# Environmental impacts from production and use of hydrogen in maritime transport


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A Master´s Thesis in Renewable Energy


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# Preface

This report is a result of the work done over the past two semesters and marks the end of a master's degree in "Renewable Energy". The thesis is written at the Geophysical Institute at the University of Bergen (UiB). The aim of the project has been to investigate whether or not hydrogen fuel can be a viable alternative as a replacement for conventional fuels used in maritime transportation today.

The problem of the thesis has been put to the test by conducting a Life Cycle Assessment (LCA) on a system that represents a specific case in relation to maritime transport. By doing so, it has been possible to make considerations that can answer the problem to be solved. The task has been executed by the collection and processing of data, use of software and by making reasonable assumptions that does not deviate from the reality to a considerable extent.

The student has come across several obstacles during the work of this project. Firstly, the contacts at corporate businesses wasn't able provide raw data as much of this information is classified. Sources of information are thereby somewhat limited. The thesis is thus formulated on the basis of the student's own interests and ambitions, rather than having a specific case set by a corporation.

Programme Director at the Institute of Marine Research and Professor at the Geophysical Institute Peter M. Haugan has acted as the main supervisor of this project. The student would like to thank Mr. Haugan for being able to access the necessary data needed to fulfill the requirements to solve the problem and for helping the student to get in contact with relevant actors within the maritime sector.

The student would also like to thank former master student, now employed in Designer Performance and Combustion systems at Hayvard, Jørgen Kopperstad, for providing insight into his own master's degree as well as tips on relevant projects for the student's own assignment.

Lastly, the cluster of NCE Maritime Cleantech has to be thanked for inviting the student to a seminar involving the development of hydrogen as a shipping fuel and the work that is done both on a locally and national scale in order to lead the maritime sector in a greener direction.

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# Abstract

In this study, hydrogen is proposed as an alternative fuel for shipping. Effects on replacing conventional fossil fuels in maritime transportation are assessed by conducting a Life Cycle Assessment on the entire transport life cycle. The system covers the impacts related to both infrastructure, vessel and fuel.

Only complete references of fuel oils, liquefied natural gas and hydrogen was able to be found, thus limiting the study. Batteries are also considered, but only as a supplementary power generating unit in hybrid systems, as they have a lack of energy compared to weight.

The LCA conducted in this study involves several impact categories including: acidification, abiotic depletion (including fossil fuels), eutrophication, ecotoxicity (accounting both freshwater, marine and terrestrial), global warming potential, human toxicity, ozone layer depletion and photochemical oxidation. Energy usage for the different fuels is investigated by applying the impact method Cumulative Energy Demand.

As the results suggests, replacing parts of the current fuel mix in maritime transport with hydrogen may lead to a significant lower impact on the environment. However, the utility of using hydrogen in maritime transport is heavily dependent on the access of a clean fuel. With production levels being low in addition to safety risks regarding the use of hydrogen onboard ships, it is necessary to continue developing the hydrogen technology in both a cost and energy efficient manner in order to compete with well-developed technologies.

# Sammendrag

I denne studien er hydrogen foreslått som et alternativt drivstoff for maritim transport. Miljøpåvirkninger fra å erstatte konvensjonelle fossile brensler i sjøtransport med hydrogen vurderes ved å utføre en livssyklusvurdering av hele transportlivssyklusen. Systemet dekker påvirkninger knyttet til både infrastruktur, fartøy og drivstoff.

Bare fullstendige referanser av fyringsoljer, flytende naturgass og hydrogen har vært mulig å oppdrive og begrenser derfor studiet. Batterier blir også vurdert, men bare som en ekstra kraftgenererende enhet i hybridsystemer, da de har en mangel på energi per vektenhet sammenlignet med andre drivstoff.

LCAen som er gjennomført i denne studien involverer flere påvirkningskategorier inkludert: forsuring, abiotisk uttømming (av fossilt brensel), overgjødsling, økotoksisitet (gjelder både ferskvann, sjø og land), globalt oppvarmingspotensial, menneskelig toksisitet, nedbryting av ozonlag og fotokjemisk oksidasjon. Energibruk for de forskjellige drivstoffene blir undersøkt ved beregning av kumulativt energibehov.

Som resultatene antyder, kan erstatning av deler av den nåværende drivstoffblandingen i sjøtransport med hydrogen føre til en betydelig mindre innvirkning på miljøet. Nytten av å bruke hydrogen i sjøtransport er imidlertid sterkt avhengig av tilgangen til et rent drivstoff. Siden produksjonsnivåene er lave i tillegg til sikkerhetsrisikoer for bruk av hydrogen ombord på skip, er det nødvendig å fortsette å utvikle hydrogenteknologien på både en kostnadseffektiv og energieffektiv måte for å konkurrere med velutviklede teknologier.

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## Nomenclature

| Abbreviation | Description |
|---|---|
| CED | Cumulative Energy Demand |
| CI | Compression Ignition |
| DWT | Deadweight Tonnage |
| ECA | Emission Controlled Area |
| EEDI | Energy Efficiency Design Index |
| EOL | End-Of-Life |
| FC | Fuel Cell |
| G&SD | Goal and Scope Development |
| GHG | Greenhouse Gases |
| GWP | Global Warming Potential |
| HFO | Heavy Fuel Oil |
| ICE | Internal Combustion Engine |
| IEA | International Energy Agency |
| IMO | International Maritime Organization |
| IPCC | Intergovernmental Panel on Climate Change |
| ISO | International Organization of Standardization |
| LCA | Life Cycle Assessment |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| LNG | Liquified Natural Gas |
| MGO | Marine Gas Oil |
| $NO_x$ | Nitrogen Oxides |
| PEM | Proton Exchange Membrane |
| SOFC | Solid Oxide Fuel Cell |
| $SO_x$ | Sulfur Oxides |
| UiB | University of Bergen |

# 1. Introduction

Maritime transportation remains an important way of transportation today with over 80 percent of the total goods in the world being transported by sea [1]. Most vessels in operation today are fueled by petroleum derived fuels which leads to greenhouse gas emissions. The effects of climate-impacting activities have gradually becoming more visible over the years, with rising temperatures and sea levels, weather changes and impacts on ecosystems to name a few [2].

Even though the emissions related to shipping only make up for about 2-3 per cent of the total emissions on Earth (measured in $CO_2$ equivalents), efforts to move the maritime industry in a greener direction are being made both on international and national levels [3]. The heavy use of fossil fuels in maritime transport releases greenhouse gases into the atmosphere. The increasing amounts of anthropogenic $CO_2$ in the atmosphere are initially what comes into mind when discussing climate impact of human activity. However, it is important to take note that shipping also contributes to other emissions that affect local air quality as well as human health where maritime activity occurs. Besides $CO_2$ emissions, emissions of nitrogen oxides ($NO_x$) and sulfur oxides ($SO_x$) are often mentioned when it comes to shipping related emissions. [4]

## 1.1 Regulations in maritime transport

While maritime transportation is not regulated by international climate agreements such as the Paris Agreement, the International Maritime Organization (IMO) has issued demands for a reduction in shipping related emissions by 50 per cent compared to levels in 2008 (see figure 1). The aim is to obtain zero emissions from the maritime industry as soon as possible in this century. [5] Improving the overall efficiency of vessels is also a critical measure to reduce the emissions. IMO has already adopted newer regulations dating back to 2011, which demand ships to become more energy efficient over time. These regulations, implemented in 2013, states that all newly built ships have to satisfy requirements according to the so-called Energy

Efficiency Design Index (EEDI). Older and existing parts of the fleet does not follow the equally stringent requirements. [4]

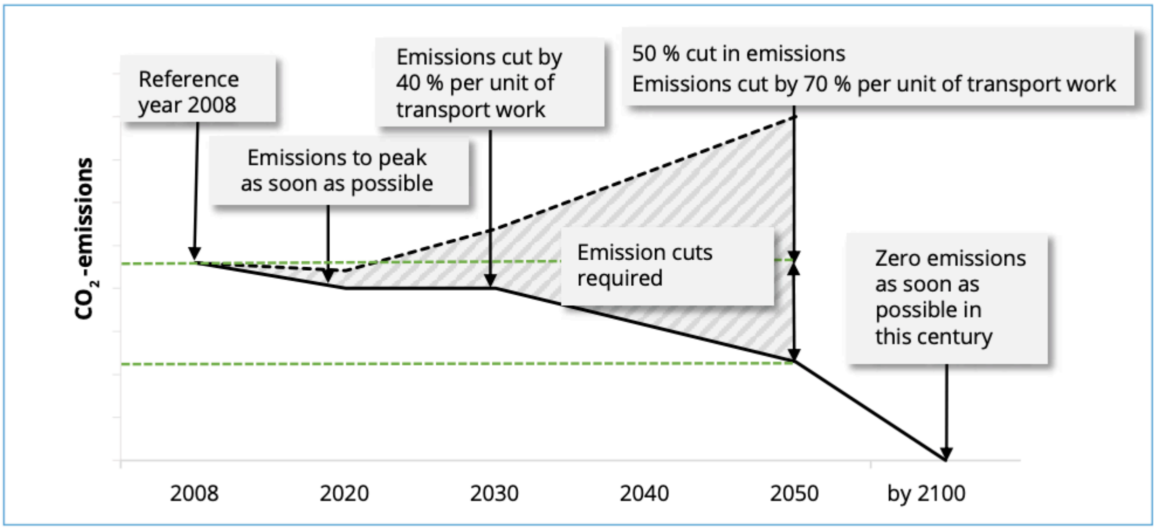


*Figure 1: IMO's climate ambition [5]*

One of the strongest measures implemented by the IMO aimed at environmental pollution from shipping is known as the MARPOL Convention (otherwise known as "The International Convention for the Prevention of Pollution from Ships"). [4] The Convention has the intention of regulate shipping in order to prevent and reduce marine pollution. MARPOL is made up of six different annexes with the sixth annex (Annex VI) specifically addressing air pollution. Annex VI was implemented in 2005 and states specific provisions regarding emissions of nitrogen oxides and sulfur oxides. According to the IMO GHG study from 2014 about 13 and 12 % of global $NO_x$ and $SO_x$ emissions respectively are caused by shipping related activities. [3]

The restrictions on emissions in shipping, particularly regarding $NO_x$ and $SO_x$ emissions, have been revised and made stricter on several occasions. As of 2020, the upper limit of sulfur content permitted in marine fuels is 0.5 percent. [4] In order to fulfill the restrictions, ships must either use fuel with a low sulfur content or scrubbers that can remove the sulfur generated through combustion of fuel from the exhaust before it is released into the atmosphere. [6] Sulfur regulations in shipping applies to all types of vessels. When it comes to regulating $NO_x$ emissions, the IMO has implemented a system of three "tiers" depending of the engine size and the time the ship was built. The basis of this system is shown in figure 2.

*Table 1: $NO_x$ regulations for marine engines set by the IMO [7]*

| Tier | Ship construction date on or after | Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm) | | |
|---|---|---|---|---|
| | | n < 130 | n = 130 - 1999 | n ≥ 2000 |
| I | 1 January 2000 | 17.0 | $45 \cdot n^{(-0.2)}$ e.g., 720 rpm – 12.1 | 9.8 |
| II | 1 January 2011 | 14.4 | $44 \cdot n^{(-0.23)}$ e.g., 720 rpm – 9.7 | 7.7 |
| III | 1 January 2016 | 3.4 | $9 \cdot n^{(-0.2)}$ e.g., 720 rpm – 2.4 | 2.0 |

While both nitrogen and sulfur regulations apply to all shipping activity globally, there are some areas that are defined by the IMO as vulnerable areas for marine activity having a set of own regulations. These areas are known as Emission Controlled Areas (ECAs) and consists of the marine areas in the North Sea south of 62 latitude, the Baltic Sea, the west and east coast of USA and Canada and parts of the Caribbean. The sulfur limit in these areas are set to 0.1 percent. [6] Meanwhile, the strictest $NO_x$ regulations (tier III) does only apply to areas that are subjected to special $NO_x$ requirements, which are the coastal areas of Canada and USA and parts of Caribbean. By 2021 the same $NO_x$ regulations will be applied within all ECAs. [7]

*Figure 2: The green areas on the map marks the Emission Controlled Areas (ECAs) set by the IMO. These areas are classified as especially vulnerable areas for maritime activity by the IMO [4]*

## 1.2 Hydrogen and LCA driving sea transportation in a greener direction

The increased focus on reducing emissions has further led to a thought of change in direction in terms of utilizing cleaner fuel options for maritime transport. To drive the maritime industry in a greener direction is challenging on different levels. Firstly, in order to reduce the emissions related to shipping, other alternative fuels have to be considered instead of continuing to use conventional fossil fuels. Secondly, alternative fuels must be easily accessible and affordable to use. The necessary infrastructure must be in place and the technologies for using low or zero emission fuels should be mature enough in order to promote broader usage.

Hydrogen has emerged as an attractive option for a clean fuel in transportation due to its high energy density. Energy that can be stored in hydrogen, can be used as a clean fuel when needed. On the other hand, there are major challenges associated with the use of hydrogen as a fuel that must be addressed in order for hydrogen to become a mechanism in the transition of making transportation greener. Hydrogen cannot be found naturally on Earth and must therefore be produced from other sources. Therefore, hydrogen should not be described as a fuel, but rather as an energy storage medium, or energy carrier. Today's situation is that there are significant inefficiencies in existing processes of transforming other energy sources into hydrogen in addition to challenges related to security when using hydrogen. Not overcoming these challenges has slowed down commercial development for hydrogen systems in transportation. [2]

When developing a project with the aim reducing emissions it might be difficult to see the bigger picture. Each solution may impact differently, and it can therefore be useful to assess which of the solutions that have the most benefits. Conducting a Life Cycle Assessment (LCA) can make the decision-making process easier. The versatility of this analytical method makes LCAs useful for several different users and uses. The common goal for every LCA study is most often to cover all of the possible impacts a project can have over its life time. This means evaluating the impacts from a process or from the production and use of a product. Other processes and products can also be compared to each other in order to make the decision-making process easier. [8]

## 1.3 Goal and scope of the thesis

This project focuses on the role of hydrogen in the transition of greening the maritime industry. Advantages and disadvantages of the production and use of hydrogen as a fuel in maritime transportation will be investigated and compared to other possible solutions. By implementing techniques from the LCA analytical method into the study, it should be possible to identify the impacts in the different process stages during the life time of a project with the use of hydrogen.

The work presented in this paper will consist of a comparable analysis of different production methods of hydrogen and the technologies of using hydrogen as a fuel in ships. The main focus of the analysis will be on the climate impacts but investigating while also investigate the energy usage. Important steps in the LCA analysis such as the production, manufacturing, fuel supply, operation and end-life stages will be covered. Other solutions, existing and non-existing, renewable and non-renewable, will be compared to the hydrogen solution. Based on the results, conclusions can be made so that it is possible to see whether or not hydrogen is a viable option as a fuel for maritime transport.

## 1.4 Previous work

The work presented in this report can be compared to several external sources that include Life Cycle Assessments focusing on hydrogen fuel in maritime transport. Due to newer technology being developed in a rapid pace, it is necessary that the information gathered in this project is not old and outdated. While most of the sources found focuses on separate parts of the so-called "hydrogen economy" (e.g. production methods or power units), this study is aimed at covering the entire transport life cycle. The article *"Clean fuel options with hydrogen for sea transportation: A life cycle approach"* has been used as a reference in developing the layout for the LCA. [9]

Furthermore, a significant part of the theory behind ship performance is based on much of the same theory used by Jørgen Kopperstad in the master's thesis *"A numerical approach for Ship Energy Analysis".* [7] For the most part this involves thermodynamic principles and descriptions of powertrains onboard ships. A potential study titled *"Energy efficient and* *climate friendly ferry operations"* has also provided essential information on the operation of maritime transport services. The report from the study was made by LMG Marin for the Norwegian Public Roads Administration back in 2016. [11]In total, the thesis is made up of data obtained from relevant data sets and own assumptions based on gathered information.

### 1.5 Outline of the Thesis

The outline of this paper is as follows: The first section gives an insight to different selections of marine fuels and propulsion systems. Advantages and disadvantages to each solution will be highlighted, with technical descriptions of both fuel production methods and the associated systems for using the various types of fuel in maritime transportation. However, the main focus of the master thesis will be on solutions promoting the use of hydrogen fuel. An introduction to the concept of LCAs will also be given in this section.

The second section provides a description of the methods used to conduct a LCA on specific cases related to the problem that this thesis seeks to solve. Assumptions and delimitations of the thesis will be presented, and the selected approach will be explained and justified. Data that have been used and the setup of the LCA conducted in this study will be explained and described in detail.

In the third section, key results from the study will be presented. The fifth section will contain a discussion of the advantages and disadvantages of using hydrogen as a fuel in marine transport compare results found in the study with other possible solutions. Finally, the last section contains a conclusion of the findings in the study and provides key areas that might have to be investigated further.

## 2. Background

The following section starts by giving an outlook of different fuels that can be used for maritime transport. Production methods as well as the level of maturity of different technologies will be highlighted in this part. Later on, a section of the paper will be credited to characteristics of combustion systems that have been identified as suitable for vessels based on the choice of fuel. Advantages and disadvantages for all alternatives viable to be used in the propulsion system onboard ships are identified. Both mature and less developed technology that has yet to achieve a large user base are taken care of.

## 2.1 Marine fuel selections

| Fuel | 2010 total consumption (million TOE/year) | Consumption for maritime transportation (million TOE/year) |
|---|---|---|
| Oil | 4,028 | »330 HFO/MDO: »280/50 |
| Natural Gas | 2,858 of which LNG: 250-280 | Very low (Approximately 40 vessels in 2013) |
| LPG | 275 | 0 |
| Methanol | 23 | 0 |
| Ethanol | 58 | 0 |
| DME | »3-5 | 0 |
| Fischer-Tropsch | »15 | 0 |
| Biodiesel | 18-20 | 0 |
| Liquefied Biogas | Very low | 0 |
| Nuclear (Uranium) | 626 | Very low |
| Hydrogen | Very low | 0 |
| Rapeseed Oil | 5 | 0 |

*Figure 3: Total consumption of variations of fuel in 2010. All figures in million tons of oil equivalents (TOE) [12]*

Fossil fuels have dominated as the primary source of fueling the shipping industry since the industrialization and the development of steam engines. Further development in propulsion technology brought the internal combustion engine which significantly increased efficiency, flexibility and safety in transportation. [13] Having high energy density is deemed as a principle feature and explains the importance of fossil fuels in transportation in general. The fact that most of the fossil fuels can be liquified, makes them easier to transport to the location of use and thereby easier to implement in different transport services. [2]

As previously described, despite having several advantages and especially related to energy content, the use fossil fuels carry a significant burden on the environment. With stricter regulations from IMO set to come over the following years, the maritime sector is in a dilemma where changes have to be made in order to meet the targets set to reduce the environmental impact from shipping. [5] Increased focus on reducing emissions has led to a thought of change in direction in terms of utilizing cleaner fuel options for maritime transport. With everything described above in mind, this section of the paper seeks to outline different marine fuels, both conventional and alternative, and identify advantages and disadvantages of each choice of fuel.

### 2.1.1 Fuel oils

The fuel mix in maritime transport is currently dominated by fossil fuels in the form of ***heavy fuel oil*** (HFO) and ***marine gas oil*** (MGO). [12] Fuel oils originates from crude oil. [13]Different crude oils contain different combinations of hydrocarbon molecules, ranging from light gases like methane to larger molecules with a high number of carbon atoms. For commercial purposes, it is necessary that the distribution of hydrocarbons differs from the makeup of the crude oil. In order to produce more useful petroleum products, refineries can be used to either separate lighter hydrocarbons or use methods to crack heavier hydrocarbon molecules. [2]

Refining of crude oil consists primarily of three different processes: separation, conversion and purification. [13] In the beginning of the refinery process non-hydrocarbon components like salt and water are removed. The crude oil is further distilled. In the distillation tower (as shown in figure 2) the fractions at the top of the so-called fractionating column have lower boiling points than fractions at the bottom. The products obtained from the distillation tower ranges from gases at the top to heavier and more viscous liquids at the bottom. Later on, the temperature can gradually be raised so that lighter hydrocarbon molecules can be separated out first, followed by gradually heavier hydrocarbons.

