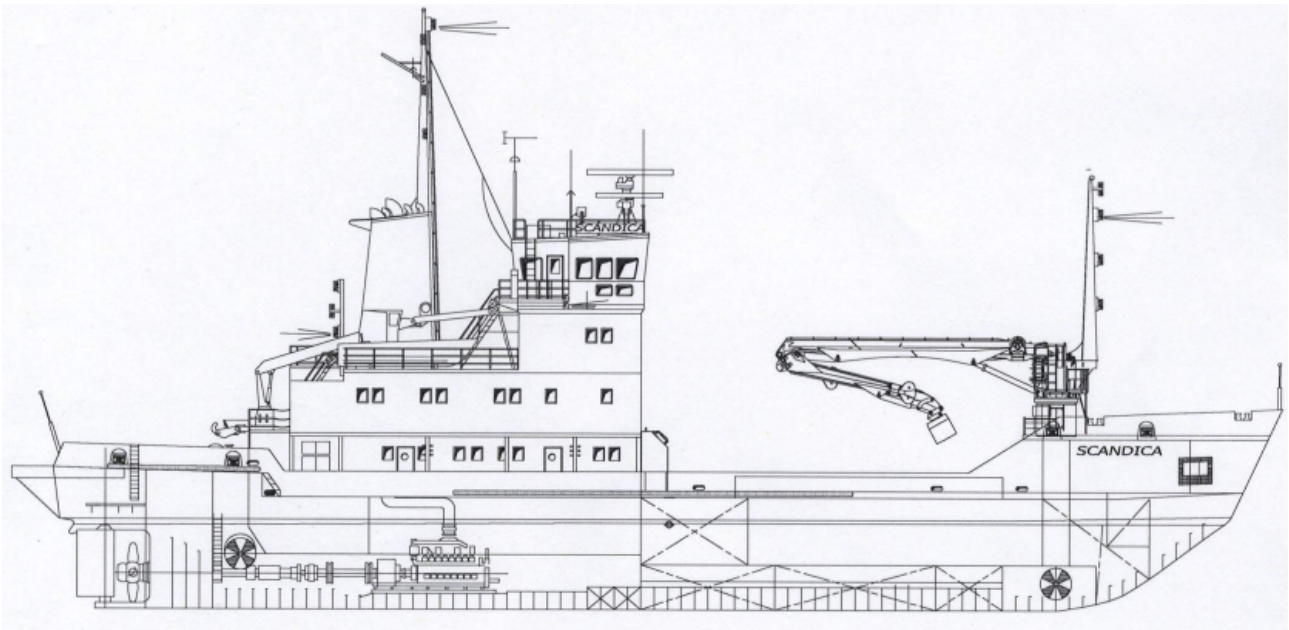


CHALMERS UNIVERSITY OF TECHNOLOGY

MASTER THESIS

Concept design for a hydrogen or an ammonia driven ship

June 30, 2022



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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

The world is facing environmental challenges and shipping industry has to adapt and be a part of the solution rather than staying a contributor of CO_2 emissions. To reduce the CO_2 emissions new fuels with low or zero emissions and propulsion systems with higher efficiencies are needed. Two potentially low climate impact options are hydrogen and ammonia. The aim of this thesis is to assess the possibility to use hydrogen and ammonia on a case study ship and to develop conceptual ship designs. The case study ship is a work boat operated by the Swedish Maritime Administration.

The project starts with research on possibility of using hydrogen and ammonia as alternative fuels. The method contains several parts with the main challenge of the investigation of the operational profile of the vessel. Based on this operational profile, fuel consumption was estimated for both hydrogen and ammonia. The next part is related to the sizing of all the different tanks inside the hull to estimate the space available for new fuel tanks. This is followed by sizing of the new tanks to determine the exact amount of hydrogen and ammonia that can be stored for two different cases. Component selection for the new propulsion system was carried out to present a concept design of the two propulsion systems. Lastly, stability calculations are performed for the hydrogen propulsion system to make sure that the work boat M/S Scandica can withstand the change in the weight distribution inside the hull and that the impact on its stability is within the limits.

Part of the results is the daily operational profile of the vessel and the endurance and range that it can cover with the hydrogen and ammonia propulsion system. The operational profile is investigated for fairway maintenance, ice breaking and transport operations for the case study ship. The days of operation depends on the type of operation that the ship is performing and the space available for fuel storage. For case 1, it resulted in approximately 13 days for fairway maintenance, 13 days for ice breaking and 12 days for transport operation for hydrogen as fuel, and 20 days for fairway maintenance, 19 days for ice breaking and 18 days for transport operation for ammonia as fuel. For case 2, it resulted in 5 days for fairway maintenance and 5 days for ice breaking and 4 days for transport operation for hydrogen as fuel and 7 days for fairway maintenance and 7 days for ice breaking and 7 days for transport operation for ammonia as fuel.

It can be seen that it is feasible to operate the ship using hydrogen or ammonia as main fuels. Using ammonia as the main fuel gives an advantage in terms of the days for which the ship can operate before refilling but ammonia propulsion system is less developed as a concept compared to hydrogen. However, to use any of these propulsion systems, changes will be required in how the ship is operated.

Keywords : Propulsion system, hydrogen, ammonia, operational profile, fuel tanks, days of operation, concept, stability.

Preface

The thesis was carried out as part of the project "FP2_E_2020" Assessment of hydrogen, ammonia and battery-electric propulsion for future zero carbon shipping" funded by Swedish Transport Administration's industry program Sustainable shipping led by the Swedish Maritime Competence Centre (Lighthouse). The project is carried out by Chalmers University of Technology, SSPA and the Swedish Environmental Research Institute IVL. The Swedish Maritime Administration provided data for the case study ship in the thesis.

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May, 2022

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Acronyms

3-D	3 Dimensional
AC	Alternating Current
AIS	Automatic Identification System
CCC	Carriage of Cargoes and Containers
CCS	Carbon Capture and Storage
CH_2	Compressed hydrogen
CH_4	Methane
CNH_3	Compressed Ammonia
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CU	Control Unit
DC	Direct Current
GA	General Arrangement
GB	Gearbox
GHG	Green House Gas
GW	Gigawatt
GZ	Curve of statical stability
H_2	Hydrogen
HFO	Heavy Diesel Oil
IGC	International Code for the Construction and Equipment of Ships carrying Liquefied Gases in Bulk
IMDG	International Maritime Dangerous Goods
IMO	International Maritime Organisation
ISO	International Standardization Organization
LH_2	Liquefied Hydrogen
LNG	Liquefied Natural Gas
MGO	Marine Gas Oil
NH_3	Ammonia
NO_x	Nitrogen Oxide
PEMFC	Proton Exchange Membrane Fuel Cell
PM	Particulate Matter
SCR	Selective Catalytic Reduction
SEEMP	Ship Energy Efficiency Management Plan
SFC	Specific Fuel Consumption
SMR	Steam Methane Reforming
SOFC	Solid Oxide Fuel Cell
SO_x	Sulfur Oxide
UN	United Nations
ZLT	Zero Loss Transfer
PEM	Polymer Electrolyte Membrane Electrolsers
AEC	Alkaline Electrolysers
SOEC	Solid Oxide Electrolysers

1 Introduction

The greenhouse gas (GHG) emissions from shipping, by at least 50% are planned to be reduced compared to 2008. The UN agency for international shipping and IMO have agreed to phase them out as soon as possible in this century [IMO, 2011]. Sweden has set their own target to have zero net GHG emissions by 2045 and 70% reduction by 2030 compared to 2010 levels [Trafikverket, 2019].

Various alternative marine fuels are being explored for the contribution of the achievement of zero GHGs emissions. Many new energy conversion technologies are developing for the reduction of carbon emissions from shipping. Fuel cells is one of them. Fuel cell technology converts chemical energy mainly from fuels containing hydrogen to electrical energy which can then be used to propel the ship using motors.

Hydrogen, either in the form of gas or liquid, is identified as low-to zero-carbon fuel that can help meet the IMO GHG reduction targets for the upcoming years [International Energy Agency, 2021]. It can be used in internal combustion engines, in gas turbines or in fuel cells. There are various challenges with hydrogen such as advanced storage requirements, fire hazard mitigation, challenges of availability and high costs for production and transportation. Fuel cells directly convert the chemical energy in hydrogen to electricity, with pure water and potentially useful heat as the only by-products. Hydrogen-powered fuel cells are not only pollution-free, but most of the technologies have higher energy efficiency than traditional marine diesel engines or dual-fuel engines [Xing et al., 2021]. Gas turbines that are consuming hydrogen in pure or blended form are used mostly for land-based operations, but there is development for it to be used for marine applications. Gotlandsbolaget is planning to use hydrogen as a gas turbine fuel. It aims to be the first project in Sweden to create a large hydrogen powered vessel for passengers and freight [Gotland Horizon, 2022].

Ammonia is another potential option. Ammonia can be used as a fuel itself which can be combusted purely or blended with other fuels to reduce carbon emissions, or it can be used as a carrier for hydrogen. For combustion, ammonia can be fed to gas turbines along with fuels like kerosene and methane to reduce their carbon emissions [Erdemir and Dincer, 2021]. This is carried on stationery units which are used for power generation. Moreover, there are internal combustion engines that burn ammonia which are under development. Compared to hydrogen, ammonia has a higher boiling temperature which is at -33.1 °C at 1 bar, making it is easier to store and maintain. This liquefied and pressurized ammonia can be used as a fuel and fed to a Solid Oxide Fuel Cell (SOFC) directly, which can convert into electricity. An efficiency of over 60% can be achieved in a SOFC using ammonia as fuel [The Royal Society, 2020]. Ammonia has some disadvantages as well. It can be toxic to humans and an on board leakage can be fatal. The energy density of ammonia is lower compared to fossil fuels, so a large volume of fuel is required which takes up a lot of on board storage [ABS, 2021].

2 Aim and Scope

The aim of the project is to assess the possibility of using hydrogen or ammonia as a main fuel for vessels to be able to contribute in reducing GHG emissions. The vessels of interest in this project is M/S Scandica. It is operated by the Swedish Maritime Administration since 1982 around the Swedish coast. Some of the questions that have guided the work in this project are:

- How is the ship operated for different operations and what is the fuel consumption during these operations ?
- What changes to the propulsion system are required to use these alternative fuels ?
- How does the change in propulsion system affect the amount of fuel that can be stored and how does it impact the number of days that the ship can operate ?
- How does these changes in propulsion system affect the stability of the ship ?

The scope of this project is to develop a concept design of propulsion system using hydrogen and ammonia for the work boat M/S Scandica and perform preliminary stability calculations. The project includes the following:

- Literature study on use of hydrogen and ammonia as ship fuel, focusing on power conversion technologies and fuel storage.
- An analysis of the operational profile, sizing of components and range determination based on the available space for fuel storage.
- Development of a general arrangement layout for propulsion, power conversion and the energy storage system.
- A description of how the proposed general arrangement impacts the ship's stability.

3 Theory

3.1 Possible alternative energy carriers for ships

Conventionally, ships use fossil fuels like Marine Gas Oil (MGO) and Heavy Fuel Oil (HFO) which are derived from crude oil. They contain high amounts of carbon and sulfur and emit gases like CO_2 , SO_2 and NO_x when combusted [IMO, 2020]. To reduce emissions from shipping, alternative fuels having low or no emissions are required. There is a huge emission reduction potential by using alternative fuels like hydrogen, ammonia and biofuels. They have the highest carbon emission reduction potential as argued by Kim et al. [2020]. Hydrogen and ammonia are inherently carbon free fuels. Hence, when combusted, they have zero carbon emissions. Despite this advantage, there are many challenges to store and use them on board for marine applications. Table 1 shows the different properties of these fuels.

Table 1: Properties of different fuels

[Erdemir and Dincer, 2021]

	Unit	Hydrogen compressed	Hydrogen Liquid	Ammonia Compressed	Ammonia Liquid
Boiling Point	$^{\circ}C$ (@ 1 atm)		-252.9		-33.3
Density	kg/m^3	23(350 bar)	71	610 (10 bar)	653.1
Specific energy LHV	MJ/kg	120.1	120.1	18.6	18.6
Specific energy LHV	kWh/kg	33.3	33.3	5.17	5.17
Energy density	MJ/m^3	5040	8500	10800	14100
Energy density	kWh/m^3	1400	2357.7	3153.7	3916
Storage Temp	$^{\circ}C$	25	-252.9	25	-33.6
Storage Pressure	bar	350–700	1	10	1
Chemical compound			LH_2		NH_3
Flammability range	In air (by volume)	4-75%		14.8-33.5%	

3.2 Hydrogen

Hydrogen is colorless, odorless, tasteless, non-toxic and it can be considered as a highly combustible gas with a wide flammability range as it can be seen in table 1. Hydrogen can be found naturally in water and methane. It can be produced by converting natural gas or coal into hydrogen gas and CO_2 . There are many different pathways for hydrogen to be produced using different feedstocks. However for reducing the emissions from the production, renewable energy can be used to generate hydrogen from electrolysis [International Energy Agency, 2021].

Hydrogen has the highest energy content per mass compared to all other chemical fuels. Its specific energy is 120.2 MJ/kg which is 3 times higher than MGO and 6 times higher than alcohols. Consequently, as a fuel it has the ability to reduce the fuel consumption and increase the engine efficiency. On the other hand, liquefied hydrogen has the lowest volumetric energy density compared to other fuels. It can require 4 times more space than MGO and about 2 times more space than liquefied natural gas for the same amount of carried energy [ABS, 2021].

3.2.1 Production of hydrogen

Production of hydrogen can be achieved by many different processes. Over 95 % of hydrogen production is fossil fuel based using oil, coal, or gas as an energy source. There are different types of hydrogen in terms of the emissions released during production [ABS, 2021]:

1. Brown hydrogen

Production of hydrogen from coal using a gasification procedure is a technology that has been successfully used in the industry for many decades. During the gasification process, the coal is heated at high temperatures where it produces a syngas rich in hydrogen, Carbon Monoxide (CO) and CO_2 . With water gas shift reaction, syngas is upgraded as the CO is converted to CO_2 and more hydrogen is then produced. With the use of technologies such as Selexol and Rectisol, the CO_2 can be separated and then the procedure will become lower in the carbon content. This process enables to achieve a purity of hydrogen at around 99.8% [ABS, 2021]. More than 80% of the coal gasification plants are in China. The largest clean hydrogen plant globally is the Great Plains Synfuel plant in North Dakota, USA, producing 1,300 tonnes/day of H_2 from the gasification of lignite [ABS, 2021].

2. Grey hydrogen

Production of hydrogen from natural gas, is a procedure that builds upon the existing natural gas pipeline delivery infrastructure. Today, 95% of the Hydrogen production from natural gas takes place in USA [ABS, 2021]. Natural which contains methane (CH_4) can extract hydrogen with different methods such as:

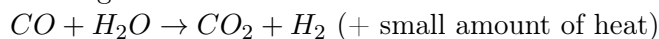
Steam reforming

Most of the hydrogen production in the USA is done by steam-methane reforming. A process that uses high temperatures of steam ($700^\circ C$ - $1000^\circ C$) is used to extract the hydrogen from the natural gas. The steam under the pressure of 3-25 bar reacts with the methane that is contained in the natural gas. From this reaction, with the presence of a catalyst, hydrogen, carbon monoxide and a small amount of carbon dioxide is produced. This procedure is endothermic, which means that heat must be applied to process. Later on, even more hydrogen is produced by the water gas shift reaction. In this process, the carbon monoxide and steam react together and produce hydrogen and carbon dioxide. The final step of this procedure is the process called pressure swing absorption. In this process carbon dioxide and other impurities are removed from the gas stream and pure hydrogen is then achieved.

Steam-methane reforming reaction:



Water-gas shift reaction:

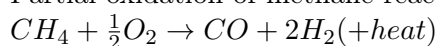


[Office of Energy Efficiency and Renewable Energy, 2020]

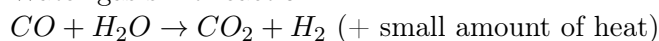
Partial Oxidation

In this procedure, methane and other hydrocarbons from the natural gas react with some amount of oxygen. The oxygen is not enough to completely oxidize the hydrocarbons to carbon dioxide and water. The reaction products contain primarily hydrogen, carbon monoxide, a small amount of carbon dioxide and in some cases nitrogen if the reaction contains air instead of pure oxygen. Similarly, water gas shift reaction produces even more hydrogen and carbon dioxide. This process is exothermic process as it gives off heat. It is relatively faster procedure than steam reforming and it requires a smaller reactor vessel. Finally, partial oxidation produces less hydrogen per unit of the input fuel compared to steam reforming process.

Partial oxidation of methane reaction:



Water-gas shift reaction:



[Office of Energy Efficiency and Renewable Energy, 2020]

Autothermal reforming

This process is a combination between steam reforming and partial oxidation. It is a low cost

and high reliability hydrogen production process. Compared to steam reforming, it can be operated with a smaller system, with better temperature control, lower operational temperature, lower energy requirements, easier start up and less coking. A downside is the large investment needed for an oxygen production plant which can become cost effective only in high production capacities. The fuel that can be used for the autothermal reforming process is highly flexible. It can be methane, natural gas, LPG, gasoline, diesel, and other liquid hydrocarbons as well [ABS, 2021][NCE Maritime Cleantech, 2020].

3. Blue Hydrogen

Blue hydrogen is produced from natural gas by steam methane reforming. The CO_2 that is generated during the manufacturing process is captured and stored underground. This process leads to the production of low carbon hydrogen. There are only two facilities that produce blue hydrogen. The amount of hydrogen that is produced from these facilities is not high enough to be accounted as a counterpart of grey hydrogen production [ABS, 2021].

4. Green Hydrogen

Green Hydrogen can be defined as the hydrogen that is produced by electrolysis of water using renewable electricity. The reaction takes place in a unit called electrolyser. Electrolysers contain an anode and a cathode, separated by an electrolyte. There are three main different types of electrolysers [ABS, 2021]:

Polymer Electrolyte Membrane Electrolysers (PEM)

In this type of electrolyser, the electrolyte is a solid plastic material. Water enters in the anode side. Positive charged hydrogen ions pass through the plastic electrolyte to the cathode side. Electrons pass from an external circuit to the cathode side as well. Hydrogen ions with the electrons form the hydrogen gas.

Anode Reaction: $2H_2O \rightarrow O_2 + 4H + 4e^-$

Cathode Reaction: $4H + 4e^- \rightarrow 2H_2$

Alkaline Electrolysers (AEC)

Alkaline electrolysers operate with the movement of hydroxide ions through the electrolyte from the cathode to the anode. In this, hydrogen is produced on the cathode side. For many years, electrolysers used liquid alkaline solution of sodium or potassium hydroxide. Using a solid alkaline exchange membrane as the electrolyte is a new approach that still requires some research.

Solid Oxide Electrolysers (SOEC)

In this type of system, solid ceramic material is used as the electrolyte. It conducts the negatively charged oxygen ions at elevated temperatures and generates hydrogen. Steam at the cathode is combined with electrons from the external circuit to form hydrogen gas and negatively charged oxygen ions. The oxygen ions that pass through the solid ceramic membrane react at anode and oxygen gas is formed and electrons are generated for the external circuit. This type of electrolysers have to operate at high temperatures in order to function properly [Office of Energy Efficiency & Renewable Energy, 2020].

5. Turquoise hydrogen

This type of hydrogen is made by thermal splitting of methane into hydrogen and solid carbon unlike other processes where it is removed in gaseous form. This process is still at experimental stage [ABS, 2021].

6. Purple hydrogen

It is made by using nuclear power. The high temperatures of the nuclear reactors can be used for other hydrogen productions as well by the production of steam for increasing the efficiency of the electrolysis [ABS, 2021].

7. Pink hydrogen

It is generated through electrolysis of water by using electricity from a nuclear power plant [ABS, 2021].

8. Red hydrogen

It is made from the high temperature catalytic splitting of water using nuclear power thermal as an energy source [ABS, 2021].

9. White hydrogen

It refers to naturally occurring hydrogen [ABS, 2021].

As shown on the Figure 1, Grey hydrogen accounts for the 75 percent of the global hydrogen production. Brown hydrogen is the second largest source and green hydrogen applies only to 2% of the global hydrogen production. The other hydrogen production alternatives are not yet in commercial use [ABS, 2021].

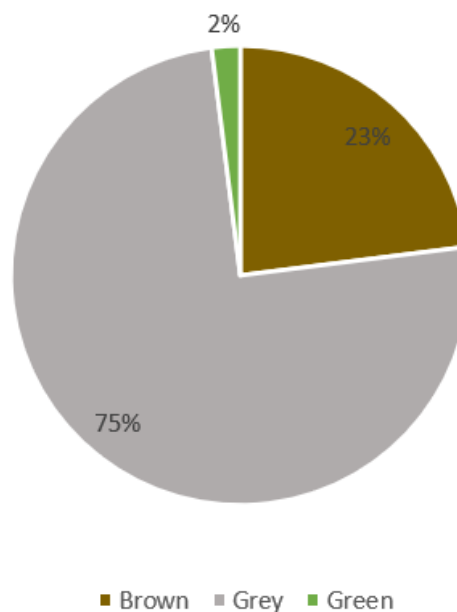


Figure 1: Global hydrogen production 2021 [ABS, 2021]

3.2.2 Hydrogen storage

Hydrogen can be stored in different forms. As a pressurized gas or in liquid form are the most common ways to be stored. Some research is going on to store it in solid form as well, something that will require zero energy for storing it in long term applications. The two most common ways are described below:

Gas

Hydrogen can be stored as a gas and it is more commonly to be in that form when it is ready to

be used in a fuel cell system or in a combustion engine. The pressurized tanks vary in pressures between 350-700 bar, two to three times higher than industrial hydrogen storage which is typically less than 200 bar. Usually for on board storage applications either steel cylinders or composite material cylinders are used [Pratt and Klebanoff, 2016].

Liquid

Liquefied Hydrogen (LH_2) is a cryogenic liquid with a boiling point of $-253\text{ }^\circ\text{C}$. The storage tanks for storing it should be highly engineered tanks, with an inner metal liner, separated from an outlet metal liner with vacuum and small glass particles in between. The insulation of the tanks are usually not perfect and always some changes in the temperature can raise the pressure on the tank. This causes a small heat leak. Storing LH_2 in larger quantities has the minimal loss from boil off. The heat leak problem is more severe for small LH_2 tanks as the radius shrinks. Thus, LH_2 storage is more challenging for storing small H_2 quantities such as 5 kg for example. On the other hand, re-liquefaction of hydrogen is also a possibility where some advanced tanks are providing this possibility. Spherical tank is used as the ideal shape where the storage volume can be maximised while the surface area will be minimized. On the other hand, cylindrical tanks are more commonly used as they are easier to manufacture and less expensive and gives a similar surface area/volume ratio compared with spherical ones. Storing hydrogen in liquid form has advantages. Based on Table 1, it can be seen that it requires smaller volume and lower pressure to store higher amount compared to compressed hydrogen [Pratt and Klebanoff, 2016]. High pressures require a more advanced and expensive tank, where there are still concerns on how safe it is to withstand these pressures and the reaction in case of an accident, such as a car crash or a fire in the engine room. Also, LH_2 storage has been used for years for space applications. The transportation of it with an excellent safety record has been achieved. Properties of LH_2 are well understood and LH_2 storage and transportation are mature technologies. Lastly, LH_2 has similar physical and combustion properties with liquid natural gas (LNG). Since LNG ships have been designed by naval architects for years, the design of an LH_2 ship will not be a completely new task [Pratt and Klebanoff, 2016].

