Louvain School of Management

How Can Hydrogen Be Introduced in the Maritime Sector?

Energy for boats at berth: a first step

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Abstract

The fight against climate change and air pollution has many fronts and shipping ports is one of them. The fuel oil used in diesel engines on ships is particularly polluting and the sector's GHG emissions account for 2.9% of global emissions. Ships in ports are responsible for one fifth of these emissions. Regulations and incentives from governments and port authorities are forcing shipowners to look at solutions to decarbonise their fleets. According to institutional actors, green hydrogen solutions would have the best prospects as a replacement against traditional fuels. However, the time for long-distance ships powered by fuel cells or hydrogen-powered combustion engines has not yet come. Research and development are still in progress, but improvements in ports can go faster, with innovative technology playing an important part.

The object of this Master’s thesis is to look at how hydrogen can be implemented in ports through a specific project: a “Power Barge” which uses hydrogen as a fuel to supply electricity to ships. This project is the property of the Compagnie Maritime Belge (CMB), a major player in the global maritime industry.

To assess the feasibility and perspectives of the project, the thesis performs a two-level approach. The financial analysis shows a promising future for this technology. It offers a slightly advantageous cost of electricity production when compared to other sources. The broader approach of a SWOT analysis allows the identification of elements that have an influence on the project. It reinforces the conclusion of the financial approach even if it highlights particularly all the current uncertainties related to the hydrogen production and distribution chain, even more so if it is green. However, negative elements appear to be strongly offset by the mandatory "zero carbon" objective, the perspective of a relative increase in the price of carbon fuels, the prospect of the availability of green hydrogen, the framework set by the authorities and, above all, the dynamism of the innovation ecosystem supported by the company.

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List of Abbreviations

ABB	ASEA Brown Boveri
ABC	Anglo Belgian Corporation
CO_2	Carbon dioxide
GDP	Gross Domestic Product
Genset	Generator and an engine combination
GHGs	Greenhouse Gases
H_2	Hydrogen
ICE	Internal Combustion Engine
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
MWh	Megawatt hour
NECA	Nitrogen Emission Control Area
NO_x	Nitrogen Oxides Emission
OECD	Organisation for Economic Co-operation and Development
$PM_{2.5}$	Particulate Matter (diameter 2.5 micrometres or smaller)
PM_{10}	Particulate Matter (diameter 10 micrometres or smaller)
Ro-Ro	Roll-on/Roll-off
ROPAX	Roll-on/Roll-off Passenger
SECA	Sulphur Emission Control Area
SMR	Steam Methane Reforming
SO_x	Sulphur Oxides Emission
SP	Shore Power

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1 Introduction

1.1 Reasons for this paper

Fossil fuels must be eliminated with an objective of neutrality by 2050, to avoid irreversible damage to the environment through GHGs (Paris Agreement, 2015). The Paris Agreement, with its goal to keep the rise of the global temperature to well below 2°C, compared to pre-industrial levels, is the main driver for maritime companies having to find less-polluting solutions in terms of fuel. Like other sectors, the merchant navy is aware of this and must evolve.

One of the solutions most frequently put forward by experts is to replace fossil fuels with hydrogen (Timperly, 2020). This (r)evolution can only take place gradually. It is assumed that a step that could be taken fairly quickly would be to supply energy to ships at berth[1] from barges equipped with hydrogen-powered electric generators. The financial and global analysis carried out in the paper at the start of the "CMB Power Barge" therefore seeks to clarify the feasibility and prospects for the technical development and realisation of this project as a step towards the use of hydrogen in maritime transport.

The purpose of this text consists in exploring this particular “CMB Power Barge” project. Findings about financial aspects and competitive environment will be discussed to evaluate the feasibility of hydrogen introduction in the maritime environment.

1.2 Data collection

Concerning the search of background and fundamental information, scientific articles, publications or European legislations constituted the basis of the background search.
Data from the Port of Antwerp-Bruges regarding the time of arrival and departure of the vessels in the harbour and their respective CO_2 emissions (see appendix A), were utilised for the financial analysis.
In addition to that, knowledge from the CMB.TECH department was of a great help. Documents regarding information about the technology of the CMB and its partners, were crucial in the achievement of the electricity production cost calculations of the Power Barge.

[1] A ship is assigned at berth when it is at port mostly for loading/unloading its freight/passengers.

1.3 Method for analysing the data

Two methods have been used for analysing the data. The first one is a financial forecasting of the production cost of electricity of the Power Barge Project. The second one is a strength, weaknesses, opportunities and threats (SWOT) analysis of the Power Barge Project. The SWOT analysis uses the results of from the electricity production costs and aspects from the background search.

The financial forecasting compares the cost of the electricity production of the Power Barge with the cost of the present solutions for ships to get their electricity from (diesel generator and shore connection). The results were obtained mainly with the treatment of the data from the port of Antwerp-Bruges. Analysing the electricity demand (of ships at berth) and determining the best cost option for the Power Barge, allowed to find a production cost for the electricity generated by the Power Barge.

The SWOT analysis is a tool that was developed in the 1970's by Albert S. Humphrey[2]. Very appreciated by marketing departments nowadays, it allows to measure the strengths and weaknesses of a project and also to evaluate the opportunities and threats in its environment. It gives a general overview of the potential success of a project or proposition.

By using these two different tools, a critical view is addressed on the question of hydrogen as an electricity supplier for ships at berth.

1.4 Changes in the maritime sector

Showing the importance that ships have had over the world, statistics demonstrate that at least 80% of all the objects that are bought on this planet, are transported by ship (Pacek, 2022).
In addition to the shift from sail to diesel, there have been many changes in the recent maritime sector that have led to the current situation. The major developments are discussed in the following pages.

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[2] American management and business consultant Albert S. Humphrey (1926-2005) was specialised in organisational management and cultural transformation. Consulted on June 10th 2022 from: https://en.wikipedia.org/wiki/Albert_S._Humphrey

A major change that has shaped maritime traffic is the Suez Canal. According to the International Maritime Organization (IMO)[3], ship's routeing appeared in the late 19th Century (1898) to make sure to reduce accidents due to the growing flow of passenger vessels. By looking at the main routes in the 19th Century and comparing them to the ones of the 21st Century, a shift from Europe-America route to the Asia-Europe and Asia-America routes, is observed.

The following images show the global shipping routes in the 19th century and the 21st century respectively:

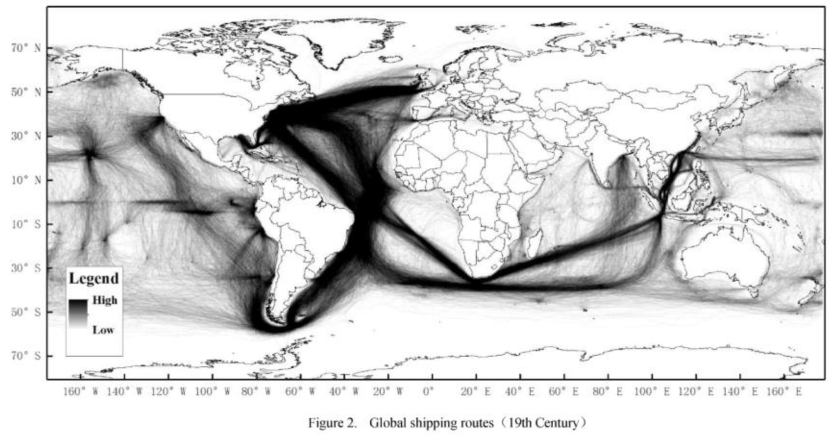

Figure 1: Shipping routes in the 19th Century

Source: Hou, 2015

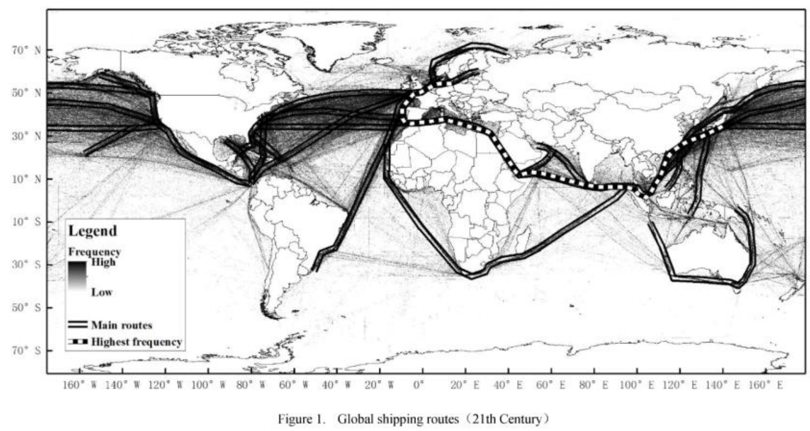

Figure 2: Shipping routes in the 21st Century

Source: Hou, 2015

[3] The International Maritime Organization is a United Nations' specialised organisation in charge of maritime regulation.

The second figure clearly shows the extent to which the Suez Canal has developed the maritime transportation, such as the Panama Canal. Suez passage is now the busiest trade route on the planet. It brought the benefit of not having to go around Africa to get to Asia from Europe, and vice versa. Finished in 1869, this passage greatly simplified the transit of goods around the planet (Hallbert, 2018).

Another major change in the sector concerns the containers. Containers have only existed since 1956 (Levinson, 2006). Before then, it could take up to three weeks for ships to load or unload their cargo (Levinson, 2006). The newspaper The Economist even stated: "The shipping container has been more of a driver of globalization than all trade agreements in the past 50 years together." (The Economist, 2013). Containers have facilitated the transport of goods to an incredible extent.

Figure 3: First containership setting sail on April 26 1956
Source: Financial Times, 2008

1.5 Today's maritime environment

1.5.1 Vessels and companies

Figure 1 and 2 show the increased traffic on the seas and oceans. Certain roads are even too busy and sometimes generate huge traffic jams. One of these happened in the Suez Canal on the 23rd of March 2022, where a large container ship got stuck sideways in the canal and made it impossible for other vessels to take that route. This cost millions to companies and according to the BBC, about one million barrels of oil and roughly 8% of LNG take this route every day[4].

[4] BBC webpage consulted July 25th 2022 from: https://www.bbc.com/news/world-middle-east-56505413.

The Canal was blocked for nearly a week which meant there were tremendous financial repercussions for shipping firms.

To get a better view of today's maritime sector it is important to look into what type of freight travels across the globe.

These are the main different types of cargoes:

1. Liquid and dry bulk cargo: The liquid carriers transport car fuel, fruit juice, different edible oils whereas the dry carriers, as their name states, move materials like coal, sugar, coffee, etc. The dry bulk transporters must remain without any moisture, otherwise there is a risk that the whole cargo could be ruined.
2. Refrigerated food cargo: These consist of perishable aliments like dairy products or vegetables. They require a lot more energy to keep the temperature low.
3. Tankers and oil carriers: They are the most vital vessels when it comes to fossil fuels. They transit the oil, the liquefied natural gas (LNG) but chemical tankers also exist which carry chemicals (e.g., fertilizers).
4. Passenger ships (ferries): Ferries, cruise ships and other Ro-Ro[5] vessels represent a large transit of people and mostly vehicles from one port to another.
5. Container ships: Container ships are cargo ships that transport all of their goods in container. They carry all types of goods and have facilitated the logistics in harbours all over the world, by their practicality.

Some main maritime companies over the world and how many TEU[6] they move are listed below:

1. Maersk: Founded in Denmark in 1904, it operates in more than 130 countries, this enterprise employs over 76,000 employees and move more than four million TEU.
2. MSC (Mediterranean Shipping Company): This shipping company also has more than 70,000 workers for them and ships over three million TEU.
3. Cosco Shipping (China Ocean Shipping Company): China has the ownership of this company which employs 130,000 people and ships over three million TEU.
4. Hapag-Lloyd: Operating from the biggest port in Europe (Hamburg), this company is connecting 128 countries over the globe and ships a bit less than three million TEU.

[5] Short term for Roll-on, Roll-off, it describes the way that the products are loaded/unloaded on the vessel. In most of the cases, they refer to ferries transporting cars or trucks.

[6] In shipping vocabulary, a measuring value called TEU (twenty-foot equivalent unit) which corresponds to the dimension of a standard twenty-foot shipping container, is commonly used.

5. Evergreen: Present mostly in the Far East and the Southern hemisphere, this corporation based in Taiwan has over one million TEU going to and from 240 ports over the world.
6. CMB (Compagnie Maritime Belge): Based in Antwerp-Bruges and founded in 1895, this old shipping line used to connect Belgium to the Congo. They have activities in Singapore, Hong Kong, Tokyo, Hamburg and work in all the different maritime sectors (containers, bulk carriers, tankers, etc.). This company will play a vital part in this thesis and will thus be further looked at.

1.5.2 Antwerp-Bruges, second largest port of Europe

According to their website[7], the Port of Antwerp-Bruges is Europe's second biggest port, with over 300 liner services to over 800 locations, assuring global connectivity. They process about 290 million tonnes of international marine freight each year and are home to Europe's biggest integrated chemical cluster.

The following figure, taken from Marine Traffic, the world's leading provider of ship tracking and maritime intelligence, gives an insight of the types of ships and their respective proportions in the port of Antwerp-Bruges.

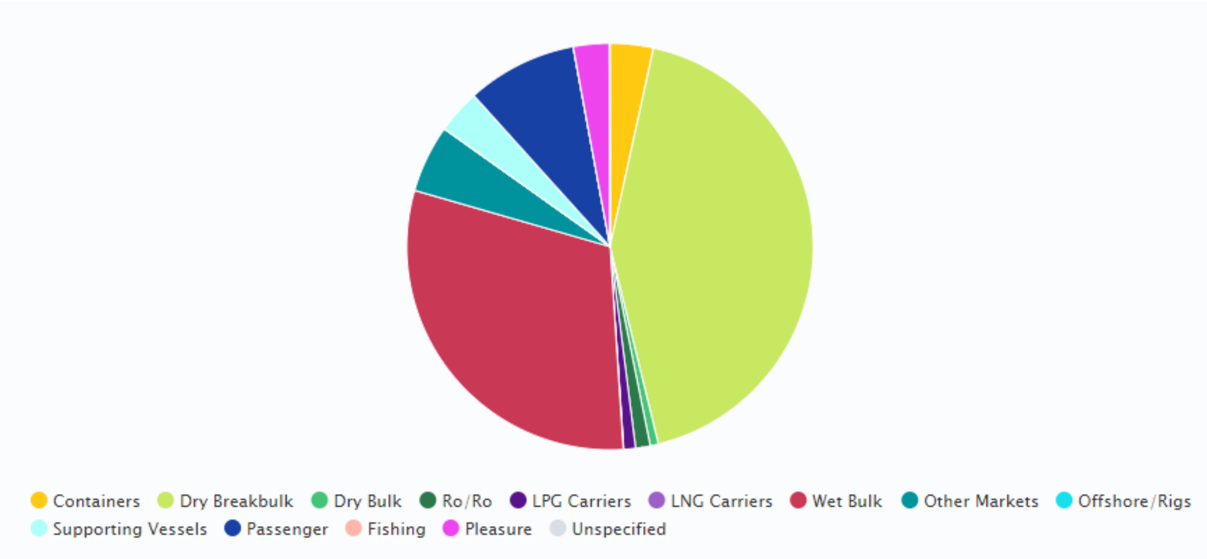

Figure 4: Average types of ships in port of Antwerp-Bruges (July 2022)

Source: Marine Traffic[8], 2022

[7] Consulted on July 24th 2022 from: https://www.portofantwerpbruges.com/en/our-port/world-port
[8] Consulted on July 25th 2022 from: https://www.marinetraffic.com/en/ais/details/ports/117?name=ANTWERP&country=Belgium#Statistics

The dry bulk carriers represent nearly half of the amount of ships transiting in the Port of Antwerp-Bruges. Combined with the liquid carriers ("wet bulk"), they make approximately three quarters of the total ships berthing.

Refrigerated cargoes, often englobed in the container ships, here represent a bit more than 3% of the whole freight.

Tankers and oil carriers, in this case, are not very numerous with only LPG Carriers and LNG Carriers (less than 1% of the total).

Finally, ferries, which in this case account for Ro/Ro and Passenger vessels, represent 10% of the amount of ships.

The Port of Antwerp-Bruges is mainly an entrance to North-Western Europe for a lot of fossil fuels (oil, gas) and for dry goods.

1.5.3 CMB a major player in maritime transport

The following paragraphs consists of information about the firm taken from their website[9].

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The CMB was anciently called the CMBC (Compagnie Maritime Belge du Congo). The CMBC was first established when King Leopold II decided to create a direct shipping line between Antwerp and the Congo in 1895.

Then, in 1911, it became possible for Belgian people to take part into the shares of the ownership. During the First World War, several ships of the of the CMBC are allocated to supplies and equipment. One vessel, the Elizabethville, is sunk to the bottom of the sea by the German troops. After the war, the company decides to diversify and keeps making investments in new ships for cargo transport. In the year of 1925 the CMBC continues to invest in passenger shipping which allows them to expand. In 1930, the CMBC becomes the CMB after acquiring Lloyd Royal Belge, a Belgian shipowner. As of then, they start connecting ports from Antwerp to ports in Africa, America and the Far East.

After this, the Second World War broke out and few transports remained possible from the Port of Antwerp, due to the German control of the country. At the end of the war, 63% of the vessels from the company had been destroyed. As of the 1950's, the shipping had mostly recovered and by the mid 1950's the CMB possessed a fleet of 27 vessels with a deadweight capacity of

[9] Consulted on July 10th 2022 from: https://www.cmb.be/en/history

more than 200,000 tonnes. Unfortunately for them, in 1960 Congo declares its independence and with the increasing air freight competition, the company took another big hit. However, the CMB never stopped its activities. On the contrary, they decided to invest in dry bulk shipping and thanks to the then-new standard for container shipping (released in 1968), they were able to transport the goods, all over the globe, in a more optimal way.

In 1975, CMB buys the company Bocimar, a major player in bulk carriers. The bulk carrier business is expanding during these years and many investments in new vessels are incentivised by Jacques Saverys, the General Manager of CMB. In 1991, his nephew, takes over control of the company. By the mid 1990's, CMB's turnover is quite diversified with revenues coming from liner service, port activities, gas, bulk and crude oil. As of 2003, CMB is composed of Exmar, Bocimar dry bulk and Euronav crude oil shipping. In 2007, Bochem adds up to enter the chemical tanker market.

Finally, in 2015, CMB Technologies (CMB.TECH) is created in the group. This department's target is to innovate and develop new technologies to improve costs and comply with growing emission regulations regarding pollution. The same year, the company acquires Delphis, a container shipping business.

1.5.4 CMB's departments and CMB.TECH's portfolio of hydrogen solutions

This section's focus is on the CMB's portfolio of hydrogen solutions for providing energy. The first subsection will detail the different departments within the CMB company and what their functions and importance are. Then the focus will be shifted on the CMB.TECH which carries the Power Barge Project.

Here are the different departments of the CMB:

1. Bocimar: Primary focus of this branch is the dry bulk carrier business.
2. Delphis: Primary focus of this branch is the container ship business.
3. Bochem: Primary focus of this branch is the chemical tanker business.
4. Maritime Campus Antwerp (MCA): Consists of a community where business, technology and knowledge connect to make the maritime industry a better place.
5. CMB.TECH: Primary focus of this branch is the design and operation of new solutions in relation to hydrogen and ammonia.

Here are representative maritime projects the CMB.TECH department details on its website[10]:

1. Straddle Carrier: Straddle carriers are vehicles that are used for transporting the containers in ports. They are the cause of a lot of pollution within ports due to the high number of them. One solution would be to retrofit the combustion engine to allow having a dual fuel engine working with hydrogen and diesel. This would drastically reduce the emissions. Some studies from CMB.TECH show that 286 tonnes of CO_2 could be saved per vehicle per year.
2. Hydrogen genset[11] park: The idea is to install hydrogen genset to ensure the delivery of clean electricity to any type of customer, even to the grid. This concept would allow industries to connect to this hydrogen park or even ships which require electricity when at berth.
3. Mobile shore power solution: In consists of having a medium speed genset (working on hydrogen) that would be capable of supplying a large sea going ship with green electricity from the shore. It has many advantages like being simple to deploy next to the vessel. Also, it doesn't require having a frequency transformer[12] which is common with shore connection usually.
4. Maritime and public hydrogen refuelling station: This station offers hydrogen for many different applications and will allow the local use of it, making it much easier for the other projects mentioned to get their supply of hydrogen. This project is actually already in place in 2022 (Antwerp, Belgium).
5. Hydrogen Power Barge: This project is the main focus of this thesis and will be looked at in detail in further sections. It consists of a mobile electricity supplier providing green electricity to ships at berth using hydrogen as an energy source.

