VLSO) for each case, as specified in the table below with a case number (nomenclature).

CASE	CASE A=2022			CASE B=2030		
	VLSFO/H2 price			VLSFO/H2 price		
	Low	Avg	High	Low	Avg	High
LH2-PEMFC	A.11	A.12	A.13	B.11	B.12	B.13
CGH2-PEMFC	A.21	A.22	A.23	B.21	B.22	B.23
LH2-ICE	A.31	A.32	A.33	B.31	B.32	B.33
CGH2-ICE	A.41	A.42	A.43	B.41	B.42	B.43
VLSFO-ICE	A.51	A.52	A.53	B.51	B.52	B.53

Table 27: Fuel Prices of Hydrogen or VLSFO in different cases

- Plus each case of VLSFO-ICE (A.51, A.51.A.53.B.51.B.52.B.53) will have three additional scenarios of Low, average, and high CARBON TAX.

VLSO-ICE	A.51	A.52	A.53
CASE A=2022	LOW VLSO PRICE +LOW C TAX	AVG VLSO PRICE + LOW C TAX	HIGH VLSO PRICE + LOW C TAX
	LOW VLSO PRICE +AVG C TAX	AVG VLSO PRICE + AVG C TAX	HIGH VLSO PRICE + AVG C TAX
	LOW VLSO PRICE +HIGH C TAX	AVG VLSO PRICE + HIGH C TAX	HIGH VLSO PRICE + HIGH C TAX
	B.51	B.52	B.53
CASE B=2030	LOW VLSO PRICE +LOW C TAX	AVG VLSO PRICE + LOW C TAX	HIGH VLSO PRICE + LOW C TAX
	LOW VLSO PRICE +AVG C TAX	AVG VLSO PRICE + AVG C TAX	HIGH VLSO PRICE + AVG C TAX
	LOW VLSO PRICE +HIGH C TAX	AVG VLSO PRICE + HIGH C TAX	HIGH VLSO PRICE + HIGH C TAX

Table 28: VLSO-ICE pricing of different cases

- So each CASE A=2022 $ CASE B=2030 will have a total of 18 scenarios as stated in the above two tables(Table 28 and 29).
- The data and assumptions for each Case are discussed in the previous chapter.