A last mention has to be made on the material selection of the tanks when H_2 is stored either as a gas or liquid. The reason that the material selection for the tanks has to be considered is that certain metallic materials and equipment that are exposed to hydrogen gas can suffer from hydrogen embrittlement [ABS, 2021]. This can include tank interior surfaces, weldments, pipes, valves, fuel nozzles and pressure relief valves. Hydrogen embrittlement occurs when hydrogen is absorbed by a metal and collects at grain boundaries. It can create that way weak spots within the material [ABS, 2021]. This can lead to failure mechanics, fractures, and material cracks. The solution to it is the selection of the proper material and possibly surface treatment and coatings to protect the surface from hydrogen contact. Another concern is the high temperature attack where low alloyed steel can be degraded from hydrogen attacks on temperatures above 200 degrees [ABS, 2021]. Hydrogen attacks may not be common for tanks and pipes unless exposed to high temperatures, such as those experienced in combustion engines, fuel reformers and fuel cells. Table 2 lists some metal and non-metal materials to describe the acceptability of use for liquid and gaseous hydrogen applications [ABS, 2021].

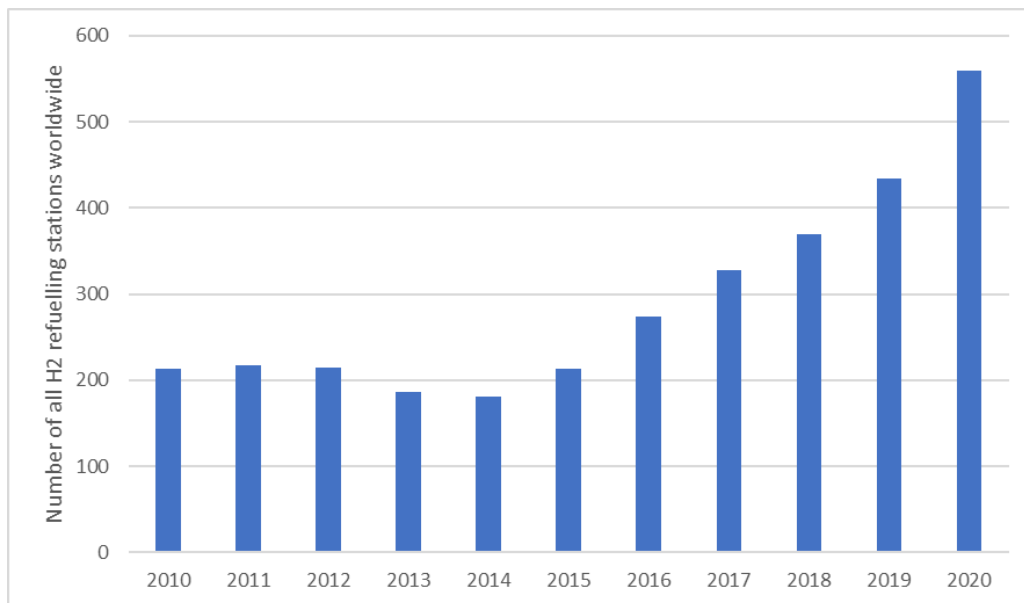
Table 2: Acceptability rate of different materials for hydrogen storage

[ABS, 2021]

Material	Hydrogen phase		Notes
	Gas	Liquid	
Aluminium	Acceptable	Acceptable	N/A
Stainless steel	Acceptable	Acceptable	Beware of martensitic conversion at low temp. if stressed above yield point
Carbon steel	Acceptable	Not acceptable	Too brittle for cryogenic service
Copper	Acceptable	Acceptable	N/A
Iron	Not acceptable	Not acceptable	Not for hydrogen service
Low alloy steels	Acceptable	Not acceptable	Too brittle for cryogenic service
Nickel alloys	Acceptable	Not acceptable	Susceptible to hydrogen embrittlement
Nickel steels	Not acceptable	Not acceptable	Beware of ductility loss
Titanium	Not acceptable	Acceptable	Beware of susceptibility to hydrogen embrittlement
Chloroprene rudder	Acceptable	Not acceptable	Too brittle for cryogenic service
Dacron	Acceptable	Not acceptable	Too brittle for cryogenic service
Fluorocarbon rudder	Acceptable	Not acceptable	Too brittle for cryogenic service
Mylar	Acceptable	Not acceptable	Too brittle for cryogenic service
Nitrile	Acceptable	Not acceptable	Too brittle for cryogenic service
Polyamides	Acceptable	Not acceptable	Too brittle for cryogenic service
Polychlorotrifluoroethylene	Acceptable	Acceptable	N/A
Polytetrafluoroethylene	Acceptable	Acceptable	N/A

3.2.3 Distribution and production infrastructure

Hydrogen demand is increasing dramatically. Since 2016, more than hundred of refueling infrastructure projects have been developed worldwide. The development of all the H_2 refueling stations can be seen more in detail on Figure 2 [H2Stations, 2020].

Figure 2: Development of H_2 refuelling infrastructure worldwide

The data presented in Figure 2 shows a global overview of the refuelling H_2 stations. These stations

are currently limited to be used for road transport. Until now for the current marine applications, hydrogen cylinders are transported to the vessels as there are no designated filling stations for bunkering. Around 60% of them are far away from the coast line so the transportation is necessary for these applications [H2Stations, 2020]

The production has increased, as well as the bunkering infrastructure. Hydrogen is being used as a fuel for cars and industrial purposes such as refining petroleum or treating metals. For the successful adoption of hydrogen as a marine fuel, more bunkering infrastructure in ports have to become available. This will increase the availability of hydrogen so most likely the demand as well and it will lower down the market price and it may allow hydrogen to become a more cost-effective option as an alternative marine fuel. According to [International Energy Agency, 2021], globally there are 228 hydrogen projects where 17 are already announced as giga scale production projects for renewable and over 200 thousand tons a year for blue hydrogen, with the biggest in Europe, Australia, the Middle East and Chile. Another interesting project that should be mentioned is the announcement from the port of Gothenburg in 2021 [CAC, 2021]. It will open a hydrogen refueling facility for heavy goods vehicles. This facility will become operational by 2022 with a goal of reducing the carbon emissions from and to the port to 70% by 2030.

The bunkering operation of hydrogen in a ship is expected to be similar procedure as the LNG. The refueling or bunkering infrastructure has to be approved from the related authorities. The bunkering facilities for liquid hydrogen will require higher expenses compared to LNG because of the low temperatures that hydrogen is required to be stored and the advanced components needed. For bunkering operation of hydrogen as a compressed gas, similar procedure as the land based truck bunkering can be applied [CAC, 2021].

3.2.4 Costs

Majority of the hydrogen produced today, is grey hydrogen. Grey hydrogen is the option having the lowest production cost. What raises the costs is the carbon emission capture systems (blue hydrogen). Green hydrogen is more expensive as the renewable electricity that it requires is expensive and not available at all locations. The most attractive production markets of green hydrogen can be found in places with low-cost renewable resources. In parts of Middle East, Russia, Africa, US, and Australia the production costs are much lower. The production costs are expected to decrease over time so green hydrogen can be assumed to be more promising long-term solution. Figure 3 based on [FCH, 2020] provides information about the average cost of hydrogen worldwide.

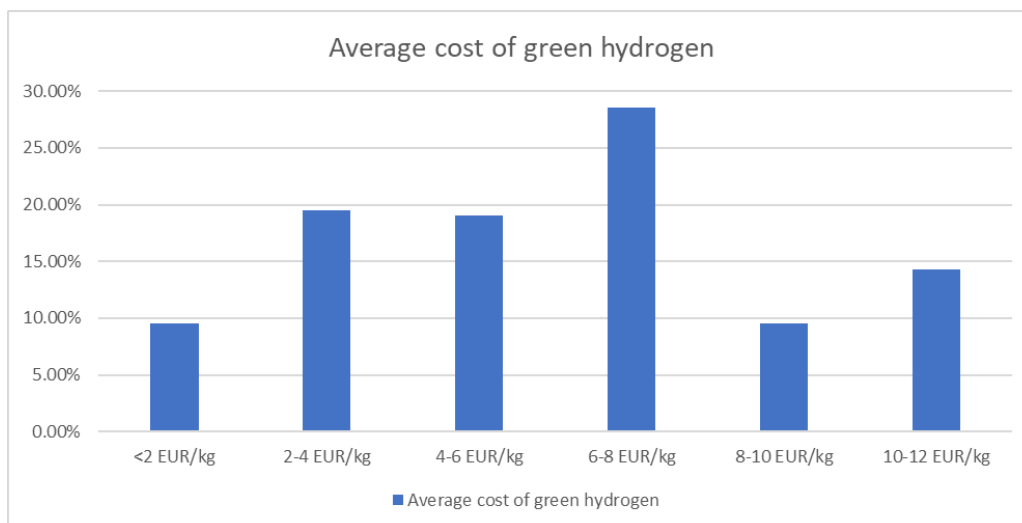


Figure 3: Average cost of green hydrogen [FCH, 2020]

3.2.5 Safety

The main concerns on hydrogen safety are related to its flammable properties and the wide flammable range. The flammability range also increases when it is mixed with pure oxygen. Hydrogen leaks are dissipating fast in open space areas but when leaked in enclosed spaces, it can lead to fire hazard due to the quick formation of flammable gas mixture. Hydrogen has the lowest melting and boiling point after helium. It requires $-253\text{ }^{\circ}\text{C}$ to be stored as a liquid at 1 bar and for that reason any contact with other gases can lead to the liquification of them as well. It is important to be isolated without getting in contact with other materials or fuels. Serious burns and skin damages can occur in case of a human contact. Although it is not toxic on the dispersion of it on the air but it can act as an asphyxiant when the oxygen is not enough [ABS, 2021].

The risks can be minimized when proper measures and protocols are followed. Sparks and ignition of flammable concentration can be created from the flow or agitation of hydrogen. All handling equipment should be protected to avoid this kind of situation. Hydrogen also burns really fast with a maximum speed of 3.15 m/s, which is significantly faster compared to other fuels. Flaming of hydrogen can increase the pressure in an enclosed space like a tank. Detonations can result in this situation where up to 20 times atmospheric pressures can be created from gaseous hydrogen. Proper gas management, pipe purging, and ventilation practices have to be implemented and tested for avoiding this type of phenomena. Leak detection strategies will be useful for indicating the absence of leaks. In case of a fire, dry chemical extinguishers or carbon dioxide extinguishers should be used [ABS, 2021].

3.2.6 Regulations

Draft interim guidelines aimed at providing international standard provisions for ships using fuel cell power installations have been agreed by International Maritime Organization's (IMO) Sub-Committee on Carriage of Cargoes and Containers (CCC 7).

These interim guidelines have been developed to provide international standard provisions for ships using fuel cell power installations. The goal of these interim guidelines is to provide criteria for the arrangement and installation of fuel cell power installations with at least the same level of safety and reliability as new and comparable conventional oil-fuelled main and auxiliary machinery installations, regardless of the specific fuel cell type and fuel. Depending on the fuel used, other regulations (e.g. IGF Code, part A) and provisions (e.g. Interim guidelines for the safety of ships using methyl/ethyl alcohol as fuel) are applicable in addition to these Interim Guidelines. Certain fuel cell power installations use a process of fuel reforming to develop a reformed fuel for use in the fuel cell. These interim guidelines are not intended to cover the storage of reformed fuels. Detailed update on the current regulations regarding fuel cell systems can be found on the IMO publications [IMO Regulations, 2021].

3.2.7 Energy conversion technologies

Fuel Cell Technology

Fuel cell has the ability to convert the chemical energy of the fuel into electric power. Fuel cells are being used in several applications such as generators, cars, buses, and rail applications. They can reduce emissions and noise and at the same time increase the efficiency. Required maintenance is also lower compared to conventional combustion engines and turbines but cell lifetime can be lower. There are approximately 7 different fuel cell types available, where the main difference between them is the electrolyte membrane. DNV GL [2018] mentions announcement of three types of these technologies as the most promising ones for the near future. Solid oxide fuel cell, proton exchange membrane and high temperature proton exchange membrane are recognized to be the most effective compared to the others. Depending on the fuel cell type they can be powered by fuels such as natural gas. This option will significantly reduce NO_x , SO_x , and Particulate Matter emissions but not as much as hydrogen [Ryste, 2019].

1. Solid Oxide Fuel Cell (SOFC)

In this type of fuel cell, a solid material usually a ceramic material is being used as an electrolyte. The operating temperatures are between 800-1000 °C. The negative oxygen ions travel from the cathode to the anode instead of the positive charged hydrogen ions travelling from the anode to the cathode [Ryste, 2019]. The oxygen gas is inserted in cathode where it absorbs electrons to create oxygen ions. The oxygen ions then are transferred from the electrolyte in the anode and then they react with hydrogen gas. The reaction produces electricity and water. The chemical reaction of the system is described below:

Anode reaction: $2H_2 + 2O^{2-} \rightarrow 2H_2O + 4e^-$

Cathode reaction: $O_2 + 4e^- \rightarrow 2O^{2-}$

Overall cell reaction: $2H_2 + O_2 \rightarrow 2H_2O$

Challenges on this system can be the high operating temperatures as well as the slow start up time. On the other hand, the high temperatures could be used by waste heat capture systems and then increase the efficiency [Ryste, 2019].

2. Proton Exchange Membrane Fuel Cell (PEMFC)

In this type, a solid polymer is used as an electrolyte. The hydrogen enters the system, where the negatively charged electrons are absorbed from the anode and moved through a wire to an electric current. The positive hydrogen ions are absorbed from the electrolyte and moved to the cathode side. In the cathode side, oxygen enters, where together with the electrons and the hydrogen ions it produces water. Usually, the water is thrown away and the electric current is used to propel a motor or for other applications. Some issues of this technology are the high cost, water and air management, temperature management, durability, and service life. The issues with the water and air arise as the membrane should be hydrated and to do so it requires water to be evaporated on the same rate that it is produced. If it evaporates too fast the membrane gets too dry, it leads to an increased resistance and it might end up with a crack. If the water evaporates too slow the electrodes will flood and the reaction will not be successful. Regarding the temperature management, the same temperature has to be maintained throughout the procedure to prevent destruction of the cell through thermal loading [Ryste, 2019].

Internal Combustion Engines

Internal combustion engines are being used for years in both automotive and marine industry. Marine diesel engines power most of the commercial shipping fleet today. However, after the first dual fuel engine was introduced on the LNG carriers in 2006, other ships of various sizes and operating profiles began to take an advantage of this application for reducing their emissions. Hydrogen is one of the recent fuels that is being researched to be used in the near future as a fuel in a combustion engine. Typically, it is being used as a supplementary/ mixed fuel blended in conventional gas and dual fuel engines. Hydrogen's main properties that can contribute to it as a combustible fuel are the low ignition energy and high autoignition temperature. Wartsila and MAN engines state that hydrogen combustion is possible in some engine types as a dual fuel with natural gas or other gas fuels. Even small percentages of hydrogen in a blended gas fuel can improve engine efficiency and minimize the emissions. Hydrogen can be used as a monofuel as well, where in this case the engine has to be modified for combustion timing. Also, the engine possibly should be different in size as well, due to hydrogen higher autoignition temperatures compared to other fuels [Ryste, 2019].

3.2.8 Existing vessels and ongoing research projects

Several existing vessels and on going research projects are going on regarding hydrogen as the main energy carrier. In this section the ones that were found the most interesting ones will be described.

In August 2008, the first fuel cell passenger ship was put into service on the Alster lake in Hamburg. The ship Alsterwasser operated for two seasons, where the zero emissions plan was achieved. The lifetime of the ship was not so long but it prepared the ground for the development of other fuel cell ships. The construction, the technical specifications and the production of a hydrogen filling station proved that this kind of vessels can be efficient and easy to use. With regards to carbon footprint, savings around 47000 kg of CO_2 emissions/year were estimated that were avoided when compared to a diesel-electric ship [Ozden et al., 2011].

Nemo is a small passenger ship that was designed and constructed in Amsterdam in 2012. Currently, it is cruising in the canals of Amsterdam [Marine service Noord, 2020].

SF Breeze is a high speed hydrogen fuel celled vessel. It was designed in 2015 by Sandia National laboratories and it operates in San Francisco bay area [Pratt and Klebanoff, 2016].

HySeasIII a ferry which will be fuelled by hydrogen produced from local renewable energy sources in and around the Scottish Isles. It's objective is to take on the challenge of replacing the power train of a steel multi-skinned hull vessel capable of carrying cars and heavy duty vehicles as well as passengers in life-line commercial island ferry services. It is expected to be operational by the end of 2022 [Hyseas III, 2022].

The Energy Observer project was started in 2013 and the company since then explores practical solutions whilst developing new technologies to accelerate the ecological transition. Hydrogen is the keystone of the Energy Observer system. The most exciting part is that Hydrogen is being produced on board by electrolysis with renewable energy from the solar panels. This hydrogen is then used to produce electricity for propulsion using fuel cells [Energy Observer, 2022].

Future Proof Shipping is expecting to complete the project in 2022. It involves the retrofitting of a container ship to run 100% on hydrogen. The project involves the removal of the already existing main engine and gearbox, supplying it with the new hydrogen propulsion system which will include fuel cells, battery packs, electric motor, and hydrogen storage. This container ship is planned to transfer cargo between Rotterdam and Antwerp [FutureProofShipping, 2022].

Ulstein SX190 is a construction support vessel and is capable to operate 4 days with hydrogen. With the developments of hydrogen storage systems, it is predicted to increase its endurance up to two weeks. Sea trials of the new built Ulstein SX190 will take place in 2022 [Ulstein, 2020]

Stockholm's Green City Ferries released the Boat plan 2025 strategy. This strategy is aiming to replace the archipelago public transport ships to renewable and environmentally friendly vessels. This project will involve the replacement of the already existing vessels to hydrogen fuelled vessels. Energy savings up to 65% are approximated [Greencityferries, 2022].

Hydrogen Energy Supply Chain project has been proposed to transport hydrogen between Australia and Japan. Australia has a large hydrogen production from coal with CCUS system and is planning on exporting it to Japan. This project took place on 2021 with the Suiso Frontier Hydrogen carriage ship with a total LH_2 capacity of 1,250 m^3 . Technology Research Association (HySTRA) announced that it is planning to expand the transportation of hydrogen to more countries and larger quantities [Hyseas III, 2022].

Northern Xplorer company is based in Norway and produces vessels that are designed with expertise in developing low emission and energy efficiency vessels. They have already designed one of their first vessels, named as MM 130. This vessel is planned to replace the old cruising vessel in the Norwe-

gian seas by 2026 [Northern Explorer, 2022].

Providing a two-in-one solution, they will sail on a fixed schedule carrying both coastwise customer cargo and containerized liquid hydrogen (LH_2) to the bunkering hubs. Norway's west coast is dotted with bases serving the offshore industries, with base-to-base transport representing a heavy-duty transport route eminently suited to LH_2 . The bunkering hubs will in the future supply LH_2 -powered vessels including ferries and seagoing tonnage [Wilhelmsen Group, 2022].

3.3 Ammonia

Ammonia inherently is a carbon free molecule. It is chemically expressed as NH_3 . It contains 17.65% hydrogen by weight [The Royal Society, 2020]. Therefore, it can be a good carrier for hydrogen. Unlike hydrogen, ammonia can be stored at lower pressure and higher temperatures as mentioned in Table 1. It can also be used as a fuel directly for spark-ignition engines, diesel engines, gas turbines or fuel cells. Hydrogen can either be separated from it and then used for fuel cells or with the help of advanced technology like Solid Oxide Fuel Cell (SOFC)[Ryste, 2019], it can be used directly and electricity can be generated. No carbon emissions are generated regardless of if ammonia is burnt in combustion engines or used in fuel cells. The by-products after combustion include nitrogen oxides and water, which can be removed using Selective Catalytic Reduction (SCR)[Haldor Topsoe, 2020]. Ammonia also does not contain any harmful sulfur oxides. Therefore, there is no need of sulfur oxide removal technologies like scrubbers.

3.3.1 Production of ammonia

The technologies for producing ammonia can be different and may have different carbon emissions but the end product will remain the same. There are three major ways by which ammonia can be produced. They are as follows:

1. Conventional/Brown Ammonia: This ammonia is produced from fossil fuels, mostly natural gas. The production method is based around the Haber-Bosch process which is shown in Figure 5 in which hydrogen obtained from steam reforming of natural gas which is shown in Figure 4 is involved in a catalytic reaction with nitrogen obtained from air separation units. The reaction happens at 150-300 bar at a temperature of 350-500 °C. This process is very energy intensive and 90% of the carbon emissions come from hydrogen generation [The Royal Society, 2020].

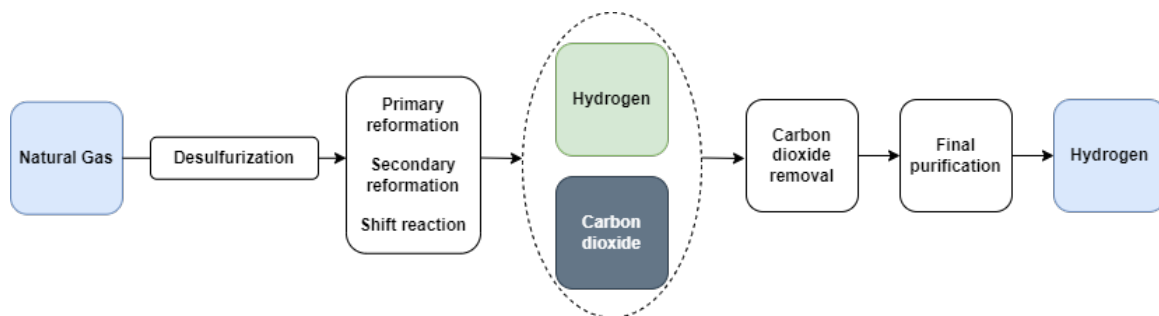


Figure 4: Production of hydrogen using steam reforming [The Royal Society, 2020]

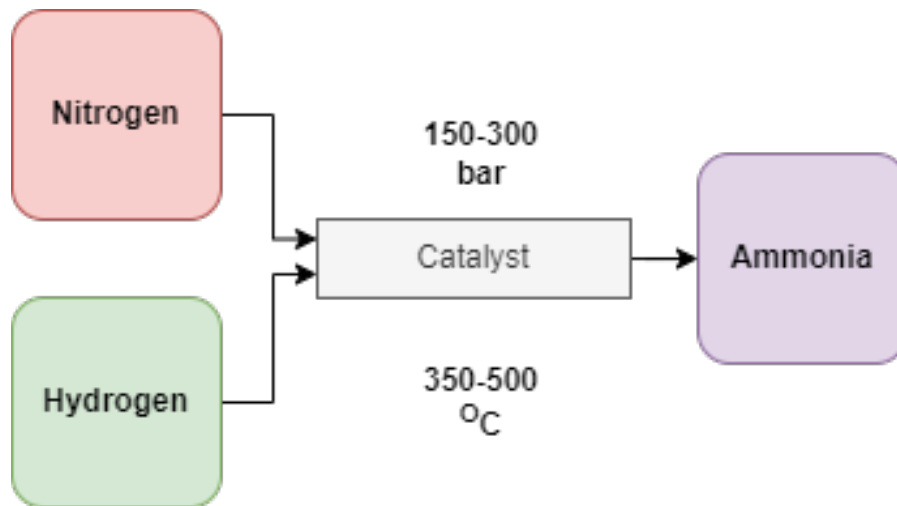


Figure 5: The Haber Bosch process
[The Royal Society, 2020]

2. Blue Ammonia: Blue ammonia is produced the same way as conventional ammonia but the carbon emitted from the process is captured, processed (liquified) and stored. This is called Carbon Capture and Storage or CCS. This process is applied to the process of Hydrogen production from steam reformation using natural gas [The Royal Society, 2020].
3. Green Ammonia: It is produced without fossil fuels and using renewable electricity and sustainable water and air. The carbon footprint of green ammonia is assumed to be zero but detailed analysis is required to estimate the insignificant emissions. Initial assessments show that 90% life cycle emission reduction can be achieved using electricity derived from wind energy and 75% reduction using solar energy. This reduction is expected to increase in the future with more application of renewable energy and sustainable construction of equipment like wind blades and photovoltaic cells [The Royal Society, 2020].

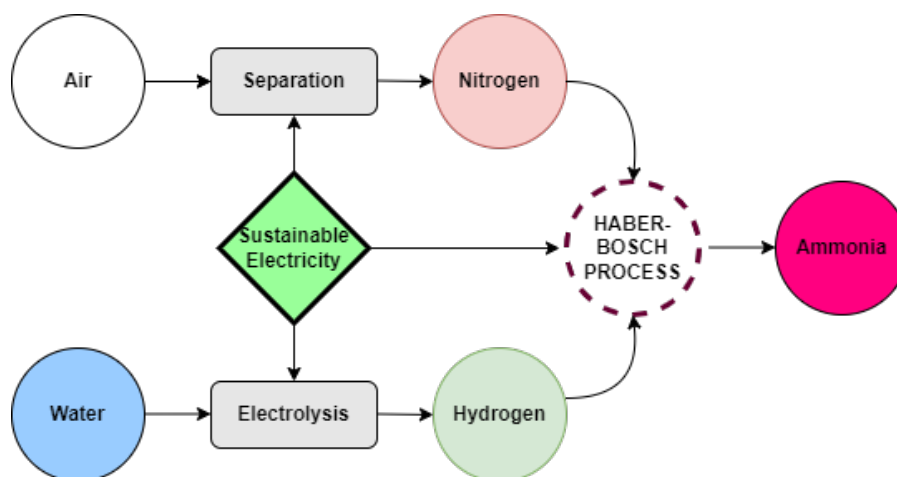


Figure 6: Production of green ammonia
[The Royal Society, 2020]

3.3.2 Storage

Ammonia can be liquified at a much higher temperature and lower pressure compared to hydrogen. It is usually stored in special isothermal tanks and spherical pressure storages in a liquified form keeping

it at a low temperature [Energy Agency, 2021]. Ammonia has a vapor pressure lower than 10 bar and 20°C. For marine applications, ammonia can be stored onboard on Type-C tanks to remain liquid at ambient temperatures. As seen in the Table 1, ammonia has very high mass density and high energy density compared to other fuels. Ammonia can either be stored at atmospheric pressure at -33 °C or at ambient temperature at 10 or 20 bar pressure depending upon the amount. For amounts higher than 10000 tons, usually the former is preferred [Haldor Topsoe, 2020].

3.3.3 Distribution and production infrastructure

Ammonia is traded as anhydrous ammonia globally. The infrastructure to store and supply networks already exists making it easier to adopt this technology. The global production of ammonia is 180 million tonnes and most of it is produced from natural gas. Out of the 180 million tons produced annually, around 80% is used for producing fertilizers. Ammonia production reached 150 million tonnes in 2021 [Statista, 2022]. More data is presented in Figure 7.

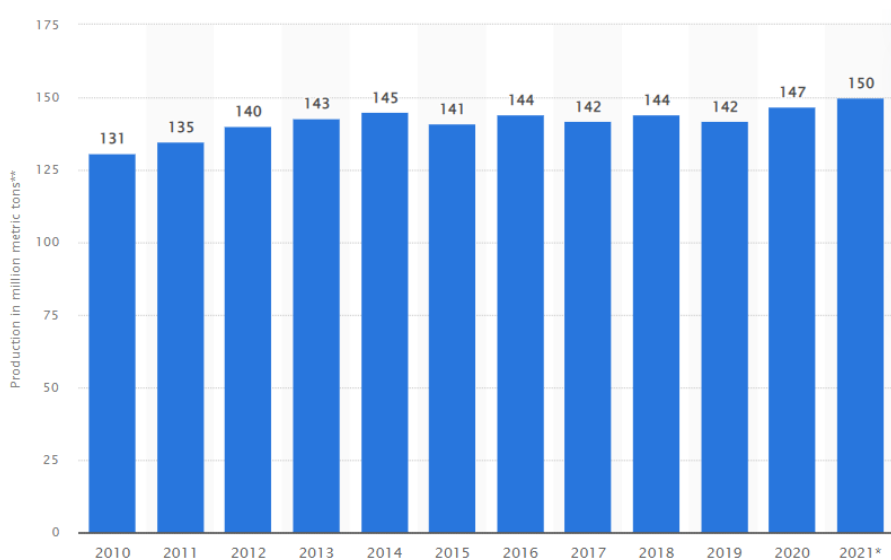


Figure 7: Global ammonia production over the years

Since most of the ammonia is produced using fossil fuels, the intensity of emissions is very high. In the present scenario, around 120 ports around the world are equipped with ammonia trading facilities. There are 38 ports that export ammonia, mostly in Asia, and 88 import ports. Ammonia is transported by 71 LPG tankers with capacities from 2500 tons to 40000 tons [Haldor Topsoe, 2020]. The current process of ammonia production is also very energy intensive. Brown ammonia production consumes 8 MWh of energy per ton of ammonia which includes processes like steam reforming and Haber-Bosch process.

3.3.4 Cost

Most of the ammonia today is produced using fossil fuels. Hence, the cost of ammonia follows a similar trend as that of fossil fuels. This can be seen in Figure 8.

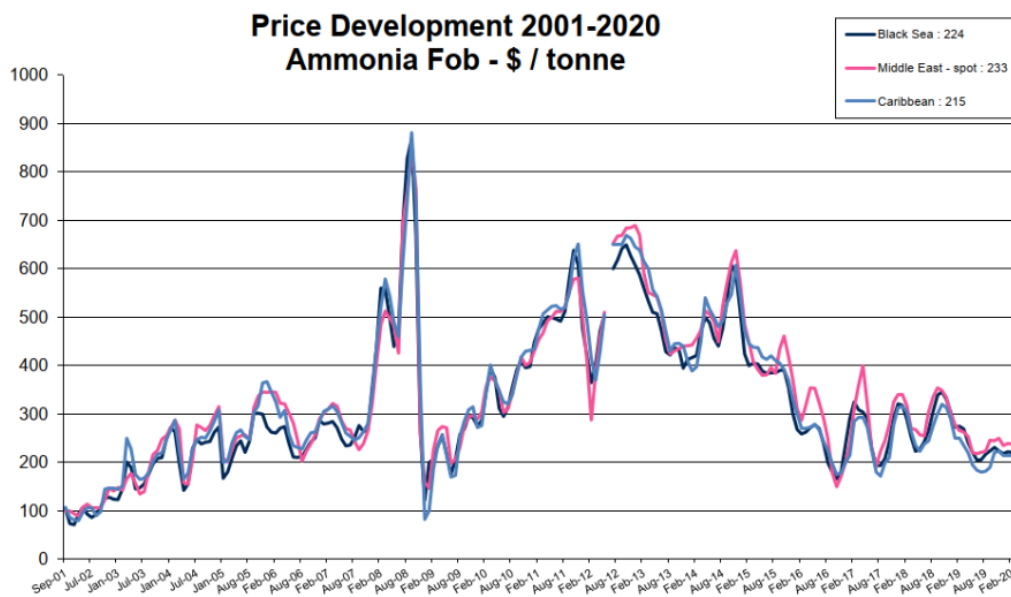


Figure 8: Global ammonia cost over the years
[Haldor Topsoe, 2020]

3.3.5 Safety

Ammonia has been transported as cargo and as refrigerant on board of ships for years. There are international rules in place to ensure safe handling of ammonia on board. The International Code for the Construction and Equipment of ships carrying Liquefied Gas in Bulk (IGC Code) gives guidelines for the protection of the personnel having ammonia onboard. This includes respiratory and eye protection devices, protective clothing and decontamination shower. Anhydrous ammonia is lighter than air and disperses easily in dry air. But it has high affinity towards water. Therefore it reacts with the humidity in the air and stays close to the ground. Because of this high affinity towards water, it can cause considerable damage to marine ecosystems since it is toxic. Although safety systems are in place to avoid any such accidents [Haldor Topsoe, 2020].

3.3.6 Regulations

There are no IMO regulations for ammonia as a marine fuel as of now. But there are regulations for ammonia as cargo. Discussions are going on for drafting the regulations for the same. There are some difficulties for drafting the regulations for ammonia because of some existing regulations and because of some properties of ammonia. The International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code) states that toxic products cannot be used as fuels. It's stated that ammonia is a toxic product in cargo form in the same code as well as in International Maritime Dangerous Goods (IMDG). Therefore, carriers that transport ammonia cannot use it as fuel. This is still under discussion and a separate committee has been formed for it [IMO, 2021].

3.3.7 Energy conversion technologies

Ammonia can be used a fuel in various technologies. Table 3 shows the different ways in which ammonia can be used and their efficiencies.

Table 3: Comparison between different technologies for ammonia usage

Technology	Efficiency (%)	Required pre-treatment
Proton Exchange Membrane Fuel Cell (PEMFC)	40-50	Ammonia decomposition, trace ammonia removal
Alkaline Fuel Cell	50-60	None
Solid Oxide Fuel Cell (SOFC)	50-65	None
Internal Combustion Engine	30-40	Partial decomposition is beneficial
Boilers and Furnace	85-90	None
Combined cycle Gas turbines	55-60	Partial decomposition is beneficial

3.3.8 Existing/Ongoing projects

There are some ongoing projects for using ammonia as a fuel for propulsion. The boat A-Tug is a research and development project to develop a tugboat powered by ammonia fueled engine. Since ammonia is difficult to ignite, a small amount of fuel oil will be used as pilot fuel to start the ignition. The aim of this project is to reduce GHG emissions by achieving ammonia fuel mixed combustion rate of 80% or higher by volume. NYK, a Japanese shipping company is in charge of the project [Prevljak, 2021].

There is another project carried out by NYK called as AFAGC. AFAGC stands for Ammonia Fueled Ammonia Gas Carrier. It involves using the ammonia vapor generated in the cargo as fuel during the voyage. It's aim is to achieve 95% ammonia fuel mixed combustion rate. The target delivery of this ship is 2026 [Prevljak, 2021].

4 Method

To be able to develop the conceptual design of the propulsion system for the case study ship, Scandica, using hydrogen and ammonia as fuels, the following steps have been followed:

- Data collection regarding the ship which includes its physical dimensions, specifications of the current propulsion system components, layout of the ship, data logs of its day-to-day activities and handbooks.
- Investigating the operational profile from the available data to understand its average and maximum daily working routine for different operations.
- Selection of fuel cells.
- Fuel consumption estimation based on the operational profile for existing propulsion system and the new propulsion systems.
- Creating a 3-D model of the existing hull to understand the layout and estimate the space available.
- Selection of motor and tanks for the new propulsion system.
- Sizing of hydrogen and ammonia tanks to optimize the utilization of all available space.
- Endurance and range estimation of the ship with the new propulsion system.
- Preliminary stability calculations to check the impact of removal of existing components that are not needed for the new propulsion system and addition of new components.

4.1 Case study ship

Main data and the general arrangement of ship is as follows:

4.1.1 Main data

The main activities that the ship performs are fairway maintenance and ice breaking. The ship travels from port to port along the coast and doing fairway maintenance as per schedule. During spring, summer and autumn, fairway maintenance is the main operation whereas ice breaking is performed during the winter months. Along with these operations, the ship also performs research activities and bottom surveys. This can be seen in Figure 11. Tables 4 and 5 shows the main parameters of the vessel.

Table 4: Ship particulars of M/S Scandica

Ship particulars	
Year of Build	1983
Deadweight (T)	361
Length Overall (m)	56.76
Length (Between the Perpendiculars) (m)	50.02
Breadth Moulded (m)	12.01
Draught (m)	3.82
Depth (m)	5.01
Gross Tonnage (T)	980
Net Tonnage (T)	294
Formula Deadweight (T)	1329

Table 5: Machinery overview of M/S Scandica

Machinery overview	
Main Engines	2 x Hedemora V16A/12 @ 1294 kW
Auxiliary Generators	4 x Volvo Penta D9 @ 239 kW
Propeller	Single shaft CPP, Dia. 2500 mm
Thrusters	2 x Tunnel thrusters (fore/after)

The efficiency of the main engines is 38 % [Offshore, 2000] and that of the auxiliary engines is 38.3 % [Volvo Penta, 2013]. Therefore, the Specific Fuel Consumption (SFC) can be calculated as follows:

$$\text{Specific energy (kg/kWh)} = \frac{1 \text{ kWh}}{\text{LHV of the fuel (kWh/kg)}} \quad (1)$$

$$\text{SFC (g/kWh)} = \frac{\text{Specific energy}}{\text{Efficiency of the energy conversion device}} * 1000 \quad (2)$$

4.1.2 General arrangement

Figure 9 shows the general arrangement of the vessel M/S Scandica and figure 10 shows the tank arrangement.

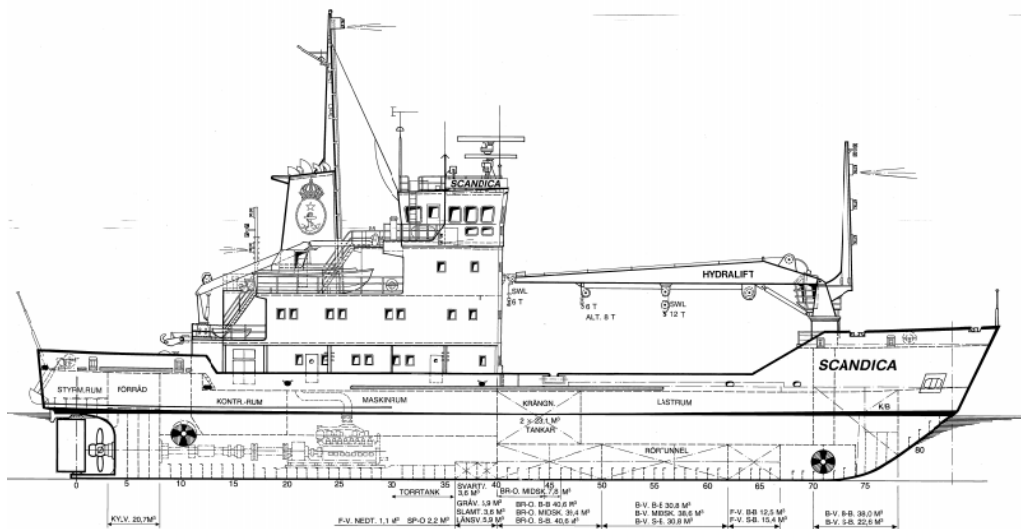


Figure 9: General arrangement drawing of M/S Scandica

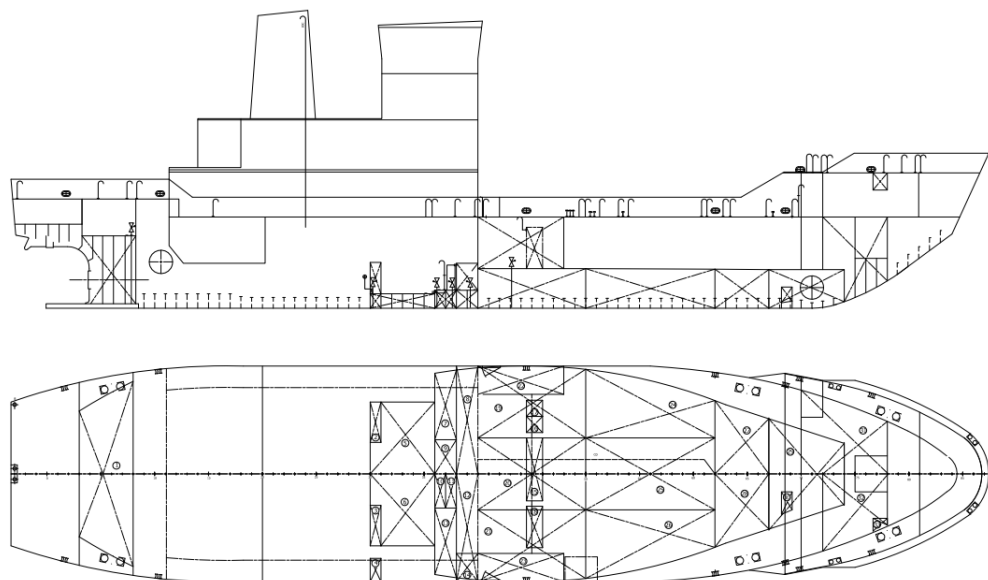


Figure 10: Tank arrangement of M/S Scandica

4.2 Data collection

The Swedish Maritime Administration provided us with the following data:

- Fuel and energy consumption data for main engine and auxiliary systems, also called as the Ship Energy Efficiency Management Plan (SEEMP) for each day from 2015 till 2021.
- The General Arrangement (GA) and layout diagrams for different machine systems.
- The Stability handbook of the ship.

The Automatic Identification System (AIS) data for the vessel from 2015 till 2021 which was provided by SSPA.

The overall consumption of the ship is in litres, which was derived by subtracting the fuel level recorded in bottom tanks between consecutive days. It is the consumption for both the main engines,

auxiliary systems and boiler. The consumption for the auxiliary systems was given in kWh and it is in litres for the main engines.

4.3 Operational profile

An operational profile, as the name suggests, is the representation of how the ships performs it's activities. It usually includes the time, average speed and the distance covered by the ship for each activity (like departing for the port, working at the location, ice breaking) in a day. To determine the energy consumption for the existing and new propulsion system, it was necessary to derive an operational profile with the help of the available data. The time, speed and distance for each activity is then used to calculate the fuel consumption by taking the efficiency, specific fuel consumption and other parameters into consideration. The analytical part of determining the operational profile is conducted in the following steps:

1. Activity pattern
2. Daily operational profile

4.3.1 Activity pattern

Determination of what activities were performed by the ship is necessary to draw an operational profile. This was extracted from the SEEMP file data sheets. It has columns that mentions the activity that was performed. For this, analysis of consumption data files was carried out. The number of days each activity was performed was tabulated and processed to get a pattern. After the analysis, it was possible to visualize the activity that was performed the most over the year. Figure 11 is for the year 2021 which shows the activity pattern. It can be observed that the activity is related to the season in regards to the task performed. The activity performed depends on the tasks that the ship needs to carry out, the weather and the intensity of the weather during that particular year.

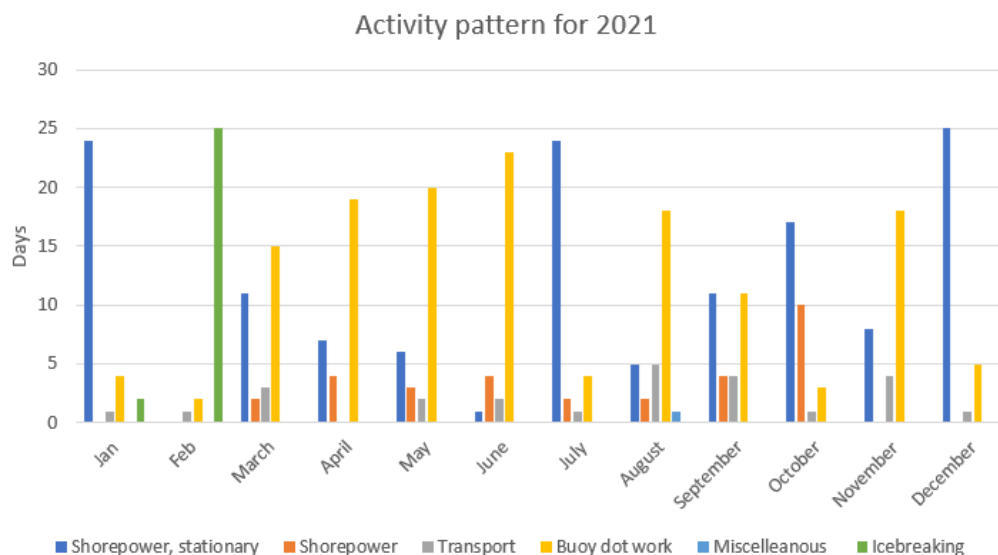


Figure 11: Activity data for 2021

4.3.2 Daily operational profile

Determining a typical operational profile for different operations of the ship in a day, means calculating its average speed, distance covered, the time for each task and the number of transits in a day. This can be analysed using the AIS data files. Fairway maintenance, ice breaking and transport operations

are performed the most over the year by the ship as seen in Figure 11. For fairway maintenance, a typical working day involves:

1. Departure from the port to reach the location.
2. Working on a buoy which may include maintenance and positioning.
3. Transiting to the next buoy.
4. Repeating this process multiple times in a day.
5. Returning to the port at the end of the day.

For ice-breaking, a typical working day involves:

1. Going to the working location which may involve heavy ice-breaking.
2. Ice-breaking at the location, which can be considered as working, usually carried out at lower speeds compared to going to the location.
3. Maneuvering, which may involve cutting the ice in a specific location at very low speeds.
4. Returning back to the port.