1.5.5 Global warming and pollution

According to the European Commission, global shipping emission are responsible for 2.9% of global emissions caused by human activities, with scientists forecasting that it will be at least double that number by 2050 (European Commission, 2018). According to Wann (2018), greenhouse gases in shipping are projected to rise by 250% until 2050, from their 2012 levels (Wan, 2018).

[10] Consulted on July 25th 2022 from: https://cmb.tech/
[11] A genset refers to the term generator set which is a generator and an engine combination.
[12] A frequency transformer is used to transmit electricity between two alternating current frequency domains. Consulted on July 27th 2022 from: https://en.wikipedia.org/wiki/Variable-frequency_transformer

Carbon dioxide is not the only gas responsible for this ecological disaster. Statistics show that maritime transport is accountable for 18 to 30% of the world's nitrogen oxide pollution and 9% of the entire sulphur oxide pollution (Vidal, 2009)

A relevant fact, is that about 20% of total emissions from ships come from when they are at berth (Moreira, 2016). This is a major problem all around the world. With the incline of using large ferries (e.g., cruise ships) and other vessels, which sometimes stay for a long period of time at berth, a lot of pollutants have been measured in the communities surrounding the ports. For example, Marseille (France) is one of the busiest ports of the Mediterranean with many ferry transits. There have been many complaints about the air pollution from the diesel generators of these vessels by the neighbouring communities (Chrisafis, 2018). Development of multiple shore connections in the harbour now helps to drastically reduce the pollutants, especially the NO_x.

To illustrate these 20% of total emissions coming from ships at berth, the following figure shows the proportion of GHG emissions (in CO_2) by operational phase ('normal cruising', 'slow transit', 'manoeuvring', 'at berth'), per type of ship, in 2018

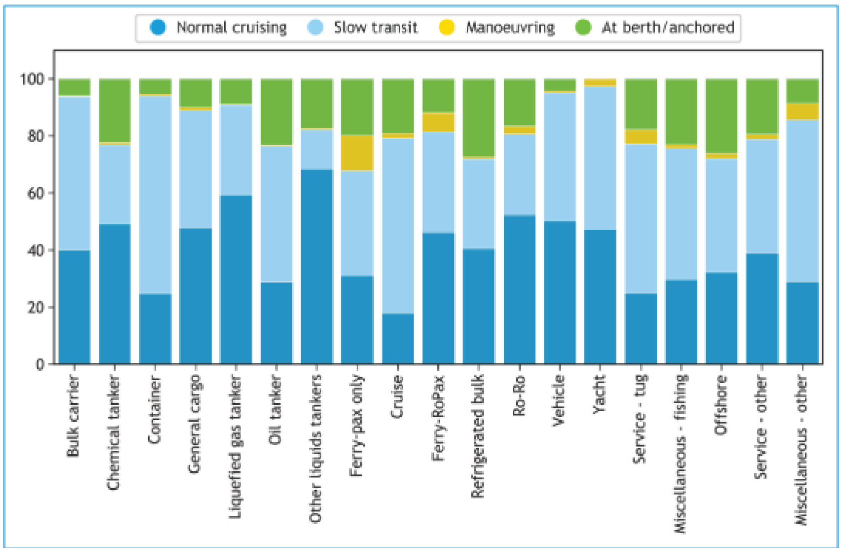

Figure 5: Proportion of international GHG emissions (in CO2e) by operational phase in 2018, according to the voyage-based allocation of emissions. Operational phases are assigned based on the vessel's speed over ground, distance from coast/port and main engine load

Source : Faber et.al, 2020 (IMO)

1.5.6 Port initiatives for GHG reduction

Solutions to reduce GHG emissions in ports already exist. Four are worth mentioning in this section:

- Green port fees: The idea behind green port fees, also known as ecologically differentiated port taxes, is to charge lower rates to ships that emit less pollution. In most circumstances, this implies that the cleanest ships receive a fixed or proportionate reduction in the usual port charge. Twenty-eight of the world's largest ports apply these fees (OECD, 2017).
- Green procurement: Green procurement is defined mostly as an acquisition process in which ecological criteria are used to choose which business receives the service contract in a port[13].
- Green berth allocations: They constitute the policies that ports apply in order to minimise the time of a ship at berth. The less time a ship stays at berth, the less it will emit GHG's.
- Carbon pricing: It is a market system where companies are allowed a certain amount of carbon emissions and if they comply with the pollution regulation, they are able to sell these carbon emissions to other companies which do not comply with the regulations. Therefore, shipping companies have either the choice of making their vessels greener or either have to pay.

More details on these incentives can be found in the OECD document about port emissions and solutions to decarbonisation (OECD, 2017).

[13] The term service contract is the written contract between shippers and ocean common carriers where the shipper commits to providing a certain amount of cargo and the ocean common carrier insures space, transit time port rotation, etc. Consulted on July 27th 2022 from: https://www.law.cornell.edu/uscode/text/46/40102#21

2 Background Search

The background search is divided into three sub-sections. The first section will focus on how hydrogen works as fuel. The second part will inform on the current solutions regarding the issue of how ships get their electricity, when at berth. Finally, the third section will present more data collection on vessel's auxiliary power, the regulations in place, the alternatives to hydrogen as a fuel and some uncertainties on the maritime sector. This will give a better understanding and overview for the Power Barge Project, which will be more closely looked at further on.

2.1 Working with H

The goal of this subsection is to have a deep understanding of hydrogen as source of energy for electricity in the maritime sector.

2.1.1 Story of hydrogen

Hydrogen was discovered in 1766 by Henry Cavendish and has since, been subject to many studies and experiments (Stwertka, 1996). Subsequently, famous names like Lavoisier and Laplace[14] undertook several experimentations on the hydrogen atom. The name "hydrogen" comes from these two people, who discovered that when burned, water was produced.

One historical technology around hydrogen, concerns the zeppelins, these huge dirigibles filled with hydrogen. The idea of transporting people thanks to this technology was emitted by Ferdinand von Zeppelin, a German general, in the beginning of the 1900's (Syon, 2022). This transportation mode thrived during the early 20th Century before the Hindenburg disaster in 1937, where dozens of people died in the explosion of the zeppelin[15]. After that incident, many realised the danger of hydrogen because of its flammability and helium became a safer option for balloons. However, hydrogen is still used for weather balloons because it is cheaper than helium. It is also a great source of production for fertilizers. It is mixed with nitrogen from the air to create ammonia[16].

[14] Pierre-Simon Laplace was a French mathematician and Antoine Lavoisier was a French chemist.
[15] Consulted July 30th 2022 from: https://en.wikipedia.org/wiki/Hindenburg_disaster
[16] Methane form natural gas is transformed by steam process in hydrogen which is mixed at high temperature and pressure with nitrogen from the air to create ammonia. Nitric acid is produced from ammonia by oxidation and in combination with the ammonia, it produces NH_4NO_3 which is the main fertilizer used in agriculture. Consulted July 30th 2022 from: https://www.fertilizerseurope.com/fertilizers-in-europe/how-fertilizers-

2.1.2 Options for the production of hydrogen

There are various options to obtain hydrogen. The classification can be sorted into three different categories, depending on the CO_2 emissions during the fabrication process. Commonly, they are known as grey hydrogen, blue hydrogen and green hydrogen (IEA, 2019).

- The grey hydrogen is the prevalent one. It consists of creating hydrogen with the use of fossil fuels like natural gas or methane. The most common process is called steam-methane reforming (SMR). It is a reaction where natural gas reacts with steam at very high temperature to create hydrogen. Thanks to the abundance of these resources, it is still the cheapest of all three processes. Unfortunately, the reaction liberates carbon monoxide[17] (CO) and carbon dioxide (CO_2), which contributes to global warming.
- Secondly, there is the blue hydrogen. It is similar to the first one with the exception that in this case, the carbon dioxide gets captured in the process and creates carbon monoxide (instead of carbon dioxide) by using a catalyst. The Carbon Capture, Utilisation and Storage (CCUS) method is used to reduce emissions[18]
- The green hydrogen, uses a completely different process, called water electrolysis. As shown on the picture below, the principle is to generate electricity using renewable sources (e.g., wind, solar, tides etc.) and to use this electricity to separate the atoms of oxygen and hydrogen from water to obtain pure hydrogen that can henceforth be stored and transported to any location.

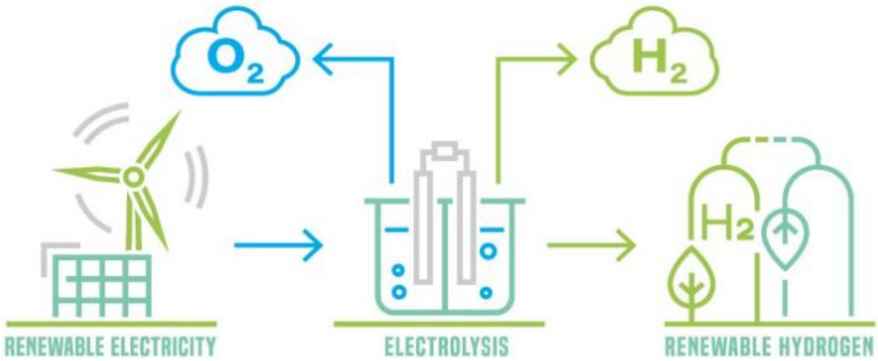

Figure 6: Production of green hydrogen

Source: Innovation News Network[19], 2022

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are-made/#:~:text=For%20nitrogen%2Dbased%20fertilizers%2C%20the,to%20power%20the%20synthesis%20process.

[17] CO is not considered as a direct contributor to climate change. Nevertheless, it reacts in the atmosphere to generate methane and ozone which both contribute to climate change.

[18] International Energy Agency, consulted of August 5th 2022 from: https://www.iea.org/fuels-and-technologies/carbon-capture-utilisation-and-storage

[19] Consulted July 10th 2022 from: https://www.innovationnewsnetwork.com/advantages-green-hydrogen-fuel-clean-energy-transition/22153/

It is important here to notify that more classifications of hydrogen production exist (brown, white, turquoise[20], etc.) but the choice has been made to simply explain the three major ones (grey, blue, green) because many of these are in pilot stage.

2.1.3 Current usage for the maritime transport

The focus in this chapter lies on the different uses that hydrogen can have for maritime transport, especially focusing on the applications in engines.
A brief explanation of the three main different innovations in the hydrogen department for engines follows (CMB.TECH, 2020):

- First, there are dual fuel internal combustion engines (ICE), which consist of using hydrogen and diesel combined. These allow emission reduction of GHG of about 65% to 85%. An example of the functioning of such an engine is detailed in appendix H.
- Secondly, there are mono fuel ICE. These engines only use hydrogen as a fuel and have proven to reduce emissions by 98%.
- Finally, there are fuel cells. These would lead to zero emissions. Nonetheless, the technology here is different, as there is no combustion engine. The principle is to use the chemical energy of hydrogen to react with oxygen and obtain electricity (inverted electrolysis). The major problem of these fuel cells is their price. It is currently not considered a good solution, because of its financial cost. More about these will be detailed in section 2.3.3.

There are some examples of these different technologies that are worth mentioning. Many applications have been tried out for the fuel cell technology. A major player in this domain is Ballard Power System (Ballard, 2019). They study and design fuel cell products all over the world. One of their projects is called H_2PORTS and it consists in the development of fuel cells in the Port of Valencia to provide a good alternative to heavy fuels. HySeas III is also one of their projects. The goal here is to construct a ferry that works only on hydrogen with fuel cells delivering a power up to 800kW.

[20] For example, the turquoise hydrogen uses the pyrolysis process and instead of having CO_2 emissions, black carbon is produced, which is easier to store than carbon dioxide (as in the blue hydrogen). The industrial production of turquoise hydrogen is still in its early stages though.

CMB Hydroville, is the first sea going ship in the world powered by hydrogen combustion (CMB.TECH, 2020). It is a passenger shuttle linking Kruibeke to Antwerp (Belgium) during the rush hour to avoid traffic jams. There are twelve 205L hydrogen tanks onboard allowing the engine to work properly (in addition to two diesel fuel tanks as backup fuel).

Figure 7: Example Hydroville, a passenger ship equipped with a dual fuel internal combustion engine

Source: CMB.TECH, 2020

2.1.4 Transportation perspectives

The aim of this section will be to look at the different ways of transporting hydrogen. Compared to classic fuels like oil or gas, there are more constraints when it comes to hydrogen. The major problem comes from its low volumetric density (71kg/m³)[21]. Therefore, the storage of this substance can demand a lot of space. For this reason, pipelines are required to transfer the hydrogen from the production site to the point of storage or use.

When transported by pipeline, the element can be either compressed or liquefied. According to Ohta (2009), there are many different pipelines for compressed hydrogen. The figure below illustrates the current pipelines that exist in Belgium, the Netherlands and Northern France.

[21] In comparison, the volumetric density of diesel is about 850kg/m³.

Figure 8: Hydrogen pipeline network in Northern France and Belgium

Source: Otha, 2009

The cost of transporting gaseous hydrogen with pipelines is 1.5 to 1.8 times higher than for transporting natural gas (Otha, 2009).

To transport liquid hydrogen by pipeline requires the element to be cooled down to approximately -253°C, which can lead to problems regarding the contraction of the pipeline and infiltrations among it.

It is also possible to transport hydrogen by vehicles like trucks or boats in a pressurized or liquefied form. In these two cases, usually lorries loaded with hydrogen tanks are used. Unfortunately, the amount of hydrogen that can be transported using pressure tanks is relatively low. For the liquified hydrogen, tanker trucks are often used, which make it possible for the hydrogen to be transported long distance. Nevertheless, the energy balance stays quite low (Otha, 2009). A solution to that problem is to use slush hydrogen (a combination of liquid hydrogen and solid hydrogen) at the temperature of -259°C and a pressure of 7.2 kPa. Thanks to this, the density can be 20% higher than for liquid hydrogen (Otha, 2009). In the 1990's, the NASA[22] conducted research about slush hydrogen to be used in space. It revealed that doing so would make the fuel tanks lighter. Nevertheless, some uncertainties like the ability for long term storage or the actual use of it in zero gravity environment, were pointed out (Friedlander et al., 1991). The use of it in the maritime sector is still to be looked at.

[22] NASA is the National and Aeronautics and Space Administration

Another solution to transporting hydrogen, for which the perspectives are higher, can be found by using ammonia (NH_3). Famous for its fertilizer production, this molecule has proven to be good at carrying hydrogen. Its resemblance to LPG (liquefied natural gas) makes it practical to use. In addition, the storage of hydrogen in ammonia can reach up to 121kg/m^3 (CMB.TECH, 2020). Nevertheless, ammonia has several risks that are important to mention. Flammability, toxicity and environmental impact, are the ones worth looking into (Vries, 2019). Yet, comparing ammonia to other fossil fuels like oils or gas, shows that the risk is still smaller, regarding its flammability. This is mainly because the auto ignition temperature is higher than of the conventional fuels. Then again, ammonia is also under a lot of pressure, which brings the risk of explosion if heated. The second and most important risk of ammonia is its toxicity. Studies have shown that the molecule becomes poisonous and even lethal if a person comes into contact with it for more than ten minutes at 2,700 parts per million (Woto-Gaye, 1999). Hence, it is crucial to have good safety protocols in case of leakage or exposure. Finally, the impact of spillage on the environment of ammonia is a big concern. This is already the case in agriculture where ammonia is used as a fertilizer. Excessive concentration of ammonia in soil has a negative impact on the ecosystem (Atanasio, 2019).

One more possibility for transporting hydrogen is LOHC (liquid organic hydrogen carriers). Which is when hydrogen is chemically bonded to the LOHC. One advantage is that it can be stored at ambient conditions. The high storage energy density (1,9 MWh/m^3) is another advantage. Also, LOHC is hardly flammable, non-explosive and not toxic. The idea is promising and has been studied thoroughly by many companies over the world. One of them, Hydrogenious[23], based in Germany shows encouraging projects. As can be seen on the figure below, the idea for transportation is to realise hydrogenation with a liquid carrier like toluene, dibenzyl toluene etc., in order to carry the hydrogen. Once at destination, a dehydrogenation is applied, and hydrogen can be recuperated.

[23]Hydrogenious is a firm created in 2013 which focuses on finding solutions for storing and transporting hydrogen. Retrieved on July 17th 2022 from: https://www.hydrogenious.net/index.php/en/hydrogen-2-2/

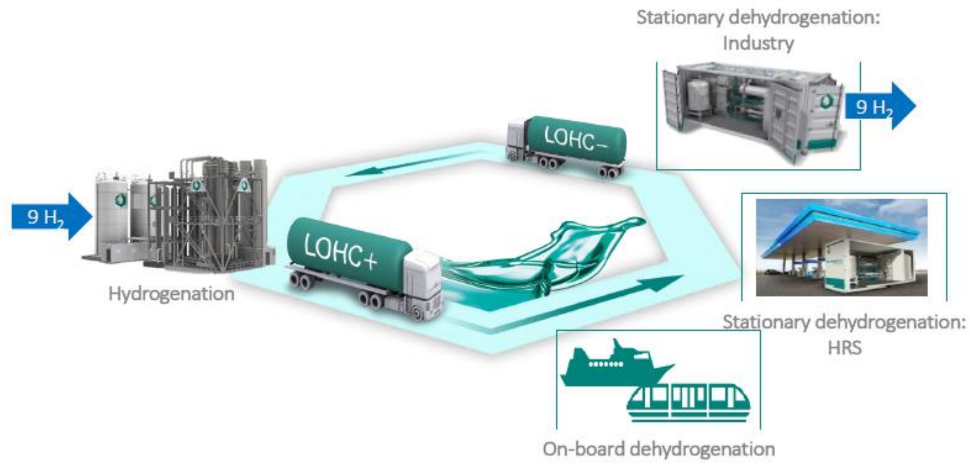

Figure 9: Principle of LOHC transportation

Source: CMB.TECH, 2020

2.1.5 Importance of hydrogen in the maritime environment

In this section, the focus will be on analysing the advantages of working with hydrogen as a fuel, especially as a marine fuel. For this purpose, three points will be addressed.

- Infinite source of energy, in comparison to fossil fuels:

  Firstly, hydrogen has the advantage of being able to be produced by various primary sources. Its origins are natural gas, oil, coal, and electrolysis. Unfortunately, up until now, 96% of all hydrogen production over the world is done through fossil fuels (Balat, 2008). The other four percent are produced through electrolysis, which means there is much space for improvement. The transition towards green hydrogen production is aided by mixing for a certain time renewable and non-renewable sources of energy.

- Secure energy source:

  Secondly, in terms of dependence on other countries, hydrogen can have a real impact. As an example, in 2019, 92% of Belgium's primary energy was imported either in form of oil products, gas or uranium[24]. Taking the example of Russia's war with Ukraine, it shows that Belgium and other European countries are reliant on Russian gas and oil, which has an impact on prices of resources, when there is a conflict[25]. Thus, mixing

[24] Belgian's Prime Minister website consulted 30th July 2022 from: https://www.premier.be/fr/hydrogene-vert-la-belgique-presente-ses-atouts-et-ses-ambitions-a-la-namibie

[25] BBC website, Consulted July 26th 2022 from: https://www.bbc.com/news/business-60642786

different sources of energy, would have the effect of regions being less affected by prices of oil. As an example of this, in February 2022, Belgian's prime minister Alexander de Croo welcomed the Namibian president in Antwerp (Belgium) in order to discuss hydrogen technology. The discussions focus on the potential advantages of producing green hydrogen in Namibia, where the large amount of sunlight could be used for producing electricity and hydrogen.

- Environmental impact of current fuel (more data):

  The use of fossil fuels contributes to the carbon footprint in the maritime sector. For reminder, 2.9% of global GHG's are coming from the maritime sector. A few numbers taken from the CMB documents are worth being mentioned (Campe, 2020):

  - ✓ In average, ships in ports emitted approximately 18 million tonnes of CO_2, 0.4 million tonnes of NO_x, 0.2 million tonnes of SO_x and 0.03 million tonnes of PM_{10}, in 2011.
  - ✓ Shipping emissions lead to significant external costs at ports, amounting to over 12 billion Euros per year in the 50 busiest ports for NO_x, SO_x, and PM emissions.
  - ✓ In the top 100 world ports, over 230 million people are directly exposed to port pollution.
  - ✓ Most port emissions (e.g., CO_2, CO, CH4, and NO_x) are expected to quadruple by 2050.

2.1.6 Experts' positions on hydrogen

According to many experts, hydrogen is the 21st Century energy source (Balat, 2008). As a matter of fact, as Roy Campe, managing director at CMB.TECH, said: "We have to start today to make certain that within 10 years we can already start producing all our ships on a low-emission level. It's not a light switch that you just flip over." (Campe, 2020). This means that it is crucial for companies to invest in research and development so that solutions to fossil fuels and greenhouse gases are found.

Tristan Smith, a shipping emissions researcher at University College London, says that hydrogen is the most promising fuel because in comparison to biofuels, hydrogen is not a limited source of energy (Bankes-Hugues, 2021).