4.1 CASE A-Project initiation in 2022

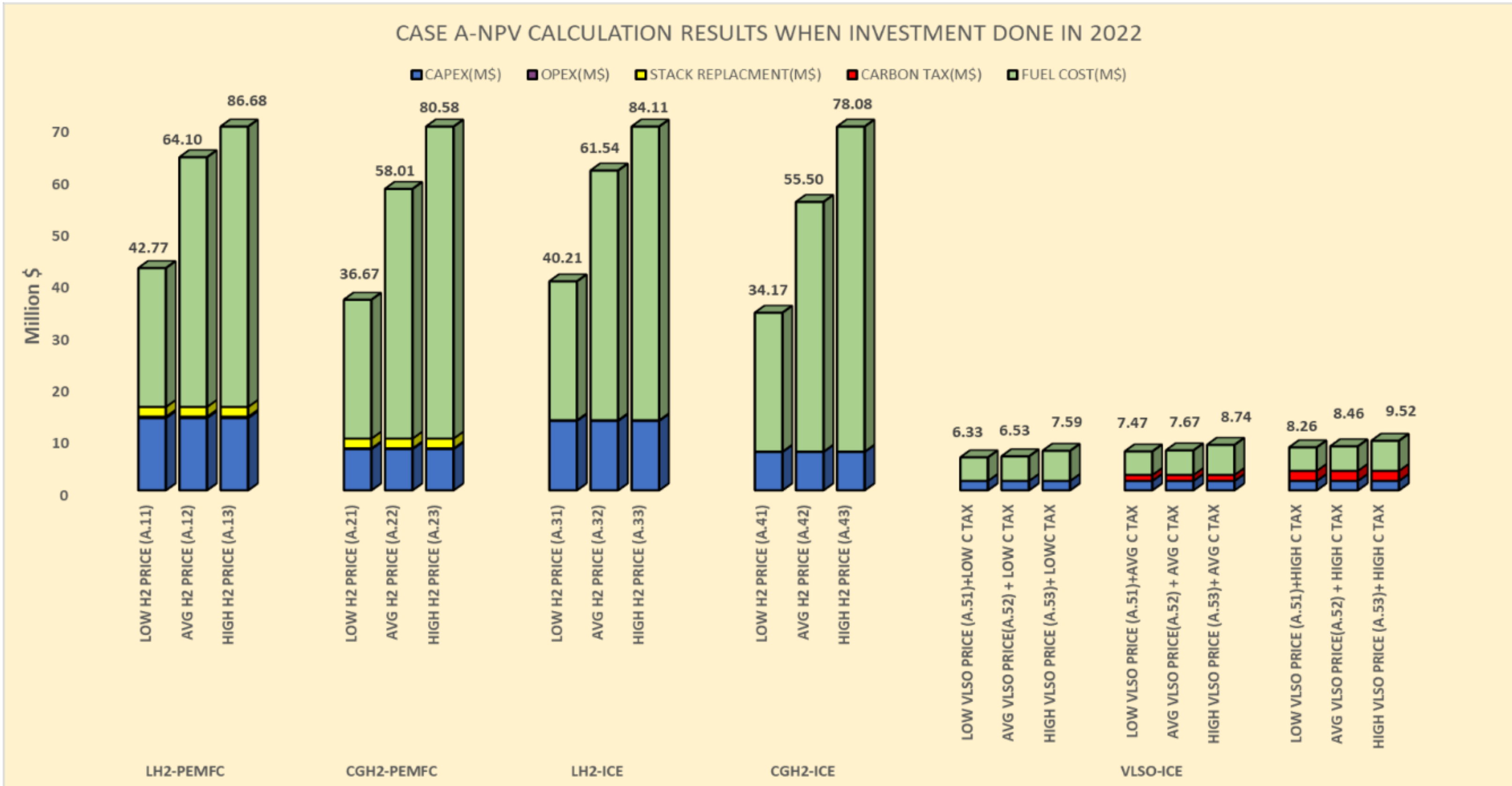

Figure 18: Case A- NPV calculations results when investment done in 2022

CASE A-NPV calculations result when Investment done in 2022

		CAPEX($)	OPEX($)	STACK REPLACMENT($)	CARBON TAX($)	FUEL COST($)	TOTAL($)
LH2-PEMFC							
	LOW H2 PRICE (A.11)	13896100.00	277922.00	1876597.59	0.00	26721834.94	42772454.53
	AVG H2 PRICE (A.12)	13896100.00	277922.00	1876597.59	0.00	48052213.73	64102833.32
	HIGH H2 PRICE (A.13)	13896100.00	277922.00	1876597.59	0.00	70629046.17	86679665.76
CGH2-PEMFC							
	LOW H2 PRICE (A.21)	7917850.00	158357.00	1876597.59	0.00	26721834.94	36674639.53
	AVG H2 PRICE (A.22)	7917850.00	158357.00	1876597.59	0.00	48052213.73	58005018.32
	HIGH H2 PRICE (A.23)	7917850.00	158357.00	1876597.59	0.00	70629046.17	80581850.76
LH2-ICE							
	LOW H2 PRICE (A.31)	13350750.00	133507.50	0.00	0.00	26721834.94	40206092.44
	AVG H2 PRICE (A.32)	13350750.00	133507.50	0.00	0.00	48052213.73	61536471.23
	HIGH H2 PRICE (A.33)	13350750.00	133507.50	0.00	0.00	70629046.17	84113303.67
CGH2-ICE							
	LOW H2 PRICE (A.41)	7372500.00	73725.00	0.00	0.00	26721834.94	34168059.94
	AVG H2 PRICE (A.42)	7372500.00	73725.00	0.00	0.00	48052213.73	55498438.73
	HIGH H2 PRICE (A.43)	7372500.00	73725.00	0.00	0.00	70629046.17	78075271.17
VLSO-ICE							
	LOW VLSO PRICE (A.51)+LOW C TAX	1798750.00	17987.50	0.00	0.00	4514168.20	6330905.70
	AVG VLSO PRICE(A.52) + LOW C TAX	1798750.00	17987.50	0.00	0.00	4713588.03	6530325.53
	HIGH VLSO PRICE (A.53)+ LOWC TAX	1798750.00	17987.50	0.00	0.00	5777730.81	7594468.31
	LOW VLSO PRICE (A.51)+AVG C TAX	1798750.00	17987.50	0.00	1143242.63	4514168.20	7474148.33
	AVG VLSO PRICE(A.52) + AVG C TAX	1798750.00	17987.50	0.00	1143242.63	4713588.03	7673568.16
	HIGH VLSO PRICE (A.53)+ AVG C TAX	1798750.00	17987.50	0.00	1143242.63	5777730.81	8737710.94
	LOW VLSO PRICE (A.51)+HIGH C TAX	1798750.00	17987.50	0.00	1928997.81	4514168.20	8259903.50
	AVG VLSO PRICE(A.52) + HIGH C TAX	1798750.00	17987.50	0.00	1928997.81	4713588.03	8459323.33
	HIGH VLSO PRICE (A.53)+ HIGH C TAX	1798750.00	17987.50	0.00	1928997.81	5777730.81	9523466.12

Table 29: Case A NPV Calculations results when investment done in 2022

Case A-project initiation in 2022 analysis (Figure 18 & Table 30)- In the case, a figure and table presented above, the outcomes of all possible scenarios in which the project is begun in 2020 are displayed. From Figure, it is evident that when hydrogen price forecasts (low, average, and high) are based on the selected literature data assumption, the total fuel cost during the life of the project is significantly greater than under the VLSFO fuel price scenario. Financially, it is irrational to build a Hydrogen propulsion system (LH2 or CGH2) with PEMFC or ICE rather than a VLSFO-ICE system based on just financial projection. CGH2-ICE LOW H2 PRICE (A.41) has the lowest total NPV cash outflow throughout the life of the project at 34.17 M$, whereas LH2-PEMFC HIGH H2 PRICE (A.13) has the highest total NPV cash outflow at 86.68 M$. In contrast, the lowest and highest total NPV cash outflows for the VLSO-ICE system are $6.33 million and $9.52 million for VLSFO-ICE LOW VLSFO(A.51)+ LOW C TAX and VLSFO-ICE HIGH VLSFO(A.53)+ HIGH C TAX, respectively. Hydrogen propulsion systems are 5-15 times more expensive than standard VLSFO-ICE systems. VLSFO-ICE is the most cost-effective alternative for a ship-owner with simply a financial focus, but the net-zero carbon emissions goal cannot be attained with this strategy. Hydrogen cannot be regarded as a viable choice until the price of hydrogen fuel decreases as a result of technological advances in renewable energy sources and electrolysers. With a decrease in the price of hydrogen, a rise in subsidies, and a decrease in the price of fuel cells, a hydrogen propulsion system with zero emissions can be the best option. Increasing the carbon tax might also potentially influence the decision choice to build ship propulsion systems. According to the carbon tax projection derived from the literature for our case study, the other propulsion does not appear to be favourable unless the average and high carbon taxes are increased by 27(2700%) and 15 times(1500%), respectively.

When comparing Liquid hydrogen (LH2) with compressed hydrogen (CGH2), the compressed gas hydrogen system is superior owing to its reduced CAPEX cost. Liquid hydrogen systems require expensive cryogenic hydrogen tanks, heaters, and evaporators. For hydrogen to be adopted as a transportation fuel in the future, the cost of hydrogen storage systems must decrease.

In the case study presented by energy observer 2, liquid hydrogen is selected for propulsion due to its lower installation space need compared to compressed gas storage systems. In cargo transportation, space is a significant constraint; reducing space on board entails compromising cargo-carrying capability, which in turn reduces income.

In Case A the gap between the average hydrogen price scenario and the high hydrogen price scenario is bigger than the difference between the low hydrogen price scenario and the average hydrogen price scenario (approx. 22 M$). Opex and Stack replacement are not significant financial issues in determining the propulsion system. The ship owner's dream of achieving a zero-emissions target and hydrogen propulsion as the preferred investment option is not impossible without additional subsidies, lower hydrogen fuel prices, lower hydrogen storage costs, lower PEMFC costs, and lower electrolysis costs, as well as an increased carbon tax on the use of fossil fuels. The decision between liquid and compressed hydrogen with PEMFC will be difficult, depending on technological advancement, and system-specific cost reduction criteria. Unlike PEMFC, H2 with ICE doesn't have zero emission benefits.