For Transport, a typical working day involves:

1. If there are multiple stops on that day, then the ship goes to it's first location.
2. Transiting to the next stop. Multiple stops can happen in a day.
3. Returning to the port.

For getting the average speed and time for each activity, the AIS data was used. The AIS data contains information like the start and stop time of every movement of the ship, the average speed during that movement, the maximum speed that the vessel achieved during that movement and the distance covered. Multiple methods were used for estimating the values for parameters like the average speed and distance covered for each activity of the operational profile. The two methods are described below.

Method 1

1. In the AIS data file, first, the type of work performed on each day was marked. This was possible with the help of data from the respective SEEMP file.
2. Next, a day's work was categorized into Departure, Work 1 , Transit 1 , Work 2 , Transit 2 and so on depending upon the number of transits in a day and the speed and distance covered by the ship during such instances and finishing off with returning to port.
3. The months from March till June were selected as the base for carrying out the analysis as most of the work regarding this activity was carried out during these months. Fairway maintenance is also conducted during rest of the year but not as regularly as during these months.
4. There were many gaps and irregularities in the data logs which needed some filling and conditioning like eliminating the unrepresentative values for activities like departure from the port (e.g. The first entry of data for many days had values less than 1 or zero. Usually the first entry of data is for departure from the port. However, if this value is zero or less than 1 for speed, distance and time, it cannot be considered as the value for departure from the port. Instead, the representative values were on the third or fourth entry of data). There are similar entries for other type of work as well. Therefore, the data had to be conditioned and filtered properly. This helped to get an estimation of the numbers.

5. To make the values even more representative, a baseline value of 8 knots for speeds for departure and arrival to the port since most of the representative values recorded for these movements had a speed above this and 5 minutes for transit between stops was set. This was because most of the significant values recorded for transit between stops having a representative speed were over 5 minutes . This meant the average of values only above baseline was taken.
6. There were multiple transits in a day. To fit the data for these transits in the operational profile, values were summed up to represent time and speed for transit.

There were many drawbacks in *Method 1*. Averaging of multiple values, setting baseline for average speed and time leads to inaccurate values. These methods lead to a cumulative error and a unrepresentative operational profile. Hence, a second method was developed with the help of SSPA.

Method 2

The data under consideration is from the AIS file, specifically the months from March till June. This was the time when most of the fairway maintenance work, that is, buoy/dot work was performed. A template was made that gave the following data for a particular day:

1. Total distance:
This is the total distance covered by the ship on that particular day.
2. Distance to work:
This is the first representative entry in the AIS data for that particular day. It is the distance covered by ship to reach its first point of work from the port.
3. Distance between buoys:
This is the distance covered by the ship transiting between the buoys.
4. Weighted average speed in work:
This is the weighted average speed of the ship while working on that particular day. This excludes the speeds during departure and arrival.
5. Total working time:
This is the total time that the ship worked on that particular day. It is the difference between the time at which the ship reached its first working point and the time at which it left from the work on it's way back to the port.
6. Time servicing the buoys:
This is the distance between the buoys divided by the weighted average speed.
7. Buoys serviced:
This is the number of buoys that the ship serviced on that particular day. This data was available from the SEEMP file.
8. Time per buoy:
This is the total time servicing the buoys divided by the number of buoys serviced.
9. Distance to the Port:
This is usually the last representative entry in the AIS data for that particular day. It is the distance that the ship covers to reach the port from it's last working point.

For ice breaking operation, the period during the winter months starting from November till February was considered. For transport operation, the whole year had to be taken under consideration since there is no particular period of months during which transportation is performed.

In the end, all the further calculations were carried out using *Method 2* as suggested by SSPA. Based on the values derived using *Method 2* , an operational profile for different operations was drawn.

4.4 Selection of components for propulsion system

For hydrogen or ammonia powered propulsion system, a fully electric layout is used. Fuel cells and electric propulsion motors are required to replace the internal combustion engines and auxiliary generators to fulfill the auxiliary load and the propulsion load, both drawing power from the main switchboard. Therefore, component selection for these components is as follows:

4.4.1 Selection of fuel cells

To estimate the consumption for hydrogen and ammonia propulsion, parameters like size, operating efficiency and Specific Fuel Consumption (SFC) of the fuel cells are required. Size gives the physical dimensions which is required to check if and how many fuel cells and are possible to fit in the hull according to the available space. SFC is required to estimate the fuel needed to produce the power required to carry out the specific operation. Based on our requirements of available space and power output required, three commercially available Proton-Exchange Membrane Fuel cell were identified.

- Ballard - FC Wave [Ballard, 2021]
- Powercell - Marine System 200 [PowerCell AB, 2022]
- Hydronics - HyPM - 180 [Hydrogenics, 2022]

The fuel cells by Powercell and Hydronics, currently do not have any safety approval or certification for marine use. Powercell has significantly lower weight [PowerCell AB, 2022] compared to Ballard and this may be related to the lack of safety related components. The fuel cell stack that is provided from Hydronics has comparatively lower energy output compared with Ballard FC Wave with similar dimensions. Therefore, the Ballard- FC Wave was selected based on its compliance to safety regulations and its power output. Its details can be seen in Table 6:

Table 6: Specifications of Ballard FC-Wave PEM Fuel Cell

[Ballard, 2021]	
Performance	
Rated power	200kW
Minimum power	30kW
Peak fuel efficiency	53.50%
Operating voltage	350 - 720 V DC
Rated current	2 x 300A or 1 x 550A
System cooling output	Max 65 ^o C
Stack technology	
Heat management	Liquid cooled
H2 Pressure	3.5 - 6.5 barg
Physical	
Dimensions (l x w x h)	1210 mm x 738 mm x 2195 mm
Weight (estimate)	1050 kg
Environmental protection	IP44
Safety Compliance	
Certifications	DNV-Type Approval
Enclosure	Sealed secondary barrier for hydrogen

Based on this selection, the SFC was determined using Equations 1 and 2

4.4.2 Electric Propulsion Motor

In a conventional power system arrangement, the ship's propellers are driven by a propulsion engine while the supply of electricity for the other shipboard loads is transmitted from the shipboard generators. In an electric propulsion system, the power used to drive the propellers becomes an electrical load meaning that the generators take care of all shipboard loads. In the case of hydrogen or ammonia fuel cell propulsion system, where there will be no engine or a generator, the system becomes fully electric powered. In that case the use of electric propulsion motors becomes a necessity.

Electric motors are either powered by alternating current (AC) or a direct current (DC). There are many differences between AC and DC motors. The main difference is the type of current each motor turns into energy. AC motors are known for their increased power output and efficiency. DC motors are known for their speed control and output range. AC motors are available in single or three-phase configurations, while DC motors are always single-phase.

The selection of the motor was decided based on the power output that is needed for propulsion. SIMOTICS HT Series HT-direct manufactured by Siemens matches the requirements closely. There are many commercially available motors on market and the selection of the ideal one requires other considerations as well. Other considerations can be the main dimensions, the weight, the price, the life-cycle cost and others [Siemens, 2022].

4.5 Fuel consumption estimation

Fuel consumption for the operational profile will determine how many days the ship will operate performing a particular operation before refilling of the tanks is required. To determine the fuel consumption, data inputs like the speed-power curve, SFC for different propulsion systems and the operation time and average speed are required. The data inputs were calculated as follows:

1. Energy for propulsion

The speed-power curve will help to calculate the power and energy required for propulsion for different operations. SSPA performed regression analysis on the AIS data and SEEMP file and a maximum power requirement of 2.17 MW was calculated to propel the ship at Load Condition 6 at a speed of 15 knots. A load condition is the term used to specify the amount of cargo or load that the ship is carrying. The Swedish Maritime Administration stated that Load Condition 6 is the most used condition. It has 30 tonnes of cargo on deck and other 30 tonnes in the holding area according to the Stability handbook. The regression analysis also led to determining the approximate load at different speeds and different conditions. Inputs from the Swedish Maritime Administration were also considered and some changes were made accordingly. Based on this, a Speed-Power curve was plotted. Figure 12 is applicable for fairway maintenance and transport operations.

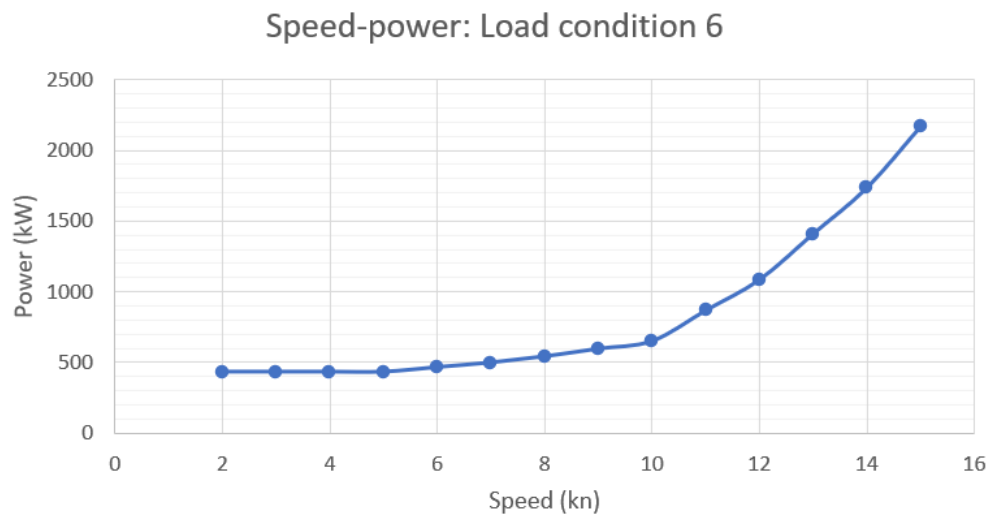


Figure 12: Speed-Power curve for fairway maintenance and transport operation

For Ice-breaking operation, the speed-power curve is different than the regular curve. Due to external conditions like climate, temperature, wind-speed, roughness in the sea, the type of water of the ice (salt water, fresh water, brackish water) and most importantly, the thickness of the ice, the engines need to operate at different loads compared to operations like fairway maintenance and transport. It is difficult to have one generic speed-power curve for this operation. Swedish Maritime Administration gave the input that the engine operates at 100% load for the speed of 12 knots. Other than this, very limited data was available on ice breaking performance. The power and load % for rest of the speeds are based on an assumption. Therefore, the applied data gives a very rough estimation of performance. The speed-power curve is as follows on Figure 13:

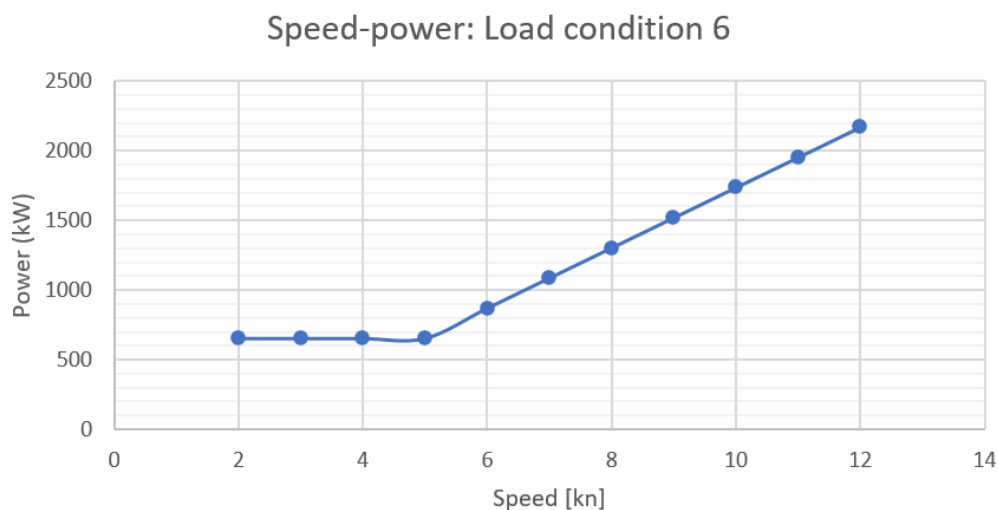


Figure 13: Speed-Power curve for ice-breaking operation

Based on these curves and input from the operational profile for time and average speed during a particular activity of an operation, the power and energy was calculated using these formulae: Power is calculated as shown in Equation 3:

The input for this equation will be the speed for that particular activity and the power required

to operate at that speed which is derived from the speed-power curve.

$$\begin{aligned} Power(kW) = & Power \text{ from the speed power curve}(kW) \\ & * (1 + Sea \text{ Margin}) \end{aligned} \quad (3)$$

Energy is calculated as shown in Equation 4:

$$Energy(kWh) = Power(kW) * Time(Hr) \quad (4)$$

For calculating the fuel consumption based on the energy consumption, SFC of the energy conversion devices is required. The SFC of the main engines is mentioned in Section 4.1.1 and for fuel cells is mentioned in Section 4.4. The SFC and efficiencies used for calculating the energy consumption for different loads for the three propulsion system can be found in Appendix A. Since the main engines are used for propulsion, the fuel consumption can be calculated as shown in Equation 5:

$$\begin{aligned} ME \text{ consumption}(kg) = & \\ Energy \text{ consumption for Propulsion}(kWh) & \\ * SFC(g/kWh)/1000 & \end{aligned} \quad (5)$$

The main engine consumption in m_3 is calculated as shown in Equation 6:

$$ME \text{ consumption}(m_3) = \frac{ME \text{ consumption}(kg)}{Fuel \text{ density}(kg/m^3)} \quad (6)$$

2. Energy for system and non-system related requirement

The system and non-system related electrical power consumption is the auxiliary load for the ship. The system related components are the ones that support the propulsion system. In case of the existing MGO propulsion, this includes components like fuel treatment systems, fuel pumps, lubrication system, cooling systems. In case of hydrogen and ammonia propulsion system, the number and power of the components required to support propulsion is reduced compared to MGO. It needs components like pumps and compressors for hydrogen, evaporators for ammonia and pressure regulators. The system and non-system related power consumption values for the existing MGO propulsion system were verified by the Chief Engineer on M/S Scandica. Although for fuel cells, more investigation was required to estimate the system related power consumption. Based on [Yuan, 2008], approximate power required for system related components is taken. The non-system related electrical consumption consists of power consumption for components like the onboard crane, navigation equipment, cooking equipment, lights, ballast pumps, etc. This load remains the same for all the propulsion systems. Although, further investigation can be performed to see the change in these loads depending on the propulsion system. The Swedish Maritime Administration also mentioned the use of heat pumps instead of conventional boilers and excess engine heat to fulfil the heating requirement of the ship during various operations. This heating load which is fulfilled by heat pumps, is accommodated in the auxiliary power consumption. The auxiliary loads for different operations are listed in Table 9.

Table 7: System and non-system related power consumption during different activities

Energy category	Energy carrier	In port	Normal transit	Transit between	DP (working)	Maneuvering	Ice breaking
<i>Non-system related power kW</i>		65	140	140	240	240	200
<i>System related power kW</i>	MGO	35	60	60	60	60	60
	H2_PEMFC	20	50	50	50	50	50
	NH3_FC	200	50	50	50	50	50
	BATT	20	30	30	30	30	30

System and non-system related electrical energy needs are fulfilled by the auxiliary engines. In case of the existing MGO propulsion system, auxiliary engines have different efficiency. It is mentioned in the Section 4.1.1. The consumption for auxiliary engines is calculated as shown in Equations 7 and 8

$$\begin{aligned}
 AE \text{ consumption}(kg) = \\
 \text{Energy consumption for (Non-system related electrical + System related electrical)}(kWh) \quad (7) \\
 * SFC(g/kWh)/1000
 \end{aligned}$$

The auxiliary engine consumption in m_3 is calculated as shown in Equation 8:

$$AE \text{ consumption}(m^3) = \frac{AE \text{ consumption } (kg)}{Fuel \text{ density } (kg/m_3)} \quad (8)$$

This process can be summarized using the following flowchart for better clarity:

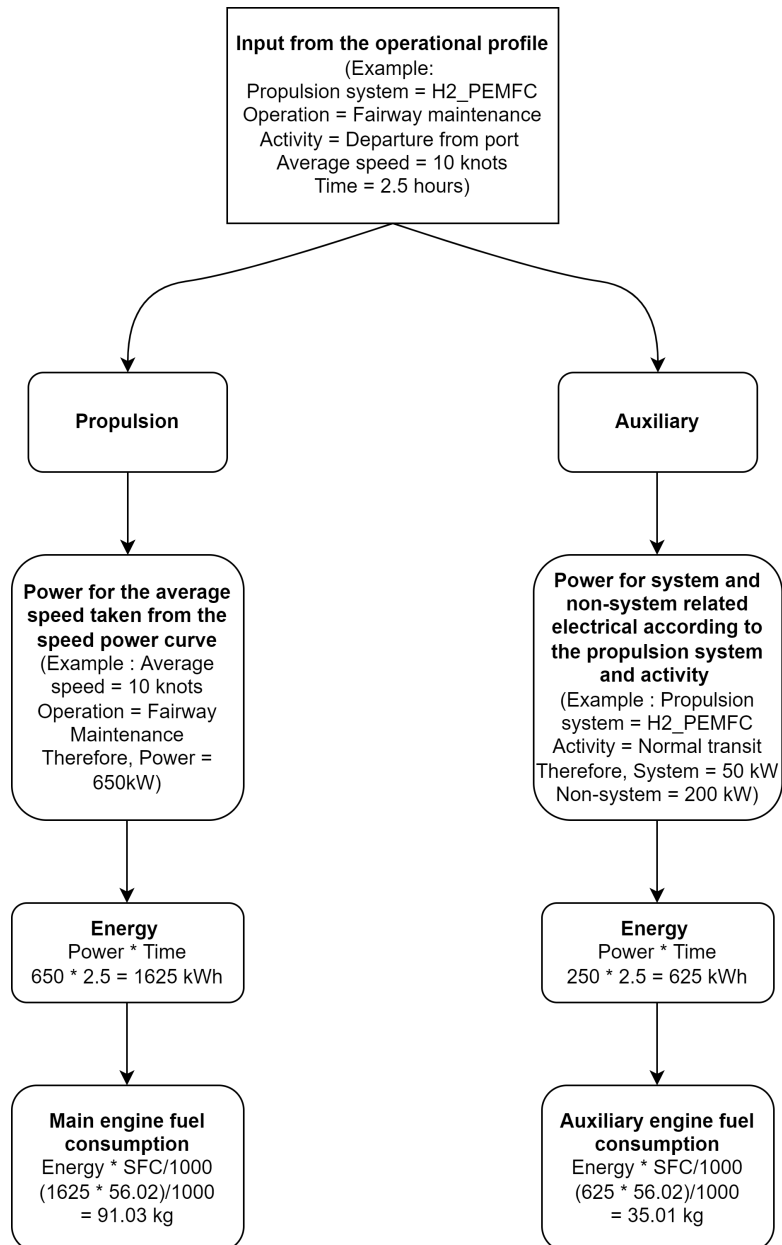


Figure 14: Fuel consumption estimation for main and auxiliary engines

With this process, the fuel consumption for average and maximum operational profile for the three different operations is calculated and depending upon the size of the tank, the endurance and range is determined.

4.6 Visualising the existing hull

4.6.1 Perspective hull view

Based on the 3D section plan that was given, a hull model was designed with the use of Rhinoceros 3D Software. It is presented in Figure 15.

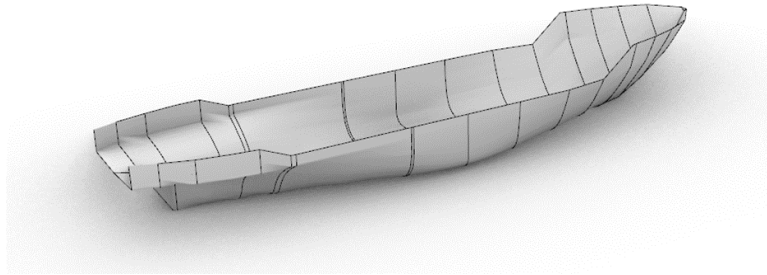


Figure 15: M/S Scandica Hull

The hull model was imported to MAXSURF later on and the new tank arrangement for different propulsion systems (hydrogen and ammonia) was tested in order to find out the different stability results.

4.6.2 Tank arrangement

The tank arrangement can be seen in Figure 16.

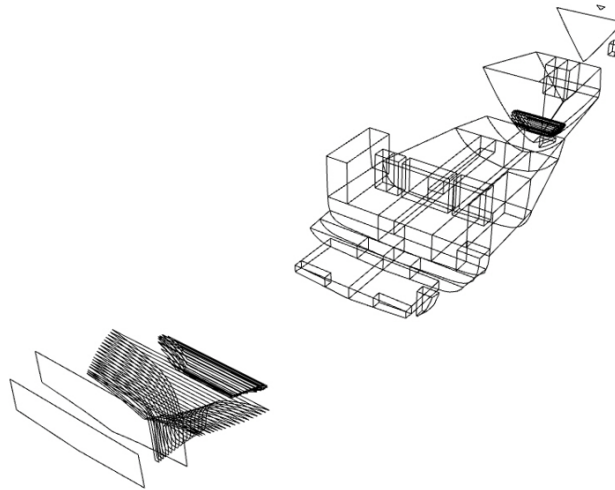


Figure 16: Existing tank arrangement

4.6.3 Sizing of the original tanks

For sizing each and every tank usually the simplest way would have been to multiply the length with the width and the depth. The problem is that it would have been inaccurate for this case as the areas of the two sides of every tank differ. So the estimation of the volume of every tank is being done by tanking an average area of the two side faces multiplying it with the length. An example of how the sizing of the tank 22 is being done can be seen in Figure 17.

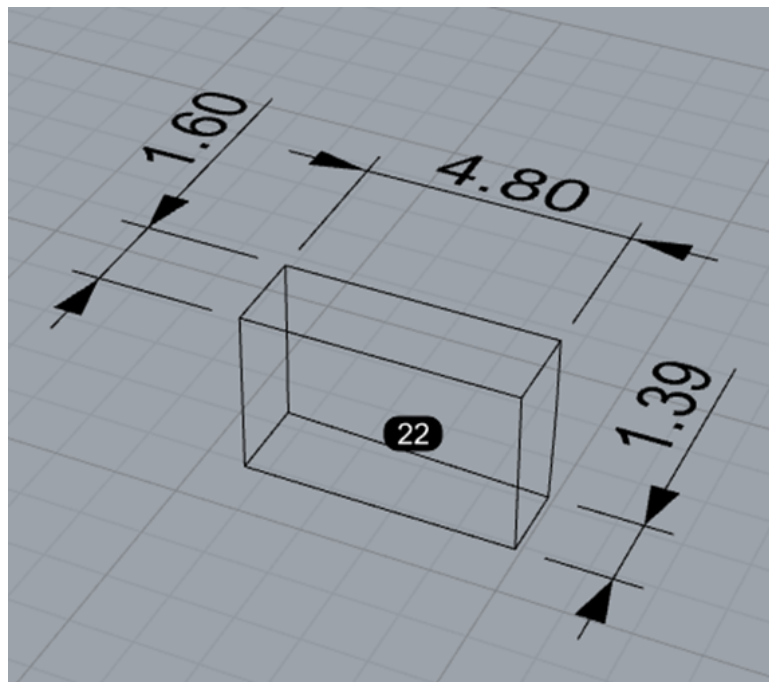
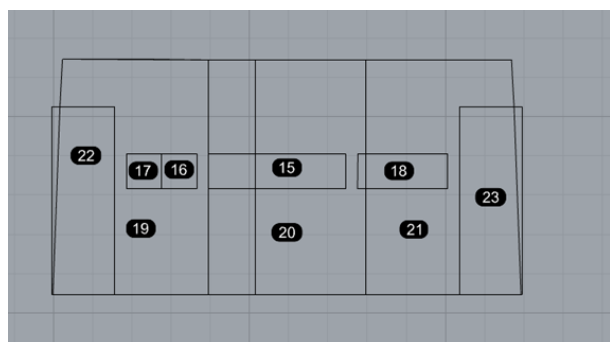


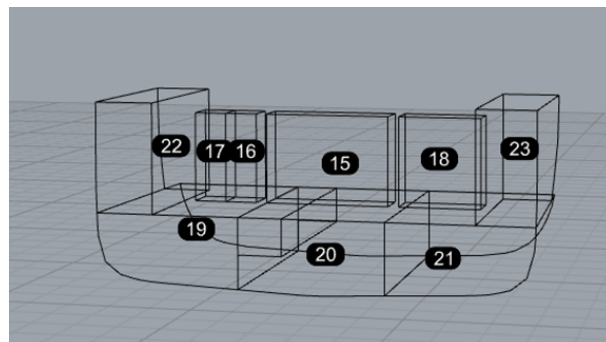
Figure 17: Tank sizing

Different views of the tanks

Each and every tank can be seen clearly from the images below in both top and perspective view. Each number co relates with the numbering below. The exploded view of every tank compartment was necessary for the sizing and estimation of the volume for every tank.

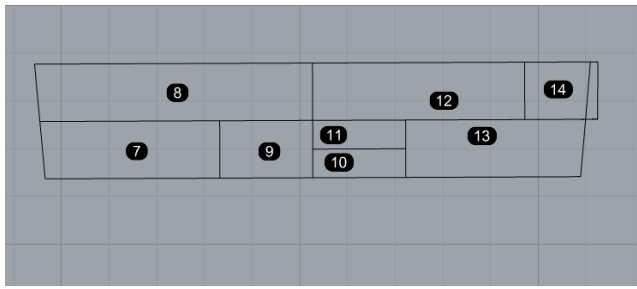


(a) Top View

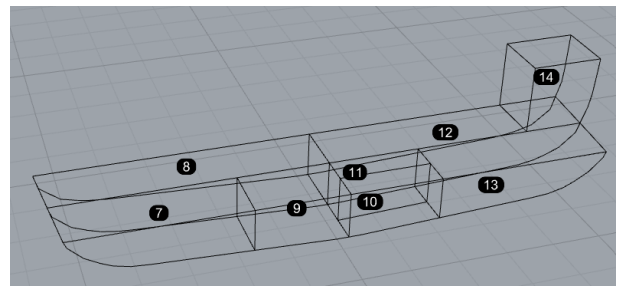


(b) Perspective View

Figure 18: Tank views

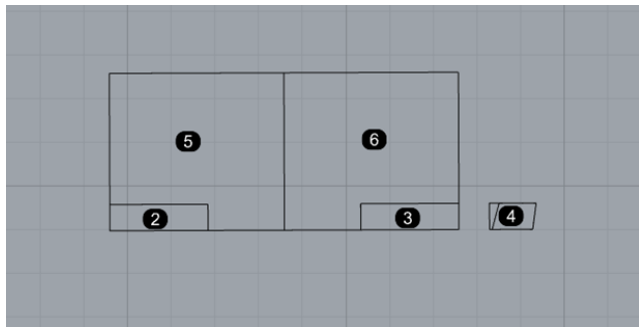


(a) Top View

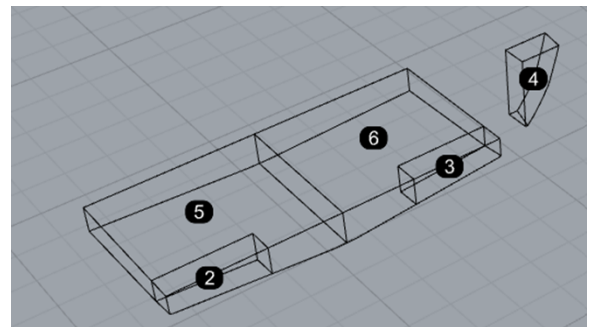


(b) Perspective View

Figure 19: Tank views

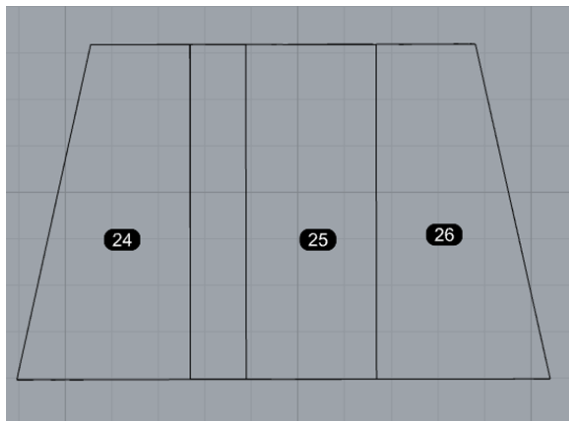


(a) Top View

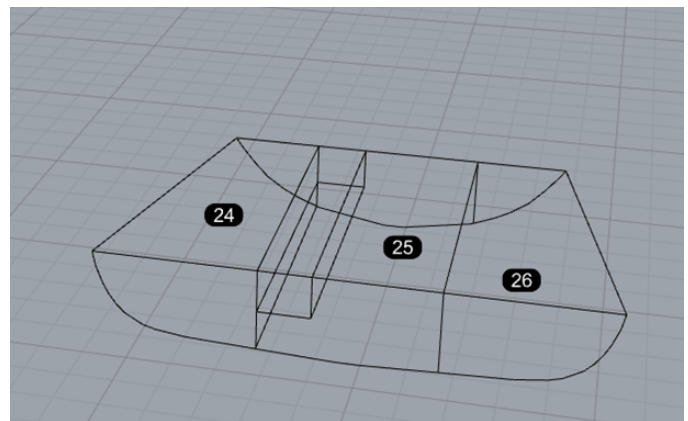


(b) Perspective View

Figure 20: Tank views



(a) Top View



(b) Perspective View

Figure 21: Tank views

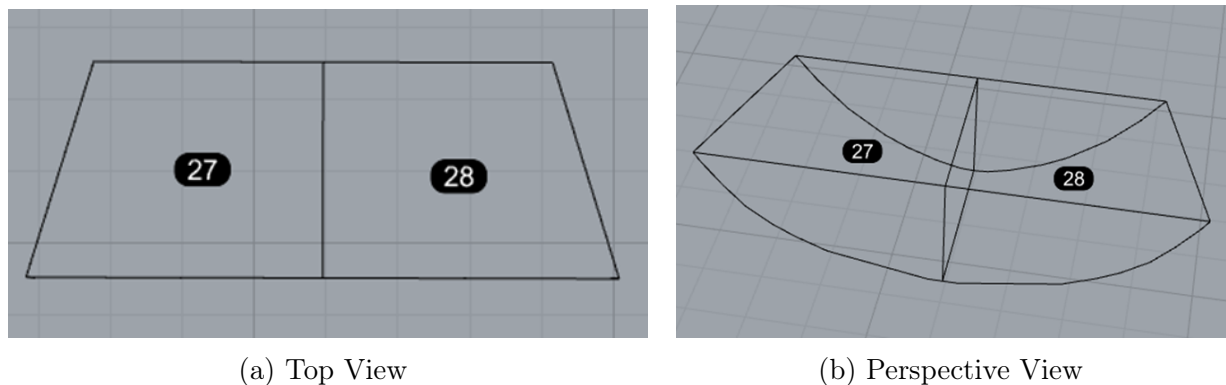


Figure 22: Tank views

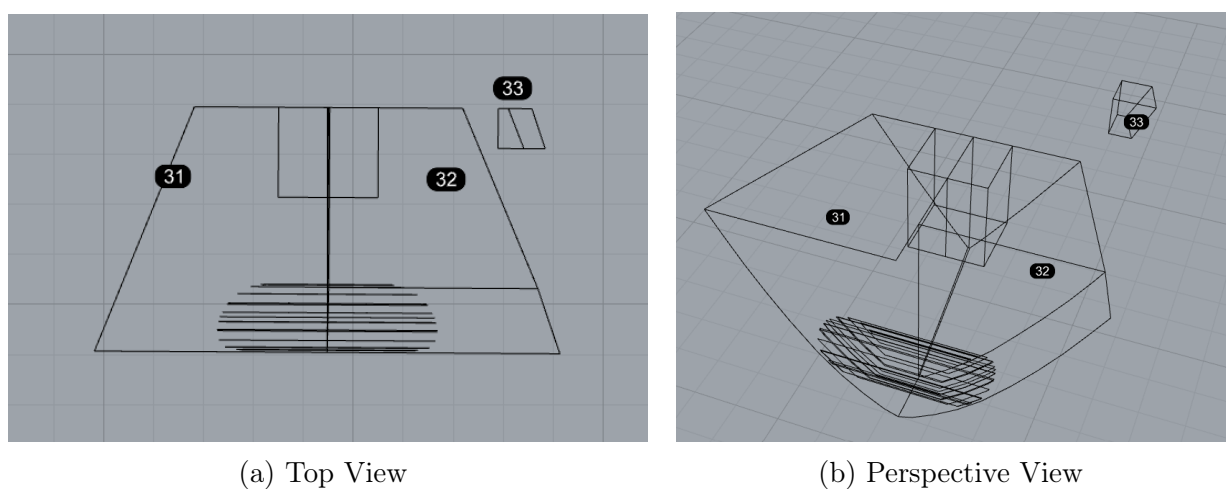


Figure 23: Tank views

4.6.4 Type of tanks inside the hull

In this part the different tanks that were sized on Section 4.6.3, are gathered all together. The name of each tank with its content and volume are presented in Table 8. That was a crucial step in order to identify the content of every tank and decide which one will be remained and which one will be removed on the new propulsion system.

Table 8: Types of existing tanks

Sr. No.	Tank	Content	Volume(m ³)
1	KYLTANK_1.C	S.W	20
2	SJOINTAG BB MASKIN	S.W	0.8
3	SJOINTAG SB MASKIN	S.W	0.8
4	HOGSJOINTAG SB MASKIN	F.O	0.7
5	TORRTANK/RES.BR.O.TANK BB	F.O	9.
6	TORRTANK/RES.BR.O.TANK SB	F.O	9
7	SLAMTANK	SLAM	3
8	LANSVATTENTANK	Bildge water	6
9	SPILOLJETANK	Spill oil	2
10	F.V.NEDTOMNINGSTANK	F.W	1
11	BR.O.SPILLTANK	F.O	1
12	GRAVATTENTANK	Grey water	6
13	SVARTVATTENTANK	Black water	3
14	TANK EVAK SANITAR	Black water	2.6
15	DAGTANK BR.O	Fuel	8
16	HYDRAULOLJETANK	Hydraul.oil	2
17	HYDRAULOLJETANK	Hydraul.oil	2
18	SMORJOLJETANK	Lubr.oil	5
19	BR.O.TANK BB	F.O	40
20	BR.O.TANK MID	F.O	40
21	BR.O.TANK SB	F.O	40
22	KRANGNINGSTANK BB	S.W	22
23	KRANGNINGSTANK SB	S.W	22
24	B.V.TANK BB	S.W	30
25	B.V.TANK MID	S.W	46.5
26	B.V.TANK SB	S.W	30
27	F.V.TANK BB	F.W	15
28	F.V.TANK SB	F.W	15
29	BOGPROPELLERUM		42
30	SJOINTAG FOR		0.2
31	B.V.TANK BB FOR	S.W	38
32	B.V.TANK SB FOR	S.W	22
33	DAGTANK HAMNGENERATOR	F.O	0.5

In the next step, a new tank arrangement was developed which means that some tanks were removed and replaced with new ones. The name of tanks in bold outline indicates the tanks that are replaced and the rest are unchanged irrespective of the change of propulsion system.

4.6.5 3D view of tank arrangement

For the stability calculations and sizing, MAXSURF software applications were used. Figure 24, represents the perspective view of the hull with the tanks that were kept.

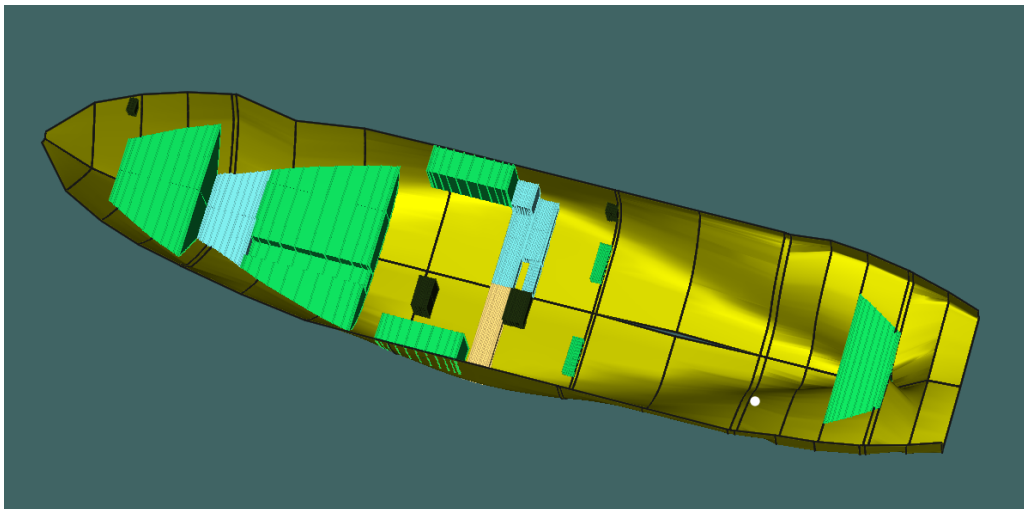


Figure 24: General Tank Arrangement

From Figure 10 and Table 8, the representation of each tank can be identified. In Section 24, the final tank arrangement of hydrogen propulsion system is illustrated. Based on the sizing, weight and positioning of each tank the stability of the ship is changing accordingly.

4.6.6 Selection of Hydrogen tank

Hydrogen can be either used as an energy provider in the form of gas or liquid. As mentioned in Section 3.2.2, gaseous hydrogen is most commonly used. In this case, where the space is limited, liquid hydrogen tanks are more suitable. A higher amount of hydrogen can be stored which will increase the days of operation. Because of this reason, a research only for a liquid tank was investigated.

There are very few commercially available liquid hydrogen tanks. MAN Cyro had announced in 2018 the development of the world first hydrogen system, but there was not enough information regarding the exact specifications of the system [MAN, 2020]. Similarly, Hylium industries have a variety of liquid hydrogen tanks for various applications which does not include marine applications [Hylium industries, 2022].

METAVISTA hydrogen tanks were found to be suitable as enough information about their specifications and characteristics was available [Metavista industries, 2022]. The HISO (Hydrogen ISO) Series tanks have suitable specifications which are as follows in Table 9:

Table 9: Metavista hydrogen tank specifications

[Metavista industries, 2022]

Metavista HISO Hydrogen Tank	
LH_2 Capacity	4 tonnes
LH_2 Volume	$57 m^3$
External dimensions	ISO 40 ft container

The technology of the tank consists a 2nd generation metallic tank which is LN2 vacuum shield. It has the CoolConnect™ ports for quick, easy and safe LH_2 loading. It has 100 % hydrogen recovery in LH_2 refueling using Zero-Loss-Transfer (ZLT™) technology and they are easily mountable on any ISO container.

4.7 Sizing of tanks

Two cases were assessed for available space to be used for fuel storage. The description of them can be seen below:

1. Case 1

Approximately 412 m^3 of space is available after removing all the existing fuel tanks and assuming the empty space in the adjacent compartments as usable. As the Metavista tank has the external dimensions of an ISO 40ft container, the sizing should be based on it. The specification of the ISO 40ft container are given in Table 10:

Table 10: Dimensions of ISO 40ft container

Area	28.37 m^2
Internal measurements	L=12.03m,W=2.35m,H=2.39m
External measurements	L=12.19m,W=2.44m,H=2.59m
External Volume	77 m^3

As it can be seen from the specifications of the ISO 40ft container, the length of 12.19 m container would not be feasible to fit as the ship breadth is 12 m. For that reason the possibility of ordering a custom design of another tank with custom dimensions would be ideal. If it is assumed that this is possible, the following procedure has been followed to estimate the total hydrogen capacity and sizing of the tanks.

For the middle tank there is space available to fit an 11.5m in length tank with a height of 2.5m and a width of 2.5m. By interpolating the initial volume of Metavista hydrogen tank, the new internal volume was estimated. The following dimensions can be obtained as on table 11:

Table 11: Middle tank dimensions

[Metavista industries, 2022]

External length	11.5 m
Height	2.5 m
Width	2.5 m
External Volume	71.87 m^3
Internal Volume	53 m^3

For the front tank there is space available to fit a 7m in length tank with a 5m in width and 2.5 m in height. By interpolating the initial volume of Metavista hydrogen tank, the new internal volume was estimated. The following dimensions can be obtained as in Table 12:

Table 12: Front tank dimensions

[Metavista industries, 2022]

External length	7 m
Height	2.5 m
Width	5 m
External Volume	87.5 m^3
Internal Volume	64.7 m^3

2. Case 2

For this case, the empty space in the adjacent compartments is not considered as usable. Hence, only the space available after removing the existing fuel tanks can be used for storing the new fuel. The Table 13 shows the tanks that will be replaced on the new propulsion system:

Table 13: Tanks that will be replaced

Sr. No.	Tank	Content	Volume(m^3)
5	TORRTANK/RES.BR.O.TANK BB	F.O	9
6	TORRTANK/RES.BR.O.TANK SB	F.O	9
7	SLAMTANK	SLAM	3
11	BR.O.SPILLTANK	F.O	1
15	DAGTANK BR.O	Fuel	8
18	SMORJOLJETANK	Lubr.oil	5
19	BR.O.TANK BB	F.O	40
20	BR.O.TANK MID	F.O	40
21	BR.O.TANK SB	F.O	40

Only the last three tanks (BR.O.TANK) have enough volume for the replacement of a hydrogen tank. These tanks can provide an approximately $120 m^3$ of space which can be used for storing hydrogen.

The HISO Metavista hydrogen tanks should be designed accordingly in order to have three tanks with an external dimension of $40 m^3$ each.

4.8 Endurance

Based on the available storage for LH_2 and C_NH_3 , the endurance for different operations can be calculated as follows: For C_NH_3 at 10 bar, the size and the capacity of the tanks can be assumed to be the same since the commercial availability of these tanks for mobility applications is limited. The general formula for estimating the endurance is as per Equation 9:

$$Endurance(Days) = \frac{Available\ fuel\ storage\ (kg)}{Maximum\ energy\ consumption\ in\ a\ day\ for\ the\ operation\ (kg/day)} \quad (9)$$

4.9 Minimum range

The minimum range of the ship with the new propulsion system can be estimated for transport operation. During transport operation, activities like buoy picking, ice breaking do not happen. These activities vary from case to case. Hence, the fuel consumption during these movements will be different for each case. Because of this reason, the range of the ship cannot be estimated for other operations. During transport operation, the ship travels from one port to another or from port to the working location. Hence, the fuel consumption pattern during this movement is fairly steady during the whole journey. The range for transport operation can be estimated as per Equation 10:

$$Range(Nm) = \frac{Available\ fuel\ storage\ (kg)}{Fuel\ consumption\ per\ Nm\ (kg/Nm)} \quad (10)$$

The fuel consumption per Nm for transport operation can be calculated by dividing the maximum fuel consumption per day (kg) by the maximum distance travelled.

4.10 Stability calculations

Stability calculations play a major role not only to ensure the safety of the crew, personnel and cargo onboard, but also to determine the angle at which the deck edge of the ship is likely to submerge. It was important to evaluate them for this project since there are major changes in propulsion system. These changes may impact various parameters of the ship and the way the ship operates mechanically. Hence, the calculations were performed for M/S Scandica so that capsizing will be prevented on different loading conditions. Stability calculations were performed for the layout of Case 1 of the hydrogen propulsion system. Case 1, as described in Section 4.7 refers to the idea of using the space which was evaluated from the space of the tanks that were removed from the initial design plus other spaces that looked empty in the adjacent compartments in the tank arrangement.

The following steps were followed:

1. Import of empty hull on MAXSURF.
2. Adding the location of all existing tanks.
3. Adding the location of the new tanks.
4. Adding the weight of every tank.
5. Adding the lightship weight.
6. Running the simulation and observing the results.

The stability calculations that were performed for the initial design of the vessel were not considered.

5 Results

5.1 Daily operational profile

After the analysis, the following results were obtained: For selecting the times for departure, working, transit and returning to the port, a bell curve for days on which fairway maintenance was carried out was plotted. Results are presented on Figure 25, Figure 26 and Figure 27. A bell curve was formed to select the optimum time for different activities conducted during the fairway maintenance operation.

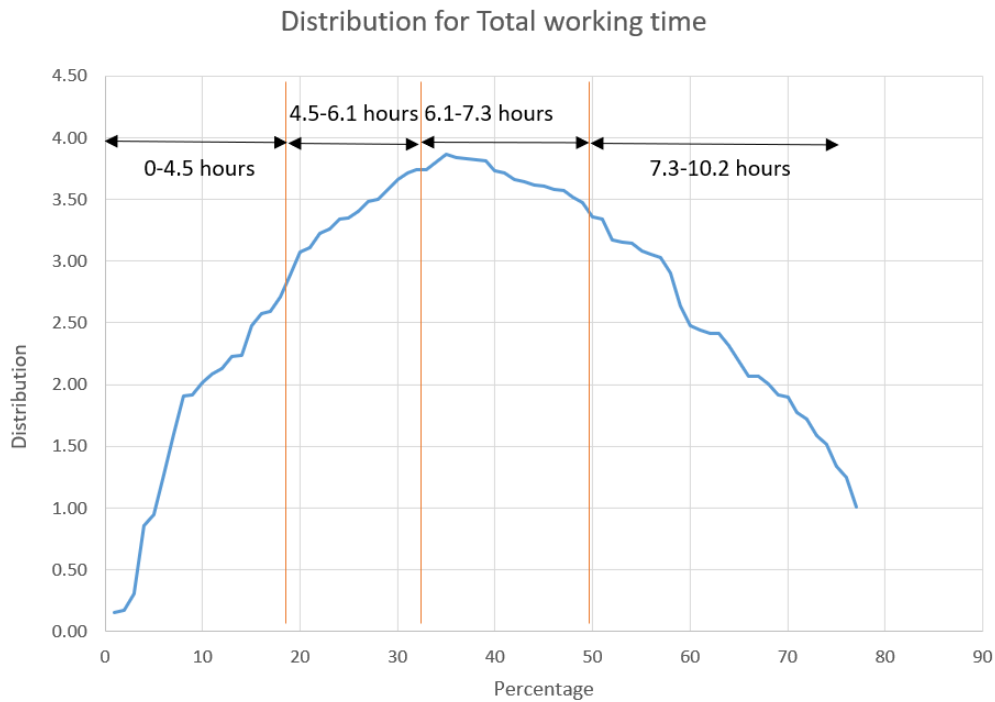


Figure 25: Bell curve for total working time for fairway maintenance

The total working time is the time from the departure of the ship from port to its arrival back at the port per day.

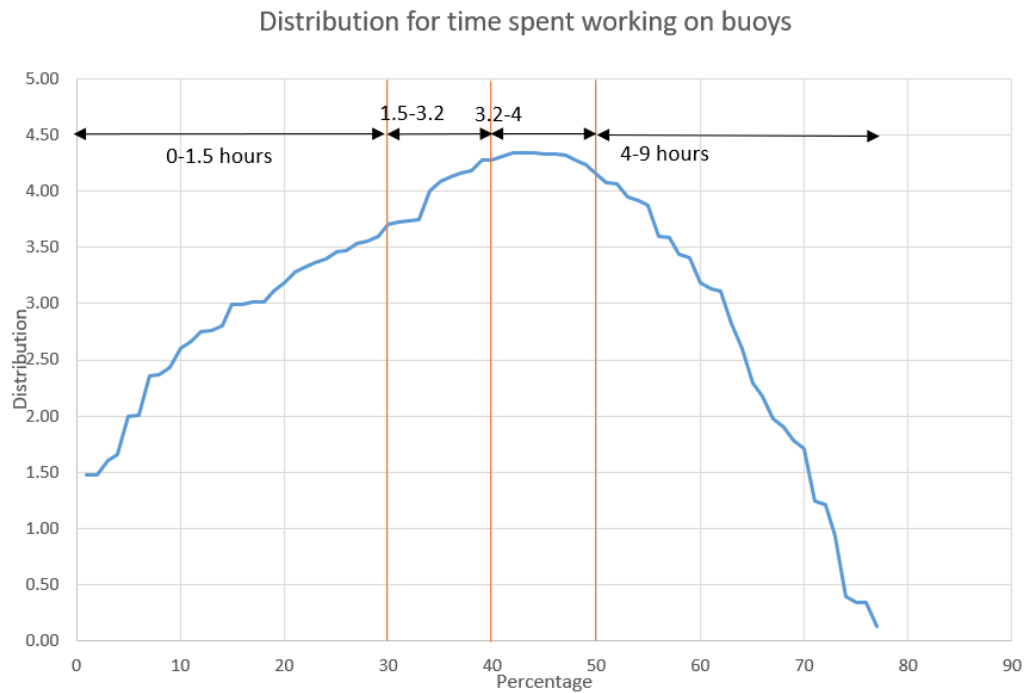


Figure 26: Bell curve for total time worked on buoys

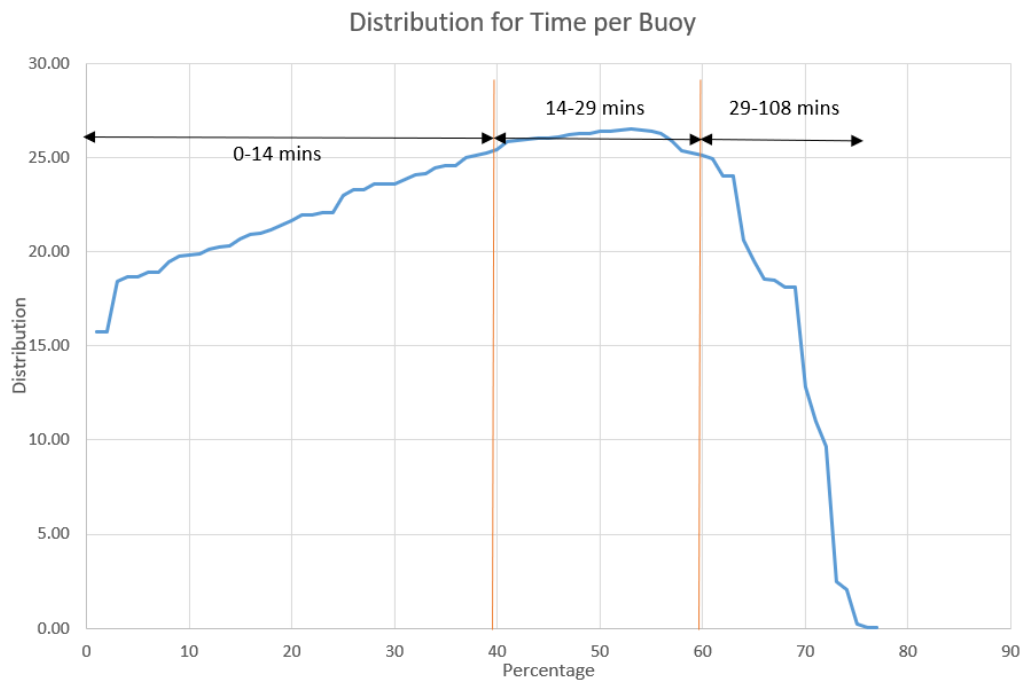


Figure 27: Bell curve for total time worked per buoy

The values at the centre of the bell curve are the most occurring values. Hence, these values were selected. The difference between total working time(which includes everything from departure until returning back to the port) and the total time worked per buoy multiplied by the number of buoys worked on that day, gave the transit time between the the stops. The actual time worked, which is the amount of time the ship spends maintaining the buoys is readily available from the curve. These times are fed in the operational profile for fairway maintenance and the Table 14 is a result of it: All the values are for Load condition 6 having a displacement of 1315 tonnes.

Table 14: Operational profile of a typical day for fairway maintenance

	El. load case	Distance	Time	Avg. speed	Sea margin
Fairway maintenance		[nm]	[h]	[knots]	[%]
<i>Over night</i>	In port	0	8	0	0
<i>To location</i>	Normal transit	20.5	2.1	10	15
<i>Working</i>	DP (working)	25.9	3.2	8	20
<i>Between locations</i>	Transit between	21.9	3.1	7	10
<i>To port</i>	Normal transit	15	1.5	10	15
<i>Over night</i>	In port	0	6.1	0	0

The operational profile for ice-breaking can be seen in Table 15. All the values are for Load condition 6 having a displacement of 1315 tonnes.

Table 15: Operational profile of a typical day for ice breaking

	El. load case	Distance	Time	Avg. speed	Sea margin
Icebreaking		[nm]	[h]	[knots]	[%]
<i>Over night</i>	In port	0	5.67	0	0
<i>To location</i>	Ice breaking	16.3	2.03	8	30
<i>Working</i>	Ice breaking	25.6	3.65	7	40
<i>Maneuvering</i>	Maneuvering	1.1	0.55	2	40
<i>To port</i>	Ice breaking	14.7	2.1	7	30
<i>Over night</i>	In port	0	10	0	0

The operational profile for transport can be seen in Table 16. All the values are for Load condition 6 having a displacement of 1315 tonnes.

Table 16: Operational profile of a typical day for transport

	El. load case	Distance	Time	Avg. speed	Sea margin
Transport		[nm]	[h]	[knots]	[%]
<i>Over night</i>	In port	0	5.7	0	0
<i>To First Location</i>	Normal transit	41.33	4.13	10	15
<i>Transit</i>	Transit between	25.48	2.3	11	15
<i>To Port</i>	Normal transit	20.35	1.85	11	15
<i>Over night</i>	In port	0	10	0	0

To put this all together, an overview of how the ship operates in a year and how it's day-to-day activities are carried out can be achieved. The Figure 28 represents it.

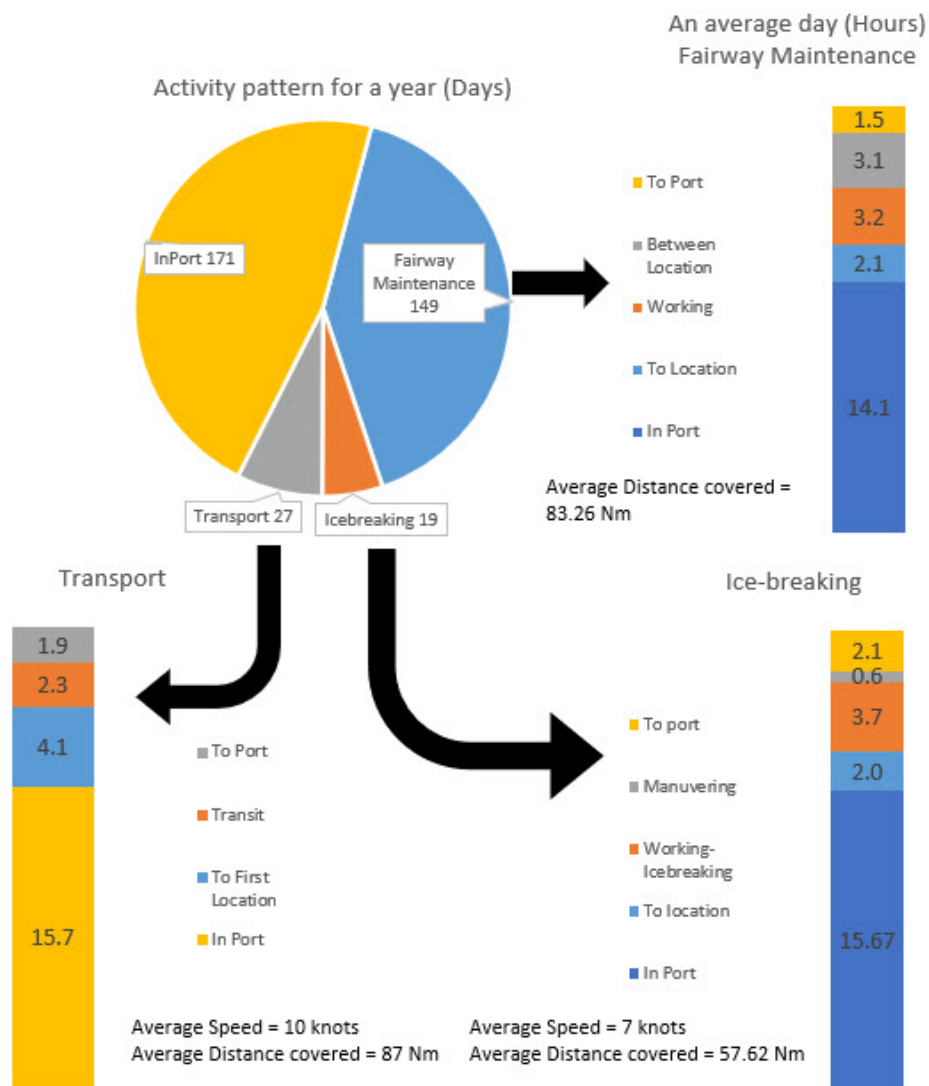


Figure 28: Activity Pattern over a year

5.2 SFC of the three different propulsion systems

For the existing propulsion system, the LHV of MGO is 42.7 MJ/kg as given in Table 1.

1 kWh = 3.6 MJ

Therefore,

$$\frac{42.7}{3.6} = 11.86 \text{ kWh/kg}$$

11.86 kWh/kg = 0.084 kg/kWh

Efficiency of main engine = 38%

Therefore, the SFC for main engines =

$$\frac{0.084}{0.38} * 1000 = 221 \text{ g/kWh}$$

For auxiliary engines,

Efficiency of auxiliary engine = 38.3%

Therefore, the SFC for auxiliary engines =

$$\frac{0.084}{0.383} * 1000 = \mathbf{219.3 \text{ g/kWh}}$$

For the hydrogen propulsion system, the LHV of hydrogen is 120.1 MJ/kg as given in Table 1.

1 kWh = 3.6 MJ

Therefore,

$$\frac{120.1}{3.6} = 33.33 \text{ kWh/kg}$$

33.33 kWh/kg = 0.030 kg/kWh

Efficiency of the fuel cell = 53.5%

Therefore, the SFC =

$$\frac{0.030}{0.535} * 1000 = \mathbf{56 \text{ g/kWh}}$$

For the ammonia propulsion system, the LHV of compressed ammonia is 18.8 MJ/kg as given in Table 1. Commercially available SOFC for mobility applications are limited to 60 kW size [Ryste, 2019].

They have an operating efficiency of 60%. The SFC for ammonia is calculated as follows:

1 kWh = 3.6 MJ

Therefore,

$$\frac{18.8}{3.6} = 5.22 \text{ kWh/kg}$$

5.22 kWh/kg = 0.191 kg/kWh

Efficiency of the fuel cell = 60%

Therefore, the SFC =

$$\frac{0.19}{0.6} * 1000 = \mathbf{319 \text{ g/kWh}}$$

5.3 Consumption estimation for a day

Based on the process mentioned in Figure 14, the following results were obtained for the three different propulsion system for the described operational profile for all three operations. Table 17 shows the fuel consumption of MGO per day for the average operational profile.

Table 17: Consumption of MGO for average operational profile per day

Average	Fuel consumption								
	MGO								
Operation	ME			AE			Total		
	(kg)	(kWh)	(m ³)	(kg)	(kWh)	(m ³)	(kg)	(kWh)	(m ³)
Fairway Maintenance	1 499	17 782	1.6	841	9 975	0.9	2 340	27 756	2.5
Ice-breaking	2 858	33 900	3.1	917	10 878	1.0	3 776	44 779	4.1
Transport	1 661	19 701	1.8	732	8 684	0.8	2 393	28 385	2.6

Table 18 shows the fuel consumption of hydrogen per day for the average operational profile.

Table 18: Consumption of LH_2 for average operational profile per day

Average	Fuel consumption								
	H2 PEMFC								
Operation	ME			AE			Total		
	(kg)	(kWh)	(m^3)	(kg)	(kWh)	(m^3)	(kg)	(kWh)	(m^3)
Fairway Maintenance	363	12 197	5.1	191	6 410	2.7	554	18 606	7.8
Ice-breaking	721	24 242	10.2	112	3 771	1.6	834	28 013	11.8
Transport	406	13 653	5.7	32	1 073	31.9	438	14 726	37.7

Table 19 shows the fuel consumption of ammonia per day for the average operational profile.

Table 19: Consumption of CNH_3 for average operational profile per day

Average	Fuel consumption								
	NH3 FC								
Operation	ME			AE			Total		
	(kg)	(kWh)	(m^3)	(kg)	(kWh)	(m^3)	(kg)	(kWh)	(m^3)
Fairway Maintenance	2 067	10 707	3.4	1 086	5 627	2.4	3 153	16 334	5.8
Ice-breaking	4 108	21 281	6.7	306	1 586	0.5	4 415	22 868	7.2
Transport	2 314	11 986	3.8	236	1 223	0.4	2 550	13 209	4.2

These are the results for the average operational profile for different operations. Although they show an average energy requirement for the ship, it is not a fair method to determine the endurance and range of the ship based on average values. There are several instances when the operational profile is more busy than the average one. Hence, it will lead to energy requirement more than the average operational profile and overestimation of endurance and range. In order to avoid this, energy requirement for the most energy intensive operational profile was also calculated. Table 20 shows the maximum fuel consumption of MGO for a day based on the operational profile of the most energy intensive day.

Table 20: Consumption of MGO for maximum operational profile per day

Maximum	Fuel consumption								
	MGO								
Operation	ME			AE			Total		
	(kg)	(kWh)	(m^3)	(kg)	(kWh)	(m^3)	(kg)	(kWh)	(m^3)
Fairway Maintenance	4 252	50 425	4.6	944	11 192	1.0	5 195	61 617	5.6
Ice-breaking	4 457	52 863	4.8	1 008	11 959	1.1	5 466	64 822	5.9
Transport	4 858	57 611	5.3	851	10 088	0.9	5 708	67 699	6.2

Table 21 shows the maximum fuel consumption of hydrogen for a day based on the operational profile of the most energy intensive day.

Table 21: Consumption of LH_2 for maximum operational profile per day

Maximum	Fuel consumption								
	H2_PEMFC								
Operation	ME			AE			Total		
	(kg)	(kWh)	(m^3)	(kg)	(kWh)	(m^3)	(kg)	(kWh)	(m^3)
Fairway Maintenance	1 068	35 893	15.1	217	7 302	3.1	1 286	43 195	18.2
Ice-breaking	1 108	37 243	15.7	197	6 629	2.8	1 306	43 873	18.4
Transport	1 229	41 279	17.4	194	6 512	2.7	1 422	47 791	20.1

Table 22 shows the maximum fuel consumption of ammonia for a day based on the operational profile of the most energy intensive day.

Table 22: Consumption of Compressed NH_3 for maximum operational profile per day

Maximum	Fuel consumption								
	NH3_FC								
Operation	ME			AE			Total		
	(kg)	(kWh)	(c)	(kg)	(kWh)	(m^3)	(kg)	(kWh)	(m^3)
Fairway Maintenance	6 083	31 510	10.0	1 237	6 410	2.0	7 320	37 920	12.0
Ice-breaking	6 312	32 695	10.3	1 124	5 820	1.8	7 435	38 515	12.2
Transport	6 996	36 238	11.5	1 104	5 717	1.8	8 099	41 955	13.3

The fuel consumption for the maximum operational profile is almost thrice as the fuel consumption for average operational profile. This shows how much the operation of the ship varies from day to day for the three different operation types. Therefore, it will be an overestimation if the endurance and the range of the ship is calculated based on the fuel consumption for average operational profile.

5.4 Size of components

Based on the components selected in Section 4, the size and the number of components selected is as follows:

5.4.1 Fuel cells

Fuel cells of same specifications are required for fulfilling the propulsion and auxiliary load. The maximum power requirement for propulsion as mentioned in section 4.5 is 2170 kW and the maximum power requirement for auxiliary load according to the operational profile is 350 kW. Hence, a total of 2520 kW is required. Therefore, 13 fuel cells of 200 kW size each, having a total output of 2600 kW are required to fulfill this requirement. In case of hydrogen, these are Ballard PEMFC and in case of ammonia, they are SOFC.

5.4.2 Motor

As mentioned in Section 4.4.2, Siemens SIMOTICS HT Series provides the closest requirements. Table 23 shows the specifications of this motor.

Table 23: Motor Specifications

[Siemens, 2022]

High-Torque Motor SIMOTICS HT Serie HT-direct	
Rated Power	2100 kW
Rated torque	42000 Nm
Rated Voltage	690 V
Efficiency	97%
Weight	9 tonnes
External dimensions	L=5.4m,W=4.33m,H=3m

5.4.3 Hydrogen storage capacity

Since there are two different cases of the available space, there are two different fuel storage capacities.

1. Case 1

For the middle tank as the depth of the ship is 5 meters, it is assumed that two tanks on top of each other can be fitted. This will give a total LH_2 storage volume of $106 m^3$.

For the front tank as the depth is 5 meters and it is assumed that two tanks can be fitted, one on the top of the other. This will give a total LH_2 storage volume of $129.4 m^3$.

The LH_2 storage volume of the tanks were estimated based on the original value of Metavista hydrogen tank.

To conclude **235.4** m^3 of LH_2 can be stored for case 1.

2. Case 2

For this case, the external volume of each tank, as mentioned before, is $40 m^3$. By interpolating the original values of a Metavista HISO Series tanks with this case, approximately $29.6 m^3 LH_2$ can be stored in each tank. There are three tanks. Hence, **88.8** m^3 of LH_2 can be stored.

5.4.4 Ammonia storage capacity

For ammonia, the volume of the available space will to be the same as hydrogen. There is not enough information to provide sufficient data on the selection of an approved ammonia tank for this application, but some approximations can always be helpful for future work. Therefore, volumetric availability on both case one and two can be seen below.

1. Case 1

It is assumed that same amount of ammonia in m^3 can be stored as hydrogen. Therefore, approximately, **235.4** m^3 of ammonia can be stored in compressed form at a pressure of 10 bar.

2. Case 2

For this case, approximately, **88.8** m^3 of ammonia can be stored in compressed form at a pressure of 10 bar.

The size of the components selected can be summarized in Table 24.

Table 24: Size of different components

Component	Size	Units	Total
PEMFC / SOFC	200 kW	13	2.6 MW
Motor	2237 kW	1	2.2 MW
Tank Case 1	235.4 m^3	1	235.4 m^3
Tank Case 2	88.8 m^3	1	88.8 m^3

Based on this component selection and size, the concept design for hydrogen propulsion system can be seen in Figure 29 and that for ammonia can be seen in Figure 30.

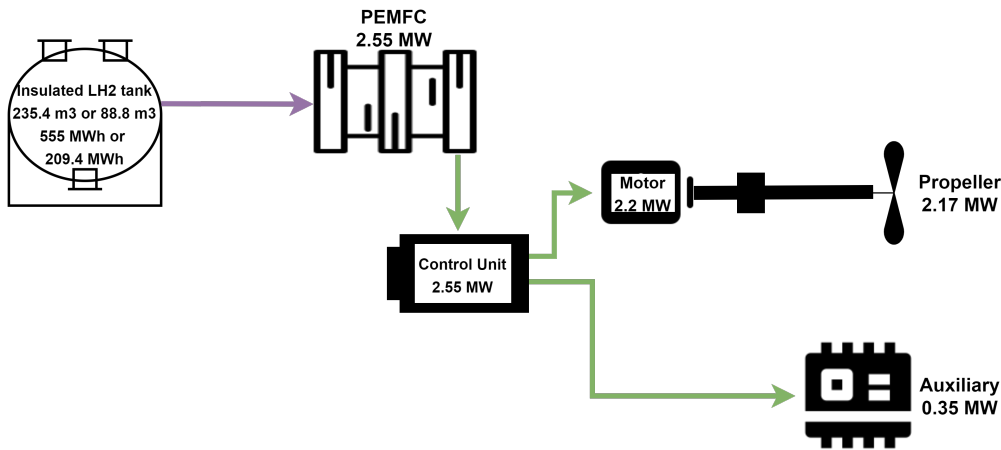


Figure 29: Concept design for hydrogen propulsion

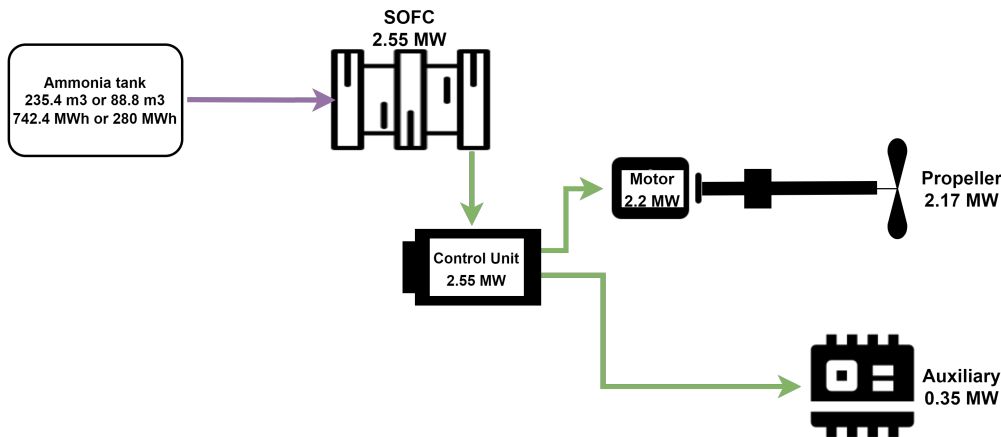


Figure 30: Concept design for ammonia propulsion

Although the volumetric size of both the tanks is the same, the amount of fuel that they can store in terms of energy content and weight is different. This is because of different energy density of hydrogen and ammonia as mentioned in Table 1.

5.5 Endurance

Based on the tank size available for LH_2 and Compressed NH_3 , the amount of fuel that can be stored for both cases is given in Table 25.

Table 25: Fuel storage capacity

	Space Available	Tank Size	Amount of LH ₂	Energy Content	Amount of C_NH ₃	Energy Content
	m ³	m ³	kg	MWh	kg	MWh
Case 1	412	235.4	16666.3	555.0	143594.0	742.4
Case 2	153	88.8	6287.0	209.4	54168.0	280.0

The endurance of the ship depends on the available fuel storage capacity and on the type of operation that the ship is performing. The endurance of the case study ship during different operations for hydrogen and ammonia is shown in Figure 31.

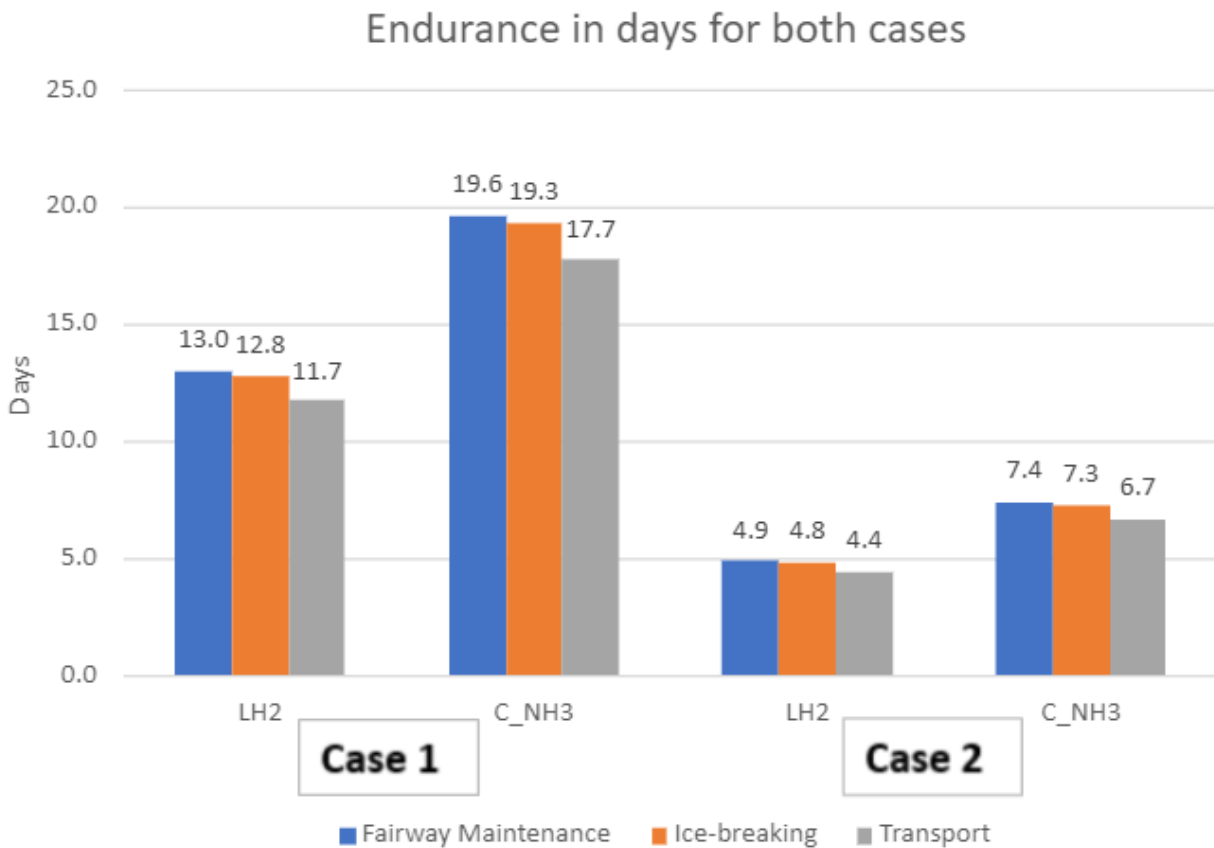


Figure 31: Endurance of the ship in days for both cases of storage space available

5.6 Minimum range

As mentioned in Section 4.9, the minimum range can be calculated using the fuel consumption per Nm for transport operation. The fuel consumption per Nm for -

H_2 _PEMFC =

$$\frac{1422.4(kg)}{175.76(Nm)} = 8.1kg/Nm$$

Compressed NH_3 _SOFC =

$$\frac{8099.4(kg)}{175.76(Nm)} = 46.1kg/Nm$$

Based on this, the estimated minimum range that the case study ship could travel for transport operation with hydrogen and ammonia is shown in Figure 32.

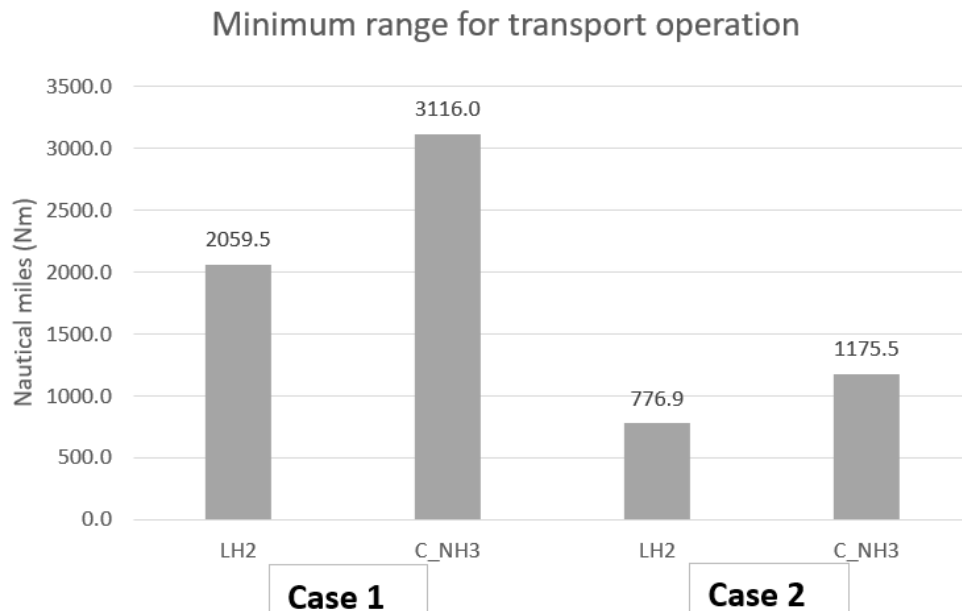


Figure 32: Minimum range for transportation in Nm

It can be seen that both the endurance and range is higher for both cases for using ammonia as fuel. Compressed ammonia has higher volumetric energy density compared to liquid hydrogen as seen in Table 1. It results in more fuel storage and hence, a higher range more days of operation.

5.7 Energy flow over the year

The energy flow for all three cases is shown in Figure 33. The energy flow diagram shows the flow of energy from primary source till they become usable while accounting for all the efficiencies and losses. This is the energy flow diagram for the average annual consumption which is calculated according to the activity pattern of the ship.

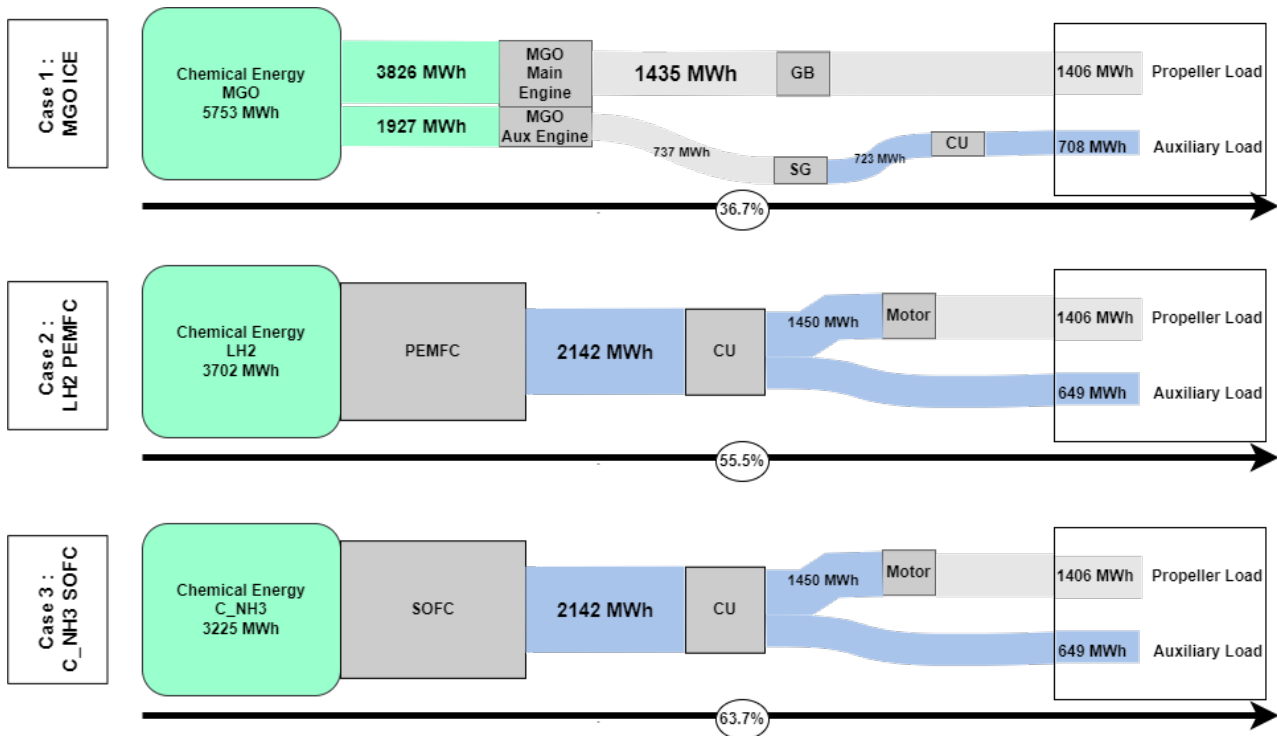


Figure 33: Energy flow for the three different propulsion systems with overall efficiencies

It can be observed that replacing the old propulsion system with the new propulsion leads to increase in overall efficiency of the system which was expected since the main power conversion technologies have a higher efficiencies than conventional engines.

The layout diagram for hydrogen propulsion system which involves various components can be seen in Figure 34.

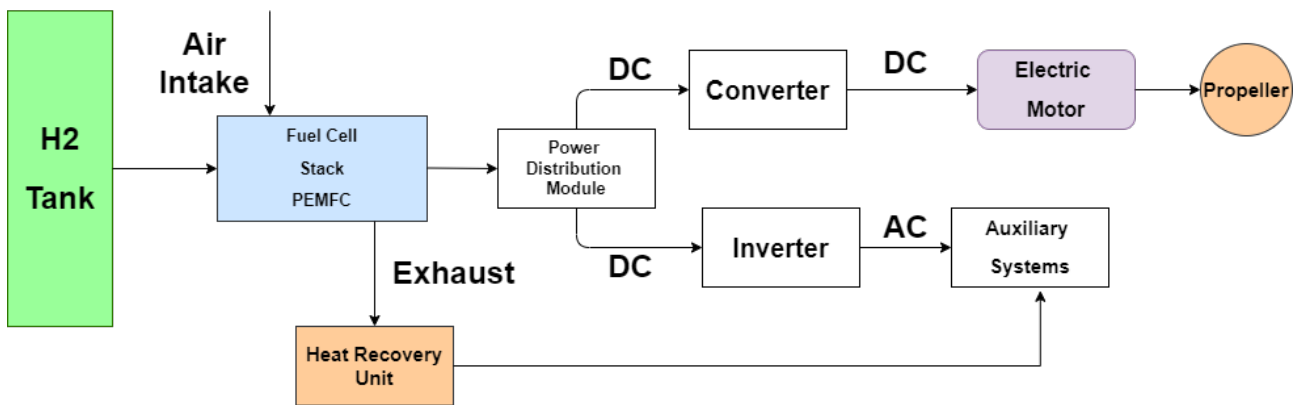


Figure 34: Layout for Hydrogen Propulsion system

The layout diagram for ammonia propulsion system which involves various components can be seen in Figure 35.

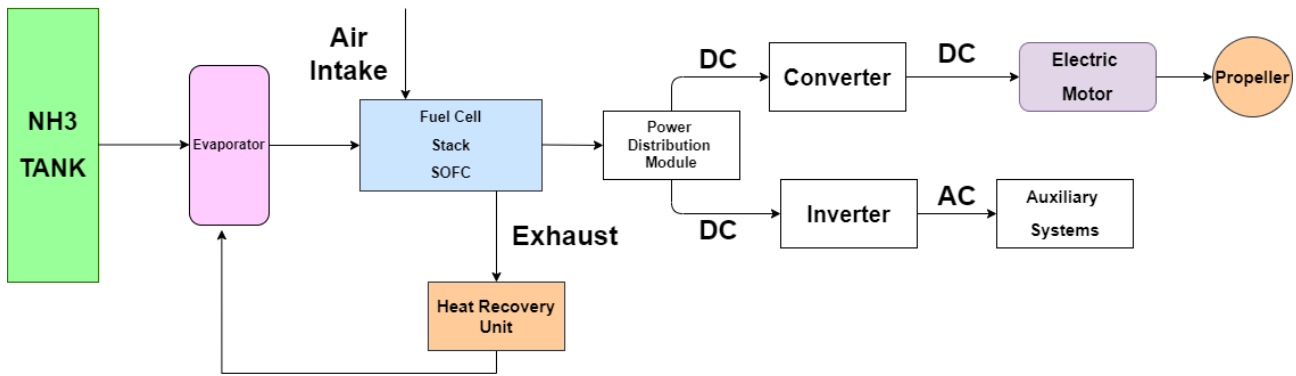


Figure 35: Layout for Ammonia Propulsion system

5.8 Tank arrangement

Similarly as before, the hydrogen tanks were implemented on MAXSURF in order to find out the capacity available as well as the stability change. In Figure 36, the new arrangement can be seen.

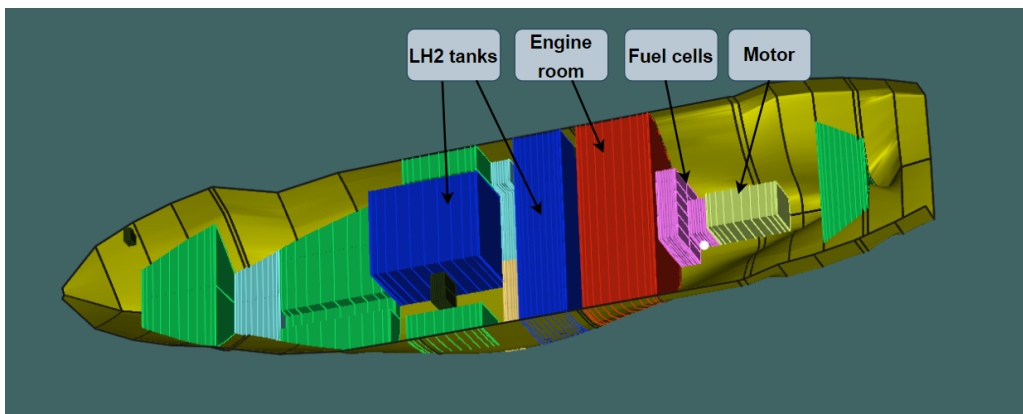


Figure 36: Hydrogen arrangement

The dimensioning of every component was based on the data that are provided under the Section 4.

5.9 Lightship estimation

The lightship weight had to be inserted on MAXSURF as it is part of the initial specifications of the vessel. The initial lightship weight differs from the new one as the propulsion system is changed. Tables 26 and 27 show the total weight of different components that are required for the estimation of the new lightship weight.

Table 26: Weight estimation of main components from the diesel propulsion system

	Weight (kg)	Total weight (kg)
Main Engine(x2)	1750	3500
Generators(x4)	1075	4300

Table 27: Weight estimation of main components for the hydrogen concept

	Weight (kg)	Total weight (kg)
Fuel cells(x13)	1050	13650
Motor	9000	9000
Middle hydrogen tank	3490	3490
Front hydrogen tank	4250	4250

The two main engines and the four generators are the components that are currently being used by the vessel M/S Scandica. Based on the information given, the main engines are the Hedemora diesel engines and it is assumed to have similar specifications with the D16-M6 Volvo Penta diesel engine [Volvo Penta, 2016]. Similarly, the generators on board are the D9 Volvo Penta diesel generators [Volvo Penta, 2019].

The initial lightship weight is **939.8 mt** based on the stability book that was provided by the Swedish maritime administration. Engines and generators are part of the initial lightship weight. For hydrogen propulsion system, the weight of the other components that are presented on the table 27 have to be added and the weight of the main engine and generators that is presented on the table 26 has to be removed. Therefore, the new lightship weight with the hydrogen propulsion system is **962.9 mt**.

5.9.1 Stability results on different loading conditions

The figure 36 represents the tank arrangement which remains the same with minor changes in the location of each tank. The changes were based on obtaining the lowest trim possible. Equilibrium, large angle stability, and safety criterion for the ship are presented in this section. The calculations are performed in four conditions including full cargo-empty ballast, full cargo-full ballast, empty cargo-empty ballast, and empty cargo-full ballast. The tests are performed for different scenarios to make sure that no matter what happens with the loading condition, the vessel will not capsize. In the end the optimal ballast conditions for full and empty cargo will be shown in order to obtain a 0 keel trim.

Equilibrium

The trim for the ideal condition should have a value that is close to zero, while the trim for all other conditions can be allowed to have values within the range of one meter. Thus, the trim angle is low enough to be neglected. Regarding a high trim on the bow, the aft perpendicular draft shall be controlled to have a value that is higher than the upper propeller tip, so the propeller emergence incident is avoided during sailing. If the propeller emerges from the water surface, the problem with cavitation, noise and vibration will occur. A ship with the higher transverse metacentric height is safer than the lower one. In this case, full load condition stability performance is safer than empty condition. However, having a higher transverse metacentric height is not always good, because the rightening moment to push the ship back to the upright position is higher and results in the higher acceleration. Therefore, it is not good from the sea keeping point of view. This is a compromise to think about. On the Table 28 below, the critical information on different load cases are presented.

Table 28: Equilibrium data for all load cases

Load case	Draft amid(m)	Draft AP (m)	Draft FP (m)	Trim (m)	Displacement (tons)	GMt(m)
Full cargo-empty ballast	3.098	3.567	2.629	0.938	1037	2.051
Full cargo-full ballast	3.594	3.139	4.049	-0.910	1248	2.054
Empty cargo-empty ballast	3.155	3.316	2.994	0.322	1056	1.946
Empty cargo-full ballast	3.563	3.113	4.012	-0.899	1233	2.040

All four load conditions were performed for the worst case scenario. The results are not the ideal in aspects of draft and trim. On the other hand they are good enough for preventing severe motions.

In Table 29, the change of the center of gravity based on the different loading conditions can be seen.

Table 29: Loading summary

Load case	Longitudinal arm m.	Transversal arm m.	Vertical arm m.
Full cargo-Empty ballast	-23.678	-0.042	-0.172
Full cargo-Full ballast	-25.494	-0.046	-0.352
Empty cargo-Empty ballast	-23.612	-0.021	-0.145
Empty cargo-Full ballast	-25.482	-0.029	-0.334

In case of an empty cargo or full cargo it is important to know how the ballast load should be compromised in order to obtain a 0 keel condition without any trim. It found, that a 0 trim can be obtained if front ballast tanks 24, 25, 26 are all loaded at 30%. The hydrogen tanks are placed close to the center of gravity so it can be assumed that no matter of their load condition they do not affect the trim of the vessel. The only difference is the change on draft. It changes depending on the amount of hydrogen that is stored. Draft at these load conditions is varying between 3.1-3.2 m.

Large angle stability

The curve of statical stability or GZ curve is shown in figure 37. It is used to determine the ship stability performance. If the ship has a positive GZ value, the ship has the righting moment that can push the ship back to the upright position when it rolls. When the ship is in the upright position, the GZ value shall be equal to zero, so the ship has no heel when it stays still. Furthermore, the area under GZ curve refers to the energy that the ship can absorb when it encounters with the heeling force such as wind or wave. The curve depicts that the ship has a higher restoring moment in ballast condition than in full loaded and is therefore more stable in ballast condition than in full loaded.

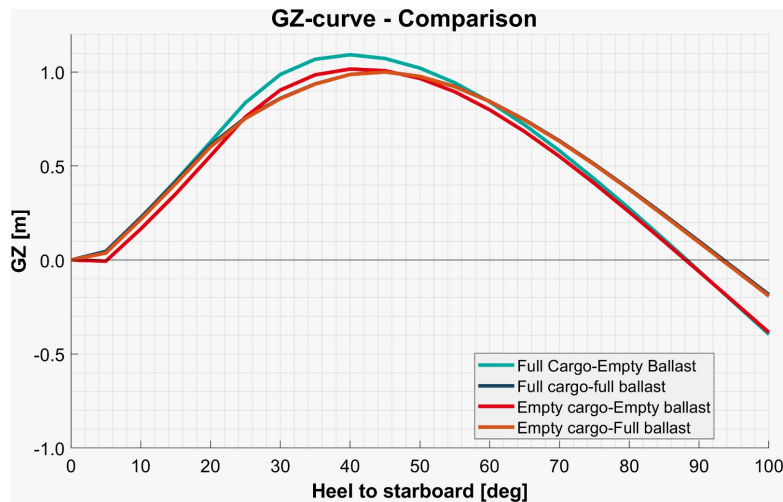


Figure 37: GZ-curves comparison

Summarized, the maximum GZ-curve at a given angle is shown in Table 30.

Table 30: Max GZ for each condition

Condition	Max GZ [m]	Angle[deg]
Full cargo-empty ballast	1.092	35
Full cargo-full ballast	1.001	39.1
Empty cargo-empty ballast	1.017	35.9
Empty cargo-full ballast	1.001	39.1

Safety criterion

After getting the result from large angle stability calculation, the stability safety criterion needs to be fulfilled. In this case, the general rule for all ships is applied referred to IMO (1993). There are six main rules for stability that the ship needs to comply with. The table 31 shows that the ship passes all regulations for all conditions safely. To sum up, the ship is safe for the intact stability point of view.

Table 31: IMO Stability Regulation

Full cargo-empty ballast			
Criteria	Requirement	Actual result	Status
The dynamic stability from 0 to 30 deg	$\geq 3.15\text{m} \cdot \text{deg}$	18.3080	Pass
The dynamic stability from 0 to 40 deg	$\geq 5.16\text{m} \cdot \text{deg}$	29.1572	Pass
The dynamic stability from 30 to 40 deg	$\geq 1.72\text{m} \cdot \text{deg}$	10.8492	Pass
Max GZ shall be at a heel angle	$> 30\text{deg}$	1.092	Pass
GZ at 30 deg heel	$> 0.2\text{m}$	35.0	Pass
GMt	$> 0.15\text{m}$	2.043	Pass
Full cargo-full ballast			
Criteria	Requirement	Actual result	Status
The dynamic stability from 0 to 30 deg	$\geq 3.15\text{m} \cdot \text{deg}$	16.8550	Pass
The dynamic stability from 0 to 40 deg	$\geq 5.16\text{m} \cdot \text{deg}$	26.6646	Pass
The dynamic stability from 30 to 40 deg	$\geq 1.72\text{m} \cdot \text{deg}$	9.8096	Pass
Max GZ shall be at a heel angle	$> 30\text{deg}$	1.001	Pass
GZ at 30 deg heel	$> 0.2\text{m}$	39.1	Pass
GMt	$> 0.15\text{m}$	2.049	Pass
Empty cargo-Empty ballast			
Criteria	Requirement	Actual result	Status
The dynamic stability from 0 to 30 deg	$\geq 3.15\text{m} \cdot \text{deg}$	16.1681	Pass
The dynamic stability from 0 to 40 deg	$\geq 5.16\text{m} \cdot \text{deg}$	26.2622	Pass
The dynamic stability from 30 to 40 deg	$\geq 1.72\text{m} \cdot \text{deg}$	10.0941	Pass
Max GZ shall be at a heel angle	$> 30\text{deg}$	1.017	Pass
GZ at 30 deg heel	$> 0.2\text{m}$	35.9	Pass
GMt	$> 0.15\text{m}$	1.946	Pass
Empty cargo-Full ballast			
Criteria	Requirement	Actual result	Status
The dynamic stability from 0 to 30 deg	$\geq 3.15\text{m} \cdot \text{deg}$	16.6573	Pass
The dynamic stability from 0 to 40 deg	$\geq 5.16\text{m} \cdot \text{deg}$	26.4611	Pass
The dynamic stability from 30 to 40 deg	$\geq 1.72\text{m} \cdot \text{deg}$	9.8038	Pass
Max GZ shall be at a heel angle	$> 30\text{deg}$	1.001	Pass
GZ at 30 deg heel	$> 0.2\text{m}$	39.1	Pass
GMt	$> 0.15\text{m}$	2.037	Pass

6 Discussion

The overall ambition of the study has been to identify the feasibility of alternative fuels to be used on a specific vessel. The approach assesses more specifically how well hydrogen and ammonia can be used as the main fuels on a working boat which is operating around the Swedish coast. Based on the results, a great potential can be seen around these fuels. Despite the fact of their low density and challenges around storage, it has been identified that it is feasible. A more detailed approach in terms of feasibility of manufacturing of the vessel and infrastructure availability needs to be carried out. Hydrogen refuelling infrastructure is developing but it is not practical enough yet for the marine applications [Pratt and Klebanoff, 2016]. The transportation of hydrogen to ports, where it is needed for refueling, takes time and lead to time management issues between the vessel and supplier. However, streamlining the transportation of these fuels with trucks and refueling the tanks onboard can be done to reduce the refuelling time. Ammonia on the other hand, is in early stage of its use as a fuel to the marine industry [Haldor Topsoe, 2020]. Comparatively, more developed energy conversion technologies are available for hydrogen than ammonia. This also applies to other supporting components like reactors and evaporators for fuel cells. Since ammonia is only recently considered as an alternative fuel for marine propulsion, components specific for marine applications are still under development. For storage, ammonia has been traded as anhydrous ammonia across the continents for decades. Potential ammonia storage options for compressed ammonia for onboard storage propulsion applications are under development and are expected to have lower cost than hydrogen storage [Haldor Topsoe, 2020].

Emissions from the production of these fuels is a bigger challenge. As explained in section 3, only a small percentage of these fuels are being produced from green sources such as solar or wind power. Further studies are required on the production of these fuels as what matters is not just the emissions from the marine industry but the overall emissions from their life cycle. On the other hand, projects such as the Energy observer, prove that there is a possibility for change. It produces green hydrogen using solar and wind power for its propulsion onboard, making it self-sufficient [Energy Observer, 2022]. However, the size and the operational profile of this boat is very different from the case study ship investigated in this master thesis.

The operational profile used for the conceptual design of the case study ship which is derived for the different operational conditions is an approximation. Better recording techniques would lead to a more accurate representation of the working of the ship. There were multiple approaches to estimate the energy consumption. This included energy estimation per day and per nautical mile from the fuel consumption that was recorded. Although this would have given an estimation of consumption, the actual requirement for different operations would have been difficult to estimate due to involvement of multiple mechanical and electrical components and their efficiencies. Therefore, a second method was followed to estimate fuel consumption for different operations based on the operational profile while taking different efficiencies into consideration.

The endurance of the ship for this particular project is calculated in days for different operations and the range is calculated only for transport operation in nautical miles since it will change with every movement for other operations. With a different operation pattern, the endurance and range will change but the power required to perform these operations will not be over the maximum conditions that have been considered in this project. The current ship bunkers almost once a month and performs all the different operations. With the use of alternative fuels, space available for storage of fuel is of more importance. Since this is a retrofitting project, the space that could be used, is limited. This limits the designing parameters and hence limits the range. Hence, a bottom up approach had to followed while estimating the endurance and range of the ship. For this project, the endurance of the ship is calculated using the maximum energy consumption case whereas similar study conducted by Klebanoff et al. [2020] for a research vessel shows calculation of days of operations using the average

energy consumption. This may result in overestimation of the days of operation. While designing a new ship, there is a liberty to determine the endurance and range of the ship according to the functions that it needs to perform and size a fuel storage accordingly. The Alsterwasser ship that operated in 2008, faced a similar problem of limitation of range by using hydrogen fuel cells.

Regarding the study of the replacement of the existing diesel engine, a couple things needs to be considered. To begin with, it has to be mentioned that limited amount of changes could be done. The work was carried out based in an already existing hull that has been designed to operate on diesel engines and generators. The available space on board for adding extra components is limited, since it is narrow. The approach was to remove the existing diesel propulsion system components and replace it with a new one. For the ammonia powered SOFC propulsion system, there is a need to use electric batteries to cover the energy demand during the startup time of the SOFC and the load changes. The possibility to use them with hydrogen powered PEMFC can also be explored to cover peak energy demands. Two different cases were considered for designing the tank arrangement. Comparing the two cases, it is obvious that case 1 can provide a higher range of operation. These storage options do not take any safety regulations into consideration and are just theoretically available spaces. Therefore, if all the required safety regulations for onboard storage of hydrogen and ammonia are taken into consideration, the amount of fuel that can be stored will decrease and it will result in decrease of the endurance and range of the ship. As it can be seen from the figure 32, the minimum range that it can be covered with case 1 is more than twice compared to case 2. Electric batteries will also be needed along with the ammonia powered SOFC. SOFCs have a longer starting time and higher temperature [Haldor Topsoe, 2020]. Batteries can cover the demand during this starting time and ensure smooth functioning of the propulsion system. Batteries can also be used along with hydrogen powered PEMFC. They can be used to cover peak demands and sudden increase in power requirement until it can be covered by the fuel cells. The addition of batteries in both the cases will lead to decrease in the space available for fuel storage and hence it will result in reduction in the endurance and the range of the ship.

Stability-wise, generic calculations were performed based on the case 1 where the load change distribution was more severe. Several loading conditions were considered. The trim was managed to be low and the draft to remain close to the original one. A higher efficiency can be achieved if the hull is designed from scratch for this specific propulsion system. Starting a ship design project from scratch with known variables to take into consideration, would have make the project more simple and straight forward. No matter of the loading condition the trim could have been managed to be zero as well as the draft would not exceed the original one in any case. The results would have been more complete and would provided a more accurate overview by performing stability calculation with added weight on deck and on crane. Moreover, having a design of a ship that was designed 40 years ago and trying to replace the propulsion system with alternative fuels brings up many difficulties and limitations. To conclude, with the design of a new hull the resistance could have been managed to be on the lowest levels, something that would increase the efficiency and decrease the consumption.

7 Conclusion

This thesis shows that it is possible to use hydrogen and ammonia as a fuel for propulsion for this case study ship. But it comes with challenges.

- The ship performs various operations and it is difficult to have a standard fuel consumption for a day's activity. The fuel consumption varies for each operation and on parameters specific to the operation like number of buoys and transits in a day for fairway maintenance, thickness of the ice and weather conditions for ice breaking.
- The change in propulsion system leads to replacing existing components like the main engines and auxiliary generators with fuel cells and electric motors along with their supporting components. This changes the weight of the ship, the fuel that it can store and the way the ship operates. Change in the propulsion system also leads to increase in the overall efficiency compared to the existing propulsion system.
- The change in propulsion system leads changes in the the fuel tanks. The existing fuel tanks are replaced by the new ones which are compatible to the new propulsion system. This leads to decrease in the amount of energy that can be stored compared to the existing MGO propulsion system. This is because of heavier and more insulated tanks required for storing hydrogen and ammonia and the lower energy density of the fuels. The fuel storage capacity in terms of weight, is higher for compressed ammonia compared to liquid hydrogen because it has a higher volumetric energy density. It is also higher in terms of energy storage since ammonia has a higher volumetric energy density compared to hydrogen. The change in fuel storage capacity compared to the existing MGO, leads to decrease in the number of days that the ship can operate before refilling. The endurance and range is dependant on the type of operation that the ship is performing and the type of propulsion system. It can be seen that the endurance and range is higher for ammonia propulsion system compared to hydrogen propulsion system. This is primarily due to higher energy conversion efficiency of ammonia SOFC compared to the hydrogen PEMFC and the higher volumetric energy density that ammonia has. Despite this advantage, there are many technological challenges when it comes to using ammonia as fuel. The energy conversion technology is not as developed as hydrogen. Commercially available SOFCs are limited in size. Regulations for using ammonia as fuel are yet to be drafted.
- Ships are complex systems to design, constantly looking for compromise between often contradictory requirements of different stakeholders and laws of physics that in one case favor the design and at the same time deteriorates it. The stability and other parameters of the ship cannot be the same as for the originally designed ship despite the efforts to fit the components in the limited space available. This, however, does not mean that the ship's ability to operate under different load conditions and different environmental conditions is compromised, as illustrated in the stability calculations.

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8 APPENDIX A

8.1 Load % and SFC for the existing MGO engine

Table 32: Load % and SFC for conventional MGO engine

Load	MGO					
	<i>Power</i>	<i>ME</i>	<i>Eff.</i>	<i>Power</i>	<i>AE</i>	<i>Eff.</i>
	[kW]	[g/kWh]	[%]	[kW]	[g/kWh]	[%]
100%	2622	227	37.1%	880	222	38%
99%	2596	227.3	37.1%	871	222.3	37.9%
98%	2570	227.6	37%	862	222.6	37.9%
97%	2543	228.4	36.9%	854	223.4	37.7%
96%	2517	229.2	36.8%	845	224.2	37.6%
95%	2491	230	36.7%	836	225	37.5%
94%	2465	230.8	36.5%	827	225.8	37.3%
93%	2438	231.6	36.4%	818	226.6	37.2%
92%	2412	231.9	36.4%	810	226.7	37.2%
91%	2386	232.2	36.3%	801	224.9	37.5%
90%	2360	232.5	36.3%	792	223.1	37.8%
89%	2334	232.8	36.2%	783	221.3	38.1%
88%	2307	232	36.3%	774	219.5	38.4%
87%	2281	230.5	36.6%	766	217.7	38.7%
86%	2255	229.1	36.8%	757	215.9	39.1%
85%	2229	227.9	37%	748	214.4	39.3%
84%	2202	226.5	37.2%	739	212.9	39.6%
83%	2176	225.1	37.5%	730	211.4	39.9%
82%	2150	223.9	37.7%	722	210.3	40.1%
81%	2124	223.1	37.8%	713	209.2	40.3%
80%	2098	222.3	37.9%	704	208.1	40.5%
79%	2071	221.5	38.1%	695	207.3	40.7%
78%	2045	220.7	38.2%	686	206.5	40.8%
77%	2019	220.5	38.2%	678	206	40.9%
76%	1993	220.3	38.3%	669	205.5	41%
75%	1967	220	38.3%	660	205	41.1%
74%	1940	220.3	38.3%	651	205.5	41%
73%	1914	220.3	38.3%	642	206	40.9%
72%	1888	220.3	38.3%	634	206.5	40.8%
71%	1862	220.3	38.3%	625	207.3	40.7%
70%	1835	220.5	38.2%	616	208.1	40.5%
69%	1809	220.5	38.2%	607	209.2	40.3%
68%	1783	220.5	38.2%	598	210.3	40.1%
67%	1757	220.5	38.2%	590	211.4	39.9%
66%	1731	220.7	38.2%	581	212.9	39.6%
65%	1704	220.7	38.2%	572	214.4	39.3%

Table 33: Load % and SFC for conventional MGO engine

Load	MGO					
	<i>Power</i>	<i>ME</i>	<i>Eff.</i>	<i>Power</i>	<i>AE</i>	<i>Eff.</i>
	[kW]	[g/kWh]	[%]	[kW]	[g/kWh]	[%]
64%	1678	220.7	38.2%	563	215.9	39.1%
63%	1652	220.7	38.2%	554	217.7	38.7%
62%	1626	221.5	38.1%	546	219.5	38.4%
61%	1599	221.5	38.1%	537	220.1	38.3%
60%	1573	221.5	38.1%	528	220.1	38.3%
59%	1547	222.3	37.9%	519	220.1	38.3%
58%	1521	222.3	37.9%	510	221.3	38.1%
57%	1495	222.3	37.9%	502	221.3	38.1%
56%	1468	223.1	37.8%	493	221.3	38.1%
55%	1442	223.1	37.8%	484	221.3	38.1%
54%	1416	223.1	37.8%	475	221.8	38%
53%	1390	223.9	37.7%	466	221.8	38%
52%	1363	223.9	37.7%	458	221.8	38%
51%	1337	223.9	37.7%	449	222.9	37.8%
50%	1311	225.1	37.5%	440	222.9	37.8%
49%	1285	225.1	37.5%	431	222.9	37.8%
48%	1259	225.1	37.5%	422	222.9	37.8%
47%	1232	225.1	37.5%	414	222.9	37.8%
46%	1206	226.5	37.2%	405	223.1	37.8%
45%	1180	226.5	37.2%	396	224.9	37.5%
44%	1154	226.5	37.2%	387	225.5	37.4%
43%	1127	227.9	37%	378	225.5	37.4%
42%	1101	227.9	37%	370	225.5	37.4%
41%	1075	227.9	37%	361	225.5	37.4%
40%	1049	227.9	37%	352	225.5	37.4%
39%	1023	227.9	37%	343	224.1	37.6%
38%	996	229.1	36.8%	334	224.1	37.6%
37%	970	229.1	36.8%	326	224.1	37.6%
36%	944	229.1	36.8%	317	224.1	37.6%
35%	918	229.1	36.8%	308	224.8	37.5%
34%	891	230.5	36.6%	299	224.8	37.5%
33%	865	230.5	36.6%	290	225.3	37.4%
32%	839	230.5	36.6%	282	225.3	37.4%
31%	813	230.5	36.6%	273	225	37.5%
30%	787	230.5	36.6%	264	225.5	37.4%
29%	760	230.5	36.6%	255	225.5	37.4%
28%	734	232	36.3%	246	225.8	37.3%
27%	708	232	36.3%	238	225.8	37.3%
26%	682	232	36.3%	229	226.6	37.2%
25%	655	232	36.3%	220	226.7	37.2%

8.2 Load % and SFC for LH_2 PEMFCTable 34: Load % and SFC for LH_2 _PEMFC

Load	H_2 _PEMFC			Load	H_2 _PEMFC		
	Power		Eff.		Power		Eff.
	[kW]	[g/kWh]	[%]		[kW]	[g/kWh]	[%]
100%	2400	56.02	53.5%	59%	1416	56.02	53.5%
99%	2376	56.02	53.5%	58%	1392	56.02	53.5%
98%	2352	56.02	53.5%	57%	1368	56.02	53.5%
97%	2328	56.02	53.5%	56%	1344	56.02	53.5%
96%	2304	56.02	53.5%	55%	1320	56.02	53.5%
95%	2280	56.02	53.5%	54%	1296	56.02	53.5%
94%	2256	56.02	53.5%	53%	1272	56.02	53.5%
93%	2232	56.02	53.5%	52%	1248	56.02	53.5%
92%	2208	56.02	53.5%	51%	1224	56.02	53.5%
91%	2184	56.02	53.5%	50%	1200	56.02	53.5%
90%	2160	56.02	53.5%	49%	1176	56.02	53.5%
89%	2136	56.02	53.5%	48%	1152	56.02	53.5%
88%	2112	56.02	53.5%	47%	1128	56.02	53.5%
87%	2088	56.02	53.5%	46%	1104	56.02	53.5%
86%	2064	56.02	53.5%	45%	1080	56.02	53.5%
85%	2040	56.02	53.5%	44%	1056	56.02	53.5%
84%	2016	56.02	53.5%	43%	1032	56.02	53.5%
83%	1992	56.02	53.5%	42%	1008	56.02	53.5%
82%	1968	56.02	53.5%	41%	984	56.02	53.5%
81%	1944	56.02	53.5%	40%	960	56.02	53.5%
80%	1920	56.02	53.5%	39%	936	56.02	53.5%
79%	1896	56.02	53.5%	38%	912	56.02	53.5%
78%	1872	56.02	53.5%	37%	888	56.02	53.5%
77%	1848	56.02	53.5%	36%	864	56.02	53.5%
76%	1824	56.02	53.5%	35%	840	56.02	53.5%
75%	1800	56.02	53.5%	34%	816	56.02	53.5%
74%	1776	56.02	53.5%	33%	792	56.02	53.5%
73%	1752	56.02	53.5%	32%	768	56.02	53.5%
72%	1728	56.02	53.5%	31%	744	56.02	53.5%
71%	1704	56.02	53.5%	30%	720	56.02	53.5%
70%	1680	56.02	53.5%	29%	696	56.02	53.5%
69%	1656	56.02	53.5%	28%	672	56.02	53.5%
68%	1632	56.02	53.5%	27%	648	56.02	53.5%
67%	1608	56.02	53.5%	26%	624	56.02	53.5%
66%	1584	56.02	53.5%	25%	600	56.02	53.5%
65%	1560	56.02	53.5%	24%	576	56.02	53.5%
64%	1536	56.02	53.5%	23%	552	56.02	53.5%
63%	1512	56.02	53.5%	22%	528	56.02	53.5%
62%	1488	56.02	53.5%	21%	504	56.02	53.5%
61%	1464	56.02	53.5%	20%	480	56.02	53.5%
60%	1440	56.02	53.5%	19%	456	56.02	53.5%

8.3 Load % and SFC for Compressed NH_3 SOFC

Table 35: Load % and SFC for Compressed NH_3 SFC

Load	NH_3_SOFC			Load	NH_3_SOFC		
	Power		Eff.		Power		Eff.
	[kW]	[g/kWh]	[%]		[kW]	[g/kWh]	[%]
100%	2400	319	60%	59%	1416	319	60%
99%	2376	319	60%	58%	1392	319	60%
98%	2352	319	60%	57%	1368	319	60%
97%	2328	319	60%	56%	1344	319	60%
96%	2304	319	60%	55%	1320	319	60%
95%	2280	319	60%	54%	1296	319	60%
94%	2256	319	60%	53%	1272	319	60%
93%	2232	319	60%	52%	1248	319	60%
92%	2208	319	60%	51%	1224	319	60%
91%	2184	319	60%	50%	1200	319	60%
90%	2160	319	60%	49%	1176	319	60%
89%	2136	319	60%	48%	1152	319	60%
88%	2112	319	60%	47%	1128	319	60%
87%	2088	319	60%	46%	1104	319	60%
86%	2064	319	60%	45%	1080	319	60%
85%	2040	319	60%	44%	1056	319	60%
84%	2016	319	60%	43%	1032	319	60%
83%	1992	319	60%	42%	1008	319	60%
82%	1968	319	60%	41%	984	319	60%
81%	1944	319	60%	40%	960	319	60%
80%	1920	319	60%	39%	936	319	60%
79%	1896	319	60%	38%	912	319	60%
78%	1872	319	60%	37%	888	319	60%
77%	1848	319	60%	36%	864	319	60%
76%	1824	319	60%	35%	840	319	60%
75%	1800	319	60%	34%	816	319	60%
74%	1776	319	60%	33%	792	319	60%
73%	1752	319	60%	32%	768	319	60%
72%	1728	319	60%	31%	744	319	60%
71%	1704	319	60%	30%	720	319	60%
70%	1680	319	60%	29%	696	319	60%
69%	1656	319	60%	28%	672	319	60%
68%	1632	319	60%	27%	648	319	60%
67%	1608	319	60%	26%	624	319	60%
66%	1584	319	60%	25%	600	319	60%
65%	1560	319	60%	24%	576	319	60%
64%	1536	319	60%	23%	552	319	60%
63%	1512	319	60%	22%	528	319	60%
62%	1488	319	60%	21%	504	319	60%
61%	1464	319	60%	20%	480	319	60%
60%	1440	319	60%	19%	456	319	60%