Underway to zero-emission shipping with the aid of fuel cells

A case study about the application of fuel cells and alternative fuels on board cargo vessels

Research Report

Author: C.A. Kluiters (00082057)

Course: CU12546V11 - 2022

Study year/semester: 2019, semester 6

Institute: HZ University of Applied Sciences

Coach: A. de Groot, J. Bruinsma

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Summary

The emission of greenhouse gasses is a trending subject worldwide. Also the maritime industry is looking for alternative options for zero-emission transport. Nedstack provides fuel cells as a solution for this challenge. This research is a first glance at the possibilities to create a feasible retrofit with Proton Exchange Membrane (PEM) fuel cells for a conventional deep-sea cargo vessel to a zero-emission vessel. The research consists of the operational profile of the vessel Falcon Triumph, a feasible PEM fuel cell lay-out and a comparison to other options.

A fuel cell is an electrochemical device which converts the chemical energy of the fuel into electrical energy with help of an anode, cathode and electrolyte. Hydrogen is split into positive and negative charged particles, from which the last creates an electric current.

To create a feasible retrofit, the power demand needs to be determined. In this report the Holtrop-Mennen method was used. As input the Automatic Identification System (AIS) data was used. Due to the fact that this data does not include weather conditions they were not taken into account. Furthermore the different components were composed into a feasible lay-out. Lastly the comparison with other types of zero-emission propulsion solutions was made.

With the AIS data of one year and the specifications on the general plan of the vessel the power demand was determined at 5500 kW, with which 86% of the voyages were covered. Due to electrical losses and weight balance, 12 500 kW units were fitted. This determination was compared with operational data from the vessel. A accuracy of 48% was found, caused by severe averse weather conditions. The weight for the engine room was reduced with 159,4 tons when using PEM fuel cells. The available space created by the retrofit was used for hydrogen storage. 134 tons of liquid hydrogen can be stored. The total power demand was 5882 kW according to the used method, for a vessel speed of 13 knots. A vessel range of 4343 nM is possible with the planned hydrogen bunker capacity. The emergency generator is also replaced by a 100 kW PEM fuel cell unit. The hydrogen for this fuel cell is stored in high pressure bottles.
The PEM lay-out was then compared to other zero-emission solution: An internal combustion engine (ICE) running on methanol, a solid oxide fuel cell (SOFC) using Liquified Natural Gas (LNG) and a PEM consuming ammonia. For the first option more space was needed and weight was added. For the SOFC solution, less space was required however the weight added was significant. Last, for the ammonia PEM more space was required but the weight after the maximum voyage length is the same. Also for all options, it was not possible to reduce emissions completely.

Due to the scope aimed on a feasibility study, the power determination did not include some parameters, for example the weather conditions. This scope also accounted for the fact that the individual components were not research extensively.

This research displayed a feasible retrofit possibility with electric propulsion and PEM fuel cells. This retrofit was compared with other possibilities and was deemed the most attractive retrofit for a zero-emission deep-sea cargo vessel, due to the fact that other options faced challenges to be completely zero-emission. For a realistic retrofit, all the components of the retrofit require additional research. This report is a first glance at the possibilities of zero-emission operations on board deep-sea cargo vessels with the aid of fuel cells or other zero-emission types of energy converters.

Samenvatting

De uitstoot van broeikasgassen is een veelbesproken onderwerp wereldwijd. Ook de maritieme industrie is op zoek naar alternatieve opties voor emissieloos transport. Nedstack levert brandstofcellen als oplossing voor dit vraagstuk. Dit onderzoek is een eerste indruk van de mogelijkheden om een wereldwijd zeegaand schip om te bouwen naar een emissieloos schip, met behulp van Proton Exchange Membrane (PEM) brandstofcellen. Dit rapport onderzoekt het operationeel profiel van het motorschip Falcon Triumph, een uitvoerbare ombouw van dit schip en een vergelijking met andere opties.

Een brandstofcel is een elektrochemisch apparaat welke chemische energie omzet naar elektrische energie met behulp van een anode, kathode en een elektrolyt. Waterstof wordt gespleten in positieve en negatieve deeltjes welke een elektrische stroom opwekken.

Om een ombouw te realiseren moet de vermogensbehoefte bepaald worden. Hiervoor is de Holtrop-Mennen methode gebruikt. Als input is er data van het Automatische Identificatie Systeem (AIS) gebruikt. Omdat deze data geen weergegevens bevatten, is dit niet meegenomen in de vermogensbepaling. Vervolgens is een uitvoerbare lay-out gecreëerd. Als laatste wordt deze lay-out vergeleken met andere emisssieloze opties.

Met de AIS data van één jaar en de scheepsspecificaties van het algemeen plan is de vermogensbehoefte van het schip bepaald op 5500 kW. Hiermee kan 86% van de reizen gemaakt worden. Vanwege elektrische verliezen en de gewichtsbalans zijn er 12 units van 500 kW geïnstalleerd. De vermogensbepaling is vervolgens gecontroleerd met operationele data van het schip. Hieruit volgde een nauwkeurigheid van 48%, welke veroorzaakt werd door tegenwerkende weerscondities. Het gewicht van de machinekamer is door het gebruik van PEM brandstofcellen gedaald met 159,4 ton. De vrijgekomen ruimte door de ombouw is gebruikt voor de opslag van 134 ton vloeibare waterstof. Het totale benodigde vermogen is volgens de methode vastgesteld op 5882 kW voor een snelheid van 13 knopen. Met de bunkercapaciteit van de lay-out kan 4343 mijl gevaren worden. De noodgenerator is vervangen door een 100 kW brandstofcel, gevoed door gecomprimeerde waterstof.
De PEM ombouw is vervolgens vergeleken met andere emissieloze opties: Een verbrandingsmotor op methanol, een Solid Oxide Fuel Cell (SOFC) op LNG en een PEM brandstofcel op ammoniak. De eerste optie had meer gewicht en nam meer ruimte in ten opzichte van de PEM ombouw. De tweede optie nam minder ruimte in, maar woog aanzienlijk meer. De ammoniak PEM weegt bij aanvang meer, maar na het afleggen van de maximum afstand is het gewicht gelijk. Wel is er meer ruimte benodigd. Ook geldt voor alle opties dat er toch uitstoot optreedt.

Dit onderzoek was gericht op de haalbaarheid van de ombouw en vanwege dit doel zijn er sommige parameters niet meegenomen in de vermogensbepaling, waaronder weersinvloeden. Ook zijn door dit doel de verschillende onderdelen van dit onderzoek niet maximaal onderzocht.

Dit onderzoek laat zien dat een ombouw met elektrische voortstuwing en PEM brandstofcellen uitvoerbaar is. Na de vergelijking is de PEM als beste optie verkozen. Om een realistische ombouw mogelijkheid te creëren is meer onderzoek nodig naar de verschillende onderdelen van deze retrofit. Dit rapport is een eerste blik op de mogelijkheden om een schip emissieloos te laten varen met behulp van brandstofcellen of andere energie omvormers.

Preface

This thesis was written as the final part of my technical maritime study at the HZ University of Applied Sciences. The subject of this thesis was to create a retrofit with fuel cells for a deep-sea cargo vessel, and the feasibility of this retrofit on board of a vessel.

First, I would like to thank Jogchum Bruinsma in special and also Nedstack for giving me the opportunity to write a thesis about hydrogen powered vessels which is a promising technology for zero-emission shipping in the future. Also, the guidance during the writing of this thesis was of great help because it helped me to create a worthy final product of my education.

Second, I want to thank Arie de Groot for his guidance and feedback during the process and his swift communication. Furthermore, also thanks to Bertha Ooms for helping with the general problems I encountered while writing this thesis.

Lastly, I want to thank my family for their constant interest which sometimes helped to create new insights on challenges I faced.

Arnhem, May 13, 2022

Cas Kluiters

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1. Introduction

This research was composed in co-operation with Nedstack. Nedstack is a leading player in the PEM fuel cell industry, for stationary equipment as well as for mobile equipment. They have expanded their focus to the maritime sector and apply hydrogen fuel cells in the different applications of the maritime industry. As a next step, the challenge is to implement these fuel cells on board of a seagoing vessel.

Nowadays, the emission of greenhouse gasses (GHG) is a trending subject worldwide. The maritime industry also contributes to these emissions, with 2,5% of the global GHG emission coming from the maritime sector. (European Commission, sd) Because of this, alternative fuels and energy converters are considered (European Alternative Fuels Observatory, 2019), which also involves the comparison between the different types of fuel and their energy converters. (Varma, 2022) Therefore, Nedstack also focusses on the maritime industry with their hydrogen fuel cells. For Nedstack, it is interesting to examine the possibility to transform vessels to zero-emission vessels. To achieve this, new vessels can be built or existing vessels can be retrofitted. However, building a new vessel is not part of the scope. A retrofit with as an example the deep-sea cargo vessel Falcon Triumph will be the scope of this research. With this scope the research goal could be defined:

Creating a zero-emission retrofit for an existing deep-sea cargo vessel like the Falcon Triumph, using PEM fuel cells. Also the comparison between the retrofit and other types of zero-emission propulsion was part of the research goal.

This research goal was converted into the following research questions, with as main question:

What are the possibilities to create a feasible retrofit with PEM fuel cells for a conventional deep-sea cargo vessel to a zero-emission vessel?

This question was divided into several sub-questions:

- What is the operational profile of the vessel regarding the sailing profile and the performance on board?
- What is a feasible lay-out to achieve the same performance on board without emission by using PEM fuel cells?
- Which different options are there for other fuel cells and fuels on board compared to PEM fuel cells?

In this research report the relevant theory regarding fuel cells, types of fuel, data of the vessel and some explanation about the calculation method was discussed. Furthermore the research was visualized in a conceptual model and the method used for this research was explained. Hereafter, the results are displayed and following the discussion and conclusion with recommendations.

This feasibility study was focused on zero-emission vessels, which is a vessel that doesn't emit any GHG during its operation. The emission to build the vessel and produce fuels will not be taken into account. Furthermore, this research was only focused on the deep-sea cargo vessel Falcon Triumph.