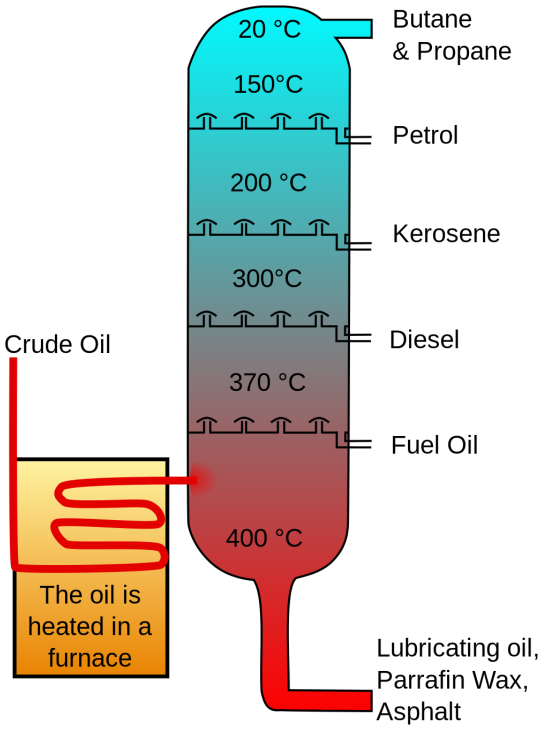


*Figure 4: Typical products produced from the distillation tower in a refinery [8]*

As mentioned before, the proportions of crude oil at first does not meet consumer demand. Generally, too small amounts of petrol and more fractions of heavier fuel oils than needed are produced during the separation stage. After lighter hydrocarbons are removed from the crude oil through distillation, the heavier components are broken down into smaller and more useful units. This is done by what is called catalytic cracking, where temperature and chemical catalysts are used to modify the hydrocarbon molecules in order to meet marked demands.

The desired hydrocarbon chains are obtained by either adding hydrogen or remove carbon, which can be done by the methods of hydrocracking and fluid catalytic cracking respectively. Hydrocracking is characterized by the fact that crude oil reacts with hydrogen at high temperature and pressure with a catalyst present. On the other hand, fluid catalytic cracking uses a catalyst at high temperature and more moderate pressure in contact with residual oils converting gas oils into mixes of petrol, diesel and other lighter hydrocarbons. Lastly, the purification process is mainly concentrated around the removal of sulfur. Sulfur is removed by hydrotreating, where hydrogen reacts with unfinished petroleum product with a catalyst present at heat and high temperature. This results in the production of hydrogen sulfide and desulfurized products.

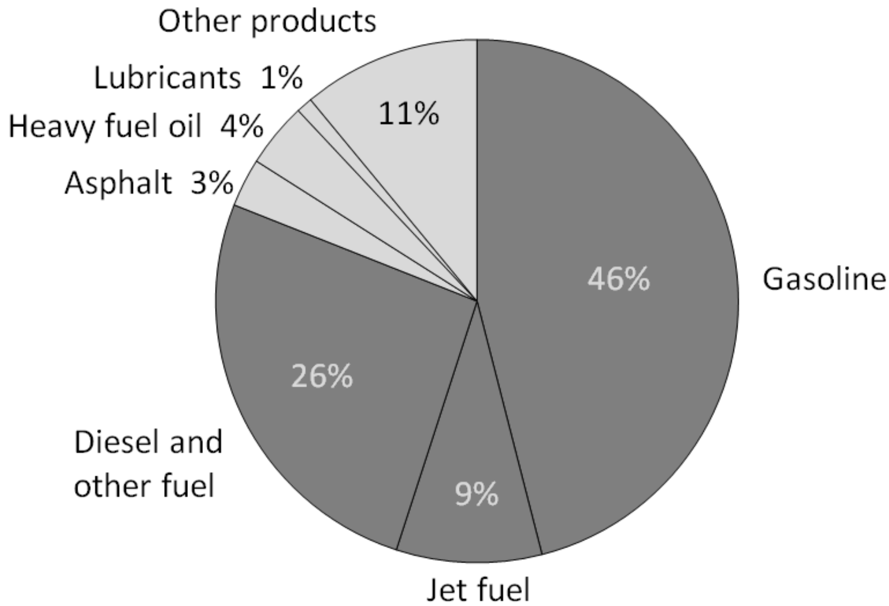


*Figure 5: Breakdown of products typically produced from a barrel of crude oil in the US [8]*

There are several ways of producing marine fuels from the refining of crude oil. Refining of oil is regarded as a critical part of the petroleum supply chain. It is also quite an energy consuming process. Typically, about 10 per cent of the energy content in the crude oil is used in the refining process. Fuel oils are known as the heavier fractions of crude oil. [2]Heavy fuel oil, or residual fuel oil, is obtained from the residue after the distillation process. Marine gas oil on the other hand is obtained from refined or cracked origins in the boiling range between 200 and 350 °C. Furthermore, the density, sulfur content and viscosity of heavy fuel oils can be adjusted by blending the HFOs with gas oils.

### 2.1.2 Natural Gas

Out of all types of fossil fuel, ***natural gas*** proves to be the least carbon intensive alternative due to higher hydrogen to carbon ratios relative to heavier hydrocarbons. Natural gases consist of combinations of gaseous hydrocarbons found naturally in organic matter. The compositions of natural gas resources vary and can be separated into three different categories. Most of natural gas resources consists mainly of methane, with resources having small amounts of liquefiable hydrocarbons being referred to as dry gas. On the other hand, resources containing substantial amounts of larger hydrocarbons is referred to as wet gas. Lastly, resources with substantial contents of sulfur is referred to as sour gas.

Before natural gas can be sold as a fuel, impurities and heavier hydrocarbons are essentially removed. Commercially sold natural gas is generally dry gas with a methane content of at least 85 % of weight. Other parts of the natural gas resources such as ethane, propane, butane and other heavier hydrocarbons are separated out to be used for other purposes. For commercial natural gas the energy content is about 50 MJ/kg (HHV). Since natural gas is commonly measured in units of cubic meters, the energy content of commercial natural gas Is measured to be in the range of 37-39 MJ/$m^3$.

Having a low amount of impurities, natural gas requires little work of refinement and burns clean. In the case of pure methane, the carbon intensity during combustion is about 14 kg/GJ, which is the lowest level of any fossil fuel. Compared to coal, which has a carbon intensity of roughly 25 kg/GJ, the amount of carbon released during combustion is about 40 % lower for natural gas. For transport purposes, liquid fuels are preferable, both in terms of easier supply and in terms of implementation in known machinery which can be modified for specific purposes. Natural gas can be made liquid at a temperature of about -162 °C at a pressure of one atmosphere. Making gases liquid also reduces the volume and in the case of liquefied natural gas (LNG) the volume is reduced by a factor of about 600. The energy density of LNG is approximately 24 MJ/L [2].

### 2.1.3 Biofuels

***Biofuels*** represent a group of liquid fuels being produced from organic materials. Per today, the main types of biofuels that are produced in a significant quantity are ethanol and biodiesel. [2]Being liquid fuels at ambient temperature and pressure, makes biofuels an easy choice of fuel in terms of transport and use. For marine purposes, the use of biofuels has been met with increasing interest in recent years. The use of biodiesel has been investigated in particular.

***Biodiesel*** is chemically produced from vegetable oils and animal fat. Vegetable oils and animal fats contain molecules called triglycerides. Through the process known as transesterification, the triglycerides are combined with alcohols in order to break the triglycerides into separate molecules known as fatty acid esters. The fatty acid esters have similar properties to hydrocarbons found in conventional diesel fuel, which makes biodiesel suitable to be combusted in traditional diesel engines. It's worth taking note that pure biodiesel can be harder to implement in internal combustion engines compared to conventional gas oils used in shipping today. Smaller blends of biodiesel, typically in the range of 5-15 %, can likely be used in industrial diesel engines without complications. Values for energy content related to biodiesel is typically in the range of around 37 MJ/kg, which is roughly 10 % lower the values of conventional diesel fuels [2].

### 2.1.4 Carbon Capture and Storage (CCS)

Even though fossil fuels are generating quite the amount of greenhouse gas emissions, there are some ways of dealing with emissions that are expelled into the atmosphere. One way is to capture the $CO_2$ before subsequently storing it in some kind of storage over a long term. This process is known as **carbon capture and storage** (CCS).

CCS has not received the same credit in mainstream debates on challenging climate change as the fast-growing renewable technologies. However, it's worth noting that both the IEA and IPCC have seen that all possible measures, including CCS, are necessary to cope with the huge challenge of reducing emissions across the entire energy sector.

Capturing the $CO_2$ at the point of emissions after the combustion of the fuel, better known as post combustion capture (PCC), is regarded as the most mature capture technology today. The $CO_2$ is in a PCC process captured by using solvents to separate the flue gas generated by the combustion of fossil fuel or biomass. While the $CO_2$-lean flue gas is able to be released into the atmosphere, the rest of the $CO_2$ can be transported and subsequently stored (see figure 5).

Other $CO_2$ capturing technologies involve pre-combustion capture and oxy-fuel combustion capture. Pre-combustion processes involves fuel or biomass reacting with air creating syngas through gasification or reforming of the inputs. The synthetic gas (or syngas) consists of carbon monoxide and hydrogen. The carbon monoxide is subsequently put through at catalytic reactor, referred to as a shift converter, creating carbon dioxide and even more hydrogen. Finally, the $CO_2$ is separated through physical or chemical absorption processes, resulting in a rich hydrogen fuel that can be used for other purposes. For oxy-fuel combustion capture, the fossil fuels or biomass react with close to pure oxygen, and not air, resulting in the formation of mainly $H_2O$ and $CO_2$ that later can be stored away.

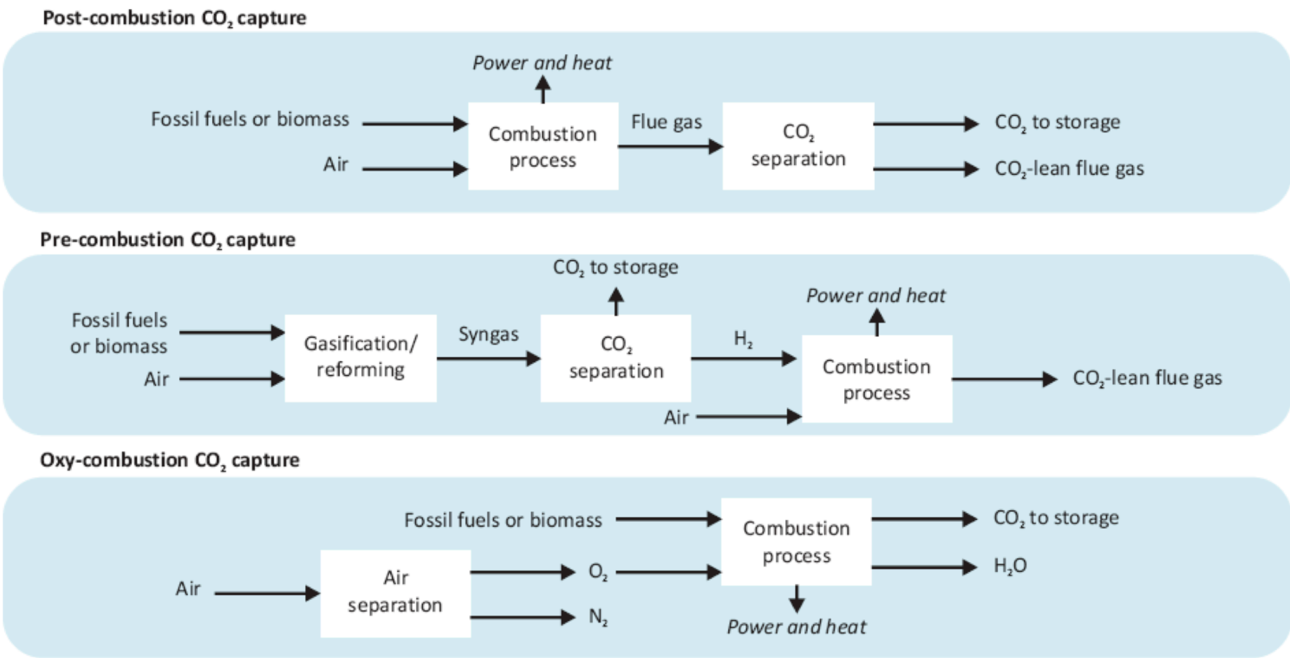


*Figure 6: Technologies for capturing CO2 [15]*

Transporting the $CO_2$ to its storage location is done by using pipelines, ships or tanks. $CO_2$ can also be transported in three different states: gas, liquid and solid. Gaseous $CO_2$ is generally compressed and transported through pipelines, as large facilities are required in order to handle gases taking up too much space at ambient pressure. The volume can further be reduced by transferring the $CO_2$ into liquid or solid states. Liquefying gases is a well-known technology for transport by ships and is widely used in production of liquefied natural gas (LNG) amongst other liquefied petroleum product. Solidifying the carbon dioxide requires more energy compared to other solutions and is consequently a less effective method for transportation when regarding both perspectives of costs and energy use.

Several different options regarding the storage of $CO_2$ have been suggested. One solution that is proposed is pumping compressed $CO_2$ back into geological repositories such as gas and oil fields from where the fossil fuels where extracted in the first place. Another solution being suggested is the storing the $CO_2$ in the deep depths of the ocean, either at depths where it can dissolve in the water or where it becomes denser than water and subsequently sink to the bottom before re-entering the carbon cycle after a long time. Methods for fixing carbon dioxide into carbonates and subsequently storage in compact solid form have also been suggested.

### 2.1.5 Hydrogen

***Hydrogen*** ($H_2$) is the simplest and most common element that can be found on Earth. It has some properties which makes it a promising alternative to the conventional fuels used in maritime transportation today. Hydrogen has a high heating value per mass and the product of combustion of hydrogen in a fuel cell is only water, which makes hydrogen a clean fuel. A drawback is that the volumetric energy content of hydrogen is on a significantly lower level. This leads to hydrogen requiring a larger volume in order to offset the differences in energy content compared to other fuels. Higher energy densities can be achieved by compression, liquefaction or transformation to hydrogen-based fuels, which in turn leads to a greater consumption of energy.

Pure hydrogen is rare in the natural state on Earth which results in hydrogen having to be produced from other sources. Today, most of the hydrogen produced on a global scale is used for further production of ammonia to be used in fertilizers. As noted before, hydrogen plays a key role in refinery operations, with a large fraction of the total supply also being used in various processes related to refining. Only a negligible part of the total demand for hydrogen is related to transportation.

Hydrogen can be produced from different types of feedstock. Color labeling of different sources for production of hydrogen has become a known term in recent years. Usually the colors black, grey or brown denotes hydrogen production from fossil fuels in the form of coal, natural gas and oil. The color blue is applied when the $CO_2$ emissions from fossil-based hydrogen production is reduced using Carbon Capture and Storage (CCS). Hydrogen production from renewable sources such as hydro, solar and wind is usually referred to as green. This study will primarily focus on two methods of producing hydrogen: steam reforming of natural gas and water electrolysis.

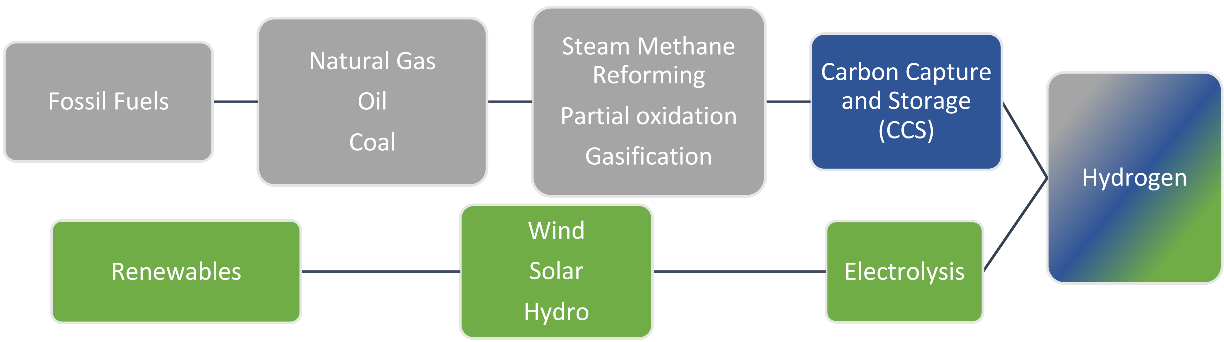


*Figure 7: Different feedstock and methods for producing hydrogen. The colors indicate the differences between grey hydrogen, blue hydrogen and green hydrogen in terms of emissions related to the different methods of producing hydrogen.*

### Steam reforming

Most of the hydrogen that is produced today comes from fossil energy sources. Steam reforming of natural gas is the most dominant way of producing hydrogen (see figure 5). In the steam reforming process, the natural gas, which mainly consists of methane, is able to react with steam with a catalyst in presence to form the products of hydrogen, carbon dioxide and carbon monoxide. The carbon monoxide can further be used to produce even more hydrogen in a so-called water-gas shift reaction. Both cases are illustrated by the following equations: [2]

*Equation 1: Steam reforming of methane*

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

*Equation 2: Water-gas shift reaction of carbon monoxide*

$$CO + H_2O \rightarrow CO_2 + H_2$$

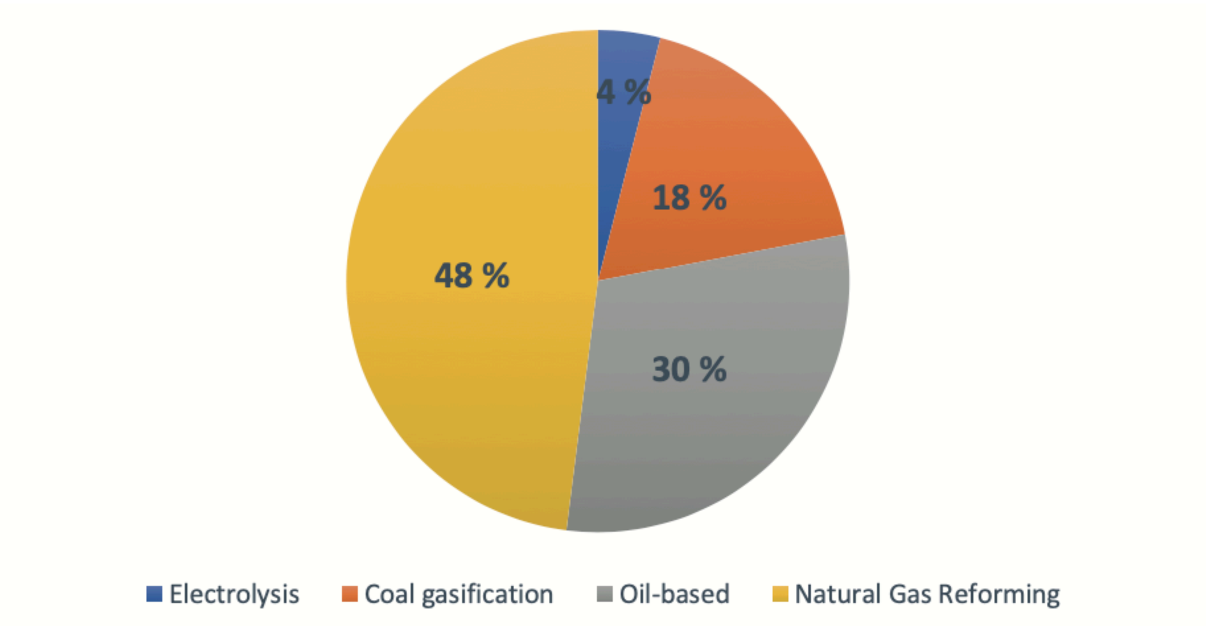


*Figure 8: The world's total hydrogen production by production method [9]*

Although steam reforming is commonly known and widely used for hydrogen production, there are still several drawbacks related to this production method. Firstly, the processes in steam reforming of natural gas, which mostly consists of methane, results in greenhouse gas emissions. Unless the carbon emitted under production is not captured and sequestrated, the advantage of having hydrogen as a clean option for fuel disappears. Opting to use CCS in in fossil fuel-based production can reduce the $CO_2$ emissions by up to 90 %. This enables hydrogen to become a low-carbon fuel, which can be labelled as "blue". Another disadvantage of steam reforming Is that one must expect a significant loss in the efficiency of converting natural gas into hydrogen. Typically, the overall conversion efficiency does not exceed more than 60 % by producing hydrogen via steam reforming of natural gas. [17]

### Electrolysis

Hydrogen can alternatively be produced through the process of electrolysis. In this case the hydrogen is produced by using electrical energy to split water into hydrogen and oxygen. There are no emissions involved in regards of the electrolysis process itself; only emissions from the source which the electricity is generated from contributes to the overall emissions in the line of production. Electricity with a source from renewables enables a form of hydrogen production without emissions of $CO_2$. An electrolyser has a typical efficiency level of about 60 percent, even though conversion rates in the range of up to 80-90 % has been achieved.