Concerning the green hydrogen production, Timperley (2020) cites researcher Xiaoli Mao, from the International Council on Clean Transportation who states that there is a "chicken and egg" problem. On one side there is a lack of technology and on the other side there is the absence of fuel improvements.

Timperley (2020) also cites Smith who mentions the importance of politics in the way towards greener shipping. His words are:
"We've got options: we can either essentially progressively ban fossil fuels on vessels, or we can try and incentivise the market for hydrogen-derived fuels." (Timperley, 2020). The organisation that Smith points out here is the IMO, which is responsible for safety and security of maritime vessels all over the globe. This branch of the United Nations, should, according to Smith, be more proactive in incentivising shipping companies to take measures to alleviate climate change (Timperley, 2020).

Therefore, experts from many horizons are relatively optimistic concerning hydrogen in the maritime sector. Many of them believe that change will take time and that it is crucial to begin trials all over the world so that in the next few decades there is no issue due to a lack of solutions.

Figure 10, from the International Energy Agency, shows the forecasted hydrogen production by source from 2020 to 2050.

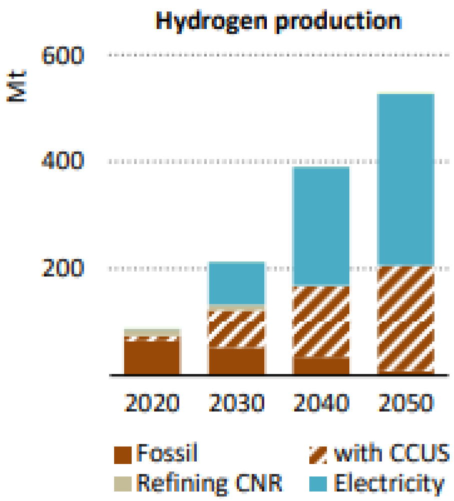

Figure 10: Global production of hydrogen by fuel and hydrogen demand in the NZE[26]
Source: IEA, 2021

[26] Scenario of Net Zero Emissions by 2050 (NZE). This is an IEA normative scenario that depicts a restricted but doable route for the global energy industry to attain net zero CO2 emissions by 2050.

It is expected that hydrogen production in 2050 will have been multiplied by six and that by then, electricity (green hydrogen) and carbon capture (blue hydrogen) will constitute the majority of the production.

2.1.7 Hydrogen suppliers over the world

Linde is the world's biggest supplier of industrial gases, when looking at market shares. Linde is present in more than one hundred countries. With a revenue of over 27 billion Euros in 2020[27], they have a diversified field of applications, going from mobility to heavy industry or power buffering. For example, in Germany, Linde possesses a factory that produces hydrogen then distributes it all over Europe. It consists of liquefied hydrogen of which the temperature is brought down to -253°C for transport. In the USA, they are looking at the storage and more precisely on "underground salt caverns" filled with gaseous hydrogen. Here is an illustration of the concept:

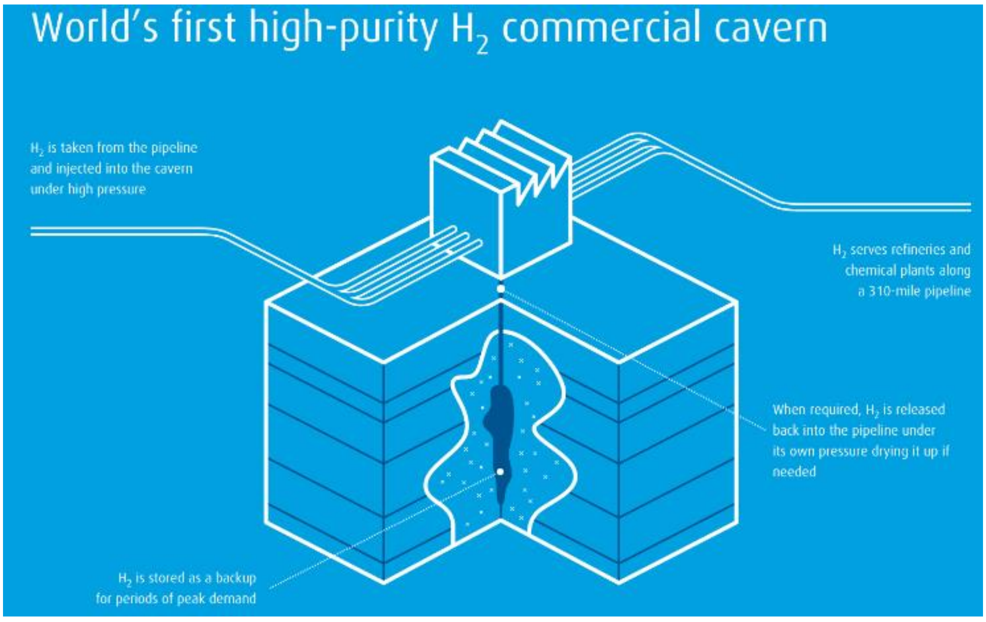

Figure 11: Explanation of the underground salt cavern storage of hydrogen

Source: LindeHydrogen[28], 2022

By injecting the gaseous hydrogen into these caverns and releasing it when needed, it makes it adjustable to the demand of refineries and chemical plants. The possibility of storing hydrogen could allow constant flow in the supply of electricity.

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[27] Consulted July 21st 2022 from: https://www.linde.com/

[28] Consulted on July 25th 2022 from: https://www.lindehydrogen.com/technology/hydrogen-storage#:~:text=Pioneering%20the%20underground%20hydrogen%20scene&text=Hydrogen%2Dfilled%20cavities%20can%20act,hydrogen%20storage%20facility%20in%20Texas.

A second big supplier for hydrogen is Air Liquide. With a revenue of 23 billion Euros in 2021[29], this company delivers molecules like hydrogen, helium, oxygen, to as many as 3.8 million clients in the world. They have developed the Turbo-Brayton technology, which helps to reduce LNG carriers' emissions. As methane evaporates during transport on these vessels, this technology makes it possible to re-liquefy it and therefore diminishes GHG emissions during transport. According to the company's website, there was a reduction of 120,000 tonnes of greenhouse gases in 2018-2019, thanks to this technology. An example of their impact in the hydrogen business is the "Air Liquide Normand'Hy". It is an electrolyser that produces green hydrogen, with a power of 200MW. The project is due for 2025 and will receive subsidies from the French government and the European Union.

On a more regional level, there is the Plug Power large-scale green hydrogen generation plant in Antwerp[30]. A 100MW electrolyser, which will be able to supply 35 tonnes of green hydrogen a day, to any customer. This construction takes time, and the actual plant commissioning is only forecasted for 2025. Nevertheless, this new supply could help the progress of hydrogen technologies. Additionally, the proximity to the port of Antwerp-Bruges makes it an advantage in terms of transportation of the gas.

2.1.8 Safety aspects

Concerning the safety aspects, it is crucial to answer the many concerns that hydrogen can bring. Use and handling of this technology demands safety requirements. The focus here will be made on the potential dangers of hydrogen.

Firstly, it is worth mentioning the problems which hydrogen entails, concerning leaks in storage. The issue comes from the fact that hydrogen, being 14 times lighter than air, has a high penetration rate in molecules, especially through metals and alloys that are used for its storage (Najjar, 2013). This can lead to leaks in the hydrogen storage container. This phenomenon is called embrittlement of metals (Najjar, 2013). It describes a material becoming breakable because of a loss of ductility, in this case, due to hydrogen deposit onto the storage container's surface. This poses a great challenge for manufacturers who have to find ways to prevent such

[29] Consulted on July 25th 2022 from: https://www.airliquide.com/fr
[30] Consulted on July 25th 2022 from: https://www.ir.plugpower.com/press-releases/news-details/2022/Plug-to-Build-Large-Scale-Green-Hydrogen-Generation-Plant-in-Europe-at-Port-of-Antwerp-Bruges/default.aspx

a hazard. One solution, to diminish hydrogen exposure, is to heat the containers up to 200°C so that the hydrogen diffuses out of the metal. Additives to hydrogen and the alloy can also be included to minimise the embrittlement.

Another danger linked to hydrogen is asphyxiation, which can happen when oxygen molecules get replaced by hydrogen molecules in the surrounding environment. It can become dangerous once oxygen concentration is below 20% by volume (Aventaggiato, 2020).

Thirdly and most famously, the subject of explosivity must be looked at. Hydrogen explosions usually occur because of leakage and are characterised differently. When there is enough hydrogen and oxygen present, there is a risk of ignition. The explosion phenomena can be divided into two main parts: the deflagration and the detonation (Najjar, 2013). The first one represents the movement of the flame through the fuel in a subsonic wave. The second one, which spreads much faster than the deflagration, is a supersonic wave. This means that detonation is far more dangerous for its surroundings. The concentration level of the fuel is very important to monitor.

2.2 Different sources of electricity for ships at berth and their price

In this section, the focus will be on the different sources of electricity of a ship when at berth. For reminder, a vessel is assigned at berth when it is in the port, either for loading or unloading its fret or for manoeuvring in the harbour.

In the context of this paper, the following are the various possibilities for a ship to get its electricity when at berth.

2.2.1 Diesel generators

The first option for a vessel to get electricity is having diesel generators. They are useful when ships cannot get power from the land. In shipping language, these are called auxiliary engines. Usually, they are used for multiple electrical requirements or cargo systems. They are a practical but polluting solution.

The fuel used for these diesel generators is Marine Diesel Oil (MDO). It consists of a mixture of fuel oil and distillates. The fuel oil can be distinguished into heavy sulphur fuel oil (HSFO) and low sulphur fuel oil (LSFO). These are most used in maritime transport nowadays. For instance, since 2020, the EU has forced the ships to use only very low sulphur fuel oil (VLSFH) to reduce pollution, which is imposed by "Directive (EU) 2016/802 of the European Parliament and of the Council of 11 May 2016 relating to a reduction in the sulphur content of certain liquid fuels"[31]. Indeed, these contain 0.5% of sulphur, in comparison to the HSFO, which contains 3.5% of sulphur. There is an exception for ships equipped with gas scrubbers[32], which are allowed to continue working with HSFO.

Ship & Bunker, the world's most read marine fuel-focused publication, has analysed marine fuel prices (HSFO, HSFO, VLSFO) and their fluctuations over the last years. VLSFO's price on average is $**1080** per tonne, when comparing 20 ports. Figure 12 represents the variation over time of HSFO and VLSFO.

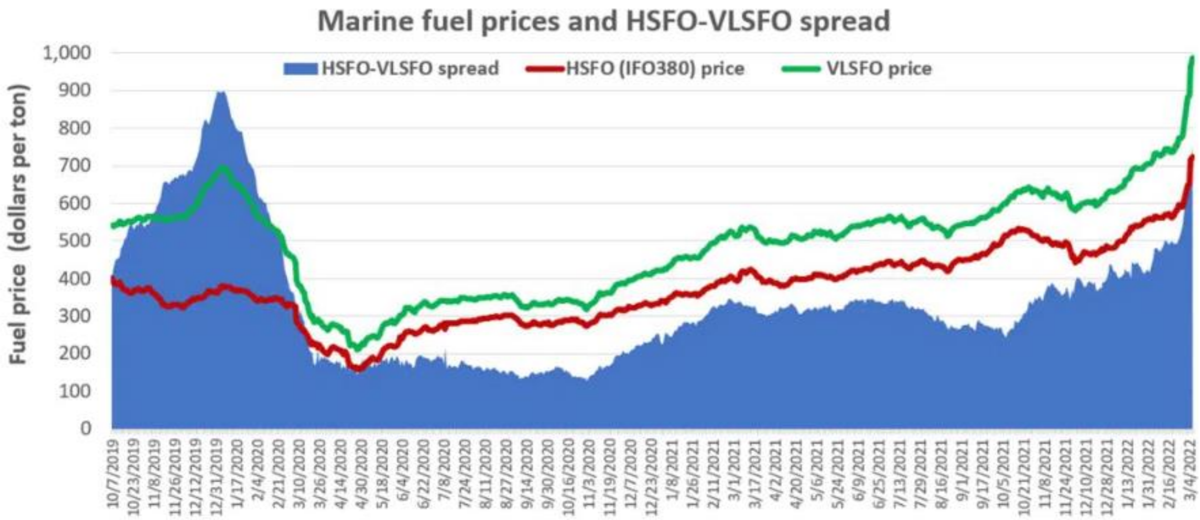

Figure 12: Prices of HSFO and VLSFO from 2019 to 2022

Source: Ship & Bunker[33], 2022

This graph shows that prices dropped drastically in February-March 2021, right when Covid-19 hit the World (Saviolakis, 2021). On the other hand, it can be seen how prices skyrocketed in March 2022, which was most likely caused by the war in Ukraine. This led to sanctions regarding import of gas and oil from Russia, leading to a rise in prices for these resources (Jagtap, 2022).

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31 Consulted August 1st 2022 from: https://eur-lex.europa.eu/eli/dir/2016/802/oj

32 Scrubber systems are a type of air pollution control equipment that remove particles and/or gases from industrial emissions.

33 Consulted on June 25th 2022 from: https://shipandbunker.com/prices

2.2.2 Shore connection to the grid

Figure 13: Representation of shore connection in ports of Antwerp and Zeebrugge
Source: CMB.TECH, 2020

The shore connection, also called "cold ironing", allows ships not having to turn on their auxiliary engines when carrying out operations at berth. Some container ships have containers that must be refrigerated and, for this, electric power from the land is practical. Other vessels, present safety systems like inert gas scrubbers[34] and for these it is important to have electricity. Cruise ships, which need a huge amount of electrical power at berth (for communications, entertainment, water treatment, etc.) are attracted by shore connections from the port.

The concept is quite trivial, a connection is needed from the national grid to a local sub-station where the current is transformed from 20-100 kV to 6-20 kV. Afterwards, underground or overhead cables are required to deliver the power from the sub-station to the port terminal. Also, the electricity might need power conversion from the grid standard of 50Hz to 60Hz, depending on the needs of the ship. Finally, a cable reel system is required for connecting land and ship.

Shore power has been installed in thirty ports from twelve EU states (European Maritime Transport, 2021). The ports of Halifax, USA and Brooklyn, USA have both recently been improved with shore connections for cruise ships. Yet there is a difficulty for ships to find the right standards in the different infrastructures around the world. For instance, problems

[34] They help to prevent fires by replacing the oxygen in the cargo.

concerning voltage and frequency are quite common. Indeed, some ships require medium voltage (6.6-11kV) when others demand low voltage (400-700V). There are also issues when it comes to the power ratings. For medium voltage, the power can go up to 20MVA per vessel when for the low voltage it only climbs up to 1MVA.

To assess the price of cold ironing, the different prices of electricity over several countries can be analysed. Data from the European Commission shows that the price of electricity in Europe varies from 0.10 to 0.35 Euro per kWh. The following graphs present the electricity prices per country in the second half of 2021.

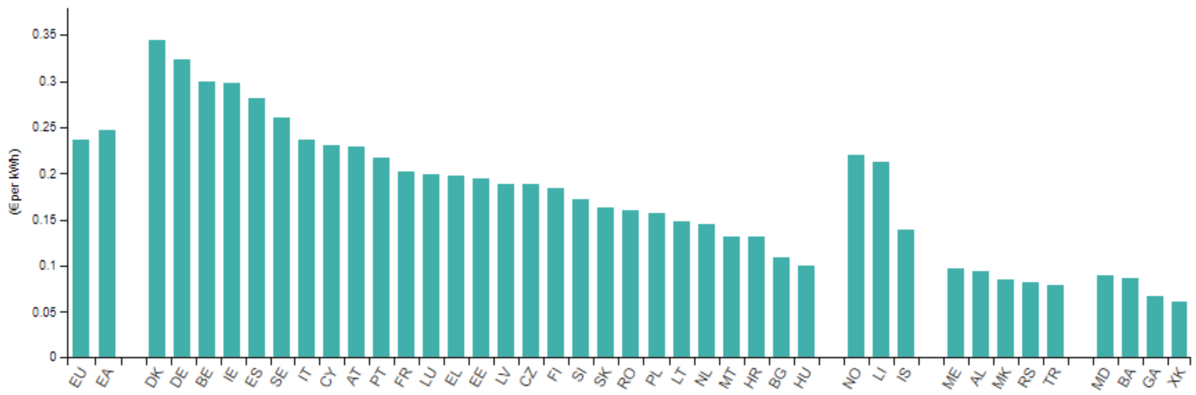

Figure 14: Price of electricity over Europe on the second half of 2021

Source: European Commission[35], 2022

The price listed for Belgium is similar to the one that can be found by consulting a map from the Department of Mobility and Public Transport in Flanders, Belgium (figure 15).

[35] Consulted on July 2nd 2022 from: https://ec.Europa.eu/Eurostat/statistics-explained/index.php?title=Electricity_price_statistics#:~:text=The%20EU%20average%20price%20in,was%20%E2%82%AC0.2369%20per%20kWh.

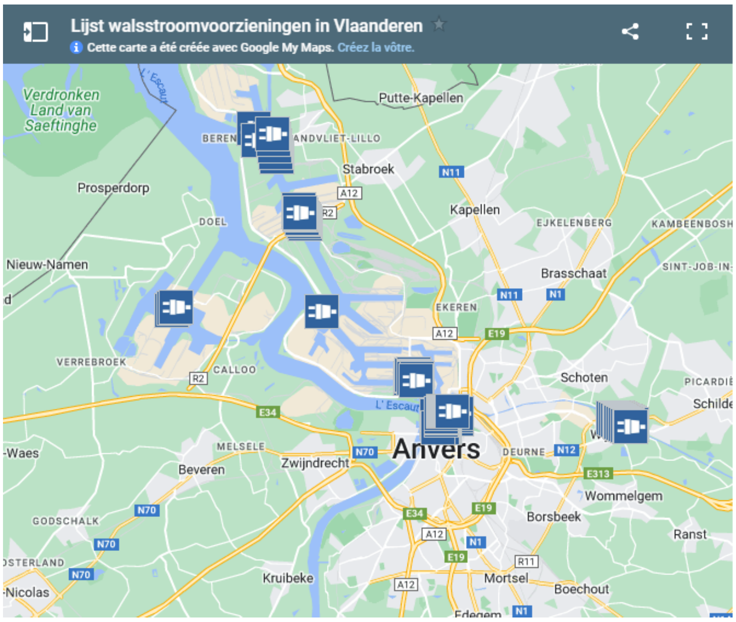

Figure 15: Price of shore connection in Antwerp

Source: Department of Mobility and Public Transport, Flanders.[36] (2022)

This map shows the current situation in the port of Antwerp-Bruges in regard to the shore power connections. Each little plug represents an access to the grid. The tariff for the electricity given in most cases is **0.27€/kWh,** on the 19th of July 2022. This is the price used for the cost calculations related to the port of Antwerp-Bruges.

2.2.3 Generators

The possibility of having a generator (an internal combustion engine combined with an electrical generator) in or close to the harbour is also conceivable. It is already the case in many ports and it makes it easier to produce clean energy.

Establishing a benchmark of the prices of hydrogen is not an easy task. Not only because of the variety of the different types (green, blue, grey) but also because it fluctuates a lot depending on the region where it is produced and can be dependent on the prices of fossil fuels.

In 2020, the prices of hydrogen were between 2.5 and 5.5 €/kg for green hydrogen and of 1.5 €/kg for the grey hydrogen (European Commission, 2020).

[36] Consulted on the 19th July 2022 from: https://binnenvaartservices.be/nl/walstroom/walstroom-aanvragen

The following figure from the International Energy Agency (IEA) shows the price range of hydrogen by production source in 2018.

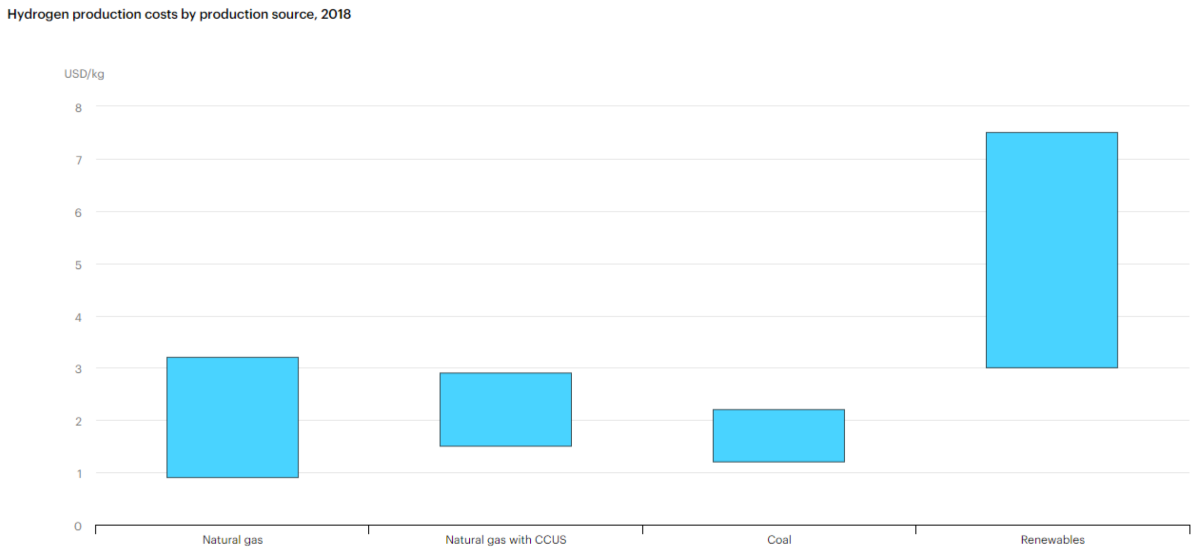

Figure 16: Hydrogen production cost by production source in 2018
Source: IEA, 2019

The first three categories represent the grey or blue hydrogen. Their prices oscillate between 1 and 3€/kg. The last category is the green hydrogen, from renewable sources. In 2018, the prices varied between 3 and 7.5€/kg.