4.2 CASE B-Project initiation in 2030

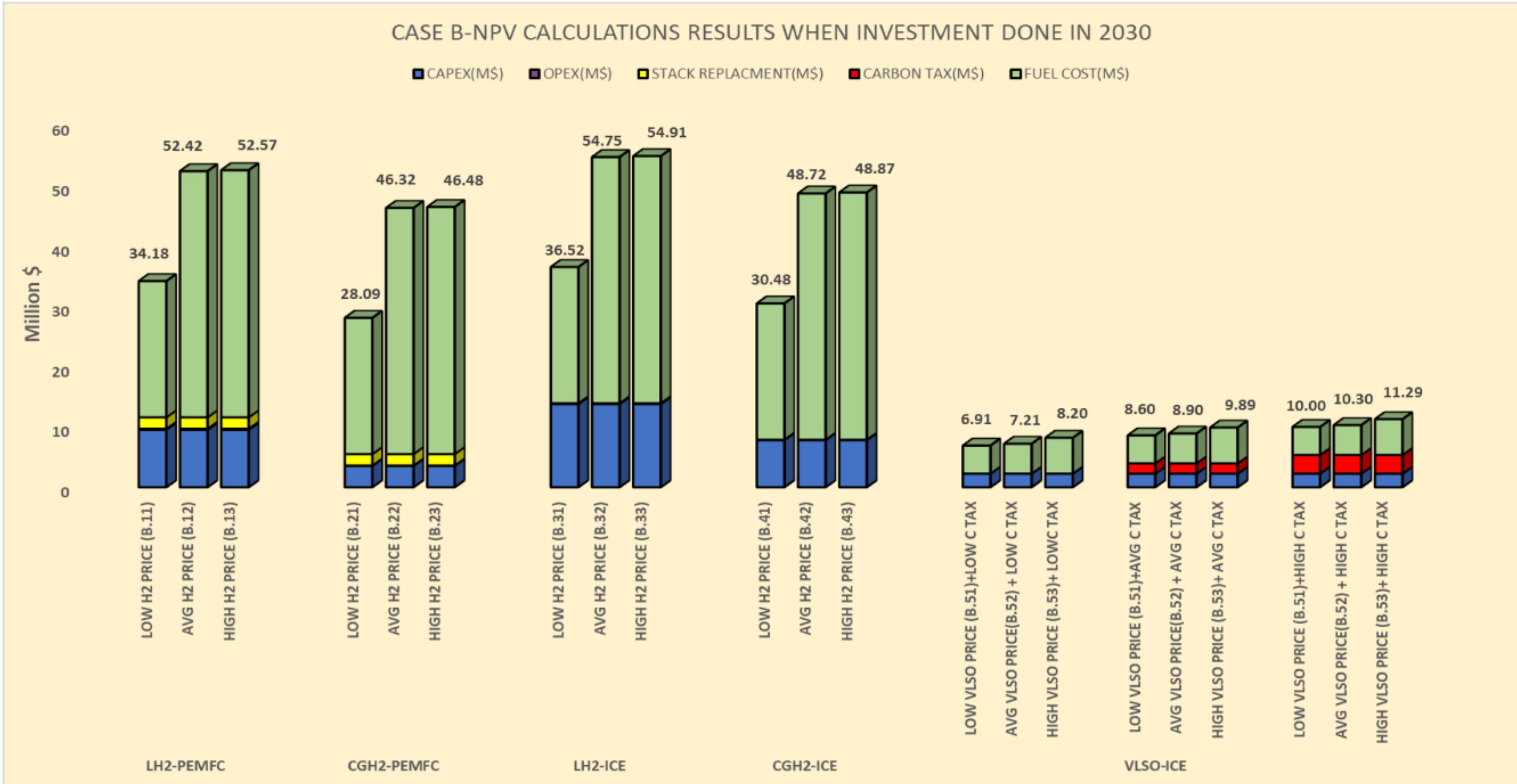

Figure 19: Case B- NPV calculations results when investment done in 2030

CASE B-NPV calculations result when Investment done in 2030

		CAPEX($)	OPEX($)	STACK REPLACMENT($)	CARBON TAX($)	FUEL COST($)	TOTAL($)
LH2-PEMFC							
	LOW H2 PRICE (B.11)	9521100.00	190422.00	1876597.59	0.00	22594849.69	34182969.28
	AVG H2 PRICE (B.12)	9521100.00	190422.00	1876597.59	0.00	40827177.25	52415296.84
	HIGH H2 PRICE (B.13)	9521100.00	190422.00	1876597.59	0.00	40985960.98	52574080.57
CGH2-PEMFC							
	LOW H2 PRICE (B.21)	3542850.00	70857.00	1876597.59	0.00	22594849.69	28085154.28
	AVG H2 PRICE (B.22)	3542850.00	70857.00	1876597.59	0.00	40827177.25	46317481.84
	HIGH H2 PRICE (B.23)	3542850.00	70857.00	1876597.59	0.00	40985960.98	46476265.57
LH2-ICE							
	LOW H2 PRICE (B.31)	13788250.00	137882.50	0.00	0.00	22594849.69	36520982.19
	AVG H2 PRICE (B.32)	13788250.00	137882.50	0.00	0.00	40827177.25	54753309.75
	HIGH H2 PRICE (B.33)	13788250.00	137882.50	0.00	0.00	40985960.98	54912093.48
CGH2-ICE							
	LOW H2 PRICE (B.41)	7810000.00	78100.00	0.00	0.00	22594849.69	30482949.69
	AVG H2 PRICE (B.42)	7810000.00	78100.00	0.00	0.00	40827177.25	48715277.25
	HIGH H2 PRICE (B.43)	7810000.00	78100.00	0.00	0.00	40985960.98	48874060.98
VLSO-ICE							
	LOW VLSO PRICE (B.51)+LOW C TAX	2236250.00	22362.50	0.00	0.00	4648911.01	6907523.51
	AVG VLSO PRICE(B.52) + LOW C TAX	2236250.00	22362.50	0.00	0.00	4953534.28	7212146.78
	HIGH VLSO PRICE (B.53)+ LOWC TAX	2236250.00	22362.50	0.00	0.00	5940947.56	8199560.06
	LOW VLSO PRICE (B.51)+AVG C TAX	2236250.00	22362.50	0.00	1690883.37	4648911.01	8598406.87
	AVG VLSO PRICE(B.52) + AVG C TAX	2236250.00	22362.50	0.00	1690883.37	4953534.28	8903030.15
	HIGH VLSO PRICE (B.53)+ AVG C TAX	2236250.00	22362.50	0.00	1690883.37	5940947.56	9890443.42
	LOW VLSO PRICE (B.51)+HIGH C TAX	2236250.00	22362.50	0.00	3087807.07	4648911.01	9995330.57
	AVG VLSO PRICE(B.52) + HIGH C TAX	2236250.00	22362.50	0.00	3087807.07	4953534.28	10299953.85
	HIGH VLSO PRICE (B.53)+ HIGH C TAX	2236250.00	22362.50	0.00	3087807.07	5940947.56	11287367.13