[2]Producing hydrogen via electrolysis constitutes only about 4 percent of the total worldwide production of hydrogen today (see figure 5). The reasoning of this low number comes generally down to electrolysis being a costlier way of producing hydrogen compared to steam reforming. [15]

There are currently three different technologies developed for production of hydrogen via electrolysis: Alkaline electrolysis, Proton Exchange Membrane (PEM) electrolysis and solid oxide electrolysis cells (SOECs). Alkaline electrolysis is regarded the most mature electrolysis technology. The electrolyser is in this case a diaphragm cell where asbestos diaphragm and nickel metal usually make up the electrodes. The diaphragm does not only separate the anode and cathode, but also separate the produced gases from their respective electrodes and avoid the mixing of gases produced in the electrolysis process.

Alkaline water electrolysis initially starts at the cathode where alkaline solution of either sodium hydroxide (NaOH) or potassium hydroxide (KOH) is reduced into one molecule of hydrogen ($H_2$) and two molecules o hydroxyl ions ($OH^-$). The concentration of the electrolyte is generally in the range of 20-30 %. The hydroxyl ions are allowed to pass through the porous diaphragm by applying electrical current. This results in one molecule of water and half a molecule of oxygen being discharged from the anode. The principle of alkaline electrolysers is shown in figure 8. [16]

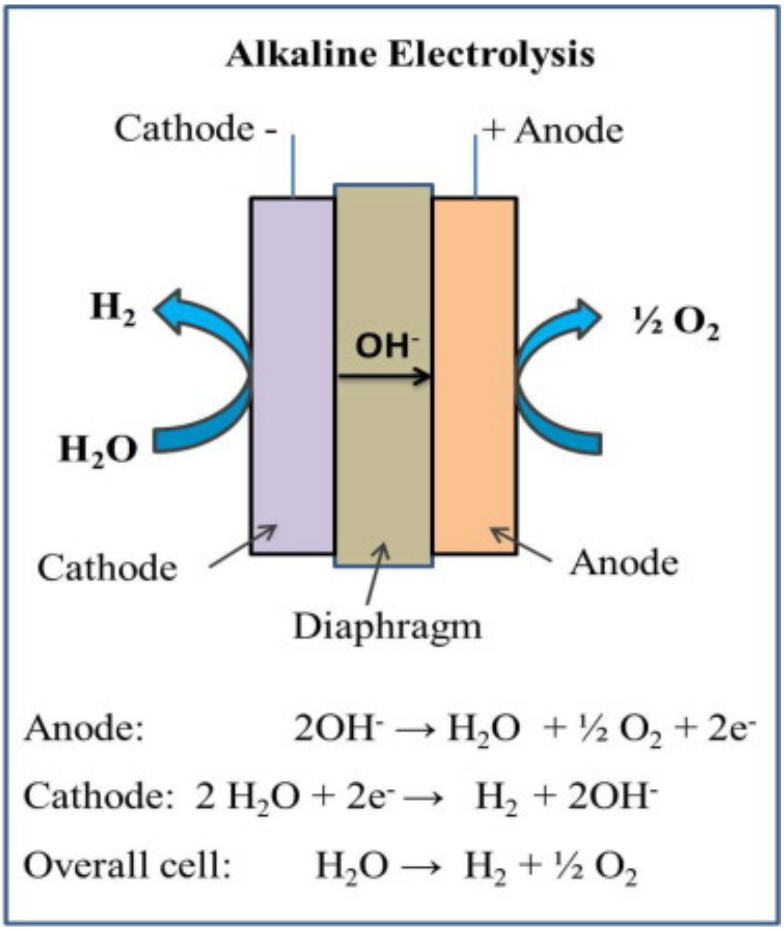


*Figure 9: Principle of alkaline electrolysis [16]*

In PEM electrolysis, water is led into the anode where it is split into oxygen ($O_2$), protons ($H^+$) and electrons ($e^-$). They operate in a similar manner like PEM fuel cells, which will be explained in later parts of this paper. PEM electrolysers use proton conducting membranes to move the protons over to the side of the cathode. Meanwhile, the electrons are led through an external circuit providing as the driving force of the reaction. The protons and the electrons meet again at the cathode where hydrogen is produced as shown in figure 9. PEM electrolysers are favorable in terms of environmental impact and sustainability when it comes to produce hydrogen from renewables in pure quantities. However, PEM eletrolysers also suffer from having a high cost of materials and lower lifetime compared to alkaline electrolysers, thus being a less widely used method of hydrogen production. [16]

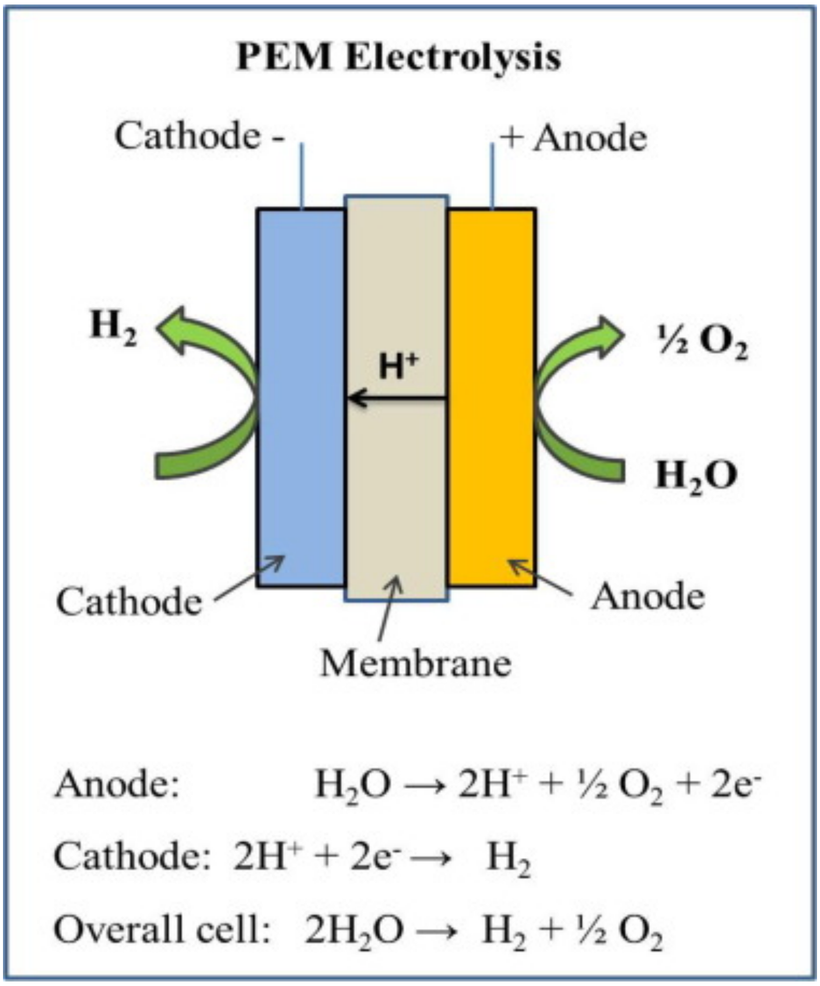


*Figure 10: Principle of PEM electrolysers [16]*

Lastly, the Solid Oxide Electrolysis (SOE) process operates at high temperatures so that the water used in the electrolysis acts as steam. The solid oxide electrolysers are known for having high efficiencies and low costs (uses cheaper materials in the electrolyte) despite being the least developed electrolysis technology. Issues regarding degradation and stability have to be solved in order to make SOE commercially attractive. The principle of SOE electrolysers is illustrated by figure 10. Here the water, which is a steam state, is split into hydrogen and superoxide ($O_2^-$). The superoxide is conducted through the membrane. Half of a molecule of oxygen is subsequently generated at the anode with the input of electrical energy. [16]

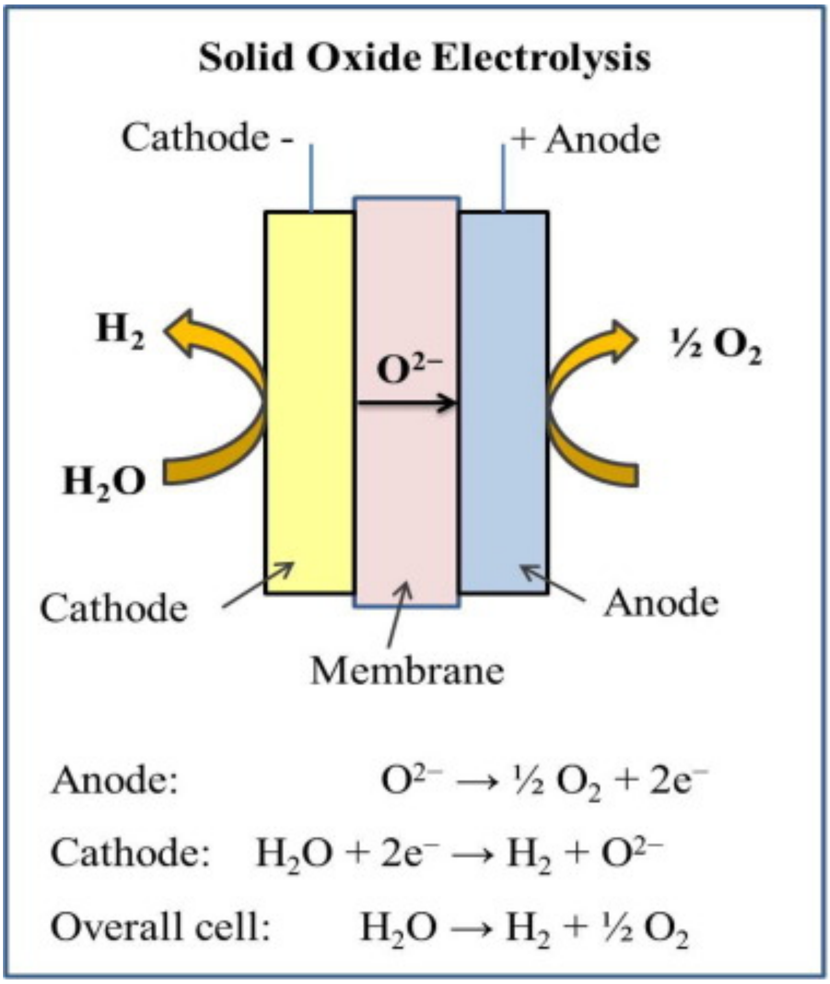


*Figure 11: Principle of Solid Oxide Electrolysis (SOE) [16]*

As mentioned before, despite hydrogen having a relatively high energy content per mass, the volumetric energy density of hydrogen remains quite low. This leads to one of the major drawbacks of using hydrogen as an energy storage. Hydrogen must either take up a large volume or be compressed at high pressures in order to compensate for the low volumetric energy density. Having to occupy large volumes makes hydrogen inconvenient to be used in mobile applications, thus requiring hydrogen to be compressed.

Gaseous hydrogen is often stored in pressures up to 700 atm, where the energy density is approximately 5.6 MJ/L. Despite this being a significantly lower number compared to conventional gasoline, having higher efficiencies when it comes to fuel combustion by utilizing fuel cells puts hydrogen in an attractive spot as an alternative fuel for mobile applications.

Liquid fuels are preferable in mobile applications as previously explained. Hydrogen liquefies at the low temperature of about -253 °C, where the density of hydrogen is at the level of 71 kg/m$^3$, corresponding to an energy density of about 10 MJ/L. Liquid hydrogen is widely being used as rocket fuel and stored in cryogenic tanks. On the other hand, large amounts of energy are required to both liquefy hydrogen and to keep the storage tanks cool, which opposes the benefits liquid hydrogen can have. The theoretical minimum amount of energy required to liquefy hydrogen at ambient conditions is 3.3 kWh/kg. In addition to the inefficiencies liquid hydrogen may have, there is also uncertainty regarding the safety associated with this type of fuel. [2] [16]

### 2.1.6 Ammonia

While primarily being used as fertilizers, ***ammonia*** ($NH_3$) can also be evaluated as a power-generating fuel. As previously noted, most of the hydrogen produced today is being used for further production of ammonia. Ammonia is created by making hydrogen, which is primarily produced from natural, react with nitrogen through what is known as the Haber-Bosch process (see eq.)

*Equation 3: Production of ammonia via the Haber-Bosch process*

$$N_2 + 3H_2 \rightarrow 2NH_3$$

Unlike hydrocarbons, ammonia is a hydrogen carrier that does not contain carbon atoms while having a high hydrogen ratio. Ammonia is also able to store a larger fraction of hydrogen per volume compared to either compressed or liquid hydrogen. Another significant benefit of ammonia which can make the it an easier fuel to implement in maritime transportation is the ability to burn ammonia directly in diesel engines modified for this specific case. Combustion of ammonia mainly produces water and nitrogen. Replacing significant parts of conventional fuels used today will therefore be a significant measure to reduce $CO_2$ emissions. [2]

## 2.2 Marine propulsion solutions

The propulsion system in a ship is the system or mechanism that is used to generate thrust to move the ship across water. Currently, most of the global commercial fleet is powered by converting chemical energy in fuels into mechanical energy, thus converting the energy into thrust. Several different technologies (e.g. internal combustion engines or gas turbines) are selected as prime movers, with all having the thermal energy generated through combustion of fuel converted into mechanical energy. The conversion process can be explained by the principles of different thermodynamic cycles.

Electrification of the fleet has gained a lot of interest in recent years. The use electricity in maritime transportation have particularly been considered when the ships are operating under variable loads. For maritime purposes, electricity can be used to cover the energy demand for electrical equipment by connecting to the grid when docked at shore. Electricity can also be a useful source of powering ships by utilizing energy storage units such as batteries and fuel cells in either fully electric or hybrid solutions.

This section of the paper seeks to identify the different technologies that can be used in the propulsion system onboard ships. The efficiency limit of each option will be explained by thermodynamic principles which several of propulsion systems are based on. Both technologies for using conventional marine fuel and low-carbon solutions will be covered.

### 2.2.1 Thermodynamics

The efficiency of a heat engine cycle is determined by the execution of the individual processes that make up the cycle. By using reversible processes which can be defined as processes requiring the least amount of work in order to deliver the largest outputs, the maximum cycle efficiency can be maximized.

On the other hand, there are no possible ways of achieving reversible cycles in practice as irreversibilities related to each process cannot be eliminated. Nevertheless, reversible cycles can give an indication on where the upper limit of efficiency lies for realistic cycles. In the development stage of actual cycles, reversible cycles can be useful starting points and modified to meet certain requirements.

The most known reversible cycle is known as the **Carnot cycle**. Described by the French physicist Sadi Carnot in 1824, this thermodynamic cycle is more or less regarded as the benchmark for efficiency related to heat engines. The Carnot cycle provides the maximum efficiency of any heat cycles operating between a fixed set of maximum and minimum temperatures, illustrated by equation 4 [20]:

*Equation 4: Thermal efficiency of reversible heat engines (Carnot engines). The temperatures $T_L$ and $T_H$ denotes the lower and higher temperatures of the cycle respectively.*

$$\eta_{th,rev} = 1 - \frac{T_L}{T_H}$$

Actual gas power cycles are rather complex. I order to simplify the analysis to a manageable level, a set of assumptions known as air-standard assumptions are applied. Following the assumptions, the working fluid is considered to be air, which always behave as an ideal gas and continuously circulates in a closed loop. All processes that make up the cycle is considered as internally reversible. Heat addition from an external source replaces the combustion process, while the exhaust process is replaced by heat rejection that restores the working fluid to its initial state. Another assumption that can be utilized is the cold-air assumptions where air is considered to have constant specific heats determined by the room temperature (25 °C).

Other thermodynamic conditions apply when chemical energy is converted into electrical energy without intermediate step of conversion to thermal energy. These conditions are specific for batteries and fuel cells. Therefore, they are not subject to the Carnot limit. For chemical storage of energy, a specific amount of energy of the substances involved applies, which can be expressed by the following equation [2]:

*Equation 5: specific energy for chemical storage of energy. $\Delta H$ is the molar enthalpy for the overall reaction that releases energy, while the molecular mass is the sum of the mass of reactants, not including gaseous inputs from external environment.*

$$\varepsilon = \frac{-\Delta H}{molecular\ mass}$$

The 2nd law of thermodynamics limits the amount of energy that can be extracted, stating that the entropy of an isolated system never decreases over time and is only constant. For combustion engines, this limit is defined by the Carnot limit as previously explained. On the other hand, chemical reactions are limited by the fact that the change in entropy ($\Delta S$) must be discharged into the environment. This leads to only the Gibbs free energy (being able to be put to useful work, with the ratio $\eta = \Delta G/\Delta H$ expressing the faction of the stored chemical energy that can be converted into electrical or mechanical energy. It is worth noting that both $\Delta H$ and $\Delta G$ are negative for electrochemical reactions [2].

### 2.2.2 Internal combustion engines

**Internal combustion engines** (or ICEs) represents a group of engines powered by combustion taking place within vapor that serves as the working fluid. Internal combustion engines operate on an open cycle and as heat is often released or unburned fuel in the exhaust process of the cycle, ICEs are generally less efficient than external combustion engines operating on a closed cycle.

Each of the main types of internal combustion engines can be classified and at the same time be associated with respective ideal thermodynamic cycles. What is important to take note of is that ideal cycles are based on a number of approximations and therefore lack some of the important characteristics of realistic processes in engines. Most of the vessel that are operative today are powered by diesel engines, which are also known as compression ignition engines.

Named after the German engineer Rudolf Diesel, who invented the first compression ignition engine in 1893, diesel engines operate as suspected according to the ideal diesel cycle (see figure 12). The use of diesel engines provides advantages in terms of efficiency, reliability and flexibility in terms of being able to maintain relatively high efficiencies even at low loads. Diesel engines are also easily maintainable, as the level of technology is well-known and established in the industry.

A four-step compression ignition cycle is depicted in figure 6. Engines operating on this type of cycle are generally medium to high-speed engines (engines having ranges of higher output speeds). Firstly, the piston is moved downwards, and the inlet valve is opened as the volume in the cylinder expands, with air being drawn into the cylinder. Secondly, the piston moves upwards again, and both the inlet and exhaust valves remain closed while the air is compressed. At the end of the stroke, fuel is injected, and the ignition can start.

The ratio between the maximum and minimum volumes of the cylinder is an important characteristic for internal combustion engines and referred to as the compression rate of the engine. The engine efficiency is greatly dependent on the compression rate. Following the compression stroke, the ignition of fuel and air increases the pressure so that the piston is forced to move downwards again. As the power stroke comes to a close, the exhaust valve is opened. Finally, as the piston moves up again, the exhaust gases generated through the combustion process of the fuel, are released from the engine.