For this paper, the price used per kilogram of hydrogen is fixed at **2€/kg**. It is an optimistic price which does not consider the current higher price of grey and blue hydrogen due to the war in Ukraine. Some experts even think that green hydrogen is already becoming less expensive than grey or blue hydrogen in some parts of the world (Meza, 2022). According to Bloomberg New Energy Finance (BNEF), a global provider of strategic research for companies, the kilogram of green hydrogen has gone below the price of the kilogram of grey hydrogen in some parts of the globe, like the Middle East or Africa (Meza, 2022). The case mentioned supra, about the protocol between Namibia and Belgium to produce green hydrogen, is an example of the growing potential around production of clean fuels thanks to renewable energy.

It is still difficult to obtain an average price for hydrogen. Most of the hydrogen currently on the market is industrial hydrogen. Whether it is used for processing food, fertilizers or treating metals, industrial hydrogen has several applications nowadays.

Nevertheless, the IEA has estimated that the production cost of renewable hydrogen could fall 30% by 2030, due to the decrease in the cost of renewable energies and the scaling up of the production (IEA, 2019).

2.3 More data collection

This section details all the different data that was collected on ships' auxiliary power, the general context (IMO and EU regulations), the current alternative fuel options for ships and some uncertainties on the growth of the maritime sector.

2.3.1 Average power from auxiliary engines

The auxiliary power of ships varies a lot depending on its type. The following table gives an overview of the average auxiliary engine power requirement for several categories of ship.

Auxiliary engine power ratios and auxiliary engine load factor in port – hoteling mode [2]

Ship Type	Average Propulsion Engine (kW)	Average Auxiliary Engines			Auxiliary to Propulsion Ratio	Auxiliary Engine Load Factor in port – hoteling mode
		Power Each (kW)	Total Power (kW)	Engine Speed		
Auto Carrier	10700	983	2850	Medium	0.266	**0.24**
Bulk Carrier	8000	612	1776	Medium	0.222	**0.22**
Container Ship	30900	1.889	6800	Medium	0.220	**0.17**
Passenger Ship	39600	2.340	11000	Medium	0.278	**0.64**
General Cargo	9300	612	1776	Medium	0.191	**0.22**
Miscellaneous	6250	580	1.680	Medium	0.269	**0.22**
RORO	11000	983	2850	Medium	0.259	**0.30**
Reefer	9600	975	3900	Medium	0.406	**0.34**
Tanker	9400	735	1985	Medium	0.211	**0.67**

Figure 17: Representation of auxiliary engine power ratios and auxiliary engine load factor in port

Source: Nicewicz, 2013

This shows that the biggest vessels in terms of power requirement are the passenger ships (cruise ships, ferries). Container ships also require a lot of power for their auxiliary engines which could make them a good candidate to get their electricity from a hydrogen Power Barge.

2.3.2 IMO and EU context

International Maritime Organization's progress

Looking at what the IMO has put into place, it can be seen that there is progress in terms of measures against maritime pollution.

The MARPOL (International Convention for the Prevention of Pollution from Ships) was established in 1973. The Convention includes provisions aimed at avoiding and mitigating pollution from ships, such as accidental and/or regular contamination. It was modified in 1978, after a big tanker spill and now has six technical Annexes. Air quality and negative effects of ship emissions were at the centre of the 1978 Protocol. Most Annexes have Special Areas with severe operating discharge regulations.

The need for more reductions of SO_x has led to the development of Sulphur Emission Control Areas (SECAs). Areas like the Baltic Sea, the North Sea, the North American region, and the United States Caribbean Sea. These regulations limited the sulphur content of marine fuel to 0.1 percent by mass in SECAs since 2015, and to 0.5 percent globally since 2020.

What is vital to know about NO_x is, that these emissions are the effect of the total weighted cycle of the engine. Annex VI of MARPOL regulates NO_x emissions from both used and new marine diesel engines with output power more than 130 kW. Depending on the ship's construction date, there are three categories of emission limits that are allowed: Tier I, Tier II, and Tier III. For example, a Tier III vessel is one that was constructed after the 1st of January 2016 (Chu Van, 2019). It is important to note that Tier III only applies to Nitrogen Oxide Emission Control Areas (NECA's) which englobe the North American and the United States Caribbean Sea regions. Tier III vessels are limited to 3.4 g/kWh of NO_x emission limit. The same logic applies for Tier I and Tier II vessels, but as they are older, their limit is higher.

<u>European Union's context</u>

The European Commission has set a series of policies in the context of the European Green Deal, approved in 2020, with the goal to make the European Union climate neutral by 2050[37]. Here are several examples:

- 'Hydrogen strategy for a climate neutral Europe' for which the goal is to make global hydrogen use viable by 2050.
- 'European Clean Hydrogen Alliance' which brings together stakeholders such as industrials and other partners to support the development of a European hydrogen industry.
- 'Hydrogen Public Funding Compass' which is a guide for stakeholders to identify public funding sources for hydrogen projects at European and country level.

In terms of regulations, as of 2010, the 'European Directive 2005/33/EC' required all ships berthed or anchored in European ports to use fuel oil with a sulphur concentration of less than 0.1 percent by mass (European Parliament, 2005).

In 2021, the EU proposed a set of legislative proposals to achieve the GHG's reduction plan, called the 'Fit for 55' package under the 'Directive 2009/16/EC, COM(2021)562'. Among them, 'FuelEU', will compel ships to berth at EEA[38] ports in order to reduce the GHG intensity of the fuels they use on trips. These criteria begin with a 2% improvement, compared to a 2020 baseline, by 2025 and increase every five years until they reach 75% in 2050. The rules would consider the GHG emissions generated by a fuel throughout its lifespan, from generation through ultimate use by the ship, rather than just its usage by the ship. This upsets many shipowners who do not understand why they should be responsible for the entire lifecycle of the fuels (Adamopoulos, 2021).

Part of this proposal is the 'EU Emission Trading System' (ETS), which is similar to carbon pricing in the sense that owners of ships have to buy emission allowances from the EU and can either use these allowances to cover their emissions or can sell them to companies which need them to cover their emissions because their ships do not comply with the environmental regulations.

[37] Consulted July 31st 2022 from: https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en#european-clean-hydrogen-alliance

[38] EEA port: Port within Economic European Area (Austria, Belgium, Bulgaria, Croatia, Republic of Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and Sweden). Retrieved on July 27th 2022 from: https://www.lawinsider.com/dictionary/eea-port

A summary of these proposals and of two others concerning the maritime sector can be found in Appendix I.

2.3.3 Alternative fuels to hydrogen

A study from the ISEMAR (Institut Supérieur d'Economie Maritime Nantes Saint Nazaire) has detailed some alternative fuels/technologies which can reduce emissions in the maritime sector in general (Valero, 2018).

In this section there are four detailed accounts of different sources. This will help to place hydrogen as a maritime fuel in its current environment and look at what these other fuels can bring to the table.

2.3.3.1 LNG

One of these sources is LNG. Liquefied natural gas is generated when natural gas' temperature is lowered to -162°C. It is favourable in terms of non-explosivity, and it answers the current regulations in terms of NO_x, SO_x and PM. This fuel has the characteristic of reducing up to 100% of SO_x and PM, 80% of NO_x and 20% of CO_2 emissions, compared to conventional fuels. According to Valero (2018), LNG is the carbon-based fuel which is the most efficient from a technical, operational and environmental point of view.
The following table shows a comparison of LNG's emission with MGO and HFO's emissions.

Evolution des émissions de polluant par rapport à un navire HFO classique

	SOx	NOx	PM	CO2	Cibles privilégiées
MGO	-90%	0%	-60%	0%	Navires circulant peu en SECA
HFO +scb -	-90%	0%	-50%	+2%	Navires trop âgés pour être convertis au GNL
GNL	-100%	-80%	-100%	-20%	Ferries / rouliers naviguant en SECA

Figure 18: Evolution of pollutant emissions compared to a conventional HFO vessel
Source: Valero, 2018

There is a downside to LNG, namely methane slip. When burning, the LNG releases some unburnt methane, which is a GHG. It has a global warming potential 28 times higher than CO_2 (OECD, 2018). As of 5.8g/kWh of methane slip, the overall GHG improvement disappears and will lead to higher GHG emissions. In China, Japan and Korea the demand is rising and manufacturers are currently working to produce engines with less than 1g/kWh of methane slip. Even though LNG complies with the current pollution emission regulations, it is clearly a short/medium term solution for reduction of GHG emissions.

2.3.3.2 Ammonia (NH_3)

Ammonia (NH_3) has already been mentioned above as a hydrogen carrier. Nevertheless, it can also be applied in fuel cells or direct combustion. The main advantage compared to hydrogen is that it allows more hydrogen per volume (121kg/m^3). The temperature of storage is also a lot warmer (-33°C). Studies have shown that when NH_3 is combined with HFO, CO_2 emissions can be reduced by 27% (Bicer 2018). With no sulphur oxide emissions and practically no nitrogen oxide emissions, ammonia is a good option in terms of pollution.
The way ammonia is produced is via the Haber-Bosch process which converts hydrogen and nitrogen. Production of hydrogen is necessary to produce NH_3. Therefore, green, blue, or grey hydrogen will determine the total assessment of CO_2 emissions. This already well-developed industrial substance, seems to have a promising future in the maritime sector. The CMB.TECH is, in addition to hydrogen, looking into ammonia solutions.

2.3.3.3 Methanol (CH_3OH)

Methanol is produced from natural gas. In comparison to HFO, its CO_2 emissions are reduced by 25%. When burnt, the SO_x is almost completely reduced (99%), the NO_x is reduced by 60% and the PM by 95% (OECD, 2018). It is also possible to produce it with renewable resources, such as CO_2 capture or biomass. It is currently used a lot in China for vehicles but due to it being produced with coal, the GHG assessment is not good.
Methanol in the maritime sector is beginning to appear. For instance, in Sweden, a ROPAX[39] was converted to a methanol-powered ship but the methanol is produced from natural gas thus, the CO_2 emissions assessment is dissatisfactory. Here again as LNG, methanol seems like a short to medium term solution for reducing GHG's.

[39] ROPAX= Ro-Ro with passengers.

2.3.3.4 Fuel cells

The fuel cell directly transforms electrochemical energy by converting the chemical energy of certain chemicals into electric power, without the use of combustion. As a result, it generates both electrical energy and heat energy. Hydrogen is utilised in fuel cells the most, but methanol, LNG, liquid organic hydrogen carriers (LOHC), and ammonia are all potential alternative fuels. The most viable ideas are hydrogen-powered Proton Exchange Membrane fuel cells (PEMFCs), the High Temperature PEMFC and the Solid Oxide fuel cell (DNV GL, 2017). The only by-product of the reaction is water. But here again, the production of hydrogen plays a big role in the total CO_2 emission assessment. In addition, fuel cells are very sensitive to impurities in the hydrogen and the storage issues are the same as for the hydrogen combustion engines. Studies have shown that efficiencies of 40% can be reached with fuel cells (Braga, 2014). Nevertheless, they have a much higher cost and usually a lower lifetime than combustion engines (Braga, 2014). The uncertainties about this technology, especially in the maritime environment which require a lot of power from the engines, are still significantly present.

2.3.4 Uncertainties concerning the growth of maritime transports

As already mentioned, experts predict a rise of 250% by 2050 of the GHGs in the maritime transport (Wan, 2018). It is not implicit that the maritime transport is going to grow at the same pace. Several uncertainties could significantly affect this growth.

Firstly, a real increase in the freight rates in the maritime market can be seen. Figure 19 shows the evolution of the freight rate from 2016 to 2022. A high price could slow down maritime business.

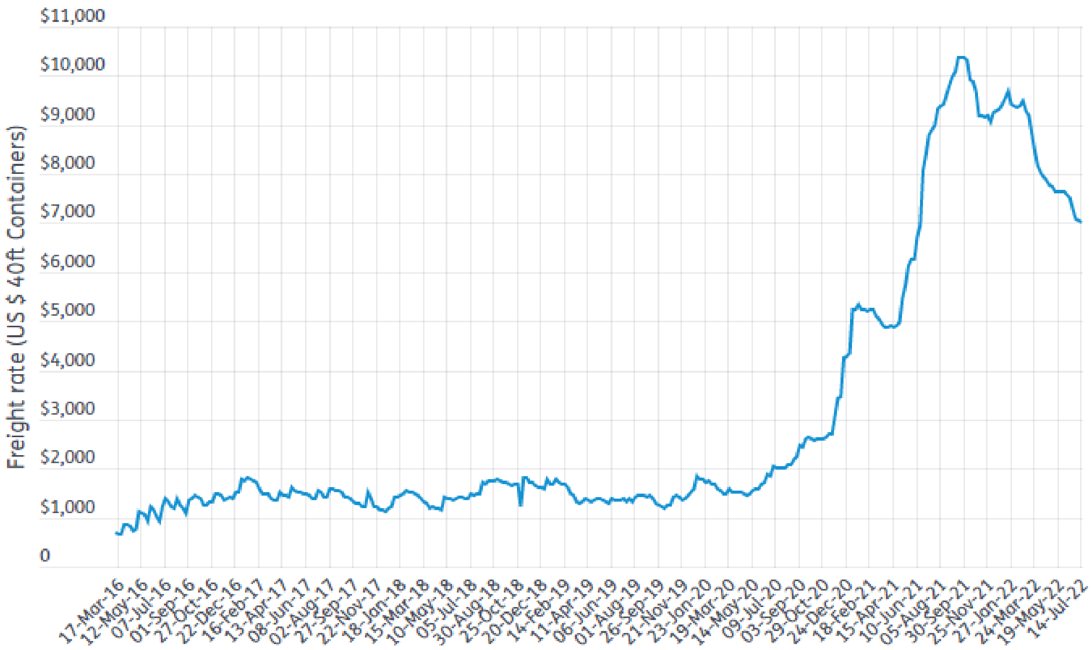

Figure 19: Weekly weighted freight rate assessment of eight major east-west trades
Source: Drewry Supply Chain Advisors, 2022

The major cause of such price surge is mainly explained by the COVID-19 pandemic. The labour shortage in port and container hubs, plus a resurgence of demand for goods, have caused prices for maritime freight to soar. Big ports over the world are confronted with congestion problems. In average, on a typical Europe-China voyage, a container takes 20 more days to arrive than before, which has a negative impact on the sector (AKANEA, 2021).

Secondly, it is worth looking at a study from the port of Barcelona, that has analysed four different figure scenarios of Europe's traffic trends for 2040 (Garrido et.al, 2021). There are four different scenarios:

- Global prosperity: world GDP growth of 3.2% and 2% for Europe
- Renascent Europe: world GDP growth of 2.5% and 1.2% for Europe.
- Declining Europe: world GDP growth of 3% and 1% for Europe.
- Global stagnation: world GDP growth of 2% and 0.5 for Europe.

Different traffic segments have been analysed in relation with the four scenarios and the following figure shows the results:

	GLOBAL STAGNATION	DECADENT EUROPE	RENASCENT EUROPE	GLOBAL PROSPERITY
LIQUID BULK	↓	↓	↓	↓
COAL & ORE	↓	↓	↓	↓
AGROBULK	→	↗	→	↗
OUT OF EUROPE	↘	↘	→	↗
INTRA - EUROPE	↗	↘	↘	↘
IMPORT/EXPORT	↗	↗	↗	↑
TRANSHIPMENT	↗	→	↗	↗
CRUISE PASSENGERS	↗	↑	↗	↑
RO-RO CARGO	↗	↗	↑	↑

Figure 20: Projected evolution of different maritime traffic segments in Europe in the 2040 horizon.
Source: Based on the study by BlueFocus and Ports & Logistics Advisory for the Port of Barcelona (Garrido et.al, 2021).

What can be taken out of this, is that in any of the four scenarios, the use of liquid bulk and coal carriers are projected to go down. This can be explained by demand becoming lower for these fossil fuels due to the reaction to climate change.

These two factors in addition to the recent political declaration and social demand about relocation of some strategic productions and circular economy (Madhok, 2021), make it difficult to forecast the future growth of the maritime sector.

3 The Power Barge Case Study

In this main section, the focus is on the CMB Power Barge Project. This section is based on technical documents and information kindly provided by the CMB.TECH team which is developing this concept.
A key element when assessing the prospects of the Power Barge Project, is the cost of producing the electricity, which is supplied to ships at berth from the mobile hydrogen-powered generator. This estimate is based on the technical specifications of the project and on the demand for ships at the quayside in Antwerp.

The main characteristics of the Power Barge Project are presented first. Then the power required for the ships in the port Antwerp-Bruges, based on the annual traffic data, will be determined. The result will allow to establish the amount of gensets, which have to be put onboard of the Power Barge and thus, the associated costs. By comparing the costs of the barge to the costs of two other options, from which ships can get their electricity, and by conducting a SWOT analysis, the competitive environment of the project is analysed.

3.1 Overview of the CMB project

The goal is to replace the electricity that ships at berth get from either shore power or either from their own diesel generators, with electricity produced by hydrogen on a barge.
The following photomontage represents the project.

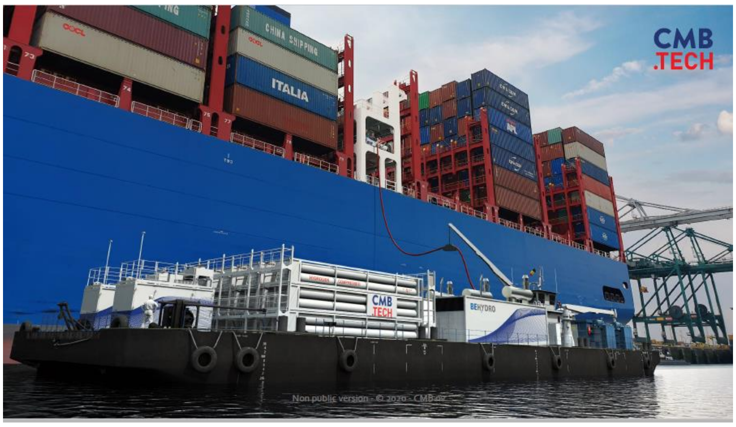

Figure 21: Power Barge representation
Source: CMB.TECH, 2020

The barge would connect to the container ship via a high voltage cable and deliver electricity for the vessel's needs.

3.1.1 Strengths highlighted by the promoters

Listed are some major benefits brought forward by the CMB.

First of all, combustion of hydrogen in the Power Barge, uses the mono-fuel type of engines. These generators allow to reduce GHG emissions by 98%. Up to 49 tonnes of CO_2 can be saved per day. Also, the NO_x, PM_{10}, $PM_{2.5}$ and SO_x reduction of emissions are estimated to 992kg, 17kg, 16kg and 28.5kg respectively.

Secondly, depending on the power requirements, the containerised gensets onboard can each feature four different types of mono-fuel engines with power ranges from 1 to 2,7MW. This makes it easier to combine these four engines. Whether only two are needed or three or four, is up to the needs of the ships.

Thirdly, it is unnecessary for ports to upgrade the power grid or invest in expensive power electronics to provide the right frequency or voltage, which is the case for shore connection.

Moreover, the hydrogen engines chosen, called BeH_2ydro engines, are immune to lower purity hydrogen. This means that by-product hydrogen from chemical plants or the refining industry, can be used in these generators, allowing significant lower operating cost.
In addition, the lifetime of the engine is over 150,000 hours. In comparison, an auxiliary diesel engine from Frontier Power Products ULC[40], usually lasts 20,000 hours before requiring a major overhaul of the system.

[40] Frontier Power Products ULC is a company offering marine industrial products like engines.

3.1.2 Design of the barge

Figure 22 shows the different elements of the Power Barge.