Table 30: Case B- NPV calculations results when investment done in 2030

Case B-project initiation in 2030 analysis (Figure 19 & Table 31)**-** In the case B figure and table presented above, the outcomes of all possible scenarios in which the project is begun in 2030 are displayed. From Figure, it is evident that when hydrogen price forecasts (low, average, and high) are based on the selected literature data assumption, the total fuel cost during the life of the project is significantly greater than under the VLSFO fuel price scenario. But the total hydrogen fuel cost is less than the CASE A-related scenarios. Financially, it is still irrational to build a Hydrogen propulsion system (LH2 or CGH2) with PEMFC or ICE rather than a VLSFO-ICE system based on just financial projection or aspect. In 2030 CGH2-PEMFC LOW H2 PRICE scenario(B.21) has the lowest total NPV cash outflow throughout the life of the project at 28.09 M$, whereas LH2-ICE HIGH H2 PRICE (B.33) has the highest total NPV cash outflow at 54.91 M$. In contrast, the lowest and highest total NPV cash outflows for the VLSO-ICE system are $6.91 million and $11.29 million for VLSFO-ICE LOW VLSFO(B.51)+ LOW C TAX and VLSFO-ICE HIGH VLSFO(B.53)+ HIGH C TAX, respectively. Hydrogen propulsion systems are 5-8 times more expensive than standard VLSFO-ICE systems. Here also VLSFO-ICE is the most cost-effective alternative for a ship-owner with simply a financial focus, but the net-zero carbon emissions goal cannot be attained with this strategy. Hydrogen cannot be regarded as a viable choice until the price of hydrogen fuel decreases as a result of technological advances in renewable energy sources and electrolysers. With a decrease in the price of hydrogen, a rise in subsidies, and a decrease in the price of fuel cells, a hydrogen propulsion system with zero emissions can be the best option. Increasing the carbon tax might also potentially influence the decision choice to build ship propulsion systems. According to the carbon tax projection derived from the literature for our case study, the other propulsion does not appear to be favourable unless the average and high carbon taxes are increased by 13(1300 %) and 8(800%) times, respectively.

When comparing Liquid hydrogen (LH2) with compressed hydrogen (CGH2), the compressed gas hydrogen system is superior owing to its reduced CAPEX cost. Liquid hydrogen systems require expensive cryogenic hydrogen tanks, heaters, and evaporators. For hydrogen to be adopted as a transportation fuel in the future, the cost of hydrogen storage systems must decrease in case we want to use liquid hydrogen as a fuel.

In Case B the average hydrogen price scenario and the high hydrogen price scenario are almost the same, there is a significant difference between the low hydrogen price scenario and the average hydrogen price scenario (approx 22 M$).Opex and Stack replacement are not significant financial issues in determining the propulsion system. The ship owner's dream of achieving a zero-emissions target and hydrogen propulsion as the preferred investment option is not impossible without additional subsidies, lower hydrogen fuel prices, lower hydrogen storage costs, lower PEMFC costs, and lower electrolysis costs, as well as an increased carbon tax on the use of fossil fuels. In 2030 the decision of choice between liquid and compressed hydrogen with PEMFC will be difficult, depending on technological advancement and system-specific cost reduction criteria. Ship owner-specific requirements regarding cargo space, installation cost, bunkering option, and safety will play a vital selection between LH2-PEMFC and CGH2-PEMFC.

4.3 General findings

In this part of the chapter, we will discuss the general findings related to both the cases such as fuel cost, stack replacement, and Fuel cost. The below table illustrates and compares the percentage of each major component of the NPV cost structure of both cases (Case A=2022 & case B).

SCENARIO		GENERAL FINDING BETWEEN CASSE A=2022 & CASE B=2030												
		CAPEX(%)		OPEX(%)		STACK (%)		C TAX (%)		FUEL COST(%)		TOTAL NPV (M$)		% DECREASE
		2022	2030	2022	2030	2022	2030	2022	2030	2022	2030	2022	2030	% INCREASE
LH2-PEMFC														in TOTAL NPV
	LOW H2 PRICE (A.11)	32.49%	27.85%	0.65%	0.56%	4.39%	5.49%			62.47%	66.10%	42.77	34.18	20.08%
	AVG H2 PRICE (A.12)	21.68%	18.16%	0.43%	0.36%	2.93%	3.58%			74.96%	77.89%	64.10	52.42	18.23%
	HIGH H2 PRICE (A.13)	16.03%	18.11%	0.32%	0.36%	2.16%	3.57%			81.48%	77.96%	86.68	52.57	39.35%
CGH2-PEMFC														
	LOW H2 PRICE (A.21)	21.59%	12.61%	0.43%	0.25%	5.12%	6.68%			72.86%	80.45%	36.67	28.09	23.42%
	AVG H2 PRICE (A.22)	13.65%	7.65%	0.27%	0.15%	3.24%	4.05%			82.84%	88.15%	58.01	46.32	20.15%
	HIGH H2 PRICE (A.23)	9.83%	7.62%	0.20%	0.15%	2.33%	4.04%			87.65%	88.19%	80.58	46.48	42.32%
LH2-ICE														
	LOW H2 PRICE (A.31)	33.21%	37.75%	0.33%	0.38%					66.46%	61.87%	40.21	36.52	9.17%
	AVG H2 PRICE (A.32)	21.70%	25.18%	0.22%	0.25%					78.09%	74.57%	61.54	54.75	11.02%
	HIGH H2 PRICE (A.33)	15.87%	25.11%	0.16%	0.25%					83.97%	74.64%	84.11	54.91	34.72%
CGH2-ICE														
	LOW H2 PRICE (A.41)	21.58%	25.62%	0.22%	0.26%					78.21%	74.12%	34.17	30.48	10.79%
	AVG H2 PRICE (A.42)	13.28%	16.03%	0.13%	0.16%					86.58%	83.81%	55.50	48.72	12.22%
	HIGH H2 PRICE (A.43)	9.44%	15.98%	0.09%	0.16%					90.46%	83.86%	78.08	48.87	37.40%
VLSO-ICE														
	LOW VLSFO PRICE (A.51)+LOW C TAX	28.41%	32.37%	0.28%	0.32%					71.30%	67.30%	6.33	6.91	8.35%
	AVG VLSFO PRICE(A.52) + LOW C TAX	27.54%	31.01%	0.28%	0.31%					72.18%	68.68%	6.53	7.21	9.45%
	HIGH VLSO PRICE (A.53)+ LOWC TAX	23.69%	27.27%	0.24%	0.27%					76.08%	72.45%	7.59	8.20	7.38%
	LOW VLSFO PRICE (A.51)+AVG C TAX	24.07%	26.01%	0.24%	0.26%			15.30%	19.67%	60.40%	54.07%	7.47	8.60	13.08%
	AVG VLSFO PRICE(A.52) + AVG C TAX	23.44%	25.12%	0.23%	0.25%			14.90%	18.99%	61.43%	55.64%	7.67	8.90	13.81%
	HIGH VLSFO PRICE (A.53)+ AVG C TAX	20.59%	22.61%	0.21%	0.23%			13.08%	17.10%	66.12%	60.07%	8.74	9.89	11.66%
	LOW VLSFO PRICE (A.51)+HIGH C TAX	21.78%	22.37%	0.22%	0.22%			23.35%	30.89%	54.65%	46.51%	8.26	10.00	17.36%
	AVG VLSFO PRICE(A.52) + HIGH C TAX	21.26%	21.71%	0.21%	0.22%			22.80%	29.98%	55.72%	48.09%	8.46	10.30	17.87%
	HIGH VLSFO PRICE (A.53)+HIGH C TAX	18.89%	19.81%	0.19%	0.20%			20.26%	27.36%	60.67%	52.63%	9.52	11.29	15.63%

Table 31: Generic Findings between case A =2022 & case B =2030

4.3.1 FUEL COST

In all scenarios, it is evident from the above table that fuel costs (60-90%) account for the majority of the overall NPV propulsion cost of the ship. In both cases, hydrogen propulsion systems have a significantly higher overall cost than conventional VLSFO-ICE systems. Due to the high price of hydrogen fuel, it became clear that fuel cost is the most influential component contributing to the NPV of the project in both scenarios A and B. As a result of the decline in hydrogen's market price, the total cost of hydrogen in case B is lower than in case A. In conventional VLSFO-ICE propulsion ships, in addition to fuel price and OPEX cost, carbon tax accounted for 13-31 percent of the overall cost. As per the analysis, the best choice of option for the given case study vessel should be the VLSFO-ICE propulsion system with no carbon tax because it is the most advantageous option compared to all other scenarios when only finance is considered among other deciding factors contributing to investment in the new ship. Theoretically, a case study ship with hydrogen propulsion may become a reality, but several obstacles must first be overcome. The Lower renewable energy source electricity price and Lower electrolysis price for the hydrogen propulsion scenario might lead to a decrease in the price of hydrogen fuel. This is only achievable with adequate coordination and a synergistic relationship between the power generator, the hydrogen producer, and the buyer. Consequently, this would only be achievable in exceptional circumstances. Nonetheless, the example picked for this thesis is deemed to be unique, and the nations and their regulations in these countries are regarded as the most favourable in the world for hydrogen production and usage, which provides opportunities, which is why LH2-PEMFC propulsion was selected despite its high overall cost. In reality, we must accept the fact that 2022 is too soon for hydrogen technology, a meaningful economic case could be made in 2030, by pushing the existing technology to evolve rapidly and fulfil the goals of the hydrogen economy.

4.3.2 CAPEX

In both cases, CAPEX accounts for 9.83 % to 33.21 % of the total cost. In the case of A=2022, the CAPEX cost of VLSFO-ICE is only 1.80 M$ compared to the high cost of hydrogen system propulsion with PEMFC or ICE ranging from 7.37 M$ to 13.90 M$.CAPEX cost for a hydrogen system is 4 % to 7.7 % higher than the traditional VLSFO-ICE system.

In case B=2030, the CAPEX cost of VLSFO-ICE is 2.24M$ and in the contrast, CGH2-PEMFC CAPEX cost has reduced to a very comparative price of 3.54 M$ only due to the additional 4M$ subsidy on PEMFC fuel cell. With such a small margin difference between these two propulsion systems, the CGH2-PEMFC could be the ship owner's choice for Greener fuel and zero emission when only CAPEX cost is considered for the choice of propulsion system.

4.3.3 PEMFC Stack replacement

In both cases, the PEM fuel cell is replaced two times during the total project lifespan of the ship (18 years). The total cost for these two replacements is same taken same for both cases **18, 76,598** $.In case A Stack replacement cost Is in the range of 2.16 % to 5.12 % and it is ranging from 3.57 % to 6.68 % of the total project cost.

4.3.4 Carbon tax

A carbon tax is only applicable in VLSFO-ICE scenarios in both cases. In case A carbon tax is 13.28 % to 23.05 % and in the case of B, it is ranging from 17.10 % to 30.89 % of the total cost of the particular propulsion system. As stated earlier carbon tax will play a crucial role in hydrogen economy transformation. It is clear that the EU is going to impose a higher carbon tax in the near future this could become a deciding factor when choosing a propulsion option for ships. For the hydrogen propulsion system to be favourable in each case, the selected data of carbon price (Average and high) should be increased between 15 to 20 times for case A and 8 to 13 times for case B.

4.3.5 Total NPV

The total overall NPV cash outflow throughout the project life of the ship investment for green hydrogen propulsion system including both PEMFC and ICE for each scenarios followed a decreasing trend from case A=2022 to case B=2030.This decrease in total cost(NPV) is mainly due to lower cost of green hydrogen in case B compared to case A.The range of total cost drop in case B compared to case A is in between 9.17 % – 42.32 %, with highest drop of 42.32 % in CGH2-PEMFC HIGH H2 PRICE SCENARIO (A.23) and the lowest drop of 9.17 % in LH2-ICE LOW H2 PRICE SCENARIO (A.31).In contrast to that, the VLSFO-ICE propulsion system followed an increasing trend in total NPV cost when compared case B=2030 with case A=2022.The increase in total cost is mainly due to high carbon tax and high ICE cost .The range of total cost increase in case B compared to case A is in between 7.37 % - 17.87 % ,with highest increase of 17.87 % in AVG VLSO PRICE(A.52) + HIGH C TAX and the lowest increase of 7.37 % in HIGH VLSO PRICE (A.53)+ LOWC TAX.

Chapter 5. CONCLUSION

This part of the paper will briefly summarize and conclude each feasibility criteria of the main research question and then conclude with the overall objective of this paper. It will also discuss the limitation of this paper and recommendations for future research.

5.1 Technical feasibility conclusion

The key finding or conclusion of the Technological feasibility analysis of green hydrogen as a marine fuel in inland shipping: Green hydrogen is created using a well-developed method called electrolysis and by a device called an electrolyzer. Different forms of electrolyzer technologies, such as PEM, AEM, Alkaline, and solid oxide electrolyte, are being created and growing at a rapid rate. Similarly, when hydrogen is employed as a fuel(LH2/CGH2), fuel cells are used as energy converters on board the ships. Another hydrogen propulsion alternative for a ship is ICE, which can use both liquid and compressed hydrogen but has got few technological limitations. Until the hydrogen infrastructure is fully constructed, hybrids or dual fuel engines can be an alternative option in the case of the ICE propulsion system. Hybrid ICE engines can use the current gasoline infrastructure for bunkering or fuelling. The infrastructure for green hydrogen is currently in place, but in order to scale up for the hydrogen economy, the network and ecosystem must be expanded further. When solely considering the inland shipping sector, Europe has the renewable energy source capacity to power the whole fleet of inland ships with hydrogen fuel, but there are also needs from other sectors that must be met, therefore RES and electrolysis have to be expanded further to meet the overall demands. Europe's RES power potential is more than overall electricity consumption and the share of hydrogen generation via electrolysis, So Europe needs to just explore this potential to achieve the required capacity. There are so many hydrogen hub nations in Europe, that the reliability of green hydrogen as a fuel for inland ships is very high. Hydrogen has been utilized in industries for a long time, and while storage technologies and procedures for both liquid and compressed gas hydrogen have been developed, the system remains expensive when compared to other fuel storage systems. The number of designated hydrogen bunkering stations must be increased to provide a consistent supply of hydrogen for extended trips. Green hydrogen transport and distribution systems are available, which include cryogenic liquid tankers, compressed gas cylinders, hydrogen pipelines, hydrogen ships, rail transport, and the option of blending with natural gas. At the moment, designated hydrogen pipeline networks are not fully developed throughout Europe, and this has to be extended further for a complete transition to a hydrogen economy.**so to sum up we can say that the technology infrastructure is ready for green hydrogen implementation as fuel in inland ships but yes advancement in technology is still needed for faster and efficient growth. Creating a reliable hydrogen system is the primary technological obstacle.**

5.2 Environmental feasibility conclusion

The following is the key finding of the Environmental feasibility analysis of green hydrogen as a marine fuel in inland shipping: Green hydrogen is one of the solutions for carbon-free emissions, and it can help Europe meet its future emission targets. The paper discussed the life cycle evaluation from well to wheel for green hydrogen as fuel in three sections: 1. GHG emissions from renewable energy resources, 2.GHG emissions from electrolysis, and 3.GHG emissions due to ship use of green hydrogen as fuel. According to the findings, RES emits 90-99% less GHG and generates 70-90% less pollution than alternative coal-fired choices. Electrolysis driven by RES produces extremely low emissions, ranging from 0.5 to 1 kg co2eq/kg H2 for wind and solar-powered systems, respectively. The utilization of hydrogen in fuel cells emits no carbon dioxide, just electricity, water, and heat. Based on these three segments, it is obvious that using hydrogen as a fuel in transportation on a greater scale will have no negative environmental impact other than improving the current emission situation. This article also performed a freshwater evaluation for green hydrogen generation for electrolysis, and the results show that Europe's inland water region has a significant amount of freshwater reserve for future hydrogen conversion in shipping. **Freshwater requirements for large-scale electrolysis can also be met by alternative water resources such as saltwater, wastewater, and so on via reverse osmosis. Plus, unlike traditional fuels hydrogen is nontoxic so there is no major cause to human health or environment, or wildlife. Thus, we can conclude that environment is ready for the green hydrogen energy transition.**

5.3 Social feasibility conclusion

The following is the primary conclusion of the social feasibility study of green hydrogen as a marine fuel in inland shipping: This paper evaluated the social feasibility of using green hydrogen based on its safety and regulatory framework. Because of its strong diffusivity, high buoyancy, extremely flammable range, invisible flame, low ignition points, and quick burning rate, hydrogen poses major safety risks when utilized in a ship system. Understanding how the characteristics of hydrogen and hydrogen derivatives affect possible risks is crucial for ensuring safety. It is far more advantageous to implement appropriate risk reduction measures at the design level and ensure that safety standards do not deteriorate over time. Many safety considerations related to green hydrogen usage are currently addressed and incorporated on ships with the support of classification societies, safety standards such as gas detection and alarm system, proper arrangement for gas venting, safety values and plugs for the storage system, fire detection with thermal sensor and extinguishing system, and so on. Safety rules and regulations are in place for hydrogen use aboard ships, however, as technology advances, the safety systems must be improved and evaluated for degradation in order to avoid future accidents. When it comes to the legal framework, it is the foundation for ship safety; it establishes requirements for ship construction, equipment type, operating rules, and everything else linked to safety. National and international regulatory organizations in Europe have already developed, monitored, and continually assessed the legal framework for the effective application of green hydrogen as a fuel in inland waterways. Various major classification societies, including as DNV, Lloyds Register (LR), Bureau Veritas (BV), ABS, and others, have also established standards and guidelines for the installation of green hydrogen propulsion systems on ships. There are a few more worldwide safety standards issued by the International Electrochemical Commission (IEC) and the International Organization for Standardization (ISO) (ISO). **To conclude, while the safety and regulatory framework are in place for green hydrogen application on inland vessels, large-scale adoption of hydrogen in shipping requires continuous monitoring and improvement.**

5.4 Economic feasibility conclusion

The primary finding of the cost-benefit analysis of green hydrogen as a marine fuel for inland commerce are as follows: The thesis analyses the net present value (NPV) of cash outflows associated with the different propulsion system of the ship "energy observer 2" under two different investment scenarios: case A, in which the investment is made in 2022, and case B, in which the investment is made in 2030.In both the cases the most cheapest option for propulsion was VLSFO-ICE though the difference in total cost reduced in 2030 invest case compared to 2022 case. In both the cases, The cost of producing hydrogen was the single largest expense for the ship throughout its entire project life and it remains a significant barrier to entry, especially for electrolysis-based production. Both electrolyzer CAPEX and electricity price are key components contributing to this cost . As a result, broad use of hydrogen as a fuel in the maritime sector is not anticipated in the coming years, especially given the prevalence of cheap, low-cost fossil fuels. However, There will always exceptions when a situation might be economically feasible even without the generalization. A hydrogen propulsion system with zero emissions may be the best alternative if the price of hydrogen drops, subsidies increase, and the cost of fuel cells drops. Increasing the carbon tax might also potentially influence the decision choice to build ship propulsion systems.   When comparing Liquid hydrogen (LH2) with compressed hydrogen (CGH2), the compressed gas hydrogen system is superior owing to its reduced CAPEX cost. Liquid hydrogen systems require expensive cryogenic hydrogen tanks, heaters, and evaporators. **The ship owner's dream of achieving a zero-emissions target and hydrogen propulsion as the preferred investment option is not impossible without additional subsidies, lower hydrogen fuel prices, lower hydrogen storage costs, lower PEMFC costs, and lower electrolysis costs, as well as an increased carbon tax on the use of fossil fuels.**

5.4 Overall conclusion

Green hydrogen has been identified as an alternative for meeting zero-emission targets; however, comprehensive research outlining various and critical elements related to the implementation of this specific fuel has not been done in detail in previous research to determine its viability in European inland shipping**. The purpose of this study report was to determine the viability of green hydrogen as a marine fuel in European inland transportation**. This study addressed and analyzed the feasibility criteria of green hydrogen as a fuel from four primary perspectives: technical, environmental, social, and financial viability. To acquire a response to the major and sub-research questions of this article, each perspective was extensively studied in distinct chapters with an economic analysis on a case study ship. The methodology section was applied to a case study of a multipurpose cargo ship in an inland waterway in Europe in order to highlight the major elements and variables that might impact the investment decision for the choice of propulsion system. The fundamental conclusion of this paper is that green hydrogen fuel can be successfully used in inland shipping provided existing constraints are overcome and bottleneck concerns connected to hydrogen use aboard ships are efficiently handled. Though a framework for hydrogen usage aboard ships exists, more comprehensive development is required for full adoption in the marine industry. This limitation can be overcome by establishing a hydrogen synergy network around Europe's inland waterways, as well as providing the necessary green hydrogen ecosystem for hydrogen production, fuel cell development, efficient electrolysis, the availability of cheap renewable electricity, effective safety and operational standards, bunkering, storage, distribution, and other parameters discussed earlier. As stated previously, fuel costs are a significant financial component in the project life of a ship and play an important function in the selection of propulsion systems on ships. The cost of hydrogen fuel and electrolysis will be one of the decisive criteria for hydrogen economy in the coming future. The conclusion section of this article will be explored in further detail in relation to the analysis results of the study from several feasibility perspectives.

This thesis has detailed the negative environmental effect of marine transportation and why hydrogen can be a solution for Europe's zero-emission goals. As previously said, hydrogen is the most plentiful element on the planet and owing to its qualities and zero-emission energy conversion, it is regarded as one of the potential fuel choices for ships. The European Union's efforts toward decarbonization and the hydrogen economy are critical in this new era of energy transformation. The EU has implemented several hydrogen-supporting policies, packages, and initiatives to meet the GHG emission reduction objective of 55% below 1990 levels. Maritime transportation contributes significantly to overall GHG emissions in Europe, and obligatory action is essential for environmental improvement. Green hydrogen, a carbon-free fuel, has the potential to become a popular fuel for ship propulsion. Government policies and financing will be crucial throughout the early phase of the hydrogen energy transition in Europe's environment. Policies and funding that indirectly assist the use of hydrogen systems on ships, such as a high carbon tax on fossil fuel usage, high ICE costs, and so on, are just as significant as direct policies, such as subsidies for electrolyzers, fuel cells, storage, and new hydrogen ships.

The progress of decarbonizing in the maritime sector is slow and has stalled in recent years. A universal carbon tax is extremely unlikely to be implemented due to competing international interests; a carbon tax that applies solely in Europe would only put Europe at a vulnerable position. Given the impossibility of foreign competition in the inland shipping industry, this carbon tax is quite appropriate. It's also a great place to develop hydrogen application technologies in anticipation of brighter days ahead. Our case study demonstrated that a suitably high (future) carbon price is one of the critical factors to the economic viability of the hydrogen-fuelled ship compared to the ICE-powered ships using VLSFO. Investors seeking to invest into this technology should have a clear vision on the specific market circumstances they will confront, thus it is crucial that Europe provides a robust legislative framework, including carbon taxes and subsidy programs for hydrogen ecosystem and network in inland shipping.

5.6 Limitation of this Thesis

This research paper results and discussing, however, is subjected to few major limitations which are as follows:

Accuracy of data: Accurate data prediction values for green hydrogen fuel cost, VLSFO fuel cost, carbon tax, PEMFC cost and ICE cost for different scenarios in every year from 2022 to 2050 are not available and it is subjected to differ from actual case values. For data prediction for each year, we have used extrapolation method.

Limitation of scope: This paper research is restricted to only Inland waterway shipping in Europe and specific routes between Rotterdam and strasbourg.

Number of components in cost structure: We have taken into consideration a limited number of cost component for capex for cost analysis of NPV unlike in real life situation where there are larger number of components involving total cost.

Project life: In our thesis we have taken 18 years as average project life of investment, which can be different for all ship depending on the condition in which it is sailing.

NPV cash inflow: NPV cash inflow from freight rates /charter parties contract are assumed to be same for all scenarios, which might change depending on various uncertainty such as global GDP, circular economy and demand /supply of goods.

Assessment assumption: Assessment of feasibility of green hydrogen as a fuel in inland ships done in literature review part is based on available documents, papers and reports at present situation. In future with experience in green hydrogen technology in shipping some of technologies might get obsolete/upgraded or newer advance technology could introduced which can further support the adoption of hydrogen as a fuel. More stringent legislation rules could be imposed on use of hydrogen on use or unprecedented Environment change effecting the green hydrogen production. All these uncertain events might influence the results of this paper and ultimately the investment in ships propulsion system.

Choice of measurement of economic analysis: This paper has used the NPV analysis for comparing the ship's propulsion system investment cost. In actual scenario a company could use a different tool for cost analysis based on their requirement and could get a different result than stated in this paper.

Maximizing the company profit: Economic analysis is one part of this paper and analysis was not done to maximize the company's profit .Due to vast range of uncertainty events while investing in new ships will always require a more specific and detail approach and cost structure ,whereas, this paper did a general economic analysis at two different timeframe ships propulsion investment.

5.7 Recommendations for future research

This study lays the groundwork for determining the viability of green hydrogen fuel in several European inland routes. This article may also be used to evaluate green hydrogen as a fuel in various other shipping segments both inside and outside of Europe, such as short-sea shipping in Europe and overseas shipping. This research can aid in a more complete investigation of the economic feasibility of the various propulsion systems mentioned in this article, allowing the optimal match for a green hydrogen economy to be attained. With this paper technique, a new hydrogen ship project with diverse power requirements can be examined and a basis concept for the best fit investment ships propulsion system in can be determined.

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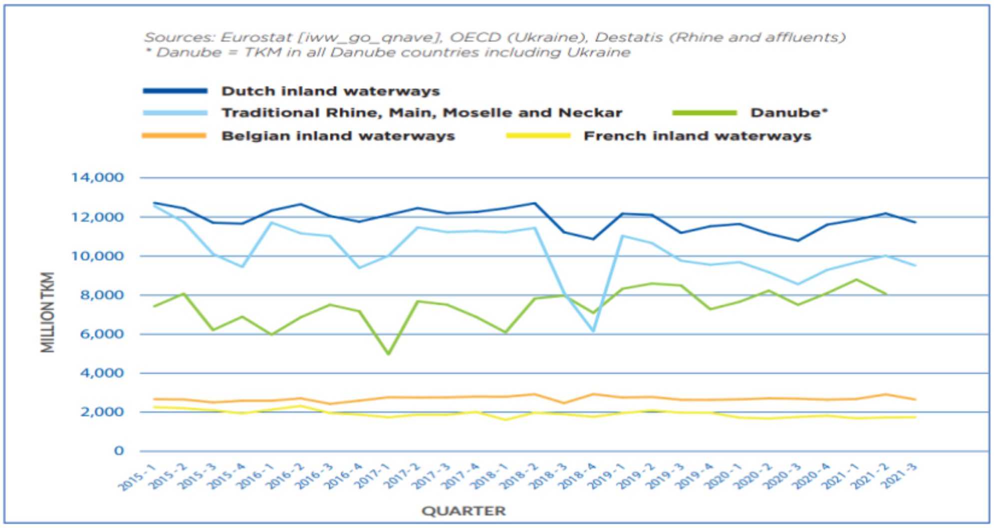
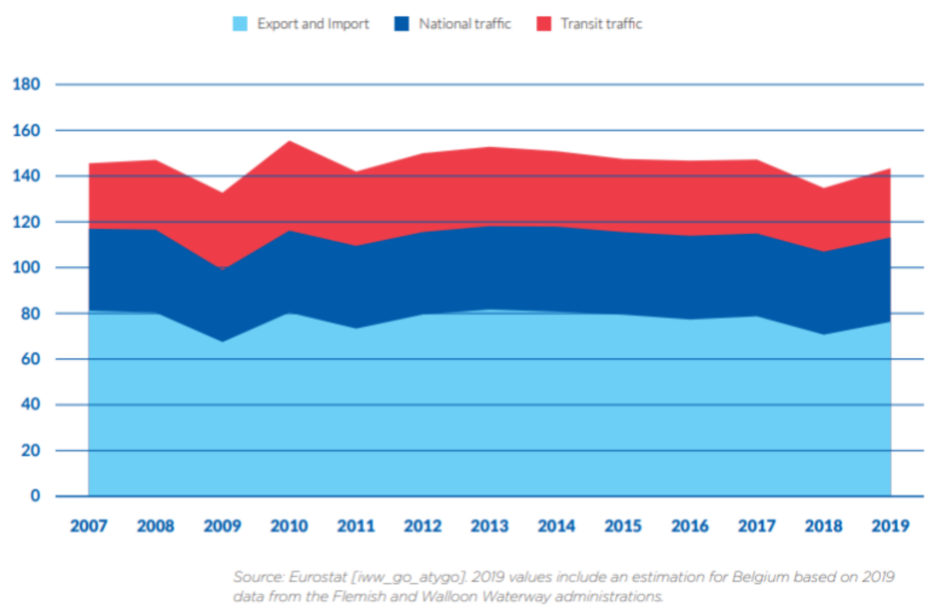
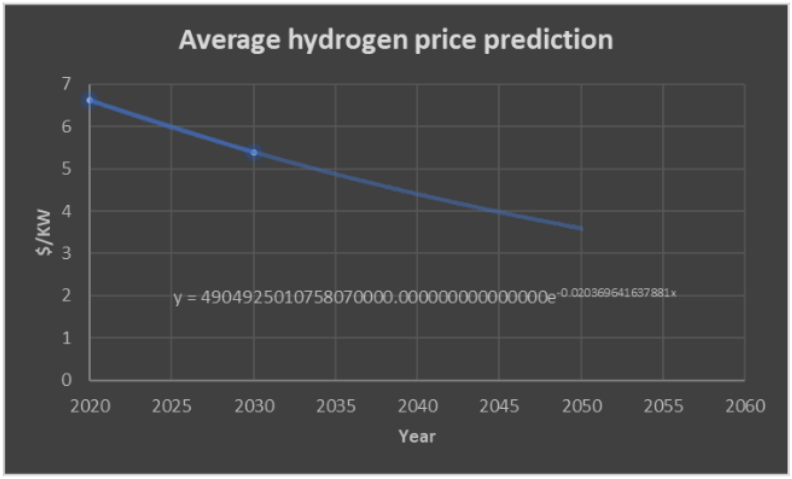
APPENDIX



APPENDIX FIGURE 1: Performance of inland water transport(IWT) in Europe by region and quarter(in million TKM)



APPENDIX FIGURE 2: Yearly inland transport performance in Europe(in billion TKM



APPENDIX FIGURE 3 - High Hydrogen Price Prediction

APPENDIX FIGURE 4 High Hydrogen Price Prediction