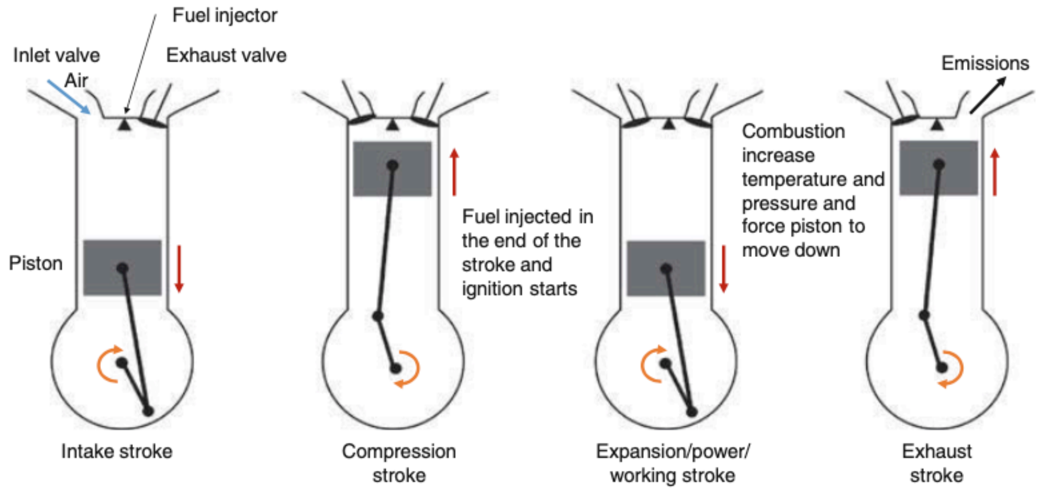


*Figure 12: Stages in a four-stroke compression ignition cycle (also known as a diesel cycle) [13]*

Other types of internal combustion engines involve spark ignition engines, which operate according to the Otto cycle. The key difference in how these types of internal combustion engines operate lies in how fuel is ignited in each case. In the spark ignition engines, a mixture of fuel and air is compressed and subsequently ignited, while in the diesel engines no fuel is taken in with the air in the intake cycle. Premature ignition of fuel, also known as autoignition, produces a characteristic sound known as “engine knock”. Knock may cause damage to the engine cylinders while also limiting the total efficiency of the engine.

Spark ignition engines suffers especially from the issues related to autoignition resulting in the upper limit of compression being restricted and thus limit the overall efficiency if the engine. For both the spark ignition and the compression engines, the compression rate is a critical factor in maximizing efficiency. Compression ignition engines are able to achieve higher compression rates compared to spark ignition engines as they are not in the risk of experiencing the effect of knock. As a result of this, diesel engines can be 30-50 % more efficient than spark ignition engines.

Diesel engines have also the opportunity to operate on several types of fuels as knock is not a concern. Besides running on conventional diesel fuel, organic fuel such as biodiesel can serve as a viable alternative. However, high compression rate requires more massive, and generally more expensive engine in order to withstand the high pressures that are generated. In addition, compression ignition engines are generally more sensitive to ambient temperatures and can be harder to start in cold conditions. The high temperatures and pressures that are generated in compression ignition engines may also result in formation of nitrogen oxides while incomplete combustion could also lead to other pollutants being generated. [2]

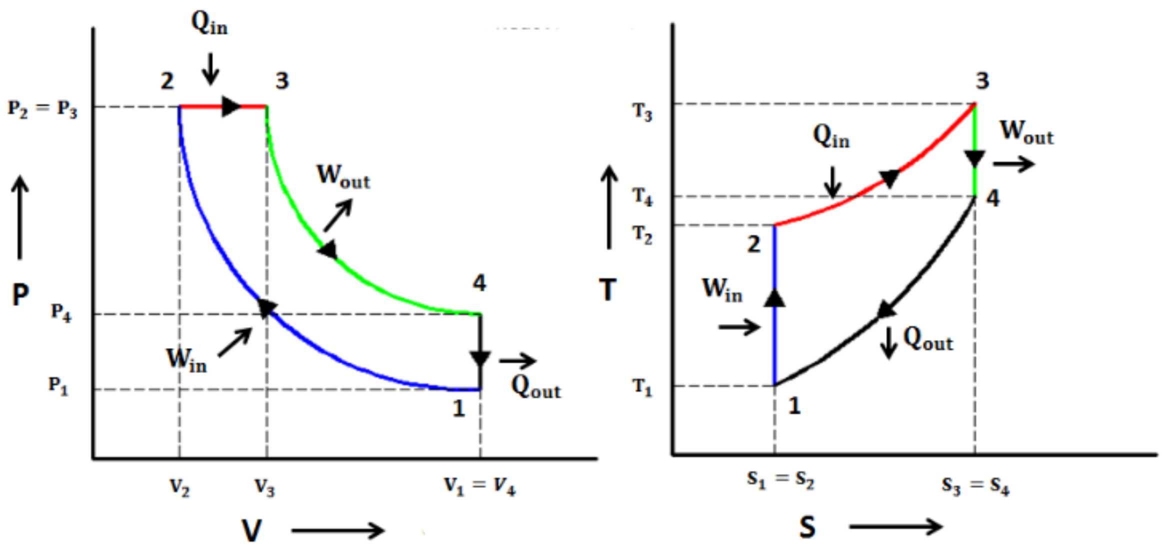


*Figure 13: P-V and T-S diagrams for the ideal Diesel cycle [17]*

As the diesel cycle ideally is executed in a closed system, the amount of heat transferred to the working fluid at constant pressure (stage 2-3 in figure 11) and the heat rejected it (stage 4-1 in figure 11) can be expressed by the following equations

$$q_{in} - w_{b,out} = u_3 - u_2$$

$$q_{in} = P_2(V_3 - V_2) + (u_3 - u_2) = h_3 - h_2 = c_p(T_3 - T_2)$$

And

$$q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$$

By applying cold-air assumptions the efficiency of the ideal Diesel cycle can be expressed by the equation:

$$\eta_{th,diesel} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{k(T_3 - T_2)} = 1 - \frac{T_1(\frac{T_4}{T_1} - 1)}{kT_2(\frac{T_3}{T_2} - 1)}$$

A new quantity known as the cutoff ratio, $r_c$, defined as the ratio of the volume after and before combustion processed

$$r_c = \frac{V_3}{V_2}$$

Can be applied and by following isentropic ideal gas relations, the efficiency of diesel engines can be expresses by the following equation [20]:

*Equation 6: Thermal efficiency of diesel cycles according to isentropic ideal-gas relations*

$$\eta_{th,diesel} = 1 - \frac{1}{r^{k-1}}\left[\frac{r_c^k - 1}{k(r_c - 1)}\right]$$

### 2.2.3 Gas Turbines

Natural gas can be burned in a gas turbine to produce superheated vapor which in turn is used to power the turbine. The ideal thermodynamic cycle for gas-turbine engines is the Brayton cycle. First proposed by George Brayton in 1870 for use in reciprocating oil- burning engines, the Brayton cycle is being used as a model for gas turbine power plants while also being used in jet engines in airplanes.

The thermodynamic efficiency of gas turbines is enhanced by the mixture of air and fuel in a similar way as for internal combustion engines. Brayton cycles are made up of four internally reversible processes. As for internal combustion engines, the first step of the Brayton cycle involves the compression of air. However, the components of the Brayton cycle use rotary motion instead of using reciprocating pistons as is the case for internal combustions engines. The compression stage of the cycle is modeled thermodynamically in an adiabatic matter with no heat exchange (stage 1-2 in figure 13). The gas is further heated under conditions of constant pressure (stage 2-3) before being expanded in a turbine in an isentropic matter (stage 3-4). Lastly heat is rejected under constant pressure (stage 4-1).

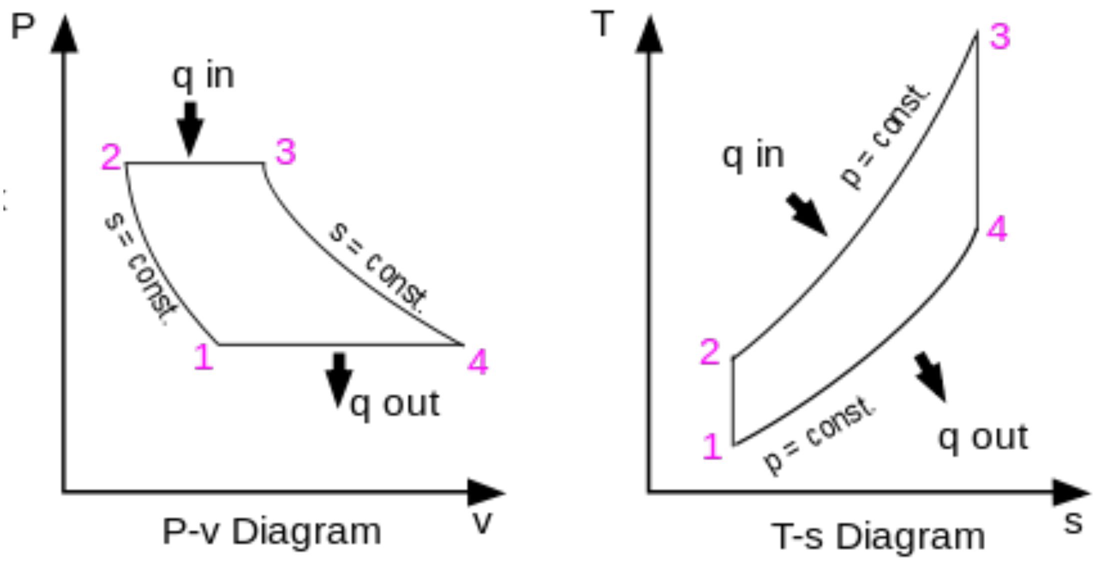


*Figure 14: P-V and T-S diagrams for the ideal Brayton cycle [18]*

The heat exchange to and from the working fluid can be expressed as:

$$q_{in} = h_3 - h_2 = c_p(T_3 - T_2)$$

And

$$q_{out} = h_4 - h_1 = c_p(T_4 - T_1)$$

Since both the process between stage 1 and 2 and between stage 3 and 4 are isentropic, and the pressure between stage 2 and 3 and between stage 4 and 1 are constant, the following expression can be applied:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = \left(\frac{P_3}{P_4}\right)^{(k-1)/k} = \frac{T_3}{T_4}$$

By applying cold air assumptions, the thermal efficiency of the ideal Brayton cycle can be expressed as:

$$\eta_{th,Brayton} = \frac{w_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{c_p(T_4 - T_1)}{c_p(T_3 - T_2)} = 1 - \frac{T_1(\frac{T_4}{T_1} - 1)}{T_2(\frac{T_3}{T_2} - 1)}$$

Thus, the equation for the thermal efficiency of the ideal Brayton cycle can be expressed as:

*Equation 7: Thermal efficiency of Brayton cycles where*

$$\eta_{th,Brayton} = 1 - \frac{1}{r_p^{(k-1)/k}}$$

Where $r_p = P_2/P_1$, is the pressure ratio and k is the specific heat ratio. [20]

### 2.2.4 Batteries

**Batteries** are devices that can directly convert chemical stored energy into electrical energy. They are composed of electrochemical cells which have three principal components in the form of an electrolyte, an anode and a cathode (see figure 6). The purpose of the electrolyte is to allow ions to move freely through without conducting free electrons. An anode contains molecules that can readily release electrons through oxidation and simultaneously release residual ions into the electrolyte. The cathode on the other hand contains molecules formed by the reduction of ions from the electrolyte, by combining each ion with one or more electrons.

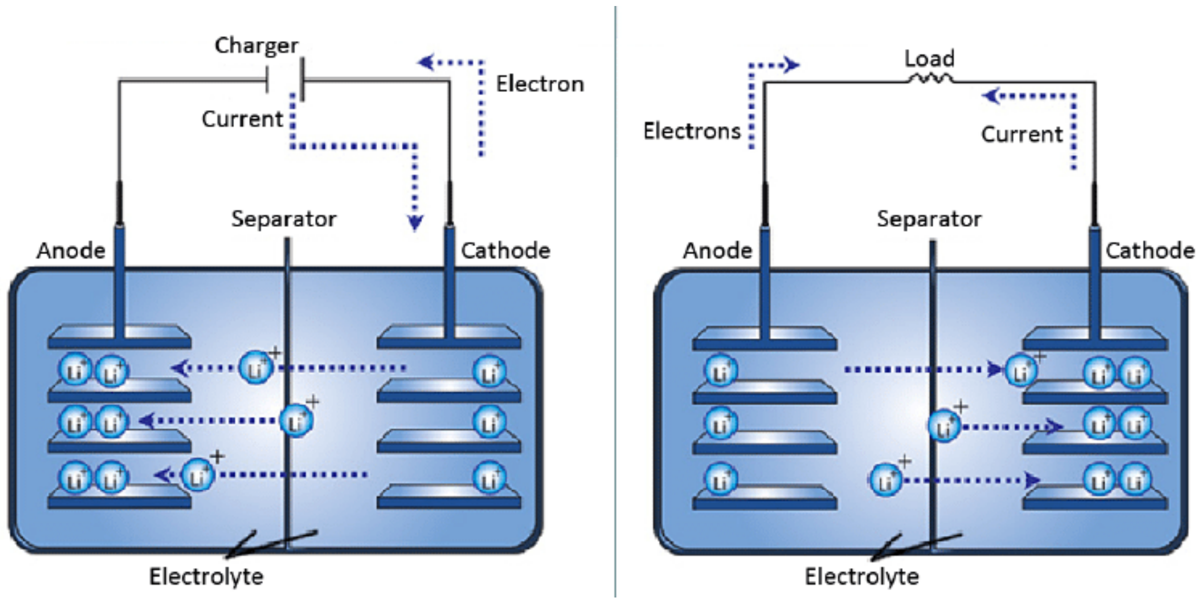

*Figure 15: Working principle of a rechargeable battery. The left side indicates the charging process of the battery, while the right side illustrate the discharge of the battery [19]*

There are several different types of batteries, each with their own characteristic. When it comes to use in mobile applications, the technology of lithium-ion batteries is by far the most dominant. Lithium-ion batteries are a sub-category of batteries whose name is derived from the anode and the cathode both containing lithium ions. Lithium is an attractive element to be used in batteries, as it has the most negative standard potential of all the elements. Also, being the least dense element in a solid state at room temperature, gives lithium batteries promising characteristics when it comes to both high voltage and energy per mass unit.

However, the energy densities of batteries are low compared to conventional fuels like diesel. This makes batteries unfavorable in replacing conventional fuels on their own as large heavy weight battery stacks are required to compensate the low gravimetric energy density. [2] However, batteries have become a mature technology in shipping in terms of hybrid prolusion systems, where batteries are used as supplementary energy storage devices, covering peak shavings as well as increasing the overall efficiency of the vessel and reduce emissions. [11]

### 2.2.5 Fuel cells

**Fuel cells** are the main components for utilizing the energy stored in hydrogen. They work in a similar way to batteries, with an anode, a cathode, and an electrolyte that conducts ions. The main difference between a fuel cell and a battery is that in fuel cells a continuous flow of consumables is entering the device. For a typical fuel cell, the chemical reaction that occurs within the cell can be compared to a combustion reaction. [2] In the case of fuel cells fueled by hydrogen the net reaction is that of the combustion reaction of hydrogen illustrated by the following reaction:

*Equation 8: Combustion of hydrogen*

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O\ (l)$$

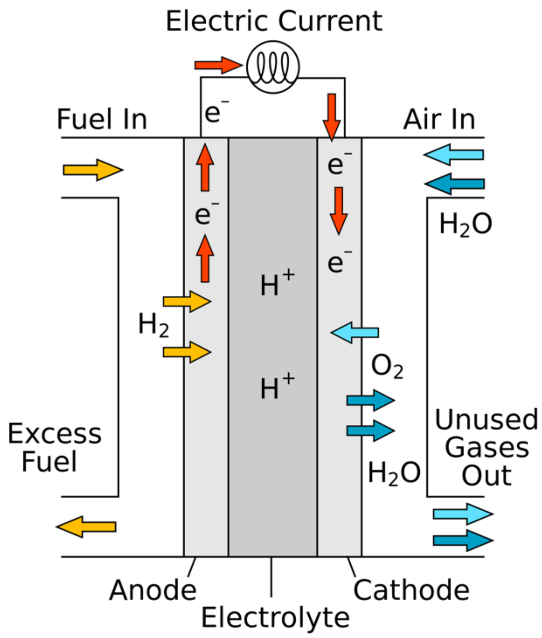


*Figure 16: Scheme of the working principle of a fuel cell [20]*

The operation of a fuel cell can essentially be explained as the reverse situation of the process of electrolysis, as previously explained. Fuel cells are also not limited by the same limitations as heat engines in regard of the Carnot efficiency limit as the electric potential energy is generated through a chemical reaction and not through the combustion of fuels. They are however limited by the 2nd law efficiency limit, which limit fuel cells to a maximum theoretical efficiency of about 83 %. Fuel cells are regarded as extremely reliable devices as they do not have any moving parts and little complications during startup.

Different types of fuel cells, each with their own characteristics are listed up in the table 4. In a study of fuel cells in shipping conducted by DNV GL the three technologies of Proton Exchange Membrane Fuel Cells (PEMFC) and Solid Oxide Fuel Cells (SOFC) were identified as the some of the most promising fuel cell technologies for use onboard ships.

PEM fuel cells are regarded as mature technology which have already been demonstrated with good results in marine applications. This type of fuel cell is based on electrodes consisting of platinum and a polymer membrane that acts as an insulator but allows hydrogen ions to conduct between the anode and the cathode. The efficiency level of PEM fuel cells is in the range of 50-60 %.

However, having a relatively low operational temperature makes heat recover not feasible. PEM fuel cells are also sensitive to impurities in the hydrogen fuel that is being used. High Temperature PEM fuel cells (HT-PEMFC) that operate on higher temperature compared to regular PEM fuel cells can help avoiding the disadvantages that PEM fuel cells suffer from. Having high operating temperatures results in the fuel cell having less sensitivity to impurities while the water treatment process becomes easier as water is only present in a gas phase.

SOFCs are types of fuel cells also operating on high temperatures generally in the range 500-1000 °C. Solid oxide fuel cells consists of a porous electrolyte with the anode being made up of nickel alloy, while the cathode normally uses a material known as lanthanum strontium manganite, which meets the requirement of porosity and will fit the electrolyte used in the fuel cell accordingly. The electrical efficiency of SOFCs is generally high, up to 60 %, with the number being able to reach up to 85 % by the use of heat recovering systems. SOFCs are also flexible regarding fuels, being able to use fuels such as LNG, hydrogen or hydrocarbon fuels such as diesel. However, the high operating temperatures of SOFCs can be seen as a safety risk, and the use of hydrocarbon fuel leads to emissions of greenhouse gases. [22]

*Table 2: Overview of different types of fuel cells [22]*

| Technology | Relative cost | Module Power levels (kW) | Lifetime | Tolerance for cycling | Fuel | Maturity | Size | Sensitivity to fuel impurities | Emissions | Safety Aspects | Efficiency |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Alkaline fuel cell (AFC)** | Low | Up to 500 kW | Moderate | Good | High purity hydrogen | High, experience from several applications including one ship | Small | High | No | Hydrogen | 50-60 % (ele |
| **Phosphoric acid fuel cell (PAFC)** | Moderate | 100-400 kW | Excellent | Moderate | LNG, Methanol, Diesel, Hydrogen | High, extensive experience from several applications | Large | Medium | $CO_2$ and low levels of $NO_x$ if carbon fuel is used. | High temperature (up to 200 C). Hydrogen and CO in reforming unit | 40 %(electric 80 % (with he recovery) |
| **Molten carbonate fuel cell (MCFC)** | High | Up to 500 kW | Good | Low | LNG, Methanol, Diesel, Hydrogen | High, extensive experience from several applications including ships | Large | Low | $CO_2$ and low levels of $NO_x$ if carbon fuel is used. | High temperature (600-700 C), Hydrogen and CO in cell from internal reforming | 50 %(electric 85 % (with he recovery) |
| **Solid oxide fuel cell (SOFC)** | High | 20-60 kW | Moderate | Low | LNG, Methanol, Diesel, Hydrogen | Moderate, experience from several applications including ships | Medium | Low | $CO_2$ and low levels of $NO_x$ if carbon fuel is used. | High temperature (600-700 C),Hydrogen and CO in cell from internal reforming | 60 %(electric 85 % (with he recovery) |
| **Proton Exchange Membrane fuel cell (PEMFC)** | Low | Up to 120 kW | Moderate | Good | Hydrogen | High, extensive experience from several applications including ships | Small | Medium | No | Hydrogen | 50-60 % (ele |
| **High Temperature PEM fuel cell (HT-PEMFC)** | Moderate | Up to 30 kW | Unknown | Good | LNG, Methanol, Diesel, Hydrogen | Low, experience some applications including ships | Small | Low | $CO_2$ and low levels of $NO_x$ if carbon fuel is used. | High temperature (up to 200 C). Hydrogen and CO in reforming unit | 50-60 % (ele |
| **Direct methanol fuel cell (DMFC)** | Moderate | Up to 5 kW | Moderate | Good | Methanol | Under development | Small | Low | $CO_2$ | Methanol | 20 % (electri |

# 3. Method

In this section, the methods behind conducting a life cycle assessment will be explained. Firstly, the key concepts of LCAs will be described according to relevant standards before the system used in the LCA conducted in this study will be introduced.

## 3.1 Life Cycle Assessment (LCA) - Concept

Life Cycle Assessment (LCA) is a scientific method based on comparative analysis and assessment of the environmental impacts of system products [1]. The key factors that distinguishes this assessment method from other environmental assessment methods can be explained by two unique features: the analysis of *cradle-to grave* and the *functional unit* [1]. Applying these features in analyzes allows the comparison of other product systems fulfilling the same, or nearly the same purposes. The guidelines and procedures of using LCA are set by international standards developed by the International Organization of Standardization (ISO) [1].

The most central concepts of the life cycle assessment method will in this section be explained by their definitions according to relevant guidelines and standards. *Cradle-to-grave* analysis means that all the important impacts steps in a products life cycle are taken into consideration in the analysis. Important steps are often related to the extraction of raw material from the environment, the production of materials and the final products, the products use phase and the end of life waste management and recycling processes. Any transportation that occurs between each of the steps should also be taken into consideration.

*Products* are by all standards defined as *goods* or *services*. In an LCA, the concept of *life cycle* is always defined as the physical life cycle of a product. The *functional unit* is the basis for comparison when different product systems that provide more or less the same function are to be compared. This concept describes quantitatively the functional the function of the product systems to be compared, in this case the production of a ship and its transport to the point of use, recycling and waste management [1]. Small differences of products are commonly neglected in an LCA, as long as they have no or only minor influence on the environmental impacts of the product system.

Behind the obvious aspects of impacts from products to be observed in daily life there is the multitude of *downstream* and *upstream* processes. These types of processes can be related to intermediate products, transport processes and energy use, to name a few. *Upstream* processes are defined as processes towards the *cradle*, while *downstream* processes are defined as processes towards the *grave*. Downstream processes that occurs after the *use phase* marks the start of the *End of Life* (EOL) phase, which includes impacts from waste management and recycling. *Use phase* can be defined as impacts related to the use of a product. The use phase is most often the central part of the life cycle defined by a LCA. [11]

When being confronted by a new problem, it's not always easy to be fully aware of the complexity of a so-called *product tree* (a graphical presentation of product life cycles), the *supply chain* and the EOL. This may lead to a significant amount of work and research of constructing a *product tree* with the best available information. Also, the system has to be tailored, so that small amounts of residual inputs and outputs are cut off. The system boundaries, which separates the system from the rest of the environment to be studied, has to be defined in a similar way.

The LCA, or more specifically the Life Cycle Inventory – LCI, may be called a simplified system analysis. In order to visualize such systems, the smallest units for which data are available (the unit processes), can be shown as boxes which are connected to other unit processes from which they obtain inputs and to which they transfer substances, materials or energy. Processes can also release into the environment (emissions) and leave the system. Imports to the system can also be in the form of fuels such as oil, gas and coal. Systems studied in LCI are parts of the Technosphere (the environment made or modified by human activity), while the environment releases and provides inputs at the interface between the Technosphere and the environment. The specific interactions that may occur between Technosphere and the environment are quantified in the Life Cycle Impact Assessment (LCIA), and later discussed in the final phase of the LCA called Interpretation.

LCA has become a successful environmental assessment tool much due to its broad applicability. All product systems for which data can be generated can be analyzed. The possibility of comparing systems with similar functions and the results with competing (or improved) systems are also available. This leads to a great opportunity of improving products and the Technosphere, thus improving the environment. [1]

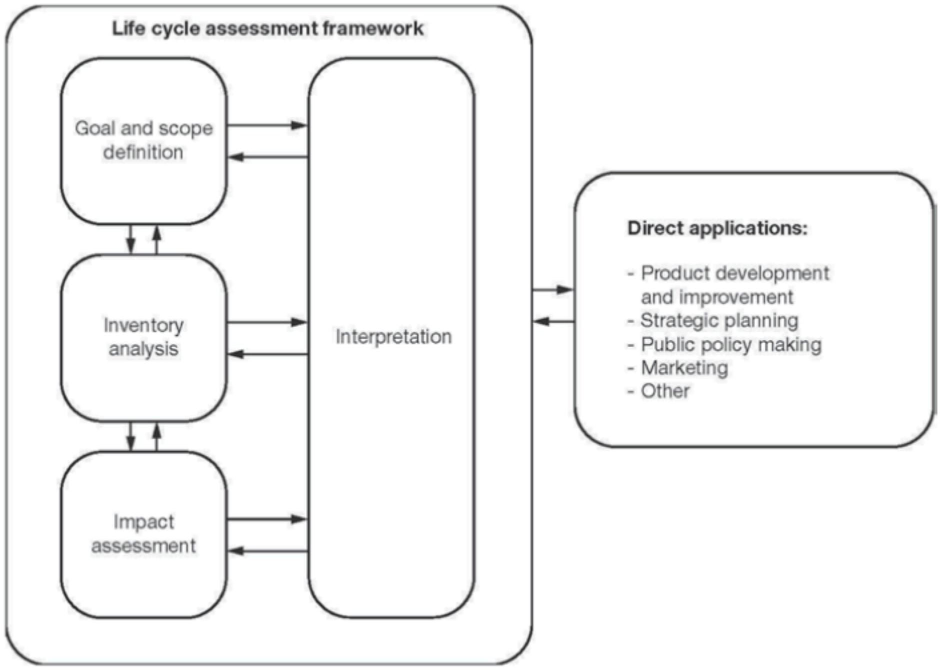


*Figure 17: Illustration of LCA phases (according to standard ISO 14040) [8]*

The structure of all LCAs are defined by international standards, following the scheme shown in figure 3. In total there are four mandatory phases which have to be included in a LCA:

1. Goal and scope definition
2. Inventory analysis
3. Impact assessment
4. Interpretation

### 3.1.1 Goal and scope definition

Any LCA starts by giving a statement of what the goal and scope of the study is. This part explains the context of the study and to who or whom the information given by the study are to be communicated. The importance of the goal and scope definition (G&SD) cannot be overestimated. The goal has to be introduced in the beginning of an LCA study as an introduction giving background information and context about the specific subject of the study.

According to international standards G&SD is a key step of the LCA required to be clearly defined and consistent with the intended application. The G&SD should, therefore, deliver a technical description to guide the work done in the LCA. The role of the G&SD varies from being strict in some areas, such as structure, origin background data etc. to being loose in other cases, even important LCAs [1]. Description of the *functional unit*, as described earlier in this paper, and defining the system boundaries could still be important points to cover in this part of the LCA.

Any assumptions or limitations needed to be made in order to perform the LCA should also be mentioned. It is worth mentioning that there is no default list of impact categories applied by international standards to be used in the assessment part of the LCA. Nevertheless, every LCA has to include a list of relevant impact categories to be chosen (one is not good enough) [1].

### 3.1.2 Inventory analysis

The inventory analysis forms the core of every LCA study. It is also considered the most scientific and quantitative part of the LCA. For all systems there are steps with a minimum number of requirements needed to be fulfilled. The system definitions must be included with a graphical presentation of the product trees. Also, the functional unit and the reference flow must be defined. These first two steps refer to individual studies to be performed, either stand-alone LCAs, or in the form of comparative LCAs.

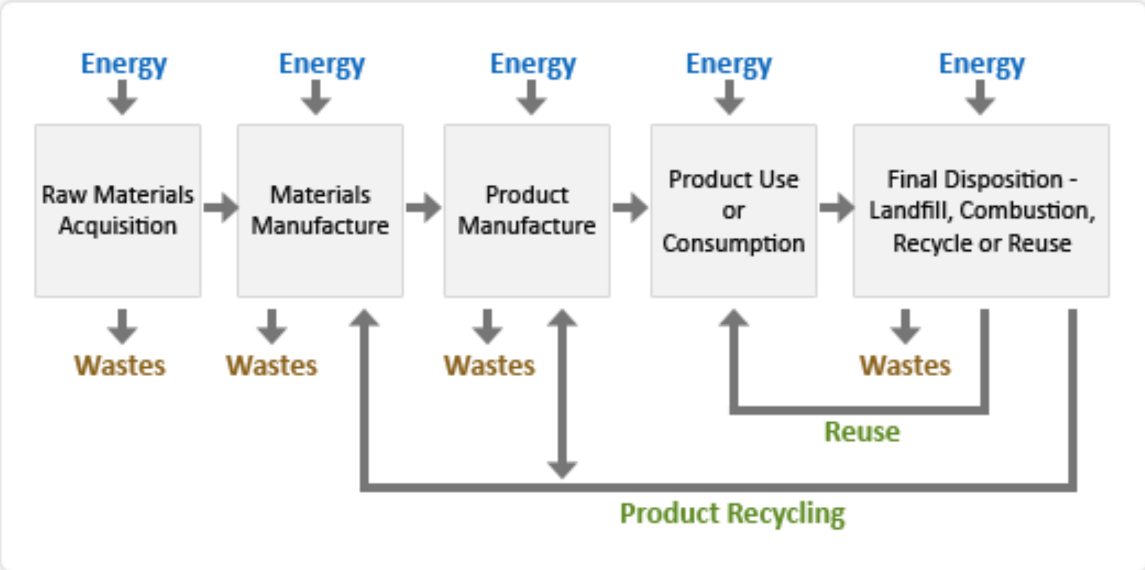


*Figure 18: Generic product life cycle flow diagram to be used in an inventory analysis. [22]*

Inventory analysis must also include data collection, including the inputs and outputs of the product systems (as shown in figure 4). It is important that the data represents the reference year or period and for the region in which the process occur. Data is usually split into foreground data and background data. Foreground data should be requested by producers and may be unobtainable due to confidentiality. Background data are mostly provided by generic data, e.g. from public or private data banks. Calculations can be done with the help of spreadsheets or similar methods. [8]

### 3.1.3 Impact Assessment (LCIA)

This phase is aimed at evaluating the significance of environmental impacts related based on the flow in the inventory analysis. Most of LCAs that are performed consists of some mandatory elements. The first element is choosing a selection of impact categories, category indicators and characterization models. This step should already be included in the G&SD section, but should also be refined in this section of the LCA. The second step is the classification stage, where parameters from the inventory are sorted and assigned to specific impact categories. [8]

Results from the inventory analysis should already have been produced in the second phase of the LCA with regards to specific impact categories. The final decision of which categories that are relevant for the specific LCA study must therefore be taken in this third phase of the LCA. A common categorization method used in LCAs is dividing the impacts of a product into separate phases (usually start, use and end-of-life impacts). The last mandatory step of the impact assessment is the calculation of category indicator results, often referred to as characterization in LCAs. This element requires knowledge of the interrelation of releases to the environment or extractions from the environment and the potential impacts from these releases and extractions. [1]

### 3.1.4 Interpretation

In the interpretation phase the results from the inventory analysis an impact assessment is summarized. The outcome of this phase is a set of conclusions and recommendations for the LCA study. First of all, the interpretation should include an identification of significant issues based on the results from the inventory analysis and impact assessment phases. The interpretation should also evaluate the LCA in case of completeness, sensitivity and consistency and draw conclusions and recommendations based on how the LCA was conducted and how the results were developed. [8]

## 3.2 Life cycle of maritime transportation

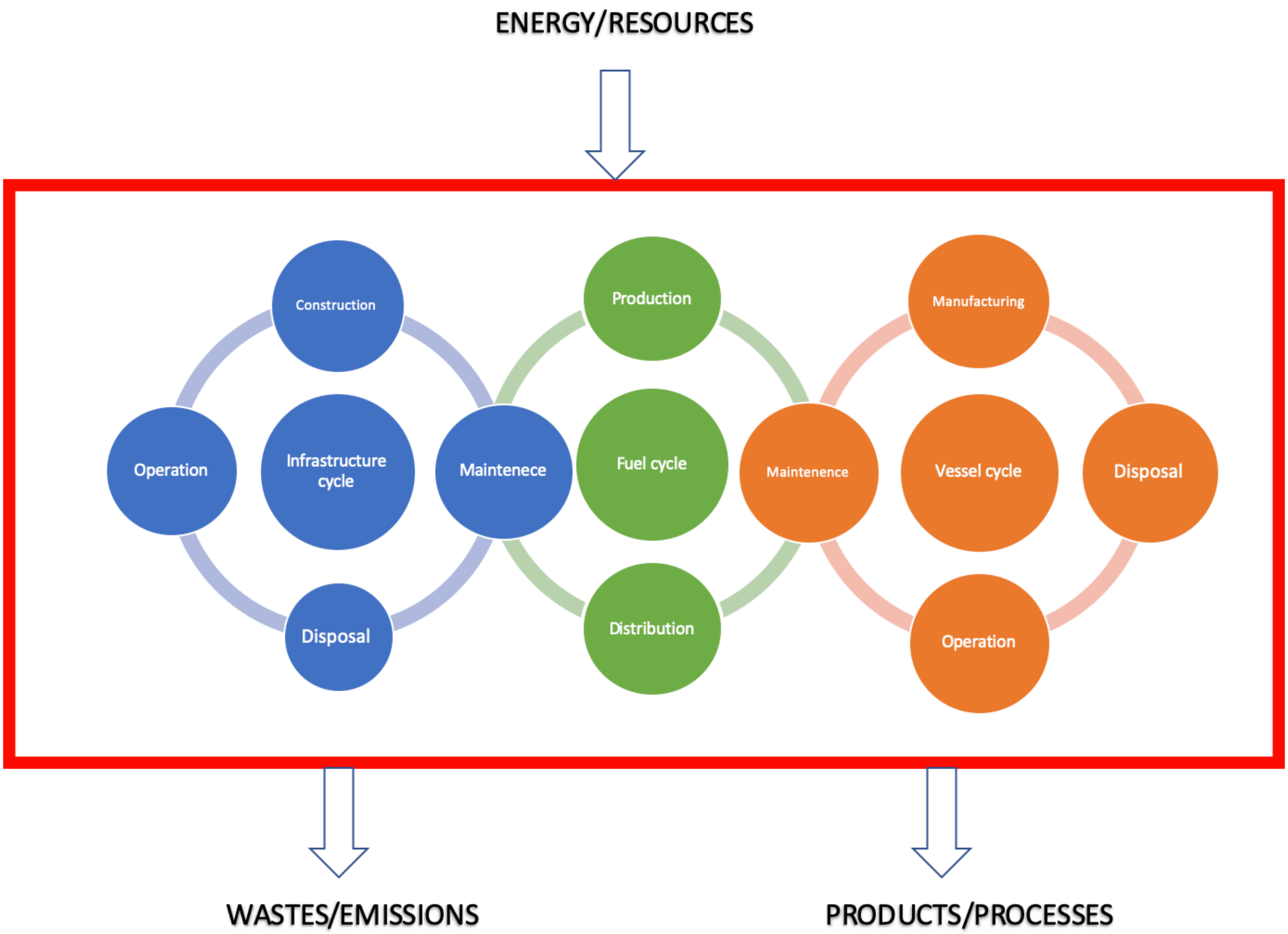


*Figure 19: Overlook over the life cycle of maritime transportation. The three parts of infrastructure, fuel and vessel are linked together and enclosed by the system boundary shown as the red line. Exchanges to and from the system is shown by the arrows.*

### 3.2.1 Setup

The LCA conducted in this study deals with the entire life cycle of maritime transport services. Based on the standards of LCA and previous work, the system to be analyzed is divided into three different parts. As a result, the total system should cover most of the parts that have the greatest influence on the total LCA score. The total system that has been chosen, is illustrated by figure 14. Here the cycles of both fuels, infrastructure and vessels are enclosed by the system boundary.

Firstly, the fuel cycle consists of two sub parts being the production and distribution parts. The production of the fuels involves the extraction and processing of resources into useful fuel products that are used in ships. Distribution is in this sense how the fuel produced is sent out to its specific users, e.g. the supply chain. Both the infrastructure and vessel cycles are made up of more or less the same sub parts: construction/manufacturing, maintenance, operation and disposal.

The system flow can be explained by figure 18, with each sub part requiring specific amounts of energy and resources that are put within the system boundary. Wastes and emissions generated within the system are released into the environment. Products or processes generated by the system, which in this case refers to the amount of transport work a vessel does throughout its life cycle, is decisive in defining the functional unit of the system. In this case the functional unit is set to metric ton kilometers (abbreviated tkm), which is a definition of the energy required to transport one ton of cargo one kilometer.

### 3.2.2. Life Cycle Inventories

Life Cycle Inventories used in the study are collected from the inventory database *Ecoinvent.* Ecoinvent is regarded as the most complete LCI database with generated data sets of numerous processes and products. The key feature of Ecoinvent as a LCI database is the transparency from manufacturers and producers as well as the consistency, with the data sets being regularly updated.

Ecoinvent provides three different system models, with the model "Allocation at the point of substitution" (APOS) chosen for this study. In the APOS system model, the product systems are expanded in order to avoid allocation within the treatment systems. Valuable by-products from treatment systems are allocated with the activity itself. Product systems can contain several different data sets for the by-products. Allocation at the point of substitution put these data sets together and combines them into one unified dataset. This reduces the complexity of the system while also giving the average value of the by-products. [23]

### 3.2.4 Software

The data sets generated in the Ecoinvent are quite complex, having large amounts of data regarding the flow of inputs and outputs in the Technosphere. In order to deal with the complexity of the data, a software tool has been applied providing the results of the Life Cycle Assessment.

The software tool that has been chosen in this study is *openLCA.* This is an open source tool developed by the company GreenDelta since 2006. As an open source tool, openLCA can be freely downloaded and used without any costs. The source code from which the program is built on can be viewed and edited by anyone. By having an open source nature, the tool is suitable to be used for sensitive data.

### 3.2.3 Impact Assessment categories

OpenLCA provides several impact assessment methods. The chosen LCIA method for this study is the "CML-IA-baseline" method. This method is developed by the University of Leiden in the Netherlands. The baseline version of the CML method is the most used assessment method in LCAs. The following categories are making up the baseline version:

**Acidification**

So-called "acid rain" is generated when acid gases like sulfur dioxide ($SO_2$) is emitted to the atmosphere and reacts with water. This type of rain causes impacts to ecosystem when falling from the sky. Gases that provide acidic content consists of ammonia, nitrogen oxides and sulfur oxides. The reference unit used to express the acidification potential is kg$SO_2$-equivalents.

**Climate change**

Climate change is a well-known term when it comes to effects global warming. The definition of climate change can be expressed as the alteration of global temperature caused by greenhouse gas emissions that is being released into the atmosphere due to human activity. For the different greenhouse gases, factors for global warming potential (GWP) are being used to express the climate change potential over different time scales, with the most common being 100 years (GWP100). The climate change potential is measured by the reference unit of kg $CO_2$-equivalents.

### Depletion of abiotic resources

Depletion of abiotic resources is generally denoted by the consumption of non-biological resources such as fossil fuels, water, minerals etc. The value of this category is commonly used to express the scarcity of a resource. This leads to the value being dependent on the amount of resources and the rate of which they are extracted. The CML baseline method has two subcategories for depletion of abiotic resources, one being measured in MJ of fossil fuel use and the other being the amount of resources that are depleted, measured in antimony equivalents.

### Ecotoxicity

Ecotoxicity is an expression of the toxic effects that chemicals can have on ecosystems. This category involves three different measures for environmental toxicity in relation to freshwater, marine and land. The impact of toxic chemicals on ecosystems is expressed by the reference unit of kg 1,4 dichlorobenzene equivalents (1,4-DB).

### Eutrophication

Eutrophication is defined as the accumulation of nutrients in aquatic systems. This may lead to abnormal productivity, e.g. excessive growth of algae in rives leading to severe reduction in water quality and animal population. This category is expressed by the reference unit of $PO_4^{3-}$ equivalents.

### Human toxicity

This category is based on a calculated index reflecting the harm of different chemicals released into the environment. The definition of the human toxicity potential is based on the toxic effect of chemicals on humans which may lead to serious illness, such as cancer. Human toxicity is measured in kg 1,4 dichlorobenzene equivalents.

### Ozone layer depletion

Ozone depleting gases causes the reduction of the ozone layer which reduces the prevention of ultraviolet (UV) light being able to enter the atmosphere on Earth. This category is measured by the ozone depletion potential of different gases relative to the reference substance of chlorofluorocarbon-11 (CFC-11). The ozone layer depletion potential is thereby expressed by the reference unit of kg CFC-11 equivalents.

**Photochemical oxidation**

While ozone is a protective part of the atmosphere against ultraviolet light, having large quantities of ozone at ground level is toxic to humans. Photochemical ozone, other known as "ground level ozone", is generated through volatile organic compounds and nitrogen oxides reacting under the presence of heat and sunlight. This impact category is heavily dependent on the amount of carbon monoxide, sulfur dioxide, nitrogen oxide and non-methane volatile compounds (NMVOC). Photochemical oxidation is expressed by the reference unit of kg ethylene ($C_2H_4$) equivalents.

The method **Cumulative Energy Demand (CED)** was used to quantify the energy usage over the entire life cycle of the products of that system being assessed. The aim of this method is to cover the entire primary energy usage over the entire life cycle of a good or service. Direct and indirect energy usage are included but wastes for energy usage are excluded. The CED method is split into eight subcategories covering both renewable and non-renewable resources. [24]

## 3.3 Case study: Sea transportation by ferry

### 3.3.1 Introduction

Norway's efforts of greening the shipping industry has already been going on for a few years, with a particular focus on the ferry sector. Scheduled maritime services serve as an important part of transport system I Norway, with around 140 ferry services in operation across the country. The fully electric car ferry MF Ampere was set in operation in 2015, becoming the first ferry powered only by batteries. Hydrogen has also been considered as an alternative fuel for shipping, having some promising characteristics that can compete with conventional fossil fuels such as heavy fuel oil (HFO) or diesel. While batteries have a lack of range, hydrogen does not suffer from the same disadvantage. In the case of hydrogen, the energy content generated per unit mass is about three times larger than the corresponding values for conventional marine fuels. A hybrid ferry powered by hydrogen and batteries is also in development and planned to be set in operation by 2021 in Norway.

Figure 21 illustrates the emissions from domestic shipping in Norway sorted by vessel type. It's clear to see that passenger vessels are some of largest contributors to the overall emissions, leading to a huge potential for reducing emissions. The Norwegian government has already put forward specific measures targeted at making shipping greener by releasing an action plan in response to the stricter regulations set by the IMO. Even though the share of low and zero emission technology was low in 2017, there has been a subsequently increase in new ship orders with an emphasize on low or zero emission solutions with a particular change in the category of passenger vessels (see figure 22).

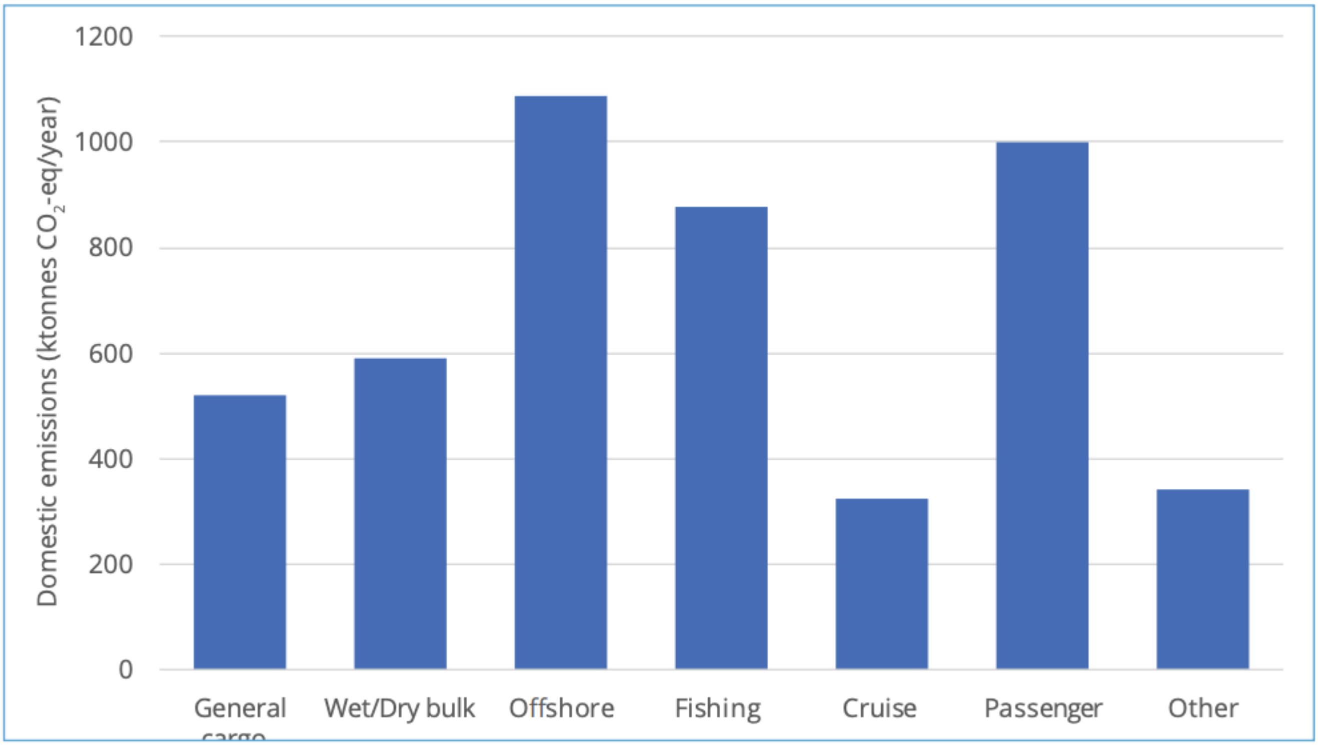


*Figure 20: Emissions from domestic shipping in Norway by different vessel categories [5]*

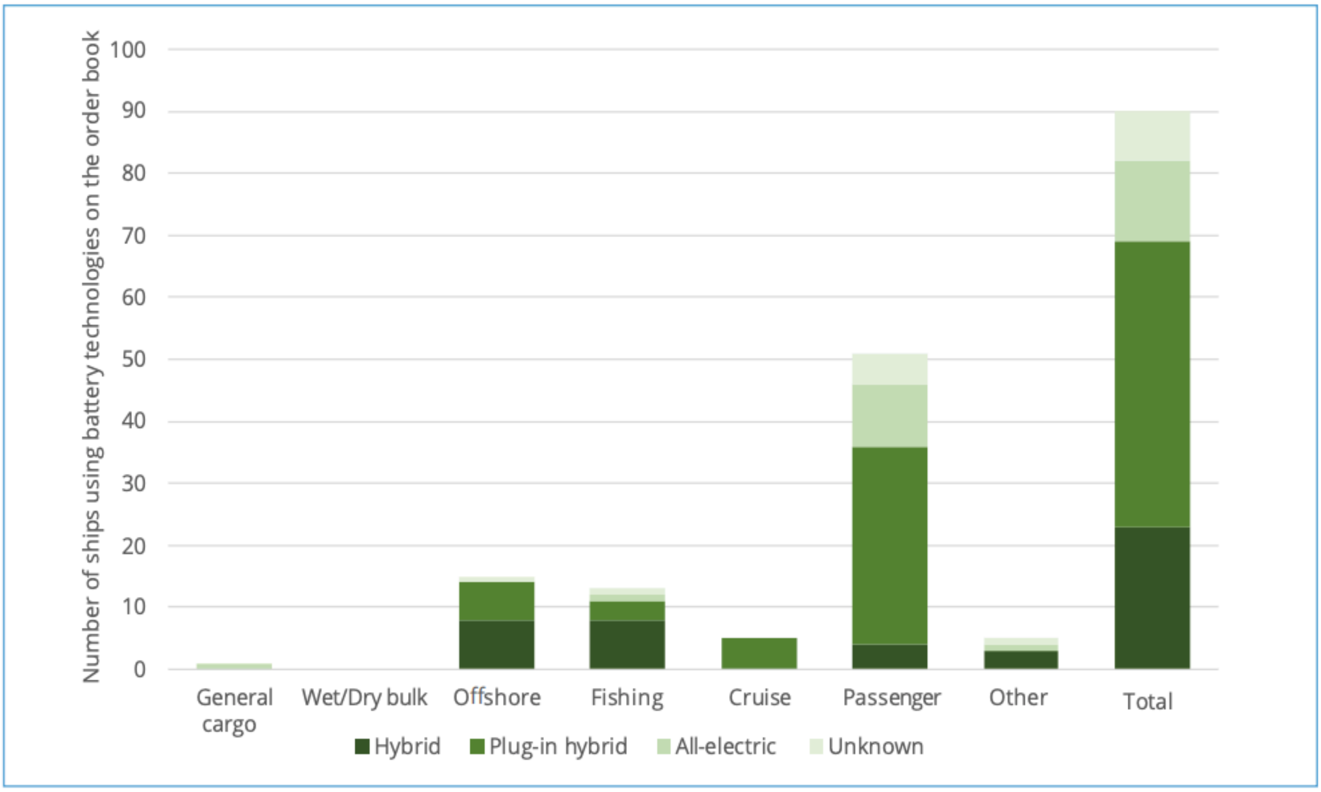


*Figure 21: Order book of ships to be delivered with low or zero emission technology sorted by vessel type [5]*

### 3.3.2 System configurations

The system to be considered involves the transport work done by an average sized ferry. Data used for calculations in openLCA are based on the data set "transport, freight, sea, ferry" in Ecoinvent. The data set is representable for the entire transport life cycle, including the production and maintenance of the vessel, the transportation of freight in bulk, and the construction of the port. The scope of the dataset is to cover the operation of the ferry with inputs from ship, maintenance and port facilities. Specific inputs on production of ferries are linked the separate data set "ferry production".

The assessment conducted in this study are centered around an average sized ferry based on fleet data from the latest IMO GHG study [3]. The material flow of the production of a ferry is based on the calculation of lightweight of the ship in the data set retrieved from Ecoinvent. [25] Lightweight of a ship is a measure of the weight of the vessel without fuel, cargo, passengers etc. In the data set from Ecoinvent, the lightweight is calculated by applying ratios of deadweight over displacement (DWT/Δ). Deadweight is defined as the load capacity of the vessel, while displacement is a measure of the amount of water that is displaced by a vessel, which in turns out as the total weight of the ship.

Table 4 shows typical sizes and percentages of weight groups for merchant vessels. In the category of ferries, the deadweight/displacement ratio is in the range of 16-33 %. A value of 25 % has been chosen for this assessment as a mean value. If the fleet data from IMO is considered (see table 5), an average ferry in the category ro-pax (roll on passenger ferry) has an average deadweight of about 1800 dwt and an average installed capacity of around 8500 kW.

*Table 3: Typical sizes and percentages of weight groups for main merchant ship types [22]*

| | 1 | **2** | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Ship type | Limits | | DWT/Δ (%) | $W_{ST}/W_L$ (%) | $W_{OT}/W_L$ (%) | $W_M/W_L$ (%) |
| | Lower | Upper | | | | |
| General cargo ships (t DWT) | 5,000 | 15,000 | 65–80 | 55–64 | 19–33 | 11–22 |
| Coasters, cargo ships (GRT) | 499 | 999 | 70–75 | 57–62 | 30–33 | 9–12 |
| Bulk carriers[a] (t DWT) | 20,000 | 50,000 | 74–85 | 68–79 | 10–17 | 12–16 |
| | 50,000 | 200,000 | 80–87 | 78–85 | 6–13 | 8–14 |
| Tankers[b] (t DWT) | 25,000 | 120,000 | 78–86 | 73–83 | 5–12 | 11–16 |
| | 200,000 | 500,000 | 83–88 | 75–88 | 9–13 | 9–16 |
| Containerships (t DWT) | 10,000 | 15,000 | 65–74 | 58–71 | 15–20 | 9–22 |
| | 15,000 | 165,000[c] | 65–76 | 62–72 | 14–20 | 15–18 |
| Ro-Ro (cargo) (t DWT) | $L \cong 80$ m | 16,000 t DWT | 50–60 | 68–78 | 12–19 | 10–20 |
| Reefers[d] ($ft^3$) of net ref. vol. | 300,000 | 500,000 | 45–55 | 51–62 | 21–28 | 15–26 |
| Passenger Ro-Ro/ferries/ RoPax | $L \cong 85$ m | $L \cong 120$ m | 16–33 | 56–66 | 23–28 | 11–18 |
| Large passenger ships (cruise ships) | $L \cong 200$ m | $L \cong 360$[e] m | 23–34 | 52–56 | 30–34 | 15–20 |
| Small passenger ships | $L \cong 50$ m | $L \cong 120$ m | 15–25 | 50–52 | 28–31 | 20–29 |
| Stern Trawlers | $L \approx 44$ m | $L \cong 82$ m | 30–58 | 42–46 | 36–40 | 15–20 |
| Tugboats | $P_B \cong 500$ KW | 3,000 KW | 20–40 | 42–56 | 17–21 | 38–43 |
| River ships (towed) | $L \cong 32$ m | $L \cong 35$ m | 22–27 | 58–63 | 19–23 | 16–21 |
| River ships (self-propelled) | $L \cong 80$ m | $L \cong 110$ m | 78–79 | 69–75 | 11–13 | 13–19 |

$W_L$ light ship weight, $W_{ST}$ weight of steel structure, $W_{OT}$ weight of outfitting, $W_M$ weight of machinery installation

*Table 4: Data describing the fleet (international, domestic, fishing) in 2012. Data from the latest IMO GHG study in 2014 [3]*

| Ship type | Size category | Units | Number active | | Decimal AIS coverage of in-service ships | Avg. dead-weight (tonnes) | Avg. installed power (kW) | Avg. design speed (knots) | Avg. days at sea | Avg.* sea speed (knots) | Avg.* consumption ('000 tonnes) | | | Total $CO_2$ emissions ('000 tonnes) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | IHSF | AIS | | | | | | | Main | Auxiliary | Boiler | |
| Oil tanker | 0–4,999 | dwt | 3,500 | 1,498 | 0.43 | 1,985 | 1,274 | 11.5 | 144 | 8.7 | 0.6 | 0.6 | 0.2 | 14,991 |
| | 5,000–9,999 | dwt | 664 | 577 | 0.87 | 6,777 | 2,846 | 12.6 | 147 | 9.1 | 1.1 | 1.0 | 0.3 | 4,630 |
| | 10,000–19,999 | dwt | 190 | 171 | 0.90 | 15,129 | 4,631 | 13.4 | 149 | 9.6 | 1.6 | 1.7 | 0.4 | 2,121 |
| | 20,000–59,999 | dwt | 659 | 624 | 0.95 | 43,763 | 8,625 | 14.8 | 164 | 11.7 | 3.7 | 2.0 | 0.6 | 12,627 |
| | 60,000–79,999 | dwt | 391 | 381 | 0.97 | 72,901 | 12,102 | 15.1 | 183 | 12.2 | 5.8 | 1.9 | 0.6 | 9,950 |
| | 80,000–119,999 | dwt | 917 | 890 | 0.97 | 109,259 | 13,813 | 15.3 | 186 | 11.6 | 5.9 | 2.6 | 0.8 | 25,769 |
| | 120,000–199,999 | dwt | 473 | 447 | 0.95 | 162,348 | 18,796 | 16.0 | 206 | 11.7 | 8.0 | 3.1 | 1.0 | 17,230 |
| | 200,000–+ | dwt | 601 | 577 | 0.96 | 313,396 | 27,685 | 16.0 | 233 | 12.5 | 15.3 | 3.6 | 1.1 | 36,296 |
| Other liquids tankers | 0–+ | dwt | 149 | 39 | 0.26 | 670 | 558 | 9.8 | 116 | 8.3 | 0.3 | 1.3 | 0.5 | 5,550 |
| Ferry – pax only | 0–1,999 | gt | 3,081 | 1,145 | 0.37 | 135 | 1,885 | 22.7 | 182 | 13.9 | 0.8 | 0.4 | 0.0 | 10,968 |
| | 2,000–+ | gt | 71 | 52 | 0.73 | 1,681 | 6,594 | 16.6 | 215 | 12.8 | 3.9 | 1.0 | 0.0 | 1,074 |
| Cruise | 0–1,999 | gt | 198 | 75 | 0.38 | 137 | 914 | 12.4 | 102 | 8.8 | 0.3 | 1.0 | 0.5 | 1,105 |
| | 2,000–9,999 | gt | 69 | 53 | 0.77 | 1,192 | 4,552 | 16.0 | 161 | 9.9 | 1.3 | 1.1 | 0.4 | 580 |
| | 10,000–59,999 | gt | 115 | 108 | 0.94 | 4,408 | 19,657 | 19.9 | 217 | 13.8 | 9.1 | 9.2 | 1.4 | 6,929 |
| | 60,000–99,999 | gt | 87 | 85 | 0.98 | 8,425 | 53,293 | 22.2 | 267 | 15.7 | 30.8 | 26.2 | 0.6 | 15,415 |
| | 100,000–+ | gt | 51 | 51 | 1.00 | 11,711 | 76,117 | 22.7 | 261 | 16.4 | 47.2 | 25.5 | 0.5 | 10,906 |
| Ferry – ro-pax | 0–1,999 | gt | 1,669 | 732 | 0.44 | 401 | 1,508 | 13.0 | 184 | 8.4 | 0.6 | 0.2 | 0.0 | 4,308 |
| | 2,000–+ | gt | 1,198 | 1,046 | 0.87 | 3,221 | 15,491 | 21.6 | 198 | 13.9 | 6.0 | 1.4 | 0.0 | 26,753 |
| Refrigerated bulk | 0–1,999 | dwt | 1,090 | 763 | 0.70 | 5,695 | 5,029 | 16.8 | 173 | 13.4 | 3.0 | 2.3 | 0.4 | 17,945 |
| Ro-ro | 0–4,999 | dwt | 1,330 | 513 | 0.39 | 1,031 | 1,482 | 10.7 | 146 | 8.8 | 1.1 | 2.5 | 0.3 | 15,948 |
| | 5,000–+ | dwt | 415 | 396 | 0.95 | 11,576 | 12,602 | 18.6 | 209 | 14.2 | 6.8 | 3.6 | 0.4 | 13,446 |
| Vehicle | 0–3,999 | vehicle | 279 | 261 | 0.94 | 9,052 | 9,084 | 18.3 | 222 | 14.2 | 5.4 | 1.6 | 0.3 | 6,200 |
| | 4,000–+ | vehicle | 558 | 515 | 0.92 | 19,721 | 14,216 | 20.1 | 269 | 15.5 | 9.0 | 1.4 | 0.2 | 18,302 |
| Yacht | 0–+ | gt | 1,750 | 1,110 | 0.63 | 171 | 2,846 | 16.5 | 66 | 10.7 | 0.4 | 0.5 | 0.0 | 3,482 |
| Service – tug | 0–+ | gt | 14,641 | 5,043 | 0.34 | 119 | 2,313 | 11.8 | 100 | 6.7 | 0.4 | 0.1 | 0.0 | 21,301 |

Calculating With the deadweight of the ferry considered in this assessment already being known (dwt: 1800 tons), and the deadweight/displacement ratio being set to 25 %, the lightweight of the ferry can be calculated based on the relation between displacement, deadweight and lightweight (see equation 9) [10]:

*Equation 9: Relation between deadweight, displacement and lightweight*

$$deadweight = displacement - lightweight$$

This results in the case ferry having the following measures:

**DWT: 1800 tons**

**Displacement (Δ): 7200 tons**

**Lightweight: 5400 tons**

The material breakdown of the ship is based on literature study. [25] Together with the estimated lightweight of the ship, the amounts of steel, copper, brass, zinc, machinery, electronics, insulation material, plastics and wood can be determined (listed in table 6). Use of electricity, fuel, paint and welding gas are also based on previous studies on LCA in shipbuilding [28] [29] [30].

| MATERIALS | MASS PERCENTAGE OF LIGHTWEIGHT [%] |
|---|---|
| ALUMINUM | 0.05 |
| MINERALS | 2.5 |
| BRONZE | 0.15 |
| COPPER | 0.16 |
| ELECTRONICS | 1.2 |
| INTERIOR | 1.3 |
| MACHINERY | 6.2 |
| PLASTICS | 1.2 |
| STEEL | 85 |
| ZINC | 0.7 |

Fuel consumption data is based on a weighted average of the weight classes from the IMO. [3]. Emission factors for the main emissions ($CO_2$, $NO_x$, $SO_x$, PM, NMVOC, CO, $CH_4$ and $N_2O$) are put in place according to IMO data. The reference vessel is set to use heavy fuel oil (HFO) even though MGO and other qualities of fuel are to be used in emission-controlled areas (ECAs). The share of trip length and port time spent within the ECAs is set to be 5 and 50 percent respectively. Weighted averages at 36 % and 50 % for speed reduction and capacity utilization factor respectively are applied according to IMO values. The port infrastructure model is based on port facilities of the port in Rotterdam in the Netherlands. A total impact of the infrastructure is based on averages of port time spent by the vessel derived from IMO.

The vessel is considered to go through maintenance a total of six times through the assumed lifetime of 25 years. This involves two sessions of complete stripping and repainting of all surfaces and four minor sessions involving stripping and painting of the hull. Only complete references of the fuels of hydrogen, liquefied natural gas and fuel oils were found, thus limiting the by these three-marine fuel alternatives. No data set containing information on hydrogen production from steam methane reforming or electrolysis was able to be found. Datasets describing hydrogen production from cracking of fossil fuels and a modified data set based on alkaline electrolysis of chlorine were used instead. Li-ion batteries are applied for a hybrid version with fuel cells based on design concepts of the first hydrogen fueled ferry to be deployed in 2021. For fuel cells (PEM), it is assumed maintenance occurs every year, or each 5300 hours. Storage tanks for cryogenic hydrogen, based on storage modules for liquid chemicals found in ecoinvent are also applied.

# 4. Results

The following section presents the results of the inputs and outputs of material flows used in the software openLCA. Firstly, different production methods of hydrogen are investigated to further determine which one has the greatest potential regarding environmental impacts.

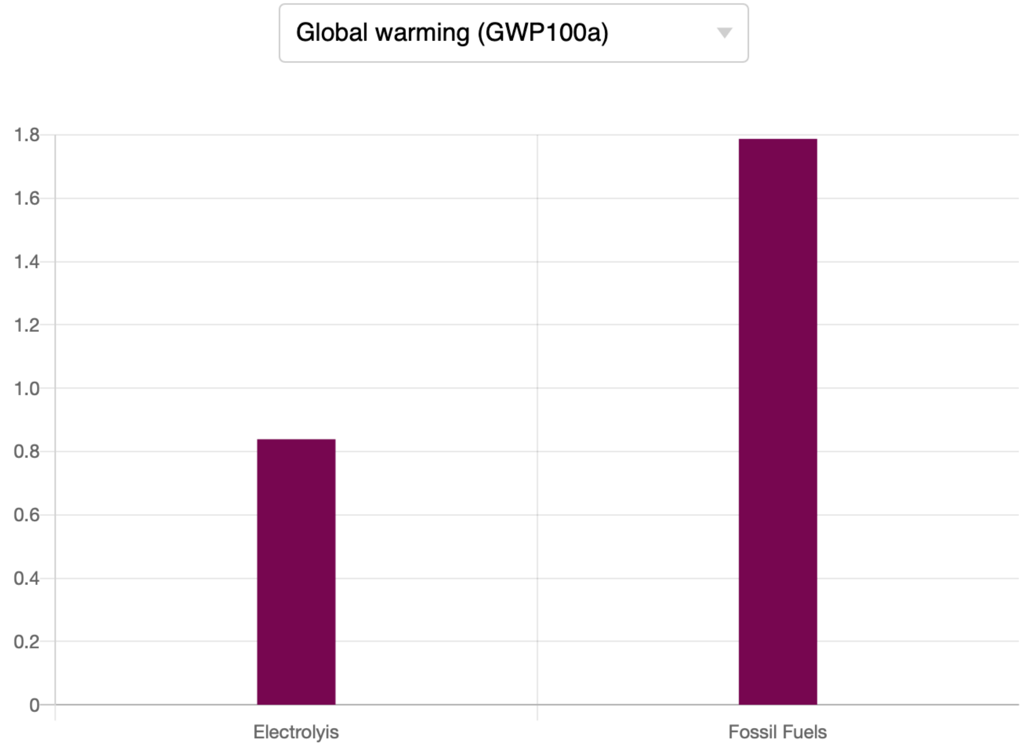


*Figure 22: Global warming potential (GWP100) for production methods of hydrogen*

Figure 22 displays the global warming potential of two different production methods of hydrogen. The electricity considered to be used in the electrolysis process is based on a Norwegian production mix. However, it is worth noting that the source of electricity greatly influence the total impact of this production method, thus having a different source of electricity leading to entirely different impacts.

As expected in this case, the impact of producing hydrogen via electrolysis is significantly lower compared to production via fossil fuels. The data set involving fossil fuel-based production of hydrogen contains impacts from not only steam methane reforming, but also other production methods based on fossil fuels. This is due to the ecoinvent database not containing any data regarding hydrogen production from natural gas. As a result, the data set "hydrogen cracking, APME" was used as a proxy instead.

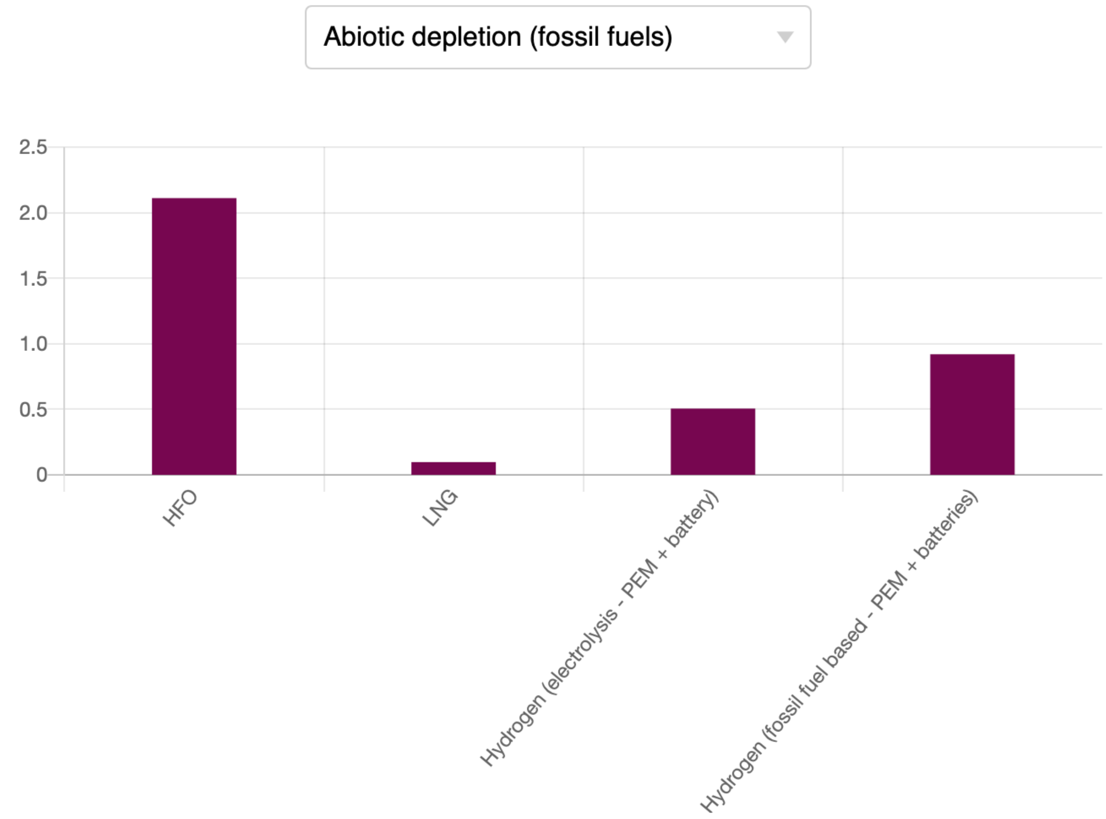


*Figure 23: Fossil fuel depletion of different set ups for ferry transport*

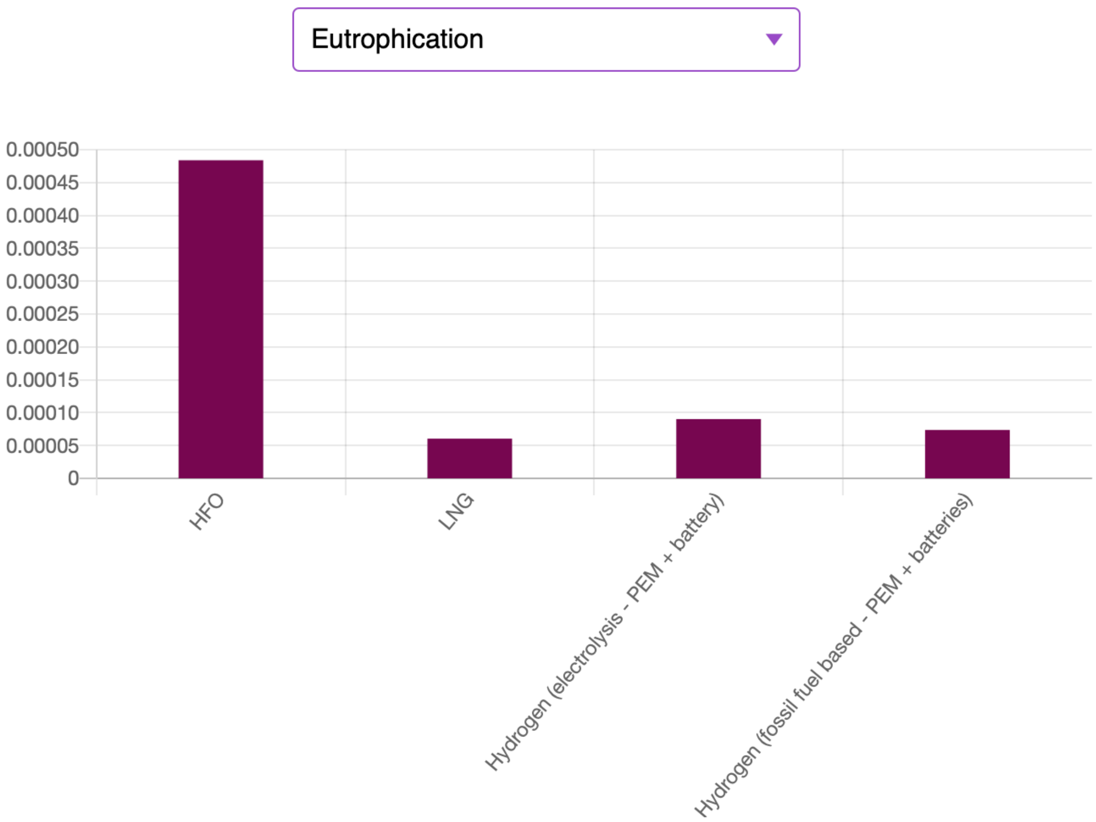


*Figure 24: Eutrophication potential of different setups for ferry transport*

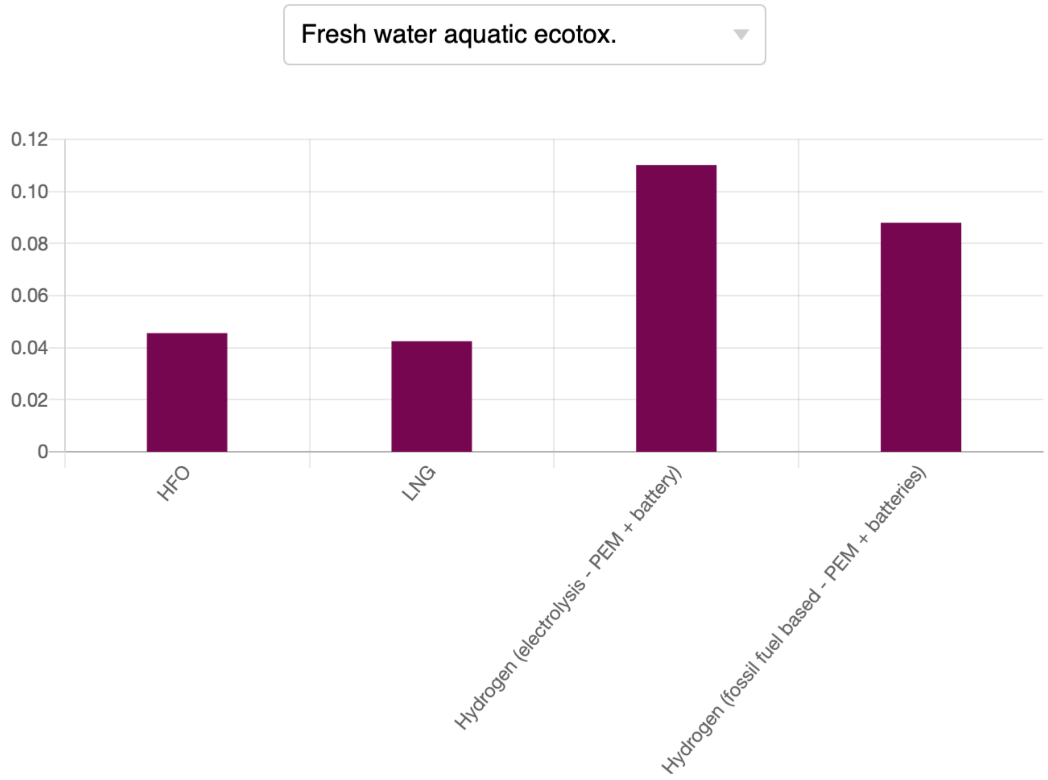


*Figure 25: Fresh water ecotoxicity of different setups for ferry transport*

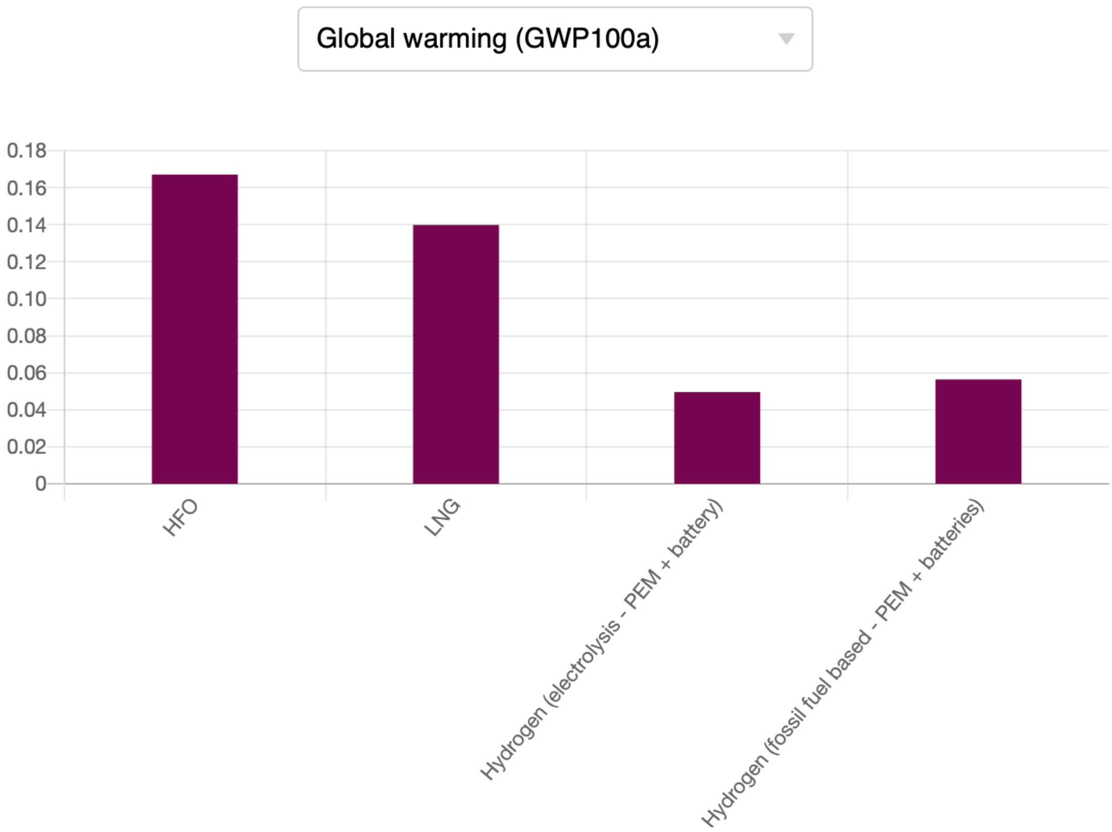


*Figure 26: Global warming potential (GWP100) of setups for ferry transport*

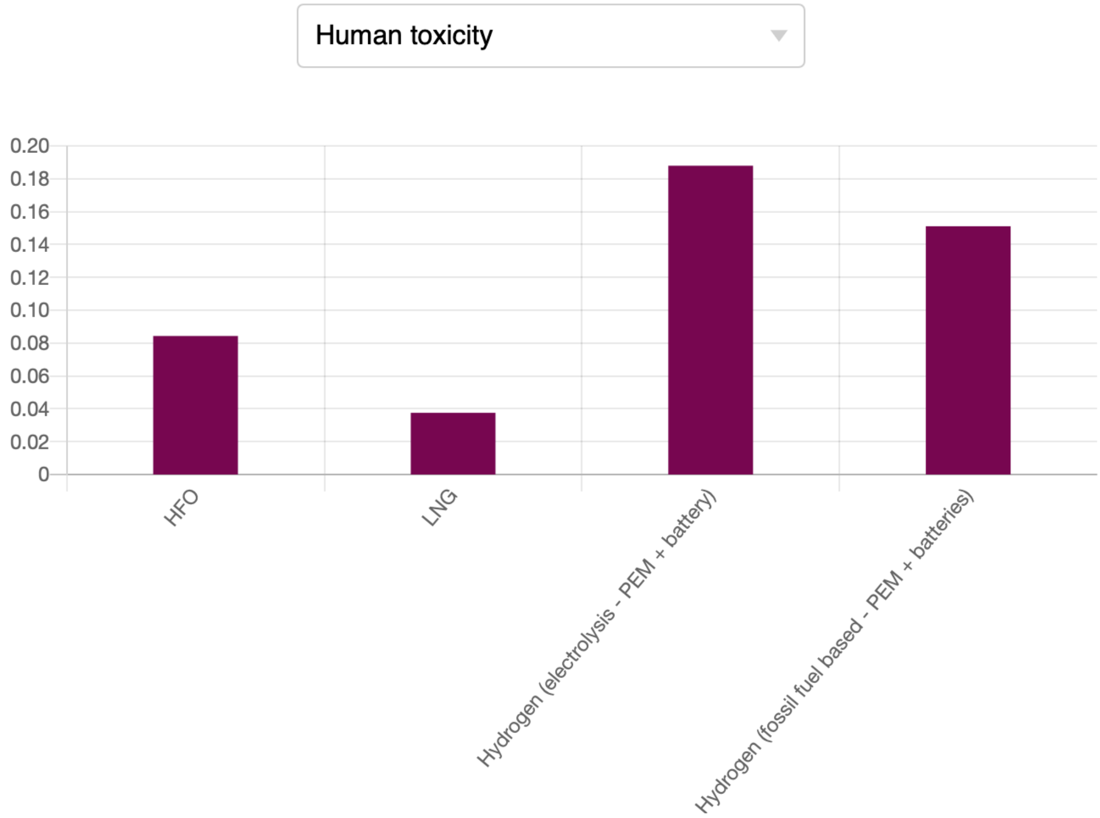


*Figure 27: Human toxicity level of different setups for ferry transport*

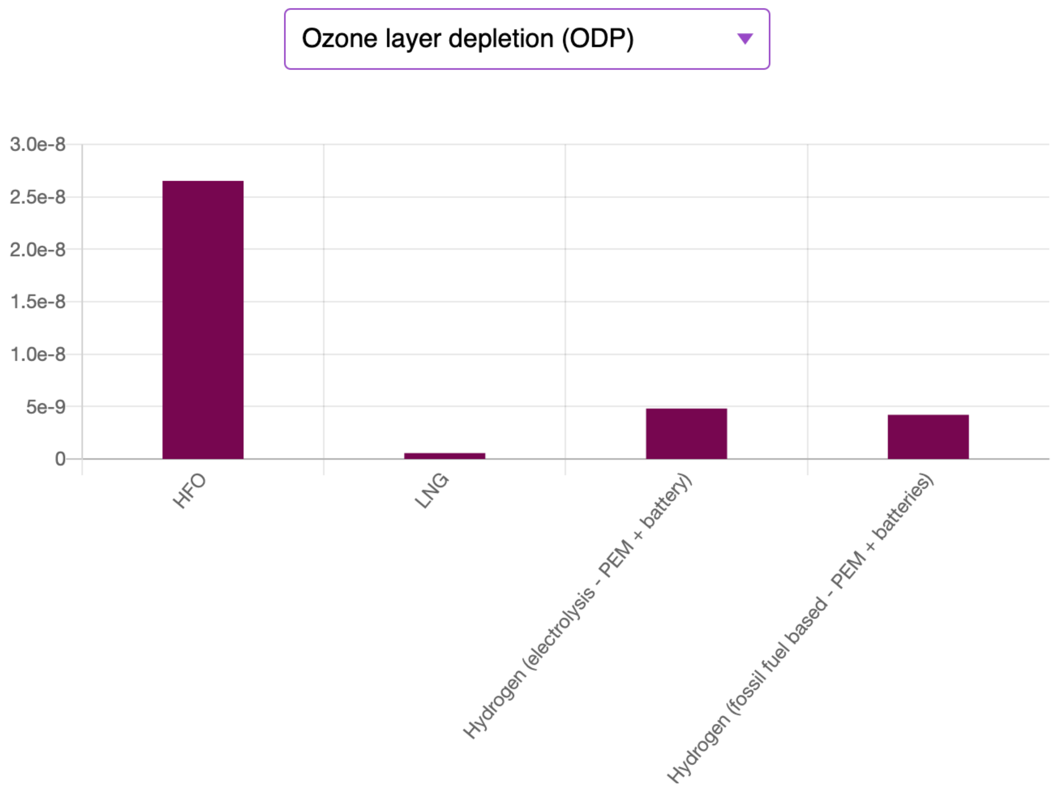


*Figure 28: Ozone Layer Depletion (ODP) of different setups for ferry transport*

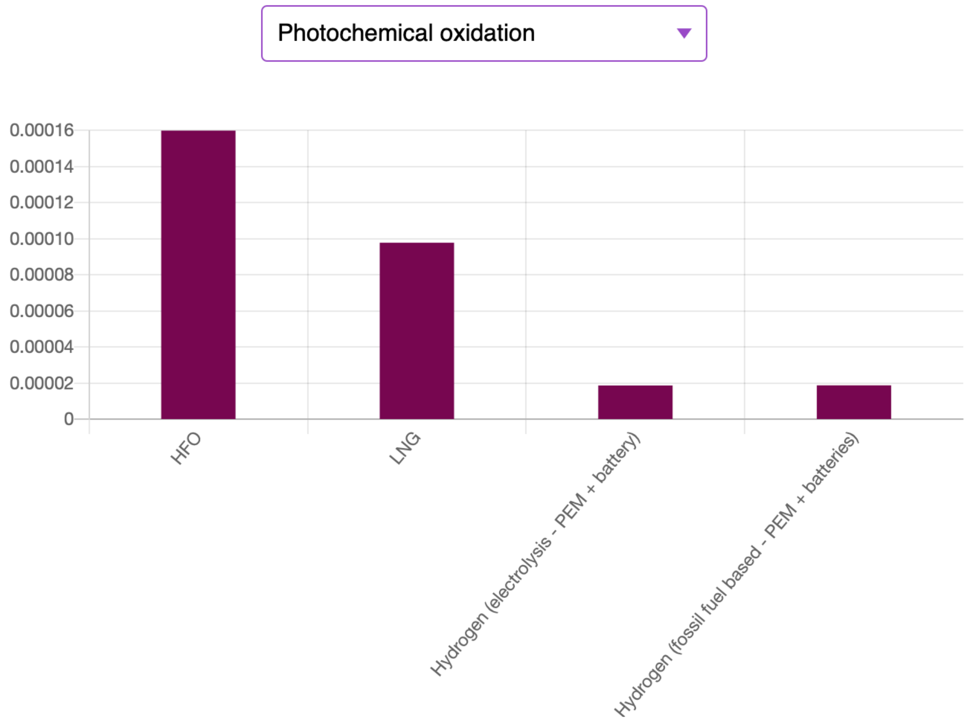


*Figure 29: Photochemical oxidation of different setups for ferry transport*

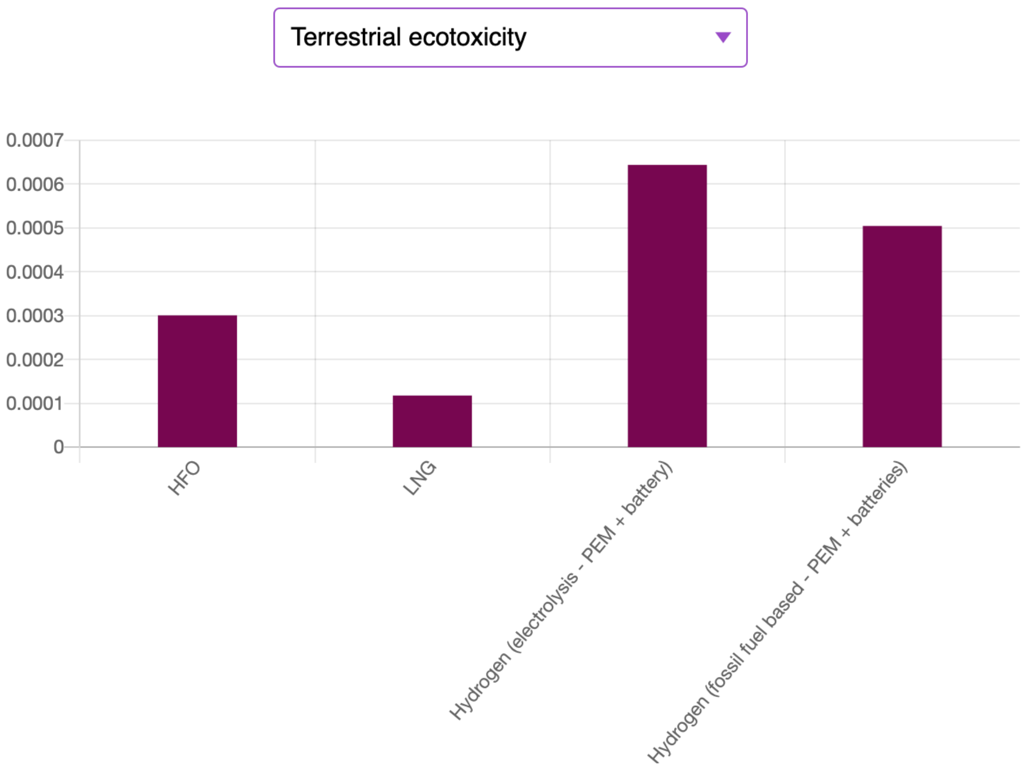


*Figure 30: Terrestrial ecotoxicity of different setups for ferry transport*

Figure 23-30 displays the different impact categories based on the CML-baseline model. Both alternatives fueled by fossil fuels (in this case HFO and LNG) have larger impacts in most categories. The exception is the categories involving ecotoxicity and human toxicity, where hydrogen options tend to have higher impacts. This might be explained by the components involved in manufacturing of these systems, with electrolysers, fuel cells and batteries all containing amounts of precious and hazardous materials (such as platinum or lithium in electrolysers/fuel cells and batteries respectively). This results also leads to an identification of possible reduction potentials. For marine and freshwater toxicity, the higher impacts from hydrogen solutions can be justified by the significant water use related to the production methods (especially hydrogen produced via electrolysis).

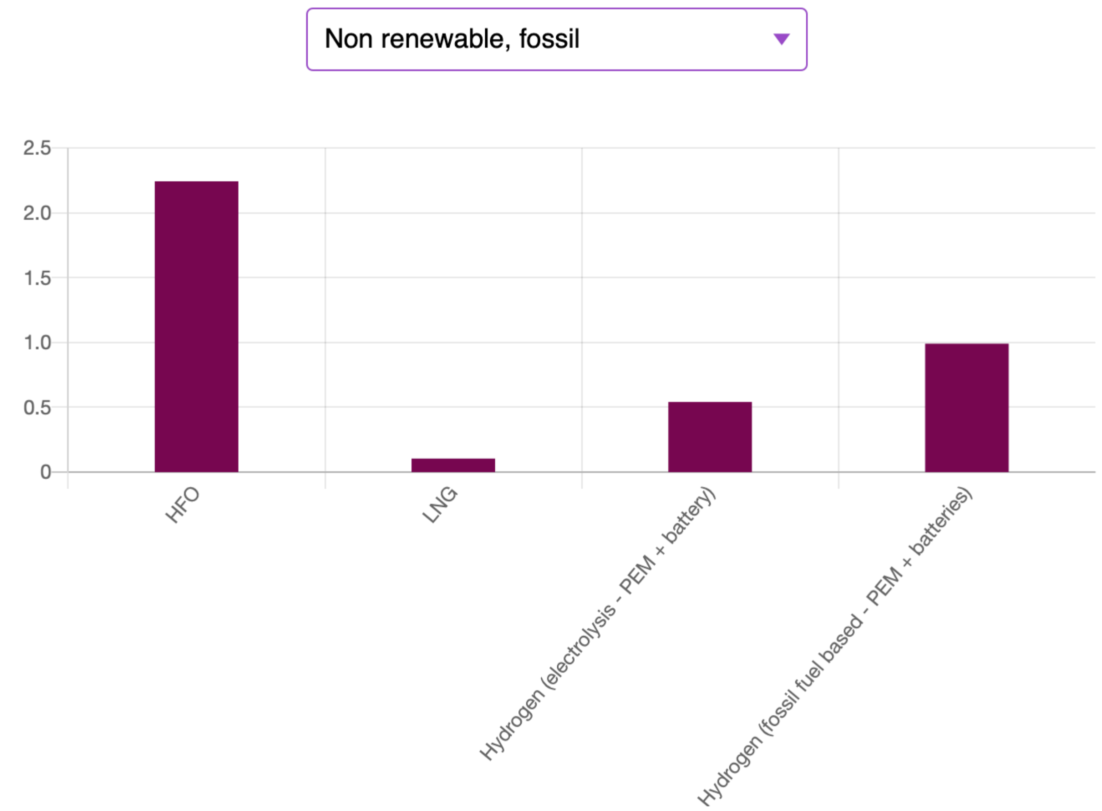


*Figure 31: Non-renewable energy use (fossil)*

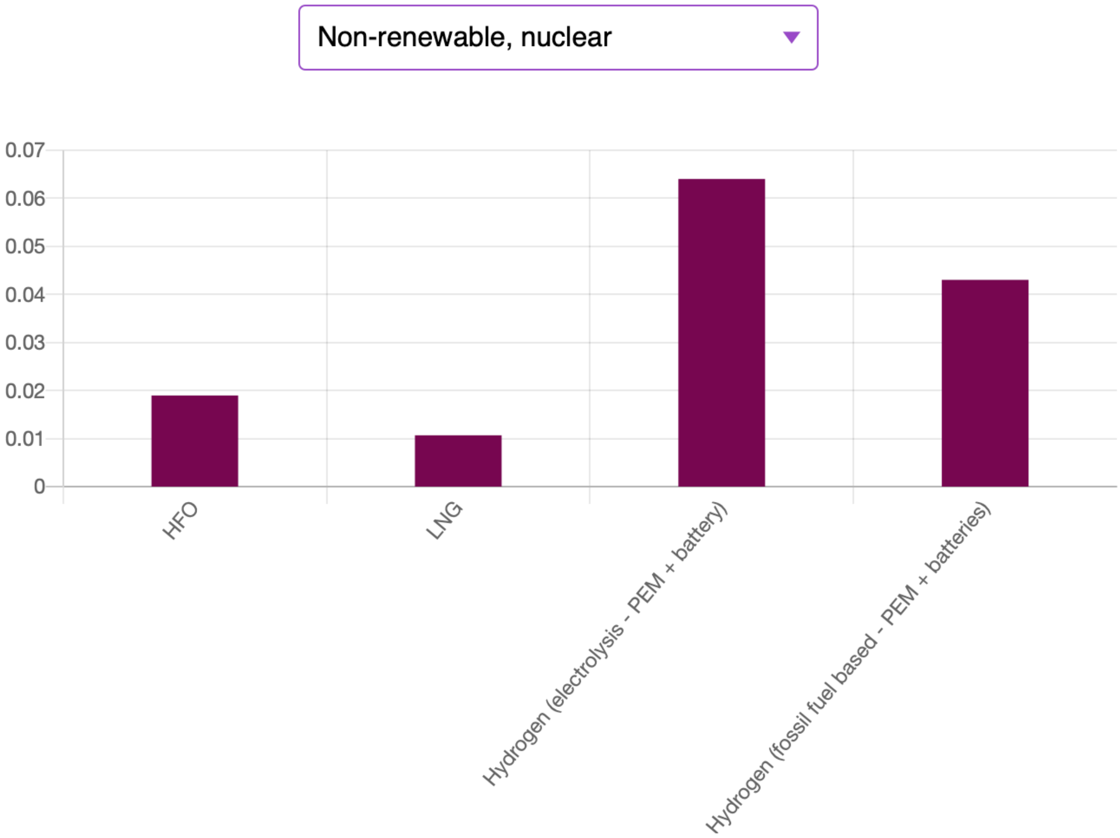


*Figure 32: Non-renewable energy use (nuclear)*

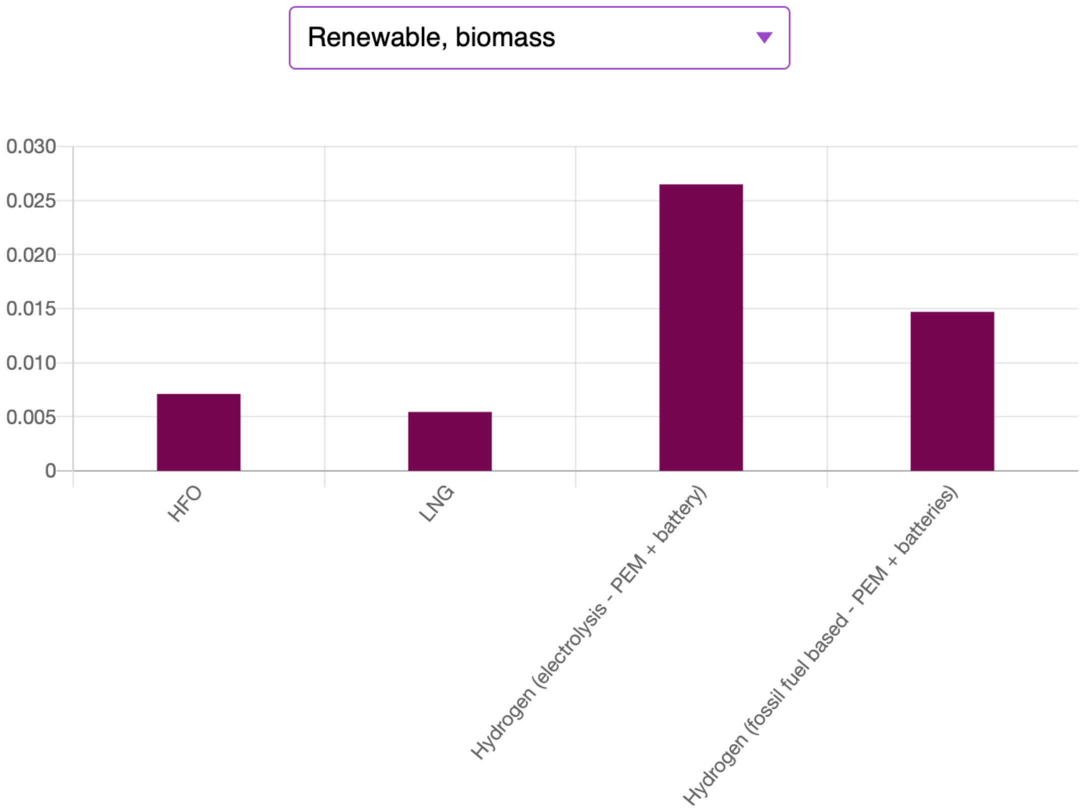


*Figure 33: Renewable energy usage (biomass)*

When it comes to energy usage the use of fossil fuels are dominated by heavier marine fuels such as HFO, while hydrogen solutions have specifically high energy use in other departments mostly due to inefficient and energy consuming production methods (as seen in figure 31-33).

# 5. Discussion/Conclusion

This study is quite limited in the sense of information being able to be used. Nevertheless, the results indicate much of the same conclusions as other similar studies [9]. Hydrogen solutions might prove superior regarding most environmental impacts. As suggested work in the future, it is recommended to gather data on specific cases regarding maritime transport. In this case, it was not possible as all of the contacts from corporations were not able to share information due to it being classified as corporate secrets.

The hydrogen economy is limited by a low production level, as well as disadvantages related to energy security (e.g. less efficient production methods, low energy densities) compared to conventional fuel alternatives used in maritime transport today. The infrastructure is not in place for hydrogen to have an serious advantage over its competitors, and safety issues related to bunkering and storage onboard ships prevents broader use of hydrogen fuel. Before any regulation is in place, hydrogen continues to play a minor role as an alternative fuel in maritime transport. However, developing stricter regulations and working towards international and national targets, like the IMO targets and the work done by the Norwegian government, a change in direction of a greener maritime sector can be achieved.

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# Appendix

## LCI data sets

For information regarding the LCI data used in this study, it is referred to the spreadsheets (Excel) found under the attachments in the assignment.