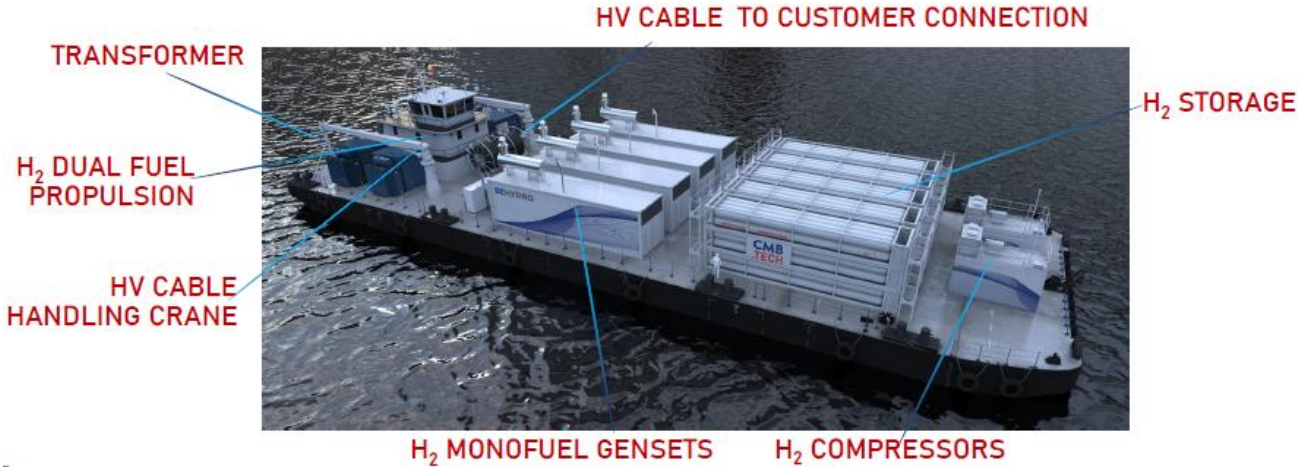

Figure 22: Design of the Power Barge
Source: CMB.TECH

The Power Barge involves a transformer, which allows a reduction of voltage. It is a common component in transmission and distribution of energy. This electricity comes from the hydrogen mono-fuel gensets, where hydrogen is used as a fuel.

As seen on the representation, the storage of hydrogen takes up a lot of space. As previously mentioned, storage and transportation of hydrogen are the greatest challenges this technology faces. The barge is capable of containing 5 tonnes of hydrogen in standardised hydrogen skids[41]. It allows safe transport, on trucks and on the barge.

The hydrogen compressors allow the barge to be connected to a pipeline or an electrolyser. This way, low pressure supply can then be compressed straight into the high-pressure hydrogen tanks. The compressor can also be used to supply another ship at higher pressure.

Concerning the design of the barge, it is also important to mention the different actors involved in the undertaking. In addition to CMB.TECH, five other partners are engaged in the conception of this project. Table 1 gives an overview of the different actors and their respective area of expertise.

[41] A skid is a low steel-framed platform-like structure that is used to transport and store heavy equipment.

	Companies					
	CMB.TECH	ABC	ABB	Multi Engineering Services	Air Liquide	Lloyd’s Register
Expertise	Power Barge requirement capture and specification	H_2 mono fuel genset specification and concept	High voltage (HV) electricals	Barge design and construction	Supply of H_2	Knowledge in engineering and technology for the maritime industry
	H_2 compression, storage and handling system		HV cable handling and connection			
	Safety requirements					
	Business proposal and exploitation					
	Project management					

Table 1: Actors involved in the conception of the Power Barge

Source: CMB.TECH, 2020

3.1.3 Genset equipment

The mono fuel BeH$_2$ydro gensets are the result of a joint venture between CMB and Anglo Belgian Corporation (ABC). The latter company is a leader in Belgium, in terms of manufacturing engines from a broad range of powers. They deliver to many different sectors, like energy and transport.

The following figure provides the main characteristics of the four different gensets.

	6DZC	8DZC	12DZC	16DZC
Cylinders	6 inline	8 inline	12 V	16 V
rpm	1000	1000	1000	1000
Power [kW]	1000	1335	2000	2670
Power [hp]	1353	1813	2706	3626
Swept vol [litre]	95.7l	127.6l	191.5l	255.2l
Dry weight [kg]	10620 kg	13905 kg	18000 kg	21750 kg

Table 2: Main characteristic of the four different types of gensets (1MW, 1.3MW, 2MW and 2.6MW)

Source: CMB.TECH

These engines have a lifespan of 150,000 hours and are known to have high efficiency with no emissions. The use of less-purified hydrogen is not a problem. A representation of this genset can be found in appendix H. For further information, refer to the BeH$_2$ydro website[42].

3.2 Determining the power requirement of the ships

The goal in this section is to find the power requirement of each ship when at berth.
For this job, data from the port of Antwerp-Bruges (see Appendix A) are used to calculate the power required by each ship.

The database entails the CO_2 emissions for each ship's visit in the port over the period of one year (03.01.19 to the 30.12.19). The database registers 9 terminals with shore connections and the "MSC PSA EUROPEAN TERMINAL (MPET), K1742" terminal was chosen as the representor. The choice of this terminal was considered by the CMB.TECH team as representative of the demand for electricity. This terminal has 12,225 port stays in a year and it only serves container ships. As seen, these vessels are among the biggest consumers of electricity in the port. Ships equipped for connection to the quay were selected ("met walstroom" in appendix A).

The following calculation was applied to determine the power requirement:

$$Power\ (MW) = CO_2(kg) \div 3.2(\frac{kg}{kg}) \times 11.8(\frac{kWh}{kg}) \times 0.33 \div 1000 \div Hours$$

[42] Consulted July 22nd 2022 from: https://www.behydro.be/en/home.html

With:

- Power = The required power for each port stay (MW).
- CO_2 = The quantity of CO_2 generated by the port stay (kg).
- 3.2 = Factor of CO_2 emission from diesel (kg/kg).
- 11.8 = Calorific power of diesel (kWh).
- 0.33 = Efficiency of the diesel engine (CMB.TECH).
- 1000 = Due to the fact that it goes from kWh to MWh.
- Hours = Number of hours of the port stay.

Table 3 is an extract of the simplified database where results of the calculations for obtaining the power required for each port stay can be seen in red.

Q7359 =[@TotaalCO2]/3,209568*11,8*0,33/1000/[@TotaalDuur]

	A	I	M	N	P	Q
1	Terminal	ScheepsTypeNaut	TotaalDuur	Walstroom	TotaalCO2	Power (MW)
7359	MSC PSA EUROPEAN TERMINAL (	container ship (full)	49,77	Met walstroom	120705,815	2,94
7374	MSC PSA EUROPEAN TERMINAL (	container ship (full)	32,20	Met walstroom	115163,897	4,34
7384	MSC PSA EUROPEAN TERMINAL (	container ship (full)	39,65	Met walstroom	82550,8734	2,53
7396	MSC PSA EUROPEAN TERMINAL (	container ship (full)	24,53	Met walstroom	43075,389	2,13
7444	MSC PSA EUROPEAN TERMINAL (	container ship (full)	24,32	Met walstroom	42282,7436	2,11
7472	MSC PSA EUROPEAN TERMINAL (	container ship (full)	21,13	Met walstroom	4117,45314	0,24
14929	MSC PSA EUROPEAN TERMINAL (	container ship (full)	31,32	Met walstroom	110810,856	4,29
14930	MSC PSA EUROPEAN TERMINAL (	container ship (full)	16,97	Met walstroom	29502,2844	2,11
14933	MSC PSA EUROPEAN TERMINAL (	container ship (full)	6,20	Met walstroom	12891,7859	2,52
14935	MSC PSA EUROPEAN TERMINAL (	container ship (full)	9,28	Met walstroom	7826,50142	1,02
14937	MSC PSA EUROPEAN TERMINAL (	container ship (full)	17,52	Met walstroom	14767,7792	1,02
14939	MSC PSA EUROPEAN TERMINAL (	container ship (full)	14,05	Met walstroom	2737,39195	0,24
14943	MSC PSA EUROPEAN TERMINAL (	container ship (full)	25,98	Met walstroom	45627,5023	2,13
14944	MSC PSA EUROPEAN TERMINAL (	container ship (full)	37,43	Met walstroom	77935,7973	2,53

Table 3: Extract from power calculation of data from Port of Antwerp-Bruges

<u>Analysis of the demand in power of the port stays:</u>

Once the power required for each port stay in the considered terminal is obtained, the distribution of this demand must be looked at. Out of the 12,225 port stays:

- 60% (7310 port stays) are below 1MW.
- 29% (3568 port stays) are between 1MW and 2MW.
- 7% (829 port stays) are between 2MW and 3MW.
- 3% (407 port stays) are between 3MW and 4MW.
- 1% (105 port stays) is between 4MW and 5MW.

We only have 5 values that are above 5MW. This value will be used as an upper limit for the size of the barge.

3.3 Calculations of the electrical production cost of the Power Barge - Financial Analysis

This section focuses on sizing the electrical power of the barge to respond to the demand through calculating the production cost of the electricity.
Sub-section 1 will give an overview of the hours and the energy supplied for different gensets' mixes onboard.
Sub-section 2 will focus on calculating the CAPEX (Capital Expenses) of the project.
Sub-section 3 will detail the OPEX (Operating Expenses) of the barge.
Sub-section 4 will give a general overview of the total electricity production cost of the project.

It should be mentioned that the following calculations are considered as a financial analysis of the production cost of electricity from the Power Barge. They do not consist of an economic analysis, in the sense that the project is analysed from the dimension of the CMB company which is looking to minimise the costs of the Power Barge while responding to the demand from the port of Antwerp-Bruges. A more economic point of view, placing the project from a broader perspective, will be addressed in the SWOT analysis and the discussions.

3.3.1 Utilisation and energy required by each genset mix

The Power Barge is equipped with gensets. These are the generators that give electricity. There are four different sizes for these gensets: 6, 8, 12, 16 cylinders. They are hydrogen engines combined with generators delivering respectively 1, 1.3, 2 and 2.6MW. The combination of gensets to be taken on board is to be determined according to the needs of the ships, so that the cost of electricity production is minimised.

<u>Choice of genset mixes for simulations</u>
The choice of the following genset mixes was established on the demand that ranges from 0 to 5MW. Therefore, four genset combinations reflect the current demand for electricity. The option of taking a fifth genset mix (7.8MW) that gathers the three biggest gensets, was made to be able to respond to the highest current demands, which could increase in the future with an upsizing trend of ships.

Table 4 shows the five different genset mixes that are analysed.

Genset mix (MW)	1.3+1.3+1.3	2+2.6	1.3+1.3+2	2+2+1	2.6+2.6+2.6
Total Power (MW)	**3.9**	**4.6**	**4.6**	**5**	**7.8**

Table 4: Different genset mixes analysed for economical assessment.

Genset mixes and electricity demand

For each combination of genset, the number of hours that the barge would actually be in use to supply the demand, is looked at. For this, a table with every hour in half a year is created. The calculations are based on half a year due to the number of hours in a year being too numerous for computations. For each hour during the six months, the electrical power needed by each ship at the quay at that time is taken. By looking at each hour and always taking the maximum value (within the genset mix's range) of the power required, it is possible to determine which power will be needed during that hour. An example is shown here under:

		Port stay			
Power kept	Hours in a year	n°1	n°2	n°3	...
2,94	1	2,94	0,00	0,00	0,00
2,94	2	2,94	0,00	0,00	0,00
2,94	3	2,94	0,00	0,00	0,00
2,94	4	2,94	0,00	0,00	0,00
2,94	5	2,94	0,00	0,00	0,00
4,34	6	2,94	4,34	0,00	0,00
4,34	7	2,94	4,34	0,00	0,00
4,34	8	2,94	4,34	0,00	0,00
4,34	9	2,94	4,34	0,00	0,00
4,34	10	2,94	4,34	0,00	0,00
4,34	11	2,94	4,34	2,53	0,00

Table 5: Hour by hour power needs for the boats at berth (MSC PSA EUROPEAN TERMINAL (MPET), K1742") for the year 2019.

In the first hour, there is only one ship which requires 2.94MW. On the other hand, for the 6th hour, there are two ships at berth, the first one requires 2.94MW and the second one 4.34MW. It has to be chosen to which ship the power is supplied, and the higher number is chosen, within the range of the genset mix, which in this case is 4.6MW. This continues for the 4380 hours in half a year and for the 5 different genset mixes.

Now that the power required for the Power Barge per hour[43] has been established, the number of hours that the Power Barge will be in use can be extracted and therefore, the energy required for each genset mix.

<u>Each genset mix has:</u>

- Number of hours in use (hours) which shows the utilisation calculated this way:

$$Utilisation = \frac{Number\ of\ hours\ that\ Power\ Barge\ is\ in\ use}{Number\ of\ hours\ in\ a\ year}$$

- Energy required (MWh) calculated this way:

$$Energy\ required\ (MWh) = Power\ required\ (MW) \times Hours\ in\ use\ (h)$$

For further illustration, see Appendix B.

<u>What is the script if a ship's demand is above the power of the barge?</u>

As an example, for a genset mix of 4.6MW (2+2.6), what can be done with the ships that require more than 4.6MW?

Two calculations for each genset mix have been made. One where the ships with a power demand higher than what the genset mix can offer is not considered ("limited to capacity scenario"). In another scenario ("unlimited to capacity"), it is assumed that the ability to give maximum power to the ship is there and that the vessel will find a complementary way to generate the added power required with diesel generators.

The percentage of ship's power which exceeds the supply of each genset mix is represented here:

Genset mix (MW)	1.3+1.3+1.3	2+2.6	1.3+1.3+2	2+2+1	2.6+2.6+2.6
Total Power	3.9	4.6	4.6	5	7.8
Percentage	0.90%	0.15%	0.90%	0.05%	0%

Table 6: Percentage of ships exceeding the possible power for each genset mix.

Seeing the low percentage of the ship's power exceeding the genset's mix power, the results do not differ much.

[43] A setup time of half the power required has been established for when the Power Barge has to switch from one vessel to another or load/unload its hydrogen tanks.

3.3.2 CAPEX cost

In this section, the CAPEX costs will be further looked at. Firstly, it is important to give a clear definition of the term. Capital Expenses (CAPEX) are funds used by a company to acquire, upgrade, and maintain physical assets such as property, plants, buildings, technology, or equipment. (Fernando, 2022).

In this present case, they refer to the different costs around the Power Barge, which are fixed (e.g., the price of the gensets, the transformer, the compressors and all the engineering surrounding the project). The following table details the cost of the 5 types of gensets.

Cost of the different types of gensets				
1	1,3	2	2,6	MW
€ **1.092.941**	€ **1.257.824**	€ **1.546.706**	€ **1.774.588**	**Total cost**

Table 7: Costs for the 5 types of gensets

Source: CMB.TECH

Table 8 gives an example of the CAPEX costs (with the additional costs: transformer, compressor, etc.) for a 5MW setup (2+2+1MW gensets):

Fixed Costs for the Power Barge			
BeHydro	1MW	€	1.092.941
BeHydro	1.3MW		
BeHydro	2 MW	€	3.093.412
BeHydro	2,6MW		
Transformer + Switchboard		€	1.500.000
Compressors		€	500.000
Barge		€	3.000.000
Cable/Electricals/Crane		€	500.000
Engineering		€	1.000.000
Total		**€**	**10.686.353**

Table 8: Example of the CAPEX cost for genset mix (2+2+1MW)

Source: CMB.TECH

Once the CAPEX is established, the IRR (internal rate of return) is applied to it. This percentage represents the amount of money earned, opposed to the money paid for the investment. An IRR of 5%, and a depreciation of 10 years have been assumed realistic by the CMB.TECH.

Therefore, once the CAPEX has been computed with the IRR, it can be divided by the amount of MWh and the CAPEX per MWh is obtained, for each combination of gensets. The following table shows the results for the CAPEX/MWh.

		(1,35+1,35+1,35)	(2,6+2)	(1,35+1,35+2)	(2+2+1)	(2,6+2,6+2,6)	Units
	Power	3,9	4,6		5	7,8	MW
	with e. eff.	3,744	4,416		4,800	7,488	
	Autonomy	90%	88%		87%	81%	
LIMITED	Hours full load	2934	3141		3141	3141	h
	MWh/half y	7263	8623		8623	8623	MWh
	MWh/half y	6501	7588		7497	6987	MWh
	Utilisation	44%	45%		41%	26%	
	CAPEX	10.273.472,00	9.821.294,00	10.562.354,00	10.686.353,00	11.823.764,00	€
	CAPEX with IRR	13.304.616,25	12.719.025,05	13.678.731,65	13.839.316,03	15.312.315,31	
	CAPEX/MWh	102,32	83,81	90,13	92,29	109,58	€/MWh
UNLIMITED	Hours full load	3141	3141		3141	3141	h
	MWh/half y	8367	8623		8623	8623	MWh
	MWh/half y	7490	7588		7497	6987	MWh
	Utilisation	51%	45%		41%	26%	
	CAPEX with IRR	13.304.616,25	12.719.025,05	13.678.731,65	13.839.316,03	15.312.315,31	€
	CAPEX/MWh	88,82	83,81	90,13	92,29	109,58	€/MWh

Table 9: Representation of CAPEX/MWh for 5 options of genset mix

<u>Additional remark:</u>

- An electrical coefficient of 0.96, which corresponds to the real electrical power, has to be applied to the gensets' power.
- Each genset mix has an autonomy that ranges from 81% to 91% depending on the genset mix (CMB.TECH).
- The utilisation ranges from 26% to 57% depending on the genset mix.

3.3.3 OPEX cost

OPEX (Operating Expenses) is a cost incurred by a company as a result of its routine business activities (Kenton, 2022). In this case, it refers to the hydrogen fuel, which is separated into two different costs, the handling, and the consumption. The objective is to obtain an electricity production cost in Euros per Megawatt hour, so that it can be added to the CAPEX per MWh.

<u>Handling of the hydrogen</u>

The costs of moving on and off the containers with the hydrogen are looked at here. The calorific power of hydrogen is 33.3 kWh, which has to be multiplied by the efficiency of the engine, which is 40% (CMB.TECH). Therefore, one kilogram of hydrogen delivers 13.32kWh. Knowing that the handing of one container costs 70 Euros and contains 450kg (CMB.TECH), the price per kg, 0.16€ per kg of hydrogen, is calculated. When combining the price per kilogram with the energy delivered per kg, the price per energy amounts to **11.67€/MWh**. It is assumed that this cost does not vary with the genset mix.

Fuel consumption

Looked at here is the actual price determination of how much to spend for the hydrogen depending on each combination of gensets (details can be found in Appendix D). These calculations have used a price of 2€/kg for hydrogen, which is a realistic hypothesis for current grey hydrogen and green hydrogen in the upcoming years, according to the bibliographical search and validated by the CMB.TECH.

A clarification of the different parameters is required:

- Load: The engine load indicates the engine's ability to create power. It is the force that opposes the power generated by the engine. Each engine is built for a specific load known as the rated load or maximum load, at a specific speed.
- Efficiency: An engine's efficiency is calculated by the proportion of useful work done with the heat produced.

For each genset mix, the minimum hydrogen quantity required for supplying the demand is calculated. The following operation is repeated for the 5 genset mixes (illustration can be found in Appendix D):

- Multiplying the power by the time (hours) spent at port.
- Obtaining the electrical energy (MWh) needed by the ship.
- Establishing the load of the engine. This is done by taking the power required and dividing it by the power that the gensets can provide.
- Finding the appropriate value of efficiency thanks to a table provided by the CMB.TECH (see Appendix 6.6), which gives information about the correlation between load and efficiency of engines. The use of it, via the VLOOKUP[44] function, allows to find the appropriate value of efficiency.

[44] VLOOKUP stands for 'Vertical Lookup'. It is a function that makes Excel search for a certain value in a column, in order to return a value from a different column in the same row.

- Applying the efficiency to the electrical energy obtained previously.

$$Electrical\ energy\ (MWh) = Power(MW)\ \div Efficiency \times Hours(h)$$

- Summing all the electrical energies required and obtaining the total electrical energy needed for supplying the demand of the ships (in kWh).
- This can be translated into the total amount of fuel (H_2) as 1kg of hydrogen delivers 33.3kWh (CMB.TECH).
- Assuming a price of 2€/kg, the price for the quantity of H_2 is obtained.
- Dividing it by the energy required, the cost per energy unit of the fuel required is established.

Table 10 shows an example of the calculation of the fuel price per MWh of genset mix (2+2+1MW).

Somme de El. E 5	Somme de TOTAL
25.310,70	67.772,36

	Option 3	
	5 (2+2+1)	
Efficiency	37,35%	
Quantity of H_2	2.035.205,88	kg
Price	4.070.411,77	€
Energy	25.310,70	MWh
Price/MWh	**172,50**	**€/MWh**

Table 10: Fuel cost for the genset mix: 2+2+1MW

3.3.4 Total cost/MWh

Finally, by adding the CAPEX and the OPEX, the total cost of the electrical production is known and the determination of which combination of gensets is the most optimal for the Power Barge can be made. Having a genset of 2MW and another one of 2.6MW leads to 45% utilisation and the lowest price of 256€/MWh. Table 11 provides an overview of the final result.

RECAP of 5 options for MPET terminal's demand

LIMITED to capacity

	3,9	4,6		5	7,8	MW
5 options	1,35+1,35+1,35	1,35+1,35+2	2+2,6	2+2+1	2,6+2,6+2,6	MW
Utilisation	44%	45%		41%	26%	
CAPEX/MWh	102,32	90,13	83,81	92,29	109,58	€/MWh
Fuel cost/MWh	171,17	169,94	172,40	172,77	174,83	€/MWh
TOTAL cost	**273,50**	**260,07**	**256,21**	**265,06**	**284,41**	€/MWh

UNLIMITED to capacity

	3,9	4,6		5	7,8	MW
5 options	1,35+1,35+1,35	1,35+1,35+2	2+2,6	2+2+1	2,6+2,6+2,6	MW
Utilisation	51%	45%		41%	26%	
CAPEX/MWh	88,82	90,13	83,81	92,29	109,58	€/MWh
Fuel cost/MWh	170,54	169,86	172,26	172,50	174,83	€/MWh
TOTAL cost	**259,36**	**259,99**	**256,07**	**264,79**	**284,41**	€/MWh

Table 11: Total cost per MWh of the 5 genset mixes

3.4 Competitive environment

The focus will be on two elements, a comparison of the price of three different solutions for electricity for ships and a SWOT analysis of the Power Barge Project.

3.4.1 Prices comparison

The different costs per MWh for each type of solution regarding electrical source at berth, is detailed in this section.

3.4.1.1 Diesel generators

Based on the price per tonne, on June 25th 2022, of the VLSFO ($1080/t) and knowing that the calorific power of diesel is 3kWh[45], the price per MWh of this fuel can be calculated. The volumetric density of diesel is 0.840kg/L.

The following formula shows how to obtain the cost per MWh of diesel:

$$Cost = \frac{1}{E.content\ diesel} \times E.density\ diesel \times Diesel\ price \times 1000$$

With:

- Cost = Cost of using diesel (MWh).
- E. content diesel. = Energy content of 1 litre of diesel (kWh/L).
- E. density diesel = Energy density of 1 litre of diesel (kg/L).
- Diesel price = Price of diesel (€/L).
- 1000 = factor to go from kWh to MWh.

Thus, the price for production of electricity with auxiliary diesel generators is **275 €/MWh**.
It has to be mentioned that, on the 25th of June 2022, Euro currency is nearly equivalent to the dollar[46]. Because of this, no exchange rate has been applied. The cost is at its highest, due to the current high price for diesel fuel.
This method for vessels to get their electricity from, is convenient because of the ease of the use of oil. The transportation does not implicate too many dangerous aspects and the technology has been in place for so long that workers do not require specific training. High fuel prices and the prospect of high and rising prices for less polluting fuels or the additional costs of equipping auxiliary engines with filters leave little long-term prospect for this solution.

3.4.1.2 Shore connections

The price of shore connections varies a lot from one country to another. For this thesis the base will be the Belgian price of **270€/MWh** (see section 2.2.2), which is similar to the cost of diesel. Having a shore connection is becoming more convenient for vessels. Therefore, many ports and companies are investing in shore connection, due to the price becoming affordable.

[45] It is actually 10kWh an efficiency of 30% is considered.
[46] According to the European Central Bank, on the 20th of July 2022, 1Euro=1.02dollar. https://www.ecb.Europa.eu/stats/policy_and_exchange_rates/Euro_reference_exchange_rates/html/Eurofxref-graph-usd.en.html

Nevertheless, the price is at the mercy of the fluctuations of fossil fuels because of the high proportion of electricity coming from non-renewable resources. Taking Belgium as an example, nuclear represents more than half of the generated electricity, wind represents 12%, and gas 21% [47].

With the price of oil reaching records, shore connections are a solution with two aspects. If the electricity is produced with non-renewable resources, then prices will go up, following the trend of these fuels. On the other hand, in countries where sustainable production of electricity is more present, investing in shore connections is smart. An example of this is Norway. In Europe, Norway is the highest producer of electricity from renewable sources and has the lowest power sector emissions. In comparison, more than 90% of their electricity comes from hydropower[48]. Therefore, their electricity is not dependent on the fluctuations of gas or oil price. This shows the importance of having renewable sources of power, to be less affected by price changes.

3.4.1.3 Power barge

The cost calculated is **256 €/MWh**. The price of hydrogen has been set at 2 €/kg. The purpose of such a pricing is to give an idea as of when this solution would become interesting from a financial point of view.

3.4.1.4 Summary table of electricity production cost of three options

	Diesel	Shore connection	Power Barge
€/MWh	275	270	256

Table 12: Summary table of price per Megawatt hour of three options for electricity

Based on the production cost criterion of the financial analysis, within the port of Antwerp, the electricity production of the Power Barge can compete with the alternatives, with a hydrogen price of 2€/kg or less. This will be further discussed later.

This quite favourable criterion is not the only part of the decision on the implementation of the project. As a complement to internal reasons of the company, the choice must integrate the position of the project in a more global context. This is the subject of the following analysis.

[47] Consulted July 23rd 2022 from: https://www.statista.com/statistics/1234898/belgium-distribution-of-electricity-production-by-source/

[48] Consulted July 23rd 2022 from: https://energifaktanorge.no/en/norsk-energiforsyning/kraftproduksjon/#:~:text=Hydropower%20is%20still%20the%20mainstay,of%20Norways%20total%20power%20production.

3.4.2 SWOT analysis

This project requires thorough research regarding the surrounding competitive environment. The Power Barge Project development is influenced by several internal and external factors. A SWOT analysis has been conducted to determine the strengths, weaknesses, opportunities and threats. This concept is used by many companies, which want to determine whether their projects can improve within its environment. Such an analysis was undertaken, for instance, by the KMI International Journal of Maritime Affairs and Fisheries (Satta et.al, 2021). In this document, a SWOT analysis was used to evaluate the pros and cons of the LNG bunkering technologies[49].

Table 13 summarises the results of the analysis. The SWOT arguments which are identified through the literature review and financial analysis are commented below.

[49] This study used the SWOT methodology to analyse the Mediterranean port context and put forward the implications for authorities and shipowners to increase their knowledge on LNG bunkering and storage.

Factors	Helpful	Harmful
Internal (elements controlled or controllable)	**Strengths** • Motivation of the company to decarbonise its activity • Effective for reducing GHG's • Effective for reducing air pollution • Flexible for ports • Reliable technology • Developing new energy technology know-how through a pilot project	**Weaknesses** • Price of Power Barge kWh subject to fluctuations • Specific implementation and safety costs regarding H2
External (elements on which there is little influence)	**Opportunities** • Rapid strengthening of institutional environmental targets • Green hydrogen development prospects • Strong partnerships with other stakeholders	**Threats** • Short to medium term solution • Competition from other energy sources • H2 transportation challenges • Local green H_2 provider lacking • Uncertainties on hydrogen's supply chain

Table 13: Overview table of the SWOT Power Barge Project analysis

3.4.2.1 Comments on the SWOT analysis of the Power Barge

1. **Strengths** of the Power Barge:

- The decarbonisation of the maritime activity is an element of motivation for the CMB/CMB.TECH which has multiple green projects ongoing like the straddle carrier or the refuelling station already in place.
- The mono-fuel engines can save up to 98% of the CO_2 in comparison to a traditional auxiliary diesel engine. With NO_x and particle number being extremely low, no aftertreatment of the fumes is required to comply with environmental objectives and regulation. With 20% of shipping emissions estimated to come from ports, this reduces markedly GHG's and air pollutants in ship's total assessment. The Power Barge meets the objectives and regulations for reducing pollution and GHG emissions in the medium term for ships and ports waiting for complete decarbonisation of boat engines, which is a long-term perspective. The condition is that green hydrogen is available, regarding the climate target. Of particular note is that it provides anyway a radical immediate solution to diesel pollution in port, which is a particularly topical environmental issue.
- The convenience of the Power Barge (i.e., making it able to move from one ship to another) simplifies the electrical infrastructure in ports, which could moreover, invest more gradually in shore connection.
- The technology itself presents few technical uncertainties as the system is ready for functioning. The BeH$_2$ydro engine is a technology already developed and proven to work. In comparison to fuel cells which require very pure hydrogen, BeH$_2$ydro engines are immune to impurity and their long lifetime expectancy constitutes a real strength of the project. The Power barge is the combination of proven technologies.
- Through a reasonable scale project, development of new energy technology know-how is at stake for industrial partners and ports. The CMB is constantly improving its knowledge by working on pilot projects. There is also no need to wait for big quantities of green hydrogen to start a pilot project like the Power Barge due to the relatively small amount required on the barge (5 tonnes). This suits the port industry, where refuelling of the barge can be more easily available in the port.

2. **Weaknesses** of the Power Barge:

   The major weakness of the project is related to the use of hydrogen. Its fluctuating price and a limited market for hydrogen as a marine fuel, are major obstacles to the competitiveness of the project. These aspects are even more crucial for green hydrogen.

The specificity of the implementation and safety of hydrogen on the barge also leads to significant new costs.

3. **Opportunities** for the Power Barge:

- This project is fostered by the continued strengthening of international environmental decarbonisation targets. The recent call for shipping decarbonisation from the Global Maritime Forum[50], shows that the maritime sector supports this evolution.
- There is an expected strong increase in hydrogen production with a decrease in cost, from the forecasting of the International Energy Agency.
- The Power Barge offers the opportunity to strengthen the positive relationships with many stakeholders, which are not initially part of the maritime industry (authorities, gas suppliers, engine manufactures, etc.).

4. **Threats** for the Power Barge are:

- Ships and port infrastructures are going to become more environmentally friendly, which puts the role of the Power Barge in 10, 20 or 30 years into question. If legislations impose on all ships berthing and on ports to have shore connection, the Power Barge might have an "expiry date". Thus, investors could be hesitant of getting involved with the Power Barge Project.
- Another threat concerns the competition from others energy sources. For example, ammonia can be seen as a threat to hydrogen because of its characteristics in terms of storage and transport which would be less burdensome. With 20% reduction of CO_2, LNG complies with the current regulations on maritime transport and also reduces the emissions of SO_x, NO_x and PM.
- Even though solutions have been found for the challenges of transporting the hydrogen, it remains a threat to the development of the project in the sense that it brings additional costs for the upstream supply chain to bare (e.g., specialised trucks, drivers, storage locations, etc.).
- The presence of local green hydrogen production plants is still relatively low compared to the blue and especially grey hydrogen's abundancy. Additionally, hydrogen is, most of the time, redirected in the production of fertilizers. The whole supply chain of the

[50] « Call to Action for Shipping Decarbonisation" is a task force englobing members from the entire maritime ecosystem including the CMB. It was delivered to world Governments in November 2021. Consulted on July 28th 2022 from: https://www.globalmaritimeforum.org/getting-to-zero-coalition/call-to-action/

procurement of green hydrogen and the safety aspects in relation to it, are sources of a global uncertainty around the project.

- The uncertainty of the growth of the maritime sector can be considered as a threat. As shown in section 2.3.4, prices of freight have surged, and some types of transport are forecasted to decrease.

3.4.2.2 SWOT analysis conclusion

The internal negative elements of the project (electricity production cost only slightly attractive, limitations related to the use of hydrogen) and the threats to the project (lack of green hydrogen supplier, uncertainties on the demand) appear to be strongly outweighed by its strong assets (effectiveness against pollution, reliable technology) and the overall prospects for the development of green hydrogen.

3.5 The Power Barge, a hopeful step towards green electricity production - Conclusion

The most obvious solution to minimise pollution and emissions in the port would be a systematic connection of ships to the land-based electricity grid (shore connection), provided that the distributed energy is produced without GHG emissions. However, this solution requires that both quays and ships are equipped accordingly. Yet this evolution will only be slow and partial in many ports where investment possibilities and perhaps the availability of electricity are limited. Provided that it is economically attractive, the proposal of barges supplying electricity at the quayside to ships equipped for connection, seems to be a good and feasible solution to accelerate the introduction of hydrogen as an energy source in maritime transport.

The financial analysis and the wider SWOT analysis, lay the foundations for discussing the original assumption, stating that electricity production from hydrogen for ships at berth, can be a good solution to limit the impact of the maritime sector’s emissions on the environment.

4 Discussions

The goal of this Master's thesis is to find out if hydrogen as a fuel for electrical generators can be introduced in the port maritime industry via boats at berth. The idea is to see how innovative projects such as the Power Barge could kickstart and even scale-up the development of the use of a decarbonised fuel in the maritime sector. This section will cover discussions about the results of the specific financial and global SWOT analysis.

Paradox between effective innovation and uncertainties

It is known in the maritime industry that it is time to change from their polluting and GHG emitting vessels to more sustainable alternatives. Therefore, hydrogen solutions are being explored. Yet they are confronted with great uncertainties. Having an innovation that responds to a long-term goal (set by the EU or IMO and the maritime sector in general) but which is challenged by short- and medium-term obstacles, is paradoxical.

There is still a lack of clarity surrounding the question on how the demand for new solutions in the maritime sector could develop in a short term. On one hand, public authorities and shipowners such as the CMB, are investing money in research for greener solutions, of which the Power Barge seems to be one of the more realistic in a short term. On the other hand, there are several factors that do not work in a rapid change in the sector, slowing down the demand for innovative solutions.

For example, the uncertainty on the shipping market's growth with the bulk and coal carrier transport which are forecasted to decrease (mainly due to the reduction of fossil fuels), makes it difficult to predict the future of hydrogen in this environment. Some other segments of the shipping transport might skyrocket but as seen in section 2.3.4, several different scenarios can happen as decline and stagnation which are not appealing for the sector (Garrido et.al, 2021).

The medium-term outlook for maritime transport remains positive but subject to increasing risks and uncertainties[51]. The influence of actual decisions on the relocation of production has recently been added to these uncertainties, as a result of the COVID epidemic and the war in Ukraine.

Another area of uncertainty is the development of the green hydrogen industry, for which the positive prospects are becoming clearer. With 28 of the world's biggest energy companies

[51] Consulted on July 28th 2022 from: https://unctad.org/fr/news/le-commerce-maritime-resiste-la-tempete-covid-19-mais-doit-faire-face-des-repercussions

signing the 'H2ZERO' at COP26 in the end of 2021[52], the path to green hydrogen production is ongoing.

The economics of the project

The financial analysis performed for the Power Barge provides a slightly competitive cost production of electricity (256€/MWh), in comparison to the current other options, if hydrogen's price is lower or equal to 2€/kg. The following paragraphs consider the sensitivity of different parameters involved.

Changing the price of hydrogen in the model drastically modifies the results for the total cost of the Power Barge. For example, with a price of 3€/kg, the total cost of the hydrogen fuel goes up from 172€/MWh to 252€/MWh. Which makes the total cost per MWh of the Power Barge 30% more expensive than the alternatives. This situation is not unlikely in the short to medium term given the fluctuation of energy prices and production costs of hydrogen. For comparison, in 2018, it was around 3€/kg (IEA, 2018). This is a probable factor for the stand-by of the Power Barge Project at CMB. By considering the hypothesis of the International Energy Agency which foresees a drop in the production cost of green hydrogen of 30% by 2030, one finds himself in the competitive cost results of the financial analysis.

The price of electricity for shore connection is also a parameter that influences significantly the results. In this case, Belgium's price (0.27€/kWh), which is high among the EU countries, is considered but the cost of electricity is not the same over Europe. Two other countries of the EU have higher electricity prices, Denmark and Germany, respectively 0.35 and 0.33€/kWh. In comparison, countries such as Poland or Romania where electricity costs between 0.15 and 0.20€/kWh, could be seen as less interesting for the Power Barge project, due to the competitiveness of shore connection costs. Therefore, changing the country's reference for electricity value in the model can drastically affect the price comparison of shore connection with the Power Barge.

Finally, the trend for MDO prices is upwards. They were already rising before the war in Ukraine, but the conflict made them soar even more as prices for fossil fuels should remain high for users, due to the carbon pricing in the context of decarbonisation. If the expected

[52] It consisted of these companies pledging to produce and use more green and blue hydrogen. Retrieved on July 29th 2022 from: https://www.rechargenews.com/energy-transition/oil-and-power-giants-launch-new-global-initiative-to-accelerate-replacement-of-grey-hydrogen/2-1-1096201

decrease in the price of green hydrogen is added, the production costs of electricity from the Power Barge will eventually become lower than those of its competitors, in the medium (i.e., 5 years) and long run.

The CAPEX costs represent about one third of the total electricity production cost produced by the Power Barge (83€/MWh). But this number could go down in a few years if production of these engines increases and more actors enter the hydrogen business. A similar drop in prices for batteries of electric cars has been observed. Since 2010, the average cost of battery packs has fallen by 89% reaching now nearly 100$/kWh (BloombergNEF, 2020). With the growing demand, factories can mass produce, which results in reducing the production costs.

The power required for ships varies a lot, depending on the type (see section 2.3.1). Difficulties could appear in terms of allocating the barge to a ship that allows the lowest electrical production cost. With the complexity of forecasting the shipping market in the future and therefore not knowing what type of ship will berth, ports could suffer from delays in supplying electricity with the Power Barge, resulting in ships turning on their auxiliary engines.

Promising industrial motivation and partnership for a pilot dissemination

As mentioned on their website[53] the CMB is accelerating the development of hydrogen solutions and expects that by 2030 it will be able to greenify a very large part of its fleet. The words from Alexander Saverys, Chief Executive Officer of the CMB are: *"With hydrogen, we want to maintain and further expand our lead."* (CMB [CMB.TECH], 2022).

The company mentions the importance of participating in an "innovation ecosystem", which is essential considering the collaboration with universities, engineering firms and international partners. Application development is vital to achieve these goals and the company has ambitions to develop more. The Power Barge proposal, is therefore obviously one of the opportunities to keep on developing cooperation with actors in and outside of the maritime industry.

The limiting factor to the expansion of the use of green hydrogen energy is its availability. In this field the CMB is also involved in partnerships for production projects. 'Cleanenergy Namibia'[54] is a project of demonstrating hydrogen production in Namibia, which should be operational at the end of 2023. CMB has created a joint venture for this project with the biggest

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[53] Consulted July 29th 2022 from: https://www.cmb.be/en/home
[54] Consulted July 31st 2022 from: https://cmb.tech/fr/partners/o-l

private firm in Namibia which focuses on the photovoltaic systems. All these elements support the interest of the barge project as being one of the innovations that will contribute to the accelerated decarbonisation of maritime transport.

The development of the production and use of hydrogen as a source of decarbonised energy is a priority among the EU as underscored in its Green Deal and more widely. Partnerships with governments and authorities are therefore essential. Research and development programmes on decarbonised energy and particularly hydrogen, are supported by public authorities.

The choice of the CMB to implement their project in the Port of Antwerp-Bruges, could be a good way of disseminating the Power Barge. Being the second largest port of Europe, this port opens them up even more to the world as a show case for demonstrating their knowledge and expertise in hydrogen innovations.

Other criticism and limits of the analysis

The parameters of the financial analysis of the power barge, can be subject to discussions. In the search for ships' demand at berth, the setup time, which takes half of the power required, is an estimation, which was given by the CMB.TECH. It illustrates the period during which the barge has to switch from one vessel to another. The barge also has two options for refuelling of hydrogen. Either it can change the container tanks in a container terminal or it can refuel them. The first one is faster whereas the second option is cheaper. The setup time does involve the refuelling of the barge but does not make a distinction between the two options for refuelling. Other than that, parameters such as maintenance of the power barge or port traffic could be inserted in this setup time. If the setup time goes up, less energy can be delivered to the vessels, thus bringing the cost of the electricity production up.

The model also considers taking the highest value of power every hour to maximise the genset's load. This consideration does not reflect reality, as the power barge would stay connected to the ship until its departure, and would not switch to another ship, where the power of this new ship is bigger than the power of the first one. Nevertheless, the scaling up of this technology with several power barges sailing from one ship to another could, in the future, help mitigate this issue. The complexity of elaborating a model as close to reality as possible, is present.

Finally, although the European Union and most stakeholders of the energy industry support the use of hydrogen as a new energy source, there is no unanimity of this. Indeed, some studies, seem to show that a hydrogen-based economy could have consequences on the environment.

For example, the leakage of hydrogen into the atmosphere could lead to an increase in lifetime of the methane already present (Warwick, 2022). In addition, the combustion of hydrogen generates water vapour, which could result in stratospheric cooling, a rise in noctilucent clouds[55], and changes in tropospheric chemistry (Tromp, 2003). But this question goes beyond the purpose of this thesis and is the subject of another debate.

[55] Noctilucent clouds are extremely rare very high clouds seen in the night sky, usually on clear, summer nights. They become visible about the same time as the brightest stars and are usually bluish or silvery. Height of base: 200,000 feet. Consulted on July 31st 2022 from: https://www.metoffice.gov.uk/weather/learn-about/weather/types-of-weather/clouds/other-clouds/noctilucent#:~:text=Noctilucent%20clouds%20are%20extremely%20rare,Height%20of%20base%3A%20200%2C000%20feet.

5 Conclusion and Prospects

This research was aimed at evaluating the green hydrogen Power Barge as a solution for reducing GHG's and ship pollution in ports, in the wider framework of hydrogen introduction as decarbonisation of maritime transport. After an extensive bibliographic search and a financial assessment of the CMB Power Barge Project, it can be said that hydrogen as a fuel for internal combustion engines, which drives electric generators on a barge, is a promising solution to answer these questions when combined with connection to the land grid.

In effect, the financial analysis of the Power Barge's electricity production cost, on basis of the data from Port of Antwerp-Bruges, has showed that with a grey hydrogen realistic current price of 2€/kg, the concept is already competitive compared to diesel ship generators and shore connection. The Power Barge production cost is 256€/MWh, respectively 7% and 5.5% less than the other options. The trend is in favour of the Power Barge with an expected reduction of 30% of the price of green hydrogen for 2030, according to the International Energy Agency (IEA, 2019). The financial analysis and the current trend from the IEA, regarding green hydrogen production costs, show that the barge solution will, without a doubt, increase its competitiveness in the upcoming years.

The SWOT analysis, allowed to put the Power Barge in its context. In addition to the financial analysis' encouraging results, the major strengths reported is that the reliable technology of the Power Barge responds exceptionally well to the growing concerns about GHG's and air pollution. The main threat is the current low availability of green hydrogen and its price. As mentioned above, price should be a temporary barrier. Availability is, according to the International Energy Agency, forecasted to be multiplied by six from 2020 to 2050 with a reduction of gey hydrogen in favour to green or blue hydrogen (IEA, 2021).

Another barrier to the development of the Power Barge had to be considered. As mentioned, the paradox of having a technology that responds to environmental concerns but in which many companies are not yet willing to invest enough, is a challenge in a sector facing uncertainties (e.g., unclear context of price fluctuations, fuel availability and maritime transport perspectives). Such a project should, nevertheless, be an asset for the CMB's ecosystem of innovations. It contributes to the continuous expansions of innovation and partnerships with other leaders such as port authorities, engine manufactures or actors of the green hydrogen supply chain.

LNG and ammonia are the other most promising alternatives to fossil fuels in maritime transport. However, LNG is a short-term solution to meet pollution regulations and is not a decarbonised fuel. Ammonia and even hydrogen, are far from being available for electricity production on board the long cruise ocean-going-vessels. Therefore, apart from electricity from the grid, there is no competition with the Power Barge to provide decarbonised electricity for ships at berth. Shipping companies and institutions (e.g., IMO, EU, port authorities) are favourable to decarbonisation and support innovation and research. The international emission reduction agreements, the development of legislations penalising emissions and promoting their reduction, are elements that minimise the current risks associated with the uncertainties of production costs and their evolution.

Thus, the global analysis reinforces the conclusion of the final statement: The Power Barge Project is a real concrete step for the quick introduction of non-carbon fuel in maritime transport With the port emissions representing 20% of the total shipping pollution (Moreira, 2016), this project can be seen as a drop in the ocean for addressing the global warming issue. Nonetheless, it constitutes of an incremental change to the environment and can be seen as a kickstart to foster more innovation towards the decarbonation of the maritime sector.

These favourable conclusions tend to encourage a socially responsible company investing in the future, to pursue the project on a pilot basis in the context of the other initiatives of its hydrogen cluster. The current low availability of green hydrogen should not hinder the development of the project. All indications show that this limitation will gradually be lifted.

Some recommendations emerge in this perspective:

- From a technical point of view, the area which probably requires in depths studies approach is safety and storage conditions (e.g., technical aspects, standardised procedures, crew training). As mentioned, the CMB has multiple hydrogen projects ongoing, thus some of these questions have surely already been answered.
- The setting up of the infrastructure guaranteeing the availability of hydrogen must be ensured. Storage, movement of hydrogen within the port facilities, service organisation, traffic and safety, are elements that must be fixed with good relations between the CMB, hydrogen providers, the port of Antwerp-Bruges and other stakeholders. Here again, the existing CMB's hydrogen initiatives on the run, are an advantage to solve these questions.

- A more in-depth study of the context where the barge could find its best economic return must be undertaken. For European ports there is a prospect of equipment for connecting ships to the grid. The European directive ‘Directive 2009/16/EC, COM (2021)562’ considers this, when it is economically viable. There will therefore be many situations, in which on a transitory or long-term basis, the Power Barge solution may be relevant. This approach should also cover cases of ports in countries where the prospect of grid connection is less obvious, notably outside Europe. The case of other ports, close to green hydrogen production sites, should be considered.
- A more in-depth study of a strategy for the optimal use of the production capacity of the Power Barge by serving the largest consumer vessels as a priority would also be relevant. This is a way to limit production costs.
- Partnerships between the CMB and port authorities should constantly raise the issue of fostering the introduction of new projects like the Power Barge. A topic to be put on the agenda should be the possibility to reduce port fees for ships powered by green electricity from the Power Barge, perhaps with public financial support.
- A pilot scale development is probably eligible to public funding such as the European Union's Interreg programme[56], which is currently co-financing a project of which the expected output is a pilot boat for passenger transport in the port of Amsterdam. Every opportunity should be considered for financing the transition towards greener shipping.

[56] Consulted July 29th 2022 from: https://www.nweurope.eu/projects/project-search/h2ships-system-based-solutions-for-h2-fuelled-water-transport-in-north-west-europe/?tab=&page=4#tab-3

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Appendices

A. Data from the port of Antwerp-Bruges

Verblijfnumm	VanReisPassageL	day aft start	Day	Hours	hour aft	TOTAL h aft st	ScheepsTypeNaut	GroepsTypeNaut	TonnenmaatBr	Capaciteit	TotaalDu	Walstroom	TotaalN(	TotaalC(	Power (M
254	3-01-19 8:30	0,00	0,00	#DIV/0!	#DIV/0!	0,00	container ship (full)	Containerschepen	131771	11668	49,77	Met walstroom	2253,3924	120705,82	2,94
225	3-01-19 14:07	0,23	0,00	5:37	5,62	6,00	container ship (full)	Containerschepen	194308	19170	32,20	Met walstroom	1852,2387	115163,9	4,34
288	3-01-19 19:10	0,44	0,00	10:40	10,67	11,00	container ship (full)	Containerschepen	113112	11010	39,65	Met walstroom	1327,7071	82550,873	2,53
311	5-01-19 1:48	1,72	1,00	17:18	17,30	41,00	container ship (full)	Containerschepen	95390	8827	24,53	Met walstroom	692,80307	43075,389	2,13
309	5-01-19 13:41	2,22	2,00	5:11	5,18	53,00	container ship (full)	Containerschepen	94469	9400	24,32	Met walstroom	680,05456	42282,744	2,11
305	5-01-19 16:34	2,34	2,00	8:04	8,07	56,00	container ship (full)	Containerschepen	10585	1036	21,13	Met walstroom	66,223062	4117,4531	0,24
338	6-01-19 13:28	3,21	3,00	4:58	4,97	77,00	container ship (full)	Containerschepen	192237	19224	31,32	Met walstroom	1782,2265	110810,86	4,29
289	7-01-19 1:14	3,70	3,00	16:44	16,73	89,00	container ship (full)	Containerschepen	94469	9400	16,97	Met walstroom	474,50003	29502,284	2,11
82	8-01-19 7:43	4,97	4,00	23:13	23,22	119,00	container ship (full)	Containerschepen	112967	10100	6,20	Met walstroom	207,34505	12891,786	2,52
377	8-01-19 15:08	5,28	5,00	6:38	6,63	127,00	container ship (full)	Containerschepen	45803	4112	9,28	Met walstroom	146,10878	7826,5014	1,02
378	9-01-19 0:45	5,68	5,00	16:15	16,25	136,00	container ship (full)	Containerschepen	45803	4112	17,52	Met walstroom	275,69178	14767,779	1,02
665	10-01-19 15:07	7,28	7,00	6:37	6,62	175,00	container ship (full)	Containerschepen	10585	1036	14,05	Met walstroom	44,026846	2737,392	0,24
504	10-01-19 22:30	7,58	7,00	14:00	14,00	182,00	container ship (full)	Containerschepen	95403	8800	25,98	Met walstroom	733,84999	45627,502	2,13
380	11-01-19 9:11	8,03	8,00	0:41	0,68	193,00	container ship (full)	Containerschepen	113112	11010	37,43	Met walstroom	1253,4805	77935,797	2,53
561	11-01-19 17:05	8,36	8,00	8:35	8,58	201,00	container ship (full)	Containerschepen	76199	6586	30,02	Met walstroom	785,9414	42099,946	1,70
560	12-01-19 14:13	9,24	9,00	5:43	5,72	222,00	container ship (full)	Containerschepen	95390	8827	27,93	Met walstroom	788,81654	49045,076	2,13
562	14-01-19 13:06	11,19	11,00	4:36	4,60	269,00	container ship (full)	Containerschepen	54304	5059	16,40	Met walstroom	306,02302	16392,51	1,21
1075	15-01-19 20:30	12,50	12,00	12:00	12,00	300,00	container ship (full)	Containerschepen	10585	1036	17,47	Met walstroom	54,733256	3403,0685	0,24
684	17-01-19 2:31	13,75	13,00	18:01	18,02	330,00	container ship (full)	Containerschepen	94684	9040	17,75	Met walstroom	497,53696	30934,618	2,11
634	17-01-19 9:55	14,06	14,00	1:25	1,42	337,00	container ship (full)	Containerschepen	96816	9408	32,33	Met walstroom	926,71888	57619,225	2,16
808	18-01-19 10:46	15,09	15,00	2:16	2,27	362,00	container ship (full)	Containerschepen	151559	13798	51,23	Met walstroom	2668,1656	142923,66	3,38
568	18-01-19 20:32	15,50	15,00	12:02	12,03	372,00	container ship (full)	Containerschepen	193489	19472	49,30	Met walstroom	2823,9278	175579,17	4,32
807	18-01-19 21:30	15,54	15,00	13:00	13,00	373,00	container ship (full)	Containerschepen	94469	9400	20,98	Met walstroom	586,83255	36486,617	2,11
803	19-01-19 9:15	16,03	16,00	0:45	0,75	385,00	container ship (full)	Containerschepen	76199	6586	20,93	Met walstroom	548,10794	29360,095	1,70
829	20-01-19 9:07	17,03	17,00	0:37	0,62	409,00	container ship (full)	Containerschepen	54771	5043	25,17	Met walstroom	473,64701	25371,501	1,22
834	20-01-19 13:13	17,20	17,00	4:43	4,72	413,00	container ship (full)	Containerschepen	75484	6492	16,53	Met walstroom	428,83849	22971,276	1,69
1076	20-01-19 19:23	17,45	17,00	10:53	10,88	419,00	container ship (full)	Containerschepen	10585	1036	15,48	Met walstroom	48,518316	3016,6514	0,24
710	21-01-19 1:28	17,71	17,00	16:58	16,97	425,00	container ship (full)	Containerschepen	54881	5059	25,72	Met walstroom	484,97028	25978,047	1,23
711	22-01-19 4:06	18,82	18,00	19:36	19,60	452,00	container ship (full)	Containerschepen	54881	5059	9,37	Met walstroom	176,63856	9461,8679	1,23
1058	22-01-19 18:36	19,42	19,00	10:06	10,10	466,00	container ship (full)	Containerschepen	45803	4112	15,42	Met walstroom	242,64025	12997,332	1,02
1079	23-01-19 2:44	19,76	19,00	18:14	18,23	474,00	container ship (full)	Containerschepen	113112	11010	43,88	Met walstroom	1469,4631	91364,628	2,53
1210	24-01-19 18:11	21,40	21,00	9:41	9,68	514,00	container ship (full)	Containerschepen	95497	8819	28,22	Met walstroom	797,71146	49598,122	2,13
1212	30-01-19 12:24	27,16	27,00	3:54	3,90	652,00	container ship (full)	Containerschepen	96816	9408	34,40	Met walstroom	985,95246	61302,104	2,16
1617	1-02-19 18:07	29,40	29,00	9:37	9,62	706,00	container ship (full)	Containerschepen	95497	8819	32,13	Met walstroom	908,43928	56482,682	2,13
1636	2-02-19 1:12	29,70	29,00	16:42	16,70	713,00	container ship (full)	Containerschepen	153115	14036	49,47	Met walstroom	2602,6083	139412,01	3,42
1621	2-02-19 5:42	29,88	29,00	21:12	21,20	717,00	container ship (full)	Containerschepen	107849	9178	24,12	Met walstroom	893,74132	47874,384	2,41
1649	2-02-19 18:19	30,41	30,00	9:49	9,82	730,00	container ship (full)	Containerschepen	94416	9115	29,17	Met walstroom	815,23495	50687,654	2,11
1792	3-02-19 0:53	30,68	30,00	16:23	16,38	736,00	container ship (full)	Containerschepen	90449	8073	28,92	Met walstroom	898,73247	48141,742	2,02
1643	4-02-19 5:48	31,89	31,00	21:18	21,30	765,00	container ship (full)	Containerschepen	193489	19472	29,53	Met walstroom	1691,6836	105181,3	4,32

B. Calculations for finding the time and the energy of each genset mix

MSC PSA EUROPEAN TERMINAL (MPET), K1742 (WITH SHORE CONNECTION!)

In half a year (4380h)						Port stay no	254	225	288	311	309	305	338	289	82
3141	Hours					Power	2,94	4,34	2,53	2,13	2,11	0,24	4,29	2,11	2,52
7128,20	MWH					Hours after start	0,00	6,00	11,00	41,00	53,00	56,00	77,00	89,00	119,00
		For each hour		For finding Utilisation		Duration (h)	49,77	32,20	39,65	24,53	24,32	21,13	31,32	16,97	6,20
With setup time	Max/hour	# vessels	Total power	Without above	With above	Hours in a year									
		5,00	12,09	3,74	3,74										
2,60	2,60	1,00	2,94	2,94	2,94	1	2,94	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2,60	2,60	1,00	2,94	2,94	2,94	2	2,94	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2,60	2,60	1,00	2,94	2,94	2,94	3	2,94	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2,60	2,60	1,00	2,94	2,94	2,94	4	2,94	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2,60	2,60	1,00	2,94	2,94	2,94	5	2,94	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2,60	2,60	2,00	7,28	2,94	3,74	6	2,94	4,34	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2,60	2,60	2,00	7,28	2,94	3,74	7	2,94	4,34	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2,60	2,60	2,00	7,28	2,94	3,74	8	2,94	4,34	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2,60	2,60	2,00	7,28	2,94	3,74	9	2,94	4,34	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2,60	2,60	2,00	7,28	2,94	3,74	10	2,94	4,34	0,00	0,00	0,00	0,00	0,00	0,00	0,00
2,60	2,60	3,00	9,81	2,94	3,74	11	2,94	4,34	2,53	0,00	0,00	0,00	0,00	0,00	0,00
2,60	2,60	3,00	9,81	2,94	3,74	12	2,94	4,34	2,53	0,00	0,00	0,00	0,00	0,00	0,00
2,60	2,60	3,00	9,81	2,94	3,74	13	2,94	4,34	2,53	0,00	0,00	0,00	0,00	0,00	0,00
2,60	2,60	3,00	9,81	2,94	3,74	14	2,94	4,34	2,53	0,00	0,00	0,00	0,00	0,00	0,00
2,60	2,60	3,00	9,81	2,94	3,74	15	2,94	4,34	2,53	0,00	0,00	0,00	0,00	0,00	0,00
2,60	2,60	3,00	9,81	2,94	3,74	16	2,94	4,34	2,53	0,00	0,00	0,00	0,00	0,00	0,00
2,60	2,60	3,00	9,81	2,94	3,74	17	2,94	4,34	2,53	0,00	0,00	0,00	0,00	0,00	0,00
2,60	2,60	3,00	9,81	2,94	3,74	18	2,94	4,34	2,53	0,00	0,00	0,00	0,00	0,00	0,00
2,60	2,60	3,00	9,81	2,94	3,74	19	2,94	4,34	2,53	0,00	0,00	0,00	0,00	0,00	0,00

C. CAPEX calculations with IRR (5%) and depreciation 10 years

MSC PSA EUROPEAN TERMINAL (MPET), K1742 (WITH SHORE CONNECTION!)

	3,744	
	Without	With
Hours full loa	2934	3141
MWh/half y	7263	8367
Utilisation	44%	51%

Electrical eff.	0,96		
half a year	4380	h	
Power	3,9	MW	
Power with e. eff.	3,744	MW	
100%	16399	MWh	(best we can give)
Depriciation	10	years	
IRR rate	5%		
Avg Power output	100%		

5000	kg	2	met sailing
Autonomy calculation			
17,07692308			
19,07692308			
90%	autonomy factor		

		(1,35+2)	(2,6+1)	(2,6+1,3)	(1,35+1,35+1,35)	(2+2)	(2,6+2)	(1,35+1,35+2)	(2,6+1,35+1)	(2+2+1)	(2,6+2,6)	(2,6+2,6+2,6)	Units
	Power	3,3	3,6	3,9		4	4,6		4,9	5	5,2	7,8	MW
	with e. eff.	3,168	3,456	3,744		3,84	4,416		4,704	4,8	4,992	7,488	
	Autonomy	91%	90%	90%		89%	88%		87%	87%	86%	81%	
LIMITED	Hours full load	2823	2934	2934		2934	3141		3141	3141	3141	3141	h
	MWh/half y	6292	7263	7263		7263	8623		8623	8623	8623	8623	MWh
	MWh/half y	5725	6554	6501		6484	7588		7517	7497	7458	6987	MWh
	Utilisation	45%	48%	44%		43%	45%		42%	41%	39%	26%	
	CAPEX	9.304.530,00	9.367.529,00	9.532.412,00	10.273.472,00	9.593.412,00	9.821.294,00	10.562.354,00	10.625.353,00	10.686.353,00	10.049.176,00	11.823.764,00	€
	CAPEX with IRR	12.049.792,03	12.131.378,62	12.344.909,64	13.304.616,25	12.423.907,44	12.719.025,05	13.678.731,65	13.760.318,24	13.839.316,03	13.014.142,67	15.312.315,31	
	CAPEX/MWh	105,24	92,55	94,94	102,32	95,81	83,81	90,13	91,53	92,29	87,24	109,58	€/MWh
UNLIMITED	Hours full load	3141	3141	3141		3141	3141		3141	3141	3141	3141	h
	MWh/half y	7976	8233	8367		8411	8623		8623	8623	8623	8623	MWh
	MWh/half y	7257	7430	7490		7509	7588		7517	7497	7458	6987	MWh
	Utilisation	57%	54%	51%		50%	45%		42%	41%	39%	26%	
	CAPEX with IRR	12.049.792,03	12.131.378,62	12.344.909,64	13.304.616,25	12.423.907,44	12.719.025,05	13.678.731,65	13.760.318,24	13.839.316,03	13.014.142,67	15.312.315,31	€
	CAPEX/MWh	83,02	81,64	82,41	88,82	82,72	83,81	90,13	91,53	92,29	87,24	109,58	€/MWh

D. Tables for calculating the fuel consumption (limited and unlimited by the demand)

Unlimited

Fuel calculation with 5 options :
1,35+1,35+1,35
2,6+2,6+2,6
2+2+1
2+2,6
1,35+1,35+2

MW Gensets

Electrical eff correction	1	1,35	2	2,6	MW
	0,96	1,28	1,92	2,56	Mwe

Option 3,9 / 3,744 — Option 7,8 / 7,488 — Option 5 / 4,8

Total duur	Power (MW)	Maxed	El. E 3,9	#1,3MW	Load 3,9	Efficiency	Total fuel E	Maxed	El.E 7,8	#2,6MW	Load 7,8	Eff. 7,8	Total fuel
14	0,24	0,24	3,22	1	0,18	0,23	13,94	0,24	3,22	1,00	0,09	0,13	24,62
17	0,24	0,24	4,13	1	0,18	0,23	17,89	0,24	4,13	1,00	0,09	0,13	31,58
20	0,24	0,24	4,68	1	0,18	0,23	20,29	0,24	4,68	1,00	0,09	0,13	35,82
14	0,24	0,24	3,32	1	0,18	0,23	14,39	0,24	3,32	1,00	0,09	0,13	25,40
21	0,24	0,24	5,00	1	0,18	0,23	21,64	0,24	5,00	1,00	0,09	0,13	38,20
15	0,24	0,24	3,66	1	0,18	0,23	15,86	0,24	3,66	1,00	0,09	0,13	27,99
15	1,02	1,02	15,77	1	0,80	0,37	42,29	1,02	15,77	1,00	0,40	0,33	47,63
18	1,02	1,02	17,92	1	0,80	0,37	48,05	1,02	17,92	1,00	0,40	0,33	54,12
24	1,02	1,02	24,72	1	0,80	0,37	66,30	1,02	24,72	1,00	0,40	0,33	74,66
26	1,02	1,02	26,41	1	0,80	0,37	70,82	1,02	26,41	1,00	0,40	0,33	79,76
27	1,02	1,02	27,53	1	0,80	0,37	73,84	1,02	27,53	1,00	0,40	0,33	83,16
28	1,02	1,02	28,35	1	0,80	0,37	76,04	1,02	28,35	1,00	0,40	0,33	85,63
18	1,02	1,02	18,87	1	0,80	0,37	50,62	1,02	18,87	1,00	0,40	0,33	57,00
23	1,02	1,02	23,22	1	0,80	0,37	62,27	1,02	23,22	1,00	0,40	0,33	70,13
27	1,02	1,02	27,36	1	0,80	0,37	73,39	1,02	27,36	1,00	0,40	0,33	82,64
26	1,02	1,02	26,08	1	0,80	0,37	69,96	1,02	26,08	1,00	0,40	0,33	78,78
20	1,02	1,02	20,46	1	0,80	0,37	54,87	1,02	20,46	1,00	0,40	0,33	61,79
23	1,02	1,02	23,99	1	0,80	0,37	64,33	1,02	23,99	1,00	0,40	0,33	72,45
25	1,02	1,02	25,52	1	0,80	0,37	68,45	1,02	25,52	1,00	0,40	0,33	77,08
25	1,02	1,02	25,06	1	0,80	0,37	67,21	1,02	25,06	1,00	0,40	0,33	75,69
12	1,02	1,02	12,12	1	0,80	0,37	32,51	1,02	12,12	1,00	0,40	0,33	36,61
27	1,02	1,02	27,21	1	0,80	0,37	72,97	1,02	27,21	1,00	0,40	0,33	82,18
41	1,02	1,02	41,58	1	0,80	0,37	111,52	1,02	41,58	1,00	0,40	0,33	125,59
28	1,02	1,02	29,03	1	0,80	0,37	77,87	1,02	29,03	1,00	0,40	0,33	87,69
25	1,02	1,02	25,81	1	0,80	0,37	69,22	1,02	25,81	1,00	0,40	0,33	77,96
25	1,02	1,02	25,76	1	0,80	0,37	69,09	1,02	25,76	1,00	0,40	0,33	77,80
23	1,02	1,02	23,61	1	0,80	0,37	63,33	1,02	23,61	1,00	0,40	0,33	71,31
22	1,02	1,02	22,33	1	0,80	0,37	59,90	1,02	22,33	1,00	0,40	0,33	67,45
21	1,02	1,02	21,67	1	0,80	0,37	58,11	1,02	21,67	1,00	0,40	0,33	65,44
12	1,02	1,02	12,21	1	0,80	0,37	32,74	1,02	12,21	1,00	0,40	0,33	36,87
9	1,02	1,02	9,50	1	0,80	0,37	25,47	1,02	9,50	1,00	0,40	0,33	28,68
25	1,21	1,21	30,40	1	0,95	0,39	78,38	1,21	30,40	1,00	0,47	0,34	89,62

Total duur	Maxed	El. E 5	Load 1	Eff	Tot fuel 1	Load 2	Eff2	Total fuel	Load 2	Eff3
14	0,24	3,22	0,25	0,26	12,16	0,00	#N/A	0,00	0,00	#N/A
17	0,24	4,13	0,25	0,26	15,59	0,00	#N/A	0,00	0,00	#N/A
20	0,24	4,68	0,25	0,26	17,69	0,00	#N/A	0,00	0,00	#N/A
14	0,24	3,32	0,25	0,26	12,54	0,00	#N/A	0,00	0,00	#N/A
21	0,24	5,00	0,25	0,26	18,87	0,00	#N/A	0,00	0,00	#N/A
15	0,24	3,66	0,25	0,26	13,82	0,00	#N/A	0,00	0,00	#N/A
15	1,02	15,77	0,00	#N/A	0,00	0,53	0,35	44,74	0,00	#N/A
18	1,02	17,92	0,00	#N/A	0,00	0,53	0,35	50,83	0,00	#N/A
24	1,02	24,72	0,00	#N/A	0,00	0,53	0,35	70,13	0,00	#N/A
26	1,02	26,41	0,00	#N/A	0,00	0,53	0,35	74,91	0,00	#N/A
27	1,02	27,53	0,00	#N/A	0,00	0,53	0,35	78,11	0,00	#N/A
28	1,02	28,35	0,00	#N/A	0,00	0,53	0,35	80,43	0,00	#N/A
18	1,02	18,87	0,00	#N/A	0,00	0,53	0,35	53,54	0,00	#N/A
23	1,02	23,22	0,00	#N/A	0,00	0,53	0,35	65,87	0,00	#N/A
27	1,02	27,36	0,00	#N/A	0,00	0,53	0,35	77,62	0,00	#N/A
26	1,02	26,08	0,00	#N/A	0,00	0,53	0,35	74,00	0,00	#N/A
20	1,02	20,46	0,00	#N/A	0,00	0,53	0,35	58,04	0,00	#N/A
23	1,02	23,99	0,00	#N/A	0,00	0,53	0,35	68,05	0,00	#N/A
25	1,02	25,52	0,00	#N/A	0,00	0,53	0,35	72,40	0,00	#N/A
25	1,02	25,06	0,00	#N/A	0,00	0,53	0,35	71,09	0,00	#N/A
12	1,02	12,12	0,00	#N/A	0,00	0,53	0,35	34,39	0,00	#N/A
27	1,02	27,21	0,00	#N/A	0,00	0,53	0,35	77,19	0,00	#N/A
41	1,02	41,58	0,00	#N/A	0,00	0,53	0,35	117,96	0,00	#N/A
28	1,02	29,03	0,00	#N/A	0,00	0,53	0,35	82,36	0,00	#N/A
25	1,02	25,81	0,00	#N/A	0,00	0,53	0,35	73,22	0,00	#N/A
25	1,02	25,76	0,00	#N/A	0,00	0,53	0,35	73,08	0,00	#N/A
23	1,02	23,61	0,00	#N/A	0,00	0,53	0,35	66,98	0,00	#N/A
22	1,02	22,33	0,00	#N/A	0,00	0,53	0,35	63,36	0,00	#N/A
21	1,02	21,67	0,00	#N/A	0,00	0,53	0,35	61,47	0,00	#N/A
12	1,02	12,21	0,00	#N/A	0,00	0,53	0,35	34,63	0,00	#N/A
9	1,02	9,50	0,00	#N/A	0,00	0,53	0,35	26,94	0,00	#N/A
25	1,21	30,40	0,00	#N/A	0,00	0,63	0,36	83,58	0,00	#N/A

PIVOT table for finding fuel price/MWh (unlimited)

Somme de Total duur	Somme de El. E 3,9	Somme de Total fuel E	Somme de El.E 7,8	Somme de Total fuel E 7,8	Somme de El. E 5	Somme de TOTAL	Somme de El E 4,6	Somme de TOTAL2	Somme de TOTAL3
10.298,03	24.744,17	65.448,67	25.361,89	68.895,06	25.310,70	67.772,36	25.252,30	67.515,91	66.508,74

H2 2 €/kg

Handeling cost
Container swap
moleculeprice will be higher, but should be more efficient than own compressor — Container specs
70,00 € container move on & off — 450 kg

0,16 € €/kg

13,32 kWh/kg
0,012 € €/kWh
11,678 € €/MWh

	Option 1	Option 2	Option 3	Option 4	Option 5
	3,9 (3*1,35)	**7,8 (3*2,6)**	**5 (2+2+1)**	**4,6 (2+2,6)**	**4,6 (1,35+1,35+2)**
Efficiency	37,81%	36,81%	37,35%	37,40%	37,97%
Quantity of H2	1.965.425,42	2.068.920,62	2.035.205,88	2.027.504,91	1.997.259,43
Price	3.930.850,83 €	4.137.841,24 €	4.070.411,77	4.055.009,82	3.994.518,86
Energy	24.744,17 MWh	25.361,89 MWh	25.310,70 MWh	25.252,30 MWh	25.252,30
Price/MWh	**170,54 €/MWh**	**174,83 €/MWh**	**172,50 €/MWh**	**172,26 €/MWh**	**169,86 €/MWh**

Limited

Fuel calculation with 5 options :

Electrical eff correction	1	1,35	2	2,6	MW
	0,96	1,28	1,92	2,56	Mwe

1,35+1,35+1,35
2,6+2,6+2,6
2+2+1
2+2,6
1,3+1,35+2

MW Gensets: 3,9 (3,744) — 7,8 (7,488)

Total duur	Power (MW)	Maxed 3,9	El. E 3,9	#1,3MW	Load 3,9	Efficiency	Total fuel E	Maxed 7,8	El.E 7,8	#2,6MW	Load 7,8	Eff. 7,8	Total fuel E 7	Maxed 5	El. E 5	Load 1MW	Eff
14	0,24	0,24	3,22	1	0,18	0,23	13,94	0,24	3,22	1,00	0,09	0,13	24,62	0,24	3,22	0,25	0,26
17	0,24	0,24	4,13	1	0,18	0,23	17,89	0,24	4,13	1,00	0,09	0,13	31,58	0,24	4,13	0,25	0,26
20	0,24	0,24	4,68	1	0,18	0,23	20,29	0,24	4,68	1,00	0,09	0,13	35,82	0,24	4,68	0,25	0,26
14	0,24	0,24	3,32	1	0,18	0,23	14,39	0,24	3,32	1,00	0,09	0,13	25,40	0,24	3,32	0,25	0,26
21	0,24	0,24	5,00	1	0,18	0,23	21,64	0,24	5,00	1,00	0,09	0,13	38,20	0,24	5,00	0,25	0,26
15	0,24	0,24	3,66	1	0,18	0,23	15,86	0,24	3,66	1,00	0,09	0,13	27,99	0,24	3,66	0,25	0,26
15	1,02	1,02	15,77	1	0,80	0,37	42,29	1,02	15,77	1,00	0,40	0,33	47,63	1,02	15,77	0,00	#N/A
18	1,02	1,02	17,92	1	0,80	0,37	48,05	1,02	17,92	1,00	0,40	0,33	54,12	1,02	17,92	0,00	#N/A
24	1,02	1,02	24,72	1	0,80	0,37	66,30	1,02	24,72	1,00	0,40	0,33	74,66	1,02	24,72	0,00	#N/A
26	1,02	1,02	26,41	1	0,80	0,37	70,82	1,02	26,41	1,00	0,40	0,33	79,76	1,02	26,41	0,00	#N/A
27	1,02	1,02	27,53	1	0,80	0,37	73,84	1,02	27,53	1,00	0,40	0,33	83,16	1,02	27,53	0,00	#N/A
28	1,02	1,02	28,35	1	0,80	0,37	76,04	1,02	28,35	1,00	0,40	0,33	85,63	1,02	28,35	0,00	#N/A
18	1,02	1,02	18,87	1	0,80	0,37	50,62	1,02	18,87	1,00	0,40	0,33	57,00	1,02	18,87	0,00	#N/A
23	1,02	1,02	23,22	1	0,80	0,37	62,27	1,02	23,22	1,00	0,40	0,33	70,13	1,02	23,22	0,00	#N/A
27	1,02	1,02	27,36	1	0,80	0,37	73,39	1,02	27,36	1,00	0,40	0,33	82,64	1,02	27,36	0,00	#N/A
26	1,02	1,02	26,08	1	0,80	0,37	69,96	1,02	26,08	1,00	0,40	0,33	78,78	1,02	26,08	0,00	#N/A
20	1,02	1,02	20,46	1	0,80	0,37	54,87	1,02	20,46	1,00	0,40	0,33	61,79	1,02	20,46	0,00	#N/A
23	1,02	1,02	23,99	1	0,80	0,37	64,33	1,02	23,99	1,00	0,40	0,33	72,45	1,02	23,99	0,00	#N/A
25	1,02	1,02	25,52	1	0,80	0,37	68,45	1,02	25,52	1,00	0,40	0,33	77,08	1,02	25,52	0,00	#N/A
25	1,02	1,02	25,06	1	0,80	0,37	67,21	1,02	25,06	1,00	0,40	0,33	75,69	1,02	25,06	0,00	#N/A
12	1,02	1,02	12,12	1	0,80	0,37	32,51	1,02	12,12	1,00	0,40	0,33	36,61	1,02	12,12	0,00	#N/A
27	1,02	1,02	27,21	1	0,80	0,37	72,97	1,02	27,21	1,00	0,40	0,33	82,18	1,02	27,21	0,00	#N/A
41	1,02	1,02	41,58	1	0,80	0,37	111,52	1,02	41,58	1,00	0,40	0,33	125,59	1,02	41,58	0,00	#N/A

PIVOT table for finding fuel price/MWh (limited)

Somme de Total duur	Somme de El. E 3,9	Somme de Total fuel E	Somme de El.E 7,8	Somme de Total fuel E 7,8	Somme de El. E 5	Somme de TOTAL	Somme de El E 4,6	Somme de TOTAL2	Somme de TOTAL3
10.298,03	21.016,89	55.811,96	25.361,89	68.895,06	24.580,78	65.929,80	24.580,78	65.779,71	64.772,54

H2	2	€/kg

Handeling cost
Container swap
moleculeprice will be higher, but should be more efficient than own compressor

70,00 €	container move on & off	Container specs 450	kg
0,16 €	€/kg		
13,32	kWh/kg		
0,012 €	€/kWh		
11,678 €	**€/MWh**		

	Option 1	Option 2	Option 3	Option 4	Option 5
	3,9 (3*1,35)	**7,8 (3*2,6)**	**5 (2+2+1)**	**4,6 (2+2,6)**	**4,6 (1,35+1,35+2)**
eff	37,66%	36,81%	37,28%	37,37%	37,95%
kg H2	1.676.034,70	2.068.920,62	1.979.873,80	1.975.366,71	1.945.121,23
Price	3.352.069,41 €	4.137.841,24 €	3.959.747,59 €	3.950.733,42 €	3.890.242,46 €
Energy	21.016,89 MWh	25.361,89 MWh	24.580,78 MWh	24.580,78 MWh	24.580,78 MWh
Price/MWh	**171,17 €/MWh**	**174,83 €/MWh**	**172,77 €/MWh**	**172,40 €/MWh**	**169,94 €/MWh**

E. Recap for the 5 Gensets options

RECAP of 5 options for MPET terminal's demand

	LIMITED to capacity								
	3,9	4,6		5	7,8	MW			
5 options	1,35+1,35+1,35	1,35+1,35+2	2+2,6	2+2+1	2,6+2,6+2,6	MW			
Utilisation	44%	45%		41%	26%				
CAPEX/MWh	102,32	90,13	83,81	92,29	109,58	€/MWh	→	With IRR =	5%
Fuel cost/MW	171,17	169,94	172,40	172,77	174,83	€/MWh	→	With hand cost =	11,68 €
TOTAL cost	**273,50**	**260,07**	**256,21**	**265,06**	**284,41**	€/MWh			

	UNLIMITED to capacity								
	3,9	4,6		5	7,8	MW			
5 options	1,35+1,35+1,35	1,35+1,35+2	2+2,6	2+2+1	2,6+2,6+2,6	MW			
Utilisation	51%	45%		41%	26%				
CAPEX/MWh	88,82	90,13	83,81	92,29	109,58	€/MWh	→	With IRR =	5%
Fuel cost/MW	170,54	169,86	172,26	172,50	174,83	€/MWh	→	With hand cost =	11,68 €
TOTAL cost	**259,36**	**259,99**	**256,07**	**264,79**	**284,41**	€/MWh			

F. Data for finding efficiency from load

DATA from CMB (linking load and efficiency)

kWm	Load	kWe	H2 kg	H2 energy	dsl kg	Dsl Energy	Tot energy	Efficiency
60	6%	57	4,71	156,843	23,65	279,07	435,913	13%
118	12%	112,1	8,68	289,044	26,24	309,632	598,676	19%
176	18%	167,2	11,64	387,612	28	330,4	718,012	23%
177	18%	168,15	12,35	411,255	26,88	317,184	728,439	23%
236	24%	224,2	15,18	505,494	28,92	341,256	846,75	26%
294	29%	279,3	18,35	611,055	28,55	336,89	947,945	29%
295	30%	280,25	18,35	611,055	28,58	337,244	948,299	30%
352	35%	334,4	20,14	670,662	28,76	339,368	1010,03	33%
408	41%	387,6	25,47	848,151	30,36	358,248	1206,399	32%
469	47%	445,55	29,46	981,018	28,18	332,524	1313,542	34%
526	53%	499,7	32,88	1094,904	27,35	322,73	1417,634	35%
603	60%	572,85	37,36	1244,088	28,05	330,99	1575,078	36%
661	66%	627,95	41,99	1398,267	28,95	341,61	1739,877	36%
717	72%	681,15	45,13	1502,829	28,74	339,132	1841,961	37%
758	76%	720,1	48,07	1600,731	28,02	330,636	1931,367	37%
816	82%	775,2	51,77	1723,941	30,08	354,944	2078,885	37%
852	85%	809,4	54,15	1803,195	26,89	317,302	2120,497	38%
869	87%	825,55	55,75	1856,475	28,04	330,872	2187,347	38%
907	91%	861,65	56,07	1867,131	30,04	354,472	2221,603	39%
960	96%	912	56,78	1890,774	39,59	467,162	2357,936	39%
1000	100%	950	57,09	1901,097	42,12	497,016	2398,113	40%

Source: CMB.TECH

G. Calculations of the cost of Diesel per MWh

If we know:	1L of diesel		3,3	kWh	
	1L of diesel		0,84	kg	
	1kg of diesel		1,08	€	
	1 MWh		1000	kWh	
Then :		1 MWh		274,9091	€/MWh

=1/3,3*0,84*1,08*1000

H. Example of a BeH₂ydro genset (6 cylinders)

6DZD / Spark Ignited

Engine configuration	6-cylinder inline engine
Power range	Up to 1000 kW (continuous rating)
Power range	Up to 1353 Hp (continuous rating)
Nominal engine speed	Max. 1,000 rpm
Engine	Four-stroke
Sense of rotation	Anti-Clock or Clock
Fuel injection	Direct fuel injection
Swept Volume	95,71l
Weight	10620 kg
Turbo	Turbocharged
Charge-air	Water-cooled

Source: BeH$_2$ydro

I. Four of the new proposal 'Fit for 55' from the European Commission (Directive 2009/16/EC, COM(2021)562)

European Commission proposal	EU Emissions Trading System	FuelEU Maritime	Energy Taxation Directive	Regulation on the deployment of alternative fuels infrastructure
Main Elements	The owners of these ships must buy emissions allowances from the EU. They can use these allowances to cover their own emissions for the year, sell them to other companies or keep them for the next year	Ship fuels used by these ships must improve their GHG intensity by X% compared to a 2020 baseline	-Impose tax sold in the EEA for voyages within the EEA: -HFO/Gas oil: €0.9 per GJ -LNG/LPG: €0.6 per GJ until 2033. €0.9 per GJ from 2033 -EU governments will have the option to extend tax to bunkers sold for international journeys	-Minimum shoreside electricity supply for containerships and passenger ships - 'Adequate' refuelling points for LNG at these "core" ports
What is the scope?	Emissions from all voyages between ports in the European Economic Area and at berth in EEA + 50% of emissions from international inbound voyages AND 50% of emissions from international outbound voyages	GHG intensity of onboard energy used during all voyages between ports in the EEA and at berth in EEA + 50% of GHG intensity from international inbound voyages AND 50% of GHG intesnity from international outbound voyages	Bunkers sold in the EEA for voyages within the EEA and electricity used to charge vessels	EEA ports that are identified in the EU's TEN-T network
When?	A ship will have to buy allowances for 20% of its emissions in 2023 increasing annually to full coverage in 2026: -20% of emissions in 2023 -45% of emissions in 2024 -70% of emissions in 2025 -100% of emissions in 2026	Required GHG intensity improvements begin in 2025 and increase every five years until 2050: -2% improvement from 2025 -6% improvement from 2030 -13% improvement from 2035 -26% improvement from 2040 -59% improvement from 2045 -75% improvement from 2050	-Taxation begins on January 1, 2023 with a 10 year transition period	-Sufficient LNG refuelling points in place from January 1, 2025 -Minimum shoreside electricity supply in place from January 1, 2030
Who does it apply to?	Vessels of 5,000 gross tonnes and above	Vessels of 5,000 gross tonnes and above	Bunkers sold in the EEA	Specific ports in the EEA
Who is responsible/ bears immediate cost?	Shipowners	Shipowners	Bunker procurer	Ports

Source: European Commission

Source: Adamopoulos, 2021 (Lloyd's List)

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