2. Theoretical framework

In this chapter all the relevant theory used in this report is discussed. First the different fuel cells will be mentioned and after that the different fuels used on board. Last, the theory about the calculations, the vessel and conventional energy converters is discussed.

2.1 Fuel cell

A fuel cell is an electrochemical device which converts the chemical energy of the fuel into electrical energy. (Maja Perčić, 2022) The major difference with a Internal Combustion Engine (ICE) is that a fuel cell converts the fuel in electrical energy, whereas the ICE needs a generator to convert the mechanical energy into electrical energy. The basic working principle of a fuel cell is identical of the principle of a battery, with the biggest difference that a fuel cell doesn't need recharging. A fuel cell will produce energy and heat as long as there is fuel supplied. (Office of Energy Efficiency & Renewable Energy, sd). The main components of a fuel cell are the anode, cathode, electrolyte and the external circuit. In figure 1 below, the components are shown in a hydrogen fuel cell, but the main working principle will remain unchanged for other fuels. As example hydrogen is used. The hydrogen is fed to the anode while the oxygen is fed to the cathode side. The hydrogen is divided into positively charged protons and negatively charged electrons by means of oxidation in the anode. The protons can migrate through the electrolyte, while the electrons can't. The electrons flow through the external circuit to the anode side of the fuel cell. The energy created in the external circuit is then used to power the load, and to produce heat. After the load at the cathode side, the protons and electrons are rejoined with the oxygen to produce water (H_2O). (S. Mekhilef, 2012)

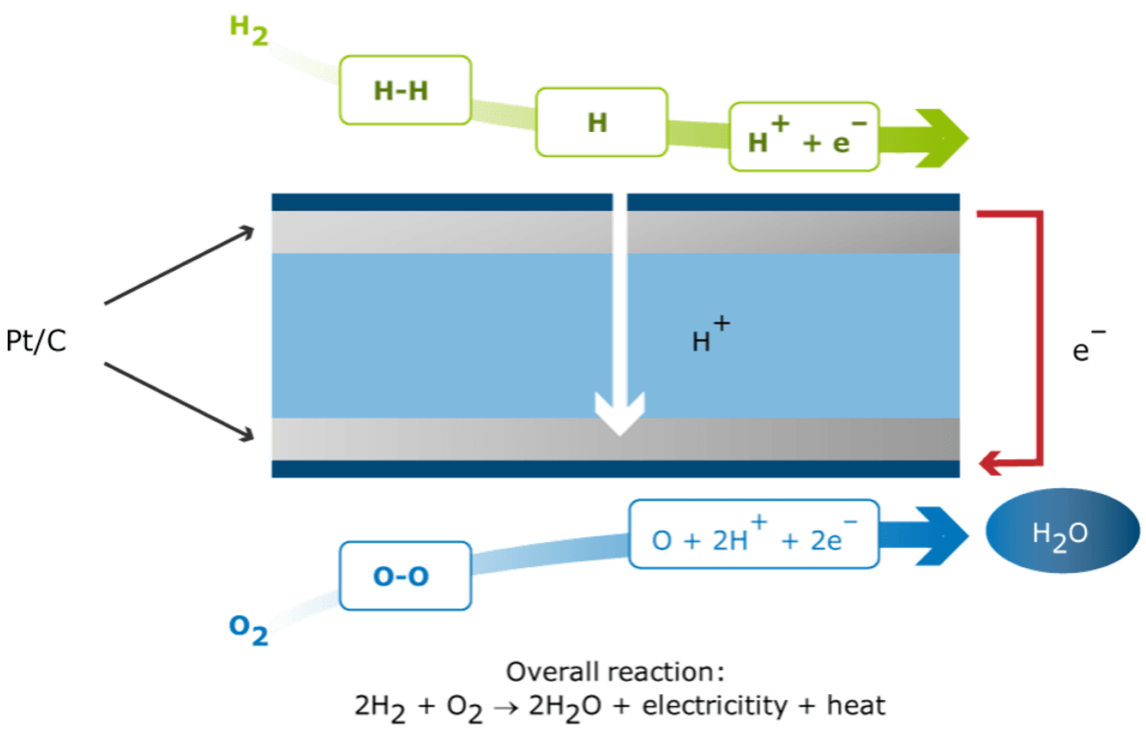


Figure 1: Fuel cell working principle (Nedstack, sd)

2.2 Types of fuel cells

There are 3 types of fuel cells. Low temperature (LT) fuel cells which operate at around 80 °C, intermediate temperature (IT) fuel cells with an operating temperature around 200 °C and high temperature (HT) fuel cells with temperatures ranging from 650 – 1000 °C. (José J. de-Troya, 2016) Furthermore the most substantial difference between the different fuel cells is the fuel being used and therefore also the material of the electrolyte. (José J. de-Troya, 2016)

2.2.1 Polymer Electrolyte Membrane Fuel Cell (PEMFC)

Polymer Electrolyte Membrane fuel cells, also known as Proton Exchange Membrane fuel cells are low temperature fuel cells. This low temperature (65°C) (Nedstack, sd) is achieved by using cooling water. This cooling water contains heat which can be used for heating purposes. The efficiency at the beginning of life (BOL) is 56%. (Nedstack, sd)The other 44% of the energy is converted into heat and is discharged through the cooling water. Because of the low energy output of a single cell, fuel cell stacks are made. When placed in series, the voltage of 0,7V (at a current of 120A) of a single cell can be increased to a voltage usable in the application, as seen in figure 2. This voltage depends on the current of the stack. With multiple stacks an efficient energy provider can be created. (Nedstack, sd) A PEMFC utilizes pure hydrogen as their fuel, and require expensive (mostly platinum) catalysts for the separation of the hydrogen. PEMFC's are capable of using hydrogen carriers, which will be discussed in the next sub-chapter, as a fuel but only in combination with a reformer. This reformer isolates the hydrogen from the other elements in the carrier. Mostly these reformers use high temperatures to detach the hydrogen from the other substances. (Maja Perčić, 2022) In comparison with most fuel cells, a PEMFC offers a high energy density with a relatively low weight and volume. (Office of Energy Efficiency & Renewable Energy, sd)

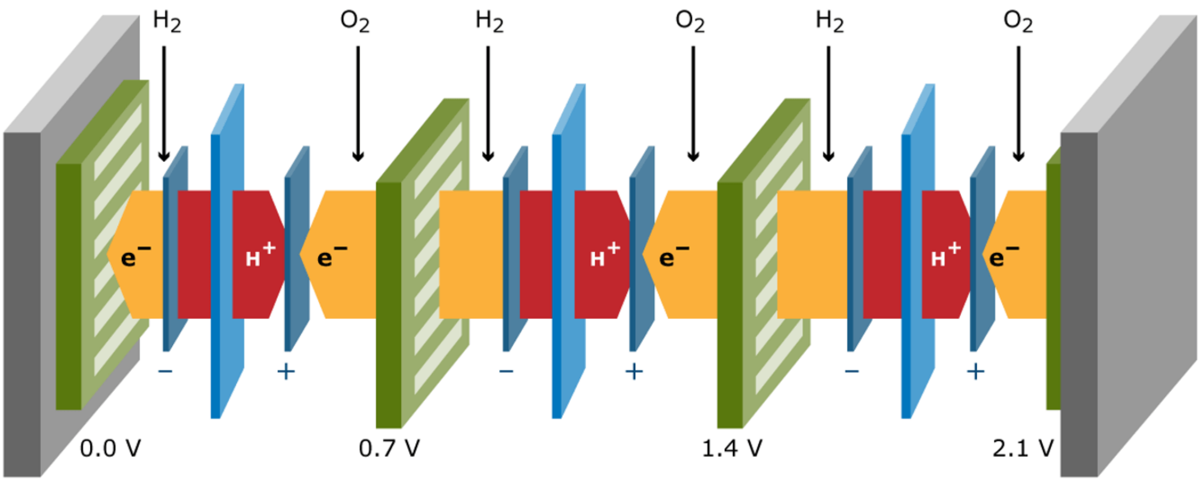


Figure 2: Fuel cell stack (Nedstack, sd)

There are also projects in progress with a higher working temperature, which can range up to 160°C. This results in a higher efficiency, a higher temperature cooling system and less poisoning of the membranes due to Carbon monoxide (CO). (Dataphysics, sd) The higher temperature also causes longer start-up times.

2.2.2 Alkaline Fuel Cell (AFC)

An AFC is a low temperature fuel cell which works at 60-100°C (José J. de-Troya, 2016) with an alkaline electrolyte, hence the name Alkaline Fuel Cell. Alkaline fuel cells were one of the first type of fuel cells, and were used by NASA for production of electrical energy. The electrolyte of the cell consists of a solution of potassium hydroxide in water, but in newer cells also a polymer membrane can be used. Because of this polymer membrane an AFC has much similarities with a PEM, but the major difference is that the membrane of an AFC is alkaline while the membrane of a PEM is acid. (Office of Energy Efficiency & Renewable Energy, sd)
The working principle of an Alkaline fuel cell is roughly the same as all other fuel cells. In an AFC on the cathode side hydroxyl ions are created. These ions can permeate the electrolyte and travel to the anode. Here the hydroxyl ions react with the hydrogen, creating electrons and water. These electrons create energy and heat and at the cathode side, form new hydroxyl ions in reaction with oxygen. (FuelCellStore, 2021) In figure 3 this process is shown.

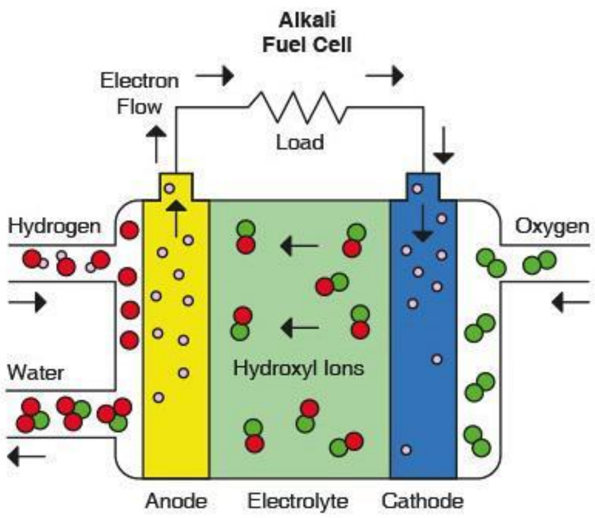


Figure 3: Alkaline fuel cell (Business Industry Reports, 2018)

Due to the lower temperatures, it is not necessary to use a platinum catalyst so as replacement non-precious metals can be used like nickel. The efficiency can reach values up to 60%. (FuelCellToday, sd) Furthermore the electrolyte can be poisoned due to reaction with CO_2 which results in the fact that only pure oxygen can be used.

2.2.3 Direct methanol Fuel Cell (DMFC)

A DMFC is a fuel cell which also operates at low temperatures around 60-130°C. (FuelCellWorks, sd) It uses a aqueous methanol solution as fuel and has the same principle as the PEMFC. The major difference with a PEM is that due to the platinum-ruthenium catalyst on the anode side, methanol can be fed directly into the fuel cell without reforming the methanol. The electrolyte is a polymer membrane.

A DMFC is fed the aqueous methanol solution at the anode side. Here the solution is oxidized into carbon dioxide (CO_2), hydronium ions and electrons. These electrons flow from the anode side to the cathode side via an outer circuit which powers the load. The ions flow through the membrane to the cathode side and react with the oxygen to form water. (Hacquard, 2005) This process is shown in figure 4.

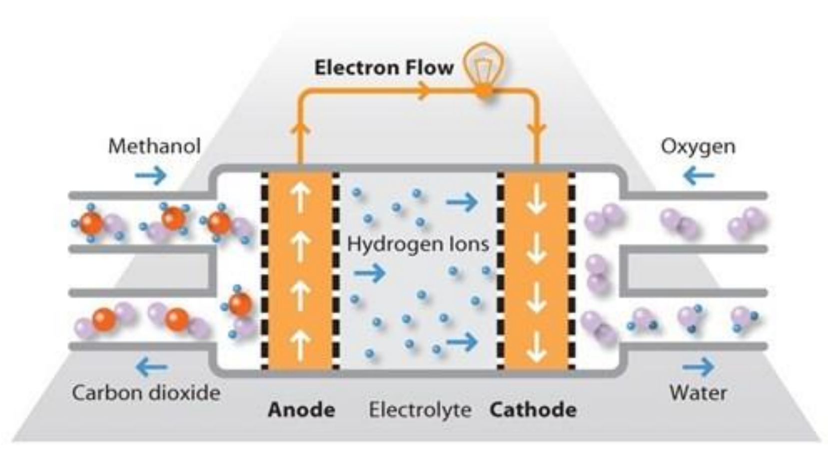


Figure 4: DMFC principle (FuelCellWorks, sd)

Direct methanol fuel cells are mostly used for small applications, but are capable of a high power output. (José J. de-Troya, 2016) The average cell voltage is around 0,6-0,8V, which is the same as the PEMFC. (Hacquard, 2005) The average efficiency is 20-30% but can be optimized up to 45%. (A. Glüsen, 2020)

2.2.4 Phosphoric Acid Fuel Cell (PAFC)

PAFC's are intermediate temperature fuel cells, which operate at a temperature of around 200°C. This type of fuel cell was one of the first that was developed. There are already plants producing up to 11 Megawatt (MW). (Nigel Sammes, 2004) The electrolyte consist of a phosphoric acid, which is not reacting with CO_2. This characteristic feature ensures that it is not necessary to use pure hydrogen and oxygen. (José J. de-Troya, 2016) The principle of the PAFC is identical to that of the PEMFC, the only difference is the operating temperature and the material difference of the electrolyte. The efficiency of the PAFC is between 37-42%, but with heat recovery equipment an efficiency up to 85% is possible. In comparison with other fuel cells, PAFC's have a lower efficiency and a higher weight. (Office of Energy Efficiency & Renewable Energy, sd)

2.2.5 Molten Carbonate Fuel Cell (MCFC)

A molten carbonate fuel cell is a high temperature fuel cell with an operation temperature of 600-650°C. The cause of this high temperature lies in the conductivity of the electrolyte. Without this high temperature the level of conductivity is not adequate enough. (José J. de-Troya, 2016) This electrolyte consists of *"a molten carbonate salt mixture suspended in a porous, chemically inert ceramic lithium aluminum oxide matrix"* according to Office of Energy Efficiency & Renewable Energy.(sd)

A MCFC forms carbonate ions (CO_3^{2-}) on the cathode side, where flue gas is being fed, which migrate through the electrolyte to the anode side. On the anode side, these ions react with the hydrogen to form water and reform CO_2. On the anode side mostly methane gas and water is fed to the fuel cell and reformed due to the high temperature into CO, CO_2 and hydrogen. The CO then reacts with the water to form more CO_2 and H_2. Due to the reaction of the carbonate ions on the anode side water, CO_2 and electrons are produced. These electrons migrate to the cathode through the outer circuit creating electricity. This is shown in figure 5. (S. Mekhilef, 2012)

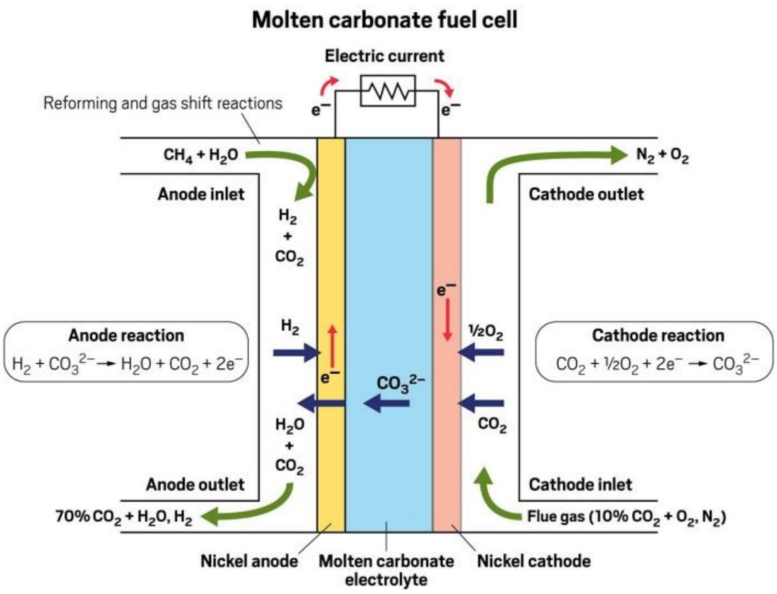


Figure 5: Molten carbonate fuel cell (Bettenhausen, 2021)

Due to the high temperature in the fuel cell, the catalyst material being used can be made of nickel, instead of platinum. Also the high temperature causes degradation which results in a shorter lifetime. There are ongoing researches on how to counter these problems, with as an example the coating of components. (Dohyeong Kim, 2021) Finally the efficiency of this fuel cell can be up to 60%. (Fuelcellsworks, sd)

2.2.6 Solid Oxide Fuel Cell (SOFC)

The SOFC is a high temperature fuel cell, which operates between 500-1000°C. Due to this high temperatures, a non-precious metal catalyst can be used, just like the MCFC. The high temperatures lead to long start up times, which is no problem for stationary applications but for mobile applications this is not desirable. (Office of Energy Efficiency & Renewable Energy, sd) The SOFC operates with a solid oxide ceramic material as a electrolyte, which is composed of zirconium oxide along with other oxides.

The SOFC mostly uses natural gas like methane, but can also consume pure hydrogen or other hydrogen carriers. Due to the high temperature the fuels used can be reformed by the cell itself. The fuel flows over the anode side, creating electrons. The electrons flow through the outer circuit to the cathode side, powering the load. On the cathode side the oxygen is fed, and reduced to oxygen ions. These oxygen ions flow through the electrolyte to the anode side where it reacts with the hydrogen creating water. (National Energy Technology Labatory, sd) The solid oxide fuel cell has a high efficiency of 60%, with can reach up to 85-90% with power generation from the residual heat. (Francesco Baldi, 2019)

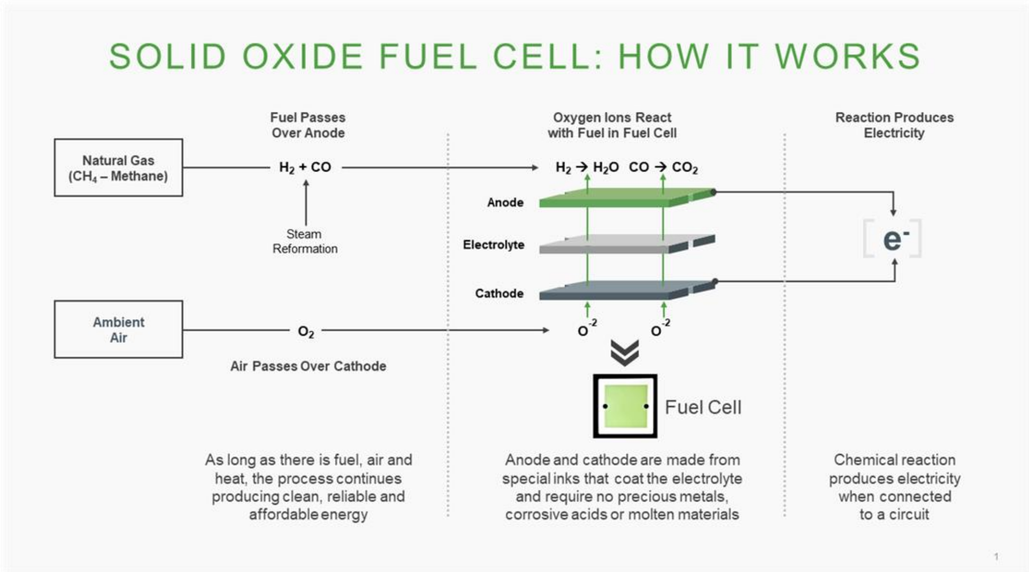


Figure 6: Working principle of a SOFC (Bloomenergy, 2019)

2.3 Key properties fuel cells

In the table below the key properties of the different fuel cells are summarized. On the top, the properties are mentioned while on the left, the different types of fuel cells are stated.

Table 1: Key properties fuel cells

Fuel cell	Efficiency	Working temperature	Heat recovery	Start up time	Catalyst	Hydrogen carriers	Emission	Lifetime (hours)	Miscellaneous
PEM	56% at BOL	40-90°C	Possible with LT heat	Less then a minute	Platinum	Yes, with reformer	H_2O	20.000	Electrolyte poisoning due to CO
AFC	Up to 60% in optimal conditions	60-100°C	Not yet used	Less then a minute (Gencell, sd)	Nickel	Yes, with reformer (AFC Energy, sd)	H_2O	5000 (Meng Ni, 2006)	Electrolyte can be poisoned due to CO_2 contamination
DMFC	20-30%, but can be optimized until 45%	60-130°C	Possible with LT heat (Ohashi)	10 minutes (Chan)	platinum-ruthenium	Only methanol	H_2O, CO_2	20.000 (Nicola Kimiaie, 2014)	
PAFC	37-42%	Around 200°C	Possible with IT, can reach total efficiency of 85%	1 to 3 hours (Abderezzak, 2018)	Platinum (higher loading)	Yes, with reformer	H_2O	Up to 40000 (Nigel Sammes, 2004)	
MCFC	Up to 60%	600-650°C	High temperature heat enables steam recovery systems (Fuelcellsworks, sd)	10 minutes (Gencell, sd)	Nickel	Yes, without reformer due to high temperatures (internal reforming)	H_2O, CO_2	10.000 (S. McPhail, 2009)	High temperatures can cause faster degradation
SOFC	60%, with generation up to 85-90%	500-1000°C	High temperature creates possibilities for usage with steam turbines	60 minutes (Gencell, sd)	Non-precious metal, like nickel	Yes, without reformer due to high temperatures (internal reforming)	H_2O, CO_2	30.000 - 40.000 (h2ePOWER, sd)	High temperatures can cause faster degradation

2.4 Different types of fuel

There are many fuels that are capable of usage on board of vessels. (DNV-GL, 2019) Most of the vessels worldwide use marine fuel oils to power conventional diesel engines. Nowadays, with the GHG emissions being limited, the demand for alternative fuels with less emissions is expanding. Liquified natural gas (LNG) is already being used in combination with diesel oils in dual fuel engines. Furthermore alternative fuels like methanol and ammonia are being considered, in combination with fuel cells. The different fuels will be mentioned below.

2.4.1 Marine fuel oils

Marine fuel oils are fuels that are mostly derived from crude oil, as in figure 7, but can also be derived from gas or biomass. Marine fuel oil can be split into different types depending on the process and viscosity of the fuel. (S. Mekhilef, 2012) Fuel oils in any form are the most commonly used fuels on board vessels, due to its excellent characteristics: It is not flammable at storage temperatures, has a relatively high lower heating value (LHV) and the combination with a high density makes it an ideal fuel for non-stationary appliances due to its high energy density mentioned in table 2. (Buitendijk, 2020) The three main categories of fuel used on board are: gas oil (GO), Marine Diesel Oil (MDO) and Heavy Fuel Oil (HFO). GO is the least 'heavy' fuel and also the lowest in emissions when combusted in an ICE. After this comes MDO and then HFO, which is the most polluting fuel oil. Due to the MARPOL 2020 legislation, many vessels switched from HFO to GO because it is the easiest way to comply with legislation. Other vessels installed a so-called scrubber, which cleans the exhaust gasses. MDO is a blend of different fuel oils, which can have many varieties. HFO is the most heavy fuel and is sometimes considered the waste product of an oil refinery. HFO needs to be heated to use as fuel, because the viscosity at ambient temperatures is not sufficient for transportation and usage.

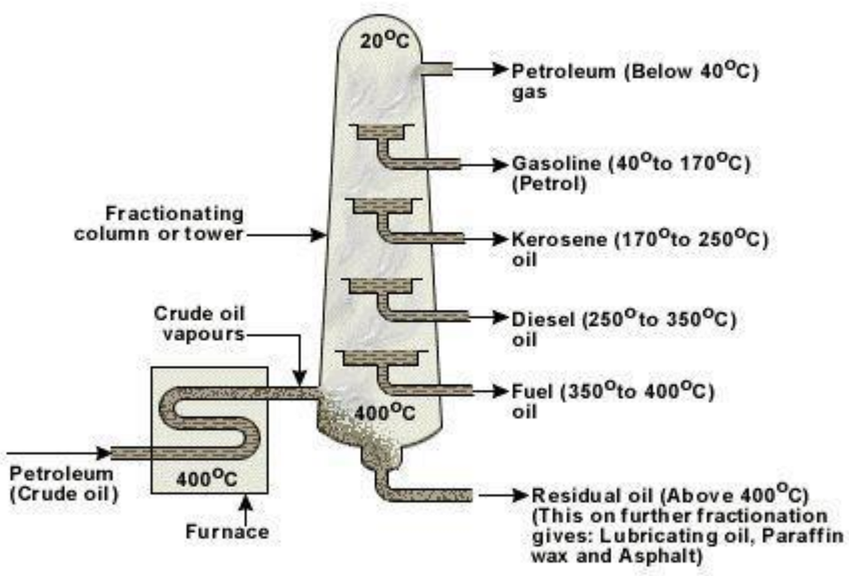


Figure 7: Crude oil fractioning (Oluchukwu Anowor, 2014)

2.4.2 Natural gas

Natural gas is mostly known in its liquefied form, LNG and is commonly used on LNG carriers which use the boil-off (a part of the cooled liquid evaporates) gas as fuel in their dual fuel diesel engines. The liquefied form is acquired by cooling the gas until -162°C. (Shell, sd). Natural gas can be used inside internal combustion engines, which will be discussed later, but also in fuel cells with the help of a reformer which reforms the natural gas to hydrogen which can be fed to the fuel cell.

2.4.3 Methanol

The chemical formula for methanol is CH_3OH, as seen in figure 8, which shows that there is carbon as well as hydrogen in the substance. Methanol is mostly produced by steam reforming natural gas, but can also be synthesized from CO_2 and hydrogen, which makes it CO_2 neutral due to the fact that the carbon dioxide emitted is converted back into methanol. (MAN Energy Solutions, sd) At ambient temperatures methanol is in a liquid form, which allows for easy transportation. The benefit of this characteristic is that it requires a minimum amount of modification to switch from fuel oil to methanol. It is also possible to reform methanol to hydrogen as a fuel for fuel cells. This is why methanol is often used as a hydrogen carrier. Furthermore methanol can be used in a common diesel engine, either together with diesel fuel or only methanol with additives. Also, methanol is toxic to humans if inhaled in gaseous state or ingested as liquid. This forms a challenge for the use on board. (Methanol Instute)

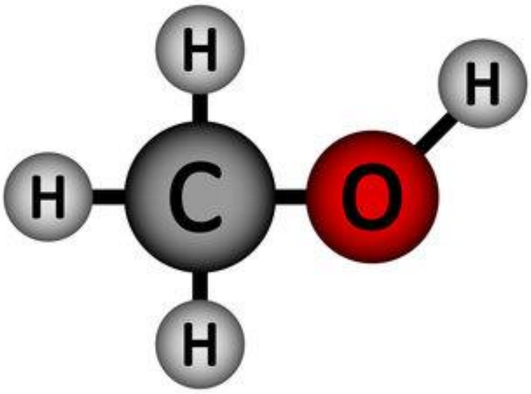


Figure 8: Methanol molecule (Adobestock, sd)

2.4.4 Hydrogen

Hydrogen is the smallest molecule in the periodic system, and is responsible for 75% of the mass of the universe. (NationalGrid, sd) The problem with hydrogen is that it never exists on its own as a substance, but always in a compound with other substances, like water (H_2O) or natural gas (CH_4). There are a few ways to create hydrogen, with steam reformation and electrolysis being the most used methods. Hydrogen is commonly divided into 3 groups: grey, blue and green hydrogen, as seen in figure 9. Grey means the hydrogen is made from gas, but without CO_2 storage. Blue hydrogen is also made from natural gas, but in this process the CO_2 is stored. The last group is green hydrogen, which is made by using renewable energy for electrolysis. (Eriksen, sd)
With steam reformation natural gas and high temperature steam react to synthesis gas, which is a mixture of hydrogen, CO and a small part of CO_2. Thereafter, the CO is reacted with water for a secondary amount of hydrogen. This method is the most used method for creating hydrogen. (U.S. Department of Energy, sd)
The second method of creating hydrogen is using electricity, which is called electrolysis. By running an electric current through pure water, the water is split into oxygen and hydrogen. This process corresponds with the fuel cell principle, only the other way around. This method is used to make so called 'Green Hydrogen', because green electricity generated with solar or wind energy can be used for the electrolysis process. This way the excess electricity generated can be used to make hydrogen. (U.S. Department of Energy, sd)

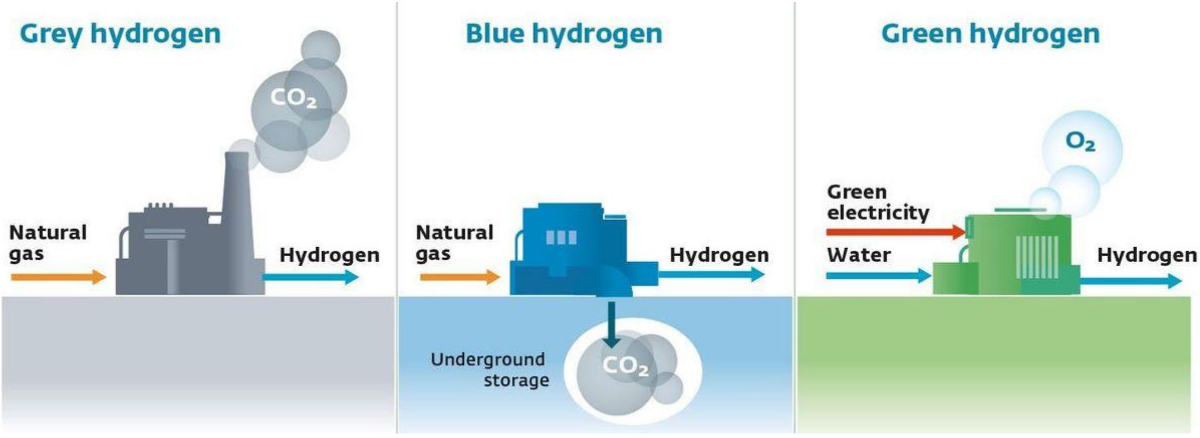


Figure 9: Types of hydrogen (Energy Education, sd)

Hydrogen can be stored in different ways. There is physical based storage and material based storage. Physical based storage is the storage of pure hydrogen, without other materials and can be achieved by cryogenic temperatures, which liquefies the hydrogen (LH_2), pressurized hydrogen (CH_2) or a combination of both. (CcH_2) Material based storage uses other material to bound hydrogen to them. This will not be further discussed in this report. To store hydrogen as a liquid, cryogenic temperatures are needed. The boiling point of hydrogen at atmospheric pressure is −252.8°C. The storage of hydrogen at such temperatures mostly use vacuum insulated tanks, which is also the case with CcH_2. Pressurized hydrogen is mostly stored between 350 and 700 bar. (Office of Energy efficiency & renewable energy, sd)

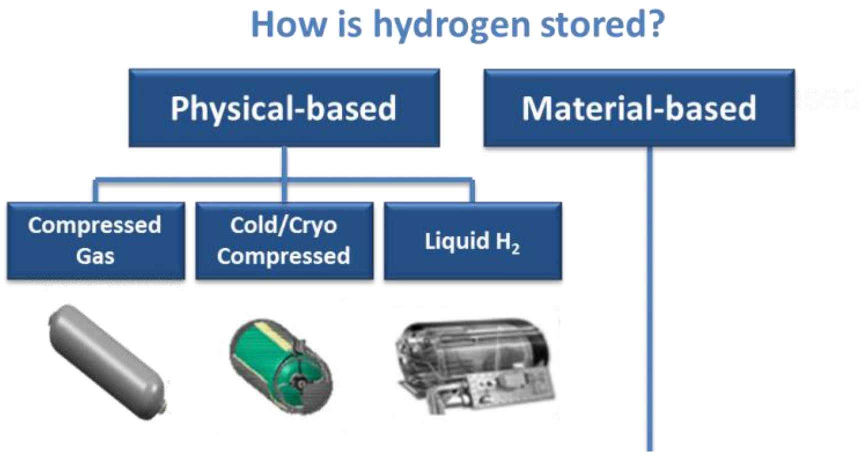


Figure 10: Hydrogen storage (Office of Energy efficiency & renewable energy, sd)

2.4.5 Ammonia

Ammonia (NH_3) is mostly used for producing fertilizers, but is also used as a hydrogen carrier. Furthermore it is used on board as a coolant for large cooling systems. Ammonia has a pungent odor which makes it easy to detect leakages, but is also very toxic. (Eriksen, sd) NH_3 is made by a reverse fuel cell process. The input of this process is hydrogen and nitrogen, which is combined to form ammonia. Ammonia is mostly stored as a liquid, due to the better density. This liquefaction is reached at 10 bara or below -33,6°C. (TheEngineeringToolbox, sd). In matters of safety on board ammonia is already frequently used on vessels. Therefore safety precautions are already in place and known to class societies.

2.4.6 Fuel properties

With the properties mentioned in table 2 the energy density can be calculated. The formula for the energy density is: $energy\ density = Energy\ content * density$. The energy density is added to table 2.

Table 2: Fuel properties (Varma, 2022)

Fuels	Chemical structure	Energy content LHV (MJ/kg)	Auto ignition temperature (°C)	Flash point (°C)	Density (kg/m³)	Energy density (MJ/m³)
Diesel	C_8 to C_{25}	42,612	316	73,89	850	36220,2
Heavy Fuel Oil (HFO)	Not specified*	39,00	Not specified*	>60	980	38220
Liquefied Natural Gas	CH_4	47,141	540	-187,78	438,9	20690,1849
Methanol	CH_3OH	20,094	481	11,11	786	15793,884
Pressurized Hydrogen	H_2	120,210	500	-253	42	5048,82
Liquid Hydrogen	H_2	120,210	500	-253	71	8534,91
Liquid Ammonia	NH_3	18,577	651	-33,34	682	12669,514

*Not specified because HFO is composed of multiple substances (McKee, 2014)

2.5 Conventional energy converters

In the current situation on board, almost every vessel uses a internal combustion engine for the generation of power. Two different principles are commonly used in engines. The first is the Otto engine, which uses a spark and is mostly fueled by petrol. This engine is not present on board vessels and therefore will not be discussed further. The second principle is the Diesel principle. A diesel engine uses high pressures to self ignite the fuel which moves the piston. The piston is connected to a crankshaft which translates the linear motion into a rotational motion. Because of this principle, an ICE converts chemical energy to mechanical energy in rotational motion. There are 2 types of diesel engines, two-stroke and four-stroke. The difference between these types are the rotations per combustion. A two-stroke engine has a revolution every combustion, while a four-stroke engine has 2 rotations per combustion. The most common type of fuels used on board are marine fuel oils and natural gas (LNG). There are engines which can use both fuels which are called dual-fuel engines. Mostly this is done by mixing the gas with the incoming air, and a small amount of fuel oil for the initial combustion causing the ignition of the gas. Furthermore, there are engines which only consume gas, hence the name gas engines.

These engines can be used in different types of lay-outs on board vessels. There is a diesel-direct (conventional) propulsion, in which the engine drives a shaft directly to a propeller or via a gearbox. Also, diesel-electric propulsion is often used. With a diesel-electric lay-out, the engine is coupled to a generator, which creates energy. This energy is then converted back to mechanical energy by an electrical motor. In figure 11, the difference between the 2 lay-outs is shown.

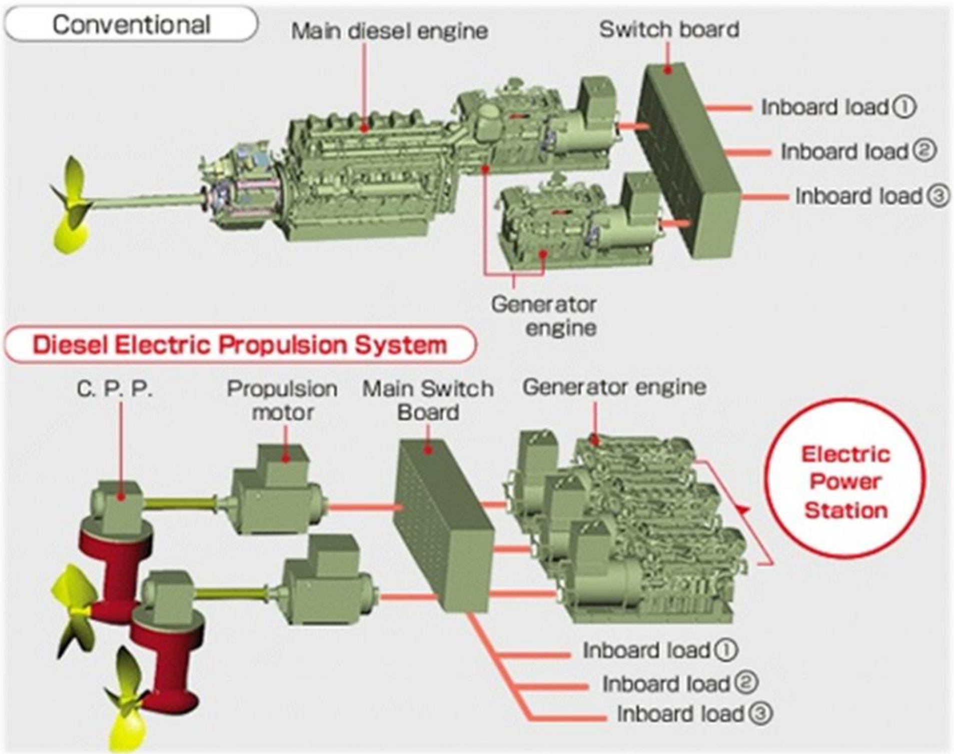


Figure 11: Conventional vs Diesel electric propulsion (Anish, 2019)

2.6 Falcon Triumph

The Falcon Triumph is a deep-sea cargo vessel built for transporting bulk cargo, sailing worldwide. The vessel was build in 2017 on the Jinling Shipyard in China. She sails under a Liberian flag with Monrovia as port of registry. The vessel is self-geared, which means the vessel has its own cargo handling equipment like cranes. A picture of the Falcon Triumph is added as figure 12. In table 3 the vessel's specifications are mentioned:

Table 3: Falcon Triumph specifications (Jinling Shipyard , 2016)

Length overall	199,90 m
Length between perpendiculars	194,50 m
Breadth	32,26 m
Depth	18,50 m
Design draft	11,30 m
Main engine	MAN B&W 5S60ME-C8.2 (2-stroke)
Engine output	8050 kW
Service speed	14,3 knots

Figure 12: Falcon Triumph (JBekkers, sd)

2.7 Calculations

In this paragraph, the used calculations will be explained. Also these calculations will be clarified with some figures. These calculations include the Holtrop-Mennen method, and also the calculations for the fuel to propeller efficiencies as mentioned by Klein Woud & Stapersma. (2002)

2.7.1 Holtrop-Mennen method

According to Birk, (2019) the Holtrop-Mennen method is *"arguably the most popular method to estimate resistance and powering of displacement type ships."* The method was founded by J. Holtrop and G.G.J. Mennen in 1982, and was developed at the TU Delft. The method is a regression analysis of random models with data from scale models as well as full-scale data. In figure 13 below the application of the method by Hoon Kim (2020) is shown, in which the unknown data is determined with different calculations. These determinations are also stated by Rakke (2016). For the implementation of this method, the input data consists of the static data of the vessel which was mentioned before and the operational data from the AIS. The operational data are the draft, average speed and voyage length. Furthermore, there are various constants which need to be calculated to determine the final resistances. The total resistance is composed of 6 individual resistances and the form factor which are: Frictional resistance, Appendages resistance, Wave-making resistance, Bulbous bow resistance, Pressure resistance of immersed transom stern and the Model ship correlation resistance.

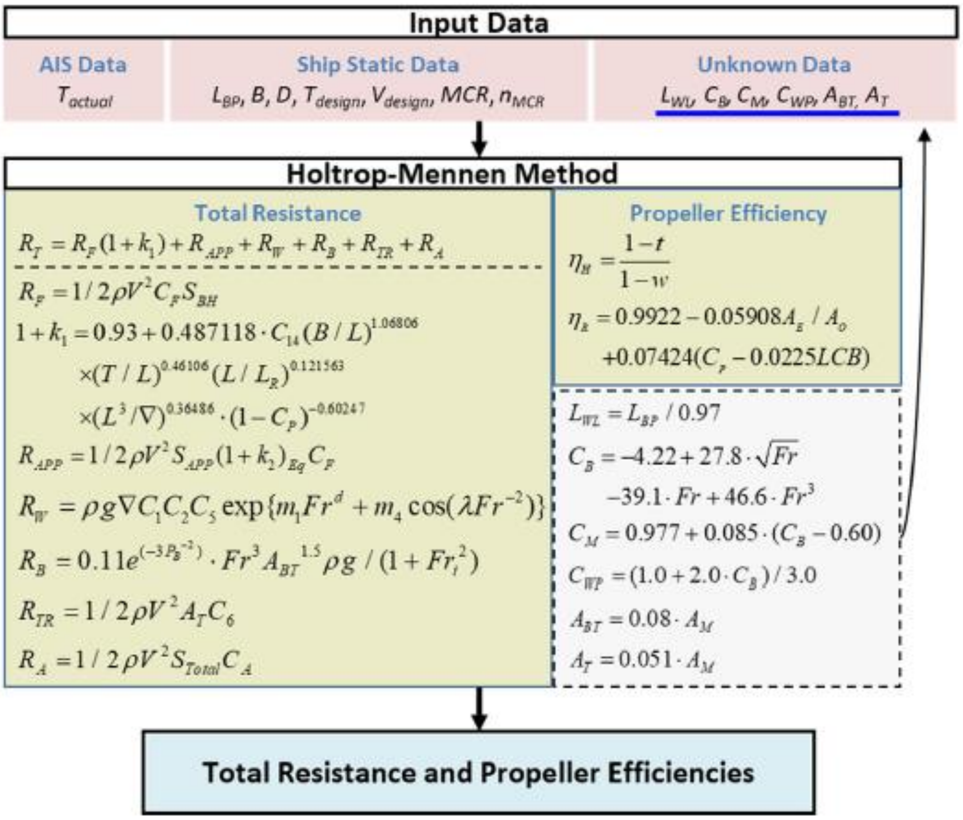


Figure 13: Holtrop-Mennen method (Hoon Kim, 2020)

2.7.2 Fuel to propeller efficiencies

The resistance of a vessel is representative for the power being delivered by the engine. Between the resistance and power output of the engine, a few efficiencies are in between. These are the propulsive efficiency and the transmission efficiency. The propulsive efficiency is composed of the hull efficiency, the open water efficiency and the relative rotative efficiency. The transmission efficiency is made up by the shaft and gearbox efficiency. This can also be seen in figure 14. (Klein Woud & Stapersma, 2002)

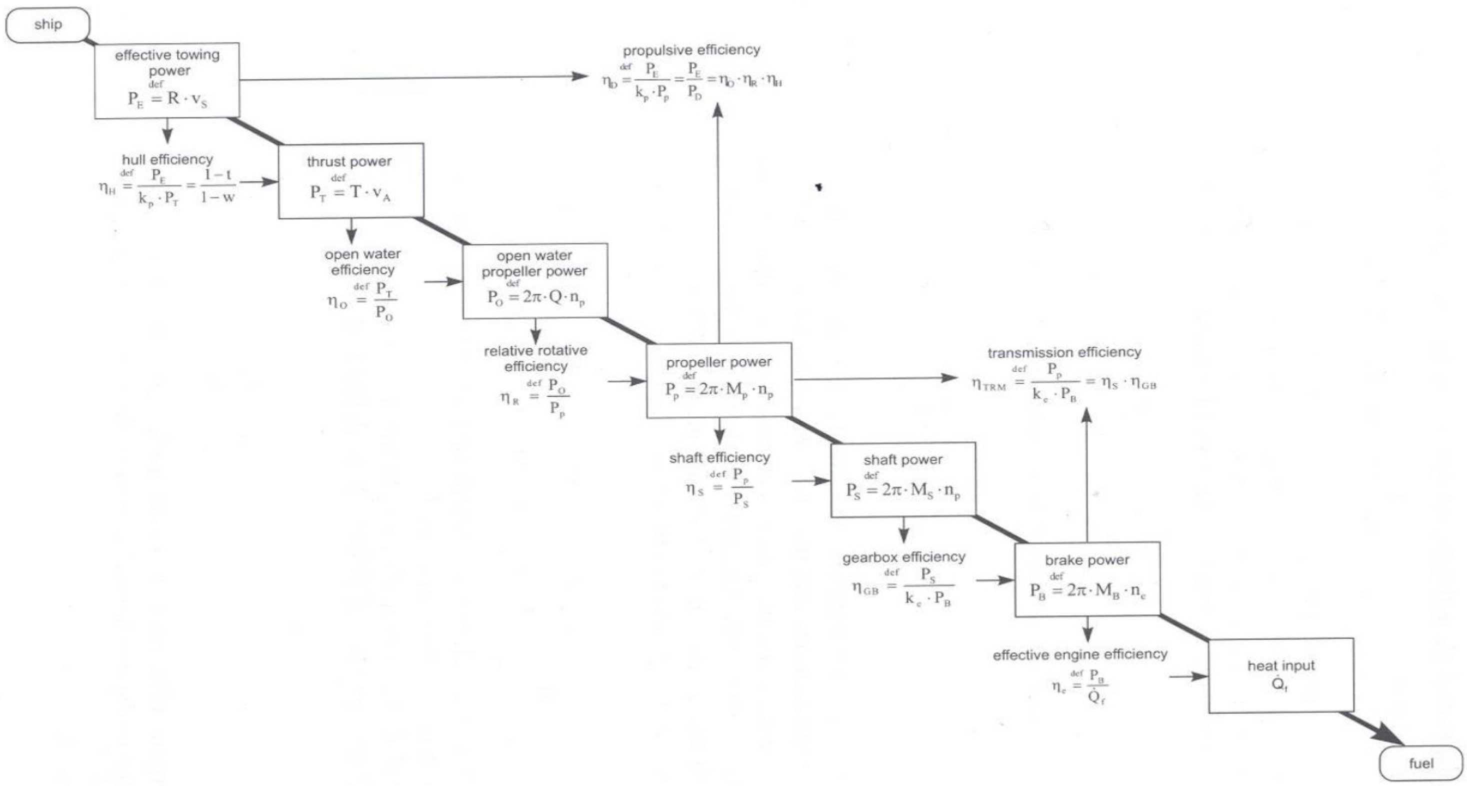


Figure 14: From effective power to fuel power (Klein Woud & Stapersma, 2002)

2.8 Definitions

In this paragraph the definitions of the terms used in this report can be found. For the nomenclature of the parameters used in the calculations a list can be found in appendix 1, which was composed by (Hoon Kim, 2020) and adjusted for this research.

Table 4: Definitions

Hotel load	The hotel load is power being consumed on a vessel that is required for all auxiliary equipment which is not needed for propulsion, mooring or cargo handling. The name hotel load is derived from passenger vessels, in which the 'hotel' requires a big amount of power generated.
Deep-sea cargo vessel	A cargo vessel suited for intercontinental transport, as a opposite of short sea.
Retrofit	A retrofit is equipment which is installed after the vessel is exploited. Mostly this is a scrubber or ballast treatment system.
Nautical mile	One nautical mile is equivalent to 1,852 kilometers.
Cargo handling equipment	All equipment used for loading and discharging cargo. These can be cranes but also other equipment like ballast pumps for heavy cargo vessels.
Operational profile	A profile of a vessel which shows the key properties like power consumption and speed.
Automatic Identification System (AIS)	A system which sends important vessel information, like static vessel properties and voyage data, to AIS receivers.
Anchorage	A place for vessels to go at anchor, while waiting for a spot at the berth. Commonly in vicinity of the port.
Maneuvering	An activity with a vessel to navigate through small waters and to position the vessel for its final mooring position.

2.9 Conceptual framework

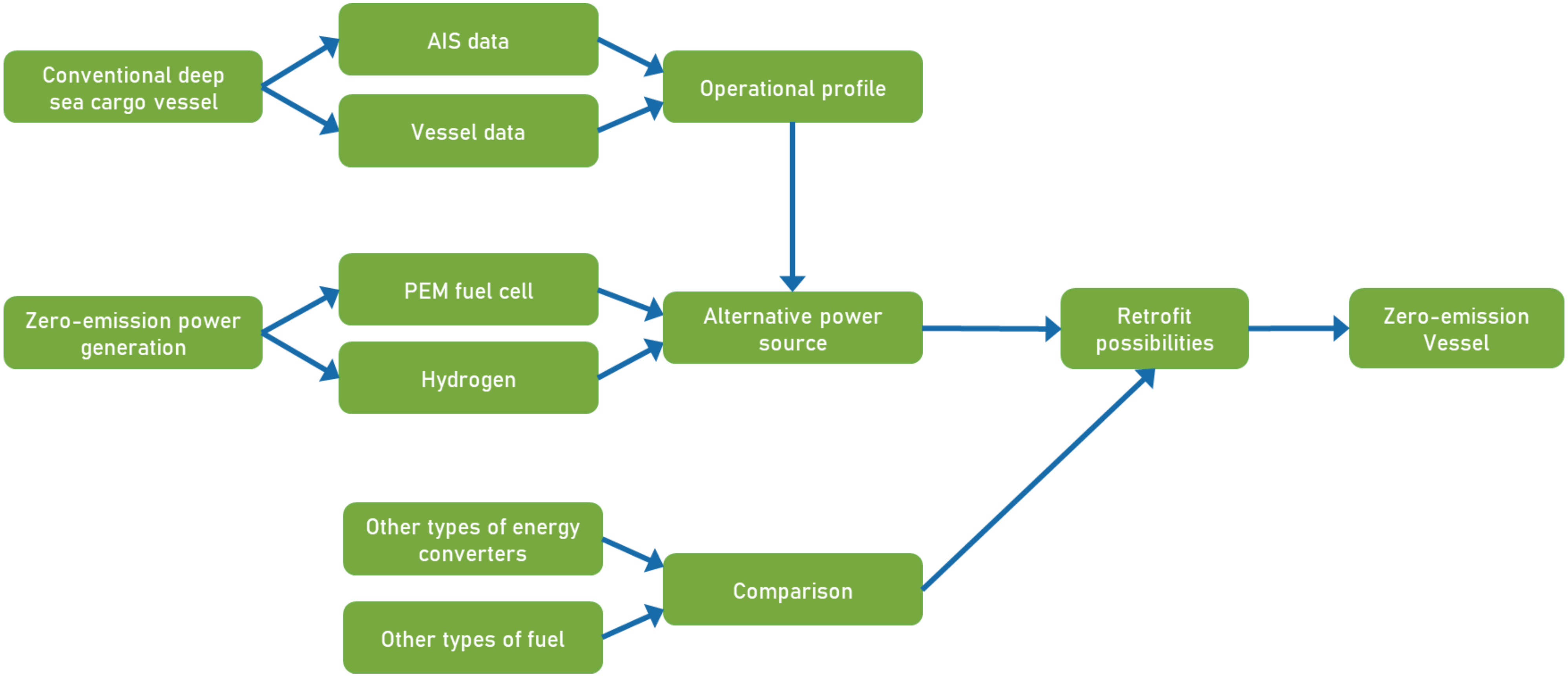


Figure 15: Conceptual framework

3. Method

In this research the possibility of a zero-emission retrofit on board the Falcon Triumph was researched. For the first sub question the operational profile was determined. The input for this part was the AIS data of the motor vessel Falcon Triumph. From this data the draft, time underway and voyage distance was obtained. The AIS data was validated with operational data from the vessel Falcon Triumph, for a single random trip. This data consisted of the fuel consumption, speed, engine revolutions and voyage data. The data regarding the fuel consumption of the fuel cells was obtained through Nedstack and other manufacturers. This data was considered reliable. Due to the fact that this research was based on acquired data, the research method was a quantitative research.

As pre-research, the Falcon Triumph particulars were received and verified on the feasibility for this report. Furthermore, the scope of the research was clarified in accordance with the supervisor at Nedstack.

The population of this research was focused on the deep-sea cargo vessel Falcon Triumph, from which a dataset of one year of voyages was used. This AIS data was derived from the website www.marinetraffic.com.

The research instrument used to gather the vessel profile was composed of a few steps. First the hotel load was examined with a power load calculation of the vessel. Then the amount of fuel cells was determined by means of the AIS data. With help of the AIS data the vessel resistance could be calculated. The method for this calculation was the Holtrop-Mennen method. The average speed of the voyage was calculated and used as input in the calculation. This method was also used by (Hoon Kim, 2020). With the outcome and other efficiencies the power generated by the main engine was determined. By using the calculated power, the used energy for the trip could also be derived from the data.

The details of the parameter determination is discussed in this paragraph. The hotel load was examined with the help of the electric power load calculation. This calculation examines all the consumers of the hotel load. This calculation was produced by the shipyard and can therefore be considered reliable.
To decide the amount of fuel cell power the AIS data was used. To test the accuracy of this method one trip was compared with actual data from the vessel. Also the draft was taken into account with the Holtrop-Mennen method. Furthermore the general specifications of the vessel were used as input for this method. The distances from port to port were derived from the Marinetraffic data and compared with sea-distances.org. As a result from this method the resistance of the vessel was obtained. In combination with the determined propeller and transmission efficiency, the power output of the engine was calculated. For every voyage, this power was calculated. All power values were compared with the speed of the vessel and displayed in a graph. This gave a clear view of the power needed for a certain speed. With this comparison a suitable speed and power output was chosen to determine the power required from the fuel cells. This method also enabled a rough method for following retrofits on other vessels.

Influences of the sea state and weather were neglected due to the fact that this research focused on the feasibility of fuel cells and alternative fuel, rather than power determination.

For the second sub question, this vessel profile was used to design a retrofit for the specific vessel. The power provided by the fuel cells was derived from the method above. For the initial design, PEM fuel cells were used. These fuel cells are capable of quick load changes and are already in a production state for marine applications, whereas other fuel cells are not. (L. van Biert, 2016) Additionally, PEM fuel cells are suitable for the environment on board, where the foundation is constantly moving. (Niet, 2021)
As a fuel, there was looked into liquid or gaseous hydrogen (LH_2/CH_2), due to the fact that LH_2 or CH_2 requires no reforming.

In this retrofit, the same propeller was used, because the main engine was replaced by an infinitely adjustable electric motor with frequency drive. Due to this frequency drive, the revolutions can be matched to the revolutions of the main engine. Data of this electric motor was requested from General Electric. Furthermore the available space on board for fuel was examined to determine the endurance of the zero-emission vessel. Data was collected from companies regarding the storage of liquid and pressurized hydrogen to analyze the possibilities and properties of the tanks.

Finally, to answer the third sub question, the retrofit was compared to other set-ups with different kinds of fuel and fuel cells. This comparison compared the weight and volume of the different set-ups. This comparison focused on the space needed for the installation, and the weight of the installation.

All confidential information received will only be shared with the researcher and it's supervisors, and will not be shared with thirds unless there is explicit permission.

4. Results

In this chapter the results of the research are presented. First the results regarding the power determination are displayed. After that the lay-out is presented, with the fuel storage and the emergency generator. Lastly the comparison regarding other zero-emission options is mentioned. All calculations were made in Excel spreadsheets and are on request available.

4.1 Hotel load and heating demand

The hotel load was derived from the power calculations of the Falcon Triumph. Below in table 5 are the categories and the load while the vessel is in port. This data is representative for the hotel load, and therefore is without the cargo handling equipment.

Table 5: Hotel load (J. Bruinsma from Nedstack (personal communication, April 11, 2022)

Category	Power (kW)
Lighting	67,4
A/C	40,2
Sec. fans	4
Galley	30
Workshop	4
Deck machinery	86
Lighting 2	57
Total	**288,6**

The heating demand on board will decrease, since there is no need to pre-heat the fuel. However, with the regasification of the hydrogen, energy is needed. This energy can be provided by the fuel cells, since the efficiency is 56% which shows that 44% is disposed through the cooling water. Also for heating of the accommodation and the warm water system on board this cooling water can be used. Optionally, a heat pump can be used. Furthermore for air-conditioning cooling purposes, a cold water system can be created with the heat retracted during the regasification process.

4.2 Vessel profile

After determining the hotel load, the following part that was examined was the power delivered by the main engine and therefore the power that needs to be provided by the fuel cells. This examination was used to create a vessel profile that was usable for the determination of the amount of fuel cell power. Via literature research, the Holtrop-Mennen method was chosen. This method was founded at the TU Delft in 1982. With this method, the resistance of the vessel at different speeds was calculated. After this the power output could be calculated with the propulsion efficiency, which was taken as a constant and derived from design conditions. The reason for the constant efficiency is that this research is a feasibility study, and is not covering all technical aspects in detail.

After applying the Holtrop-Mennen method in Excel the 22 voyages were added, and filled into the Excel worksheet. In figure 15 the input values of the calculations are marked in green. The stated parameters were the same as used in Rakke (2016) and Hoon Kim (2020). Furthermore, the ship static data was derived from the general plan and remained constant.

Voyage data input

Voyage draft	7,2	m
Departure time	22-03-22 16:21	
Arrival time	7-04-22 6:54	
Distance port-port	3583	nM
Calculated:		
Voyage time	15,6	days
	374,55	hours
Voyage speed	9,56	kn
	4,9	m/s

Ship static data input

Length overall	199,9	m
Length BP	194,5	m
Length waterline	194,5	m
Breadth	32,26	m
Depth	18,5	m
Design draft	11,3	m
Design power	6842,5	kW
Design speed	14,3	kn
	7,4	m/s
MCR	8050	kW
RPM MCR	89	rpm
	1,5	rps
Average height bulb	6	m

Stated parameters

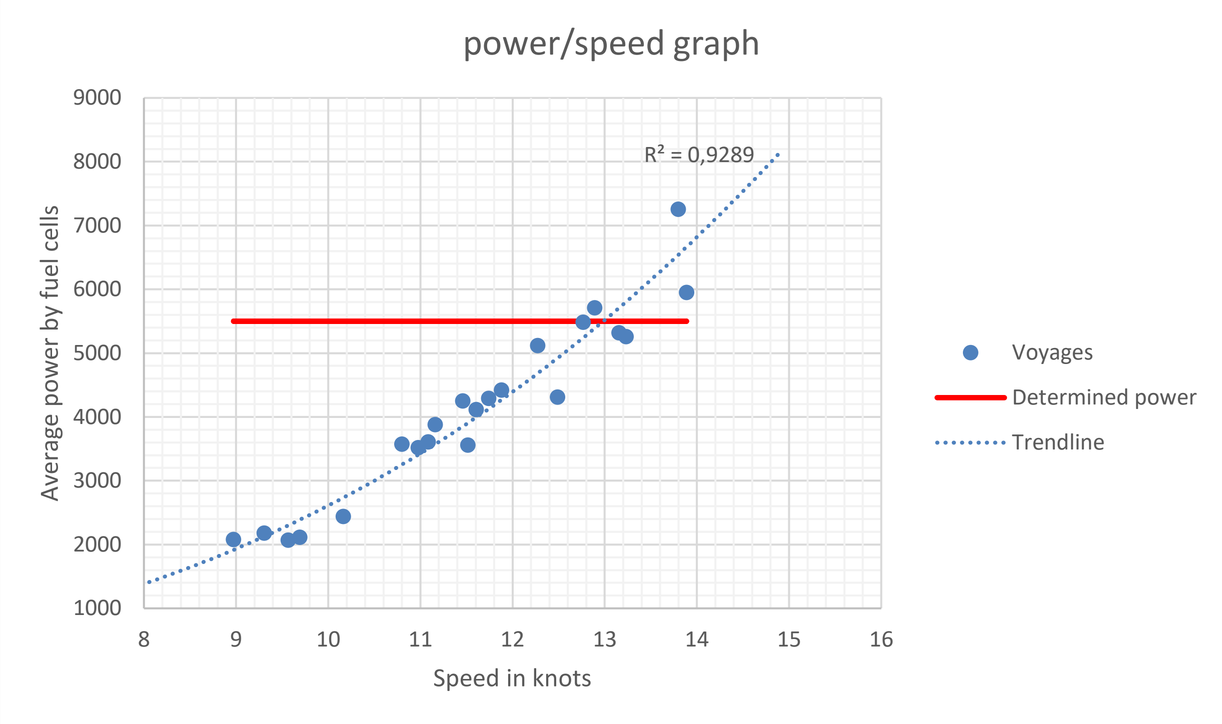
	9,81	m/s^2
ρ sea	1,025	ton/m^3
ρ air	0,0012	ton/m^3
V kin sea	0,00000118	m^2/s

Figure 16: Excel input

For these calculations the departure time, arrival time and voyage draft were adjusted. The other parameters were considered constant. With the calculated resistance, the effective power was calculated. After this, the brake power of the engine was determined. Also a 15% sea margin was added, following Rakke. (2016) The determined hotel load was added to the calculated power. The formula is added below, and the results of all voyages from the past year are shown in graph 1.

$$Total\ power = \left(\frac{(Rt * v)}{Propulsive\ efficiency * 0.85}\right) + Hotel\ load$$

In appendix 2 the voyage data can be found. The voyages from port to anchorage or the other way around are not included, due to the many maneuvering on these trips. This is also applicable for voyages between terminals in the same port. Furthermore the calculated speed was compared to the average speed provided from marinetraffic.com. In case of a deviation of 2 knots or more, the voyage was not considered reliable and not taken into account for the power determination.



Graph 1: Power compared to speed graph

With the average speed and average power demand taken into account the power demand was determined at 5500 kW. For this power determination, 86% of the voyages sailed was below this value. The trendline seen in the graph is a third-power function. The reason for a third-power function is the fact that most resistance factors depend on the vessel speed to the power 3. According to the trendline, a maximum speed of 13 knots is possible. 86% of the total voyages was considered an acceptable amount and therefore 5500 kW was deemed sufficient.

Also the trip length was examined to clarify the sailing profile of the vessel, next to the power and speed of the vessel. The average trip length was calculated and resulted in 2091 nM. The longest voyage was 6043 nM while the shortest was 96 nM. The data can be found in appendix 2.

For the comparison with the actual data of the Falcon Triumph, the fuel consumption of one trip was received. This fuel consumption, together with the engine efficiency will result in the used power. The fuel consumption of the voyage from Rotterdam to Baltimore was 287,8 tons. The specific energy of the fuel was derived from the fuel quality report and was 42,43 MJ/kg. The efficiency of the engine was stated on 49%. (Mrzljak Vedran, 2017) A calculated efficiency with the specific fuel oil consumption (SFOC) of 51,1% was found.

$$\eta = \frac{1}{b_e * H_0} = \frac{1}{165 * 10^3 * 42{,}7 * 3{,}6} * 10^6 = 0.51096 = 51.1\%$$

However this SFOC is given in the most optimal condition with the engine being new and tested in a controlled environment, while the 49% efficiency was measured in a representative situation. Therefore the 49% efficiency is used in this research. With these parameters the actual average power was calculated. The actual average power was 4372,8 kW. In table 6 the outcomes of the comparison between the Holtrop-Mennen (HM) method and the actual data from the vessel are presented.

Table 6: Comparison Holtrop-Mennen method

Unit	HM method AIS	HM method STW	HM method calc. speed	Ship data
Speed	9,566	10,6	12,3	9,566
Power	2070	2742	4179	4372,8
Power deviation	52,66%	37,29%	4,43%	0%

The table also contains the Holtrop-Mennen calculation for the speed through water (STW) and the calculated speed with the propeller rpm and the propeller fixed pitch. In the data received from the vessel, the weather conditions were also mentioned. On this trip there was a severe wind reducing the speed over ground as well as the current which flowed in opposite direction of the vessel. Furthermore, vessel movement due to high swells reduced the STW. Therefore the speed over ground provided by the AIS data provided a 52,7% deviation of the actual value, and the speed through the water a deviation of 37,3%. However, when the calculated speed was used for the Holtrop-Mennen method, the power output only deviated 4,4% from the actual value. This can be explained due to the fact that the calculated speed also relies on given fixed data, like the Holtrop-Mennen method.

4.3 Fuel cell application

To generate 5,5 MW electric power 11 units of 500 kW are needed. (Nedstack) Their information about the 500 kW system concluded that the approximate space taken by the 500 kW fuel cell is comparable with a high-cube 20 feet container. Because these 500 kW units are build in 20 ft containers, the space required when installed on a vessel will be less then the space taken by the containerized units. For this research the 20 feet dimensions will be used, which creates a space margin for an integrated system. In appendix 3 the green rectangles represent the fuel cells units. The space gathered by removing the main and auxiliary engines is sufficient for the placement of the fuel cells.

4.3.1 Weight balance ER

The available space in the engine room of the Falcon Triumph will increase due to the removal of ICE components and the engine itself. In the table below the weight deducted and added in the engine room are mentioned. Because of the losses in an electric propulsion and due to the fact that the weight balance and the available space allow it, the decision was made to install 12 units of 500 kW instead of the determined 11 units. This also helps the efficiency of the fuel cells as the operating power demand is not 100% of the capacity.

Table 7: Weight balance Engine Room (ER)

Unit	Weight (in ton)	Volume (in m^3)
MAN B&W 5S60ME-C8.2 (2-stroke)	350	± 504
ME auxiliaries (CW pumps, coolers etc.)	10	5
Total deducted	**360**	**509**
PemGen MT-FCPI-500 (12x)	180	468
E-motor GE (N3HXC 800 H8CH/5)	16,2	25,4
E-motor frequency drive GE	4,4	13,2
Converter 1 MW (6x)	30	60
Total added	**230,6**	**566,6**
Total balance ER	**-129,4**	**57,6**

The values in table 7 are derived from R.H. Bidstrip from MAN B&W (personal communication, April 11, 2022) for the engine specifications and Nedstack (sd) for the fuel cell specifications. Furthermore General Electric (GE) was contacted for information about the electrical components. GE provided a drawing of a 6 MW electrical motor and drive. Gilles from GE (personal communication, April 21, 2022)

The electrical motor used in this lay-out is manufactured by GE and is a squirrel cage rotor motor. From the fuel cells Direct Current (DC) is delivered, this will be converted to AC by the converters. These can be found in appendix 3 in yellow next to the fuel cells. The drive converts the Alternating Current (AC) from the converter to a medium voltage alternating current because otherwise the maximum power with low voltage for the converter (4 MW) would be exceeded. Gilles from GE (personal communication, April 21, 2022)
The alternating current is required for the squirrel cage type of motor. Furthermore the electric motor will be controlled by a frequency drive to achieve the ideal revolutions for the propeller.

In appendix 4 the electrical layout, also called one line diagram, is added. In this diagram, all the components of the new lay-out are shown. Also the emergency power supply is included in the diagram. This will be discussed in detail in paragraph 4.3.4. A high voltage system was included in the design due to previously mentioned reasons. Moreover a power storage possibility was considered but due to the small load variations and the limited maneuvering abilities it was regarded not necessary.

4.3.2 Fuel capacity

The space utilized on board for fuel storage is 2722 m^3, with a filling grade of 98%. The same amount of space can be used for liquid hydrogen storage. The options examined were:

- The cryo-compressed tank of BMW, mostly designed for automotive applications. (Petitpas, 2018)
- The SAG LH2 tank, designed for heavy duty trucks. (Winklhofer, 2021)
- Gardner 11000 gallon LH2 container, designed as 40 feet container, used for transport. J. Bruinsma from Nedstack (personal communication, April 14, 2022)
- NPROXX 40" 500 bar CH2, which uses 500 bar of compressed hydrogen. J. Bruinsma from Nedstack (personal communication, April 14, 2022)
- DEMACO custom tank, fitted to the available space in the current fuel tanks. S. van Velzen from DEMACO (personal communication, April 14, 2022)

To fit the 40 feet container in the existing fuel tanks, the height of the tank is not sufficient. However below fuel tanks 1 and 2 port- and starboard side a void space exists which can be used to fit these 40 feet containers. This adjustment has been implemented into the calculations of the other storage options.

The specifications of these tanks can be provided on request. The weight of the customized tanks was based on information of existing LNG tanks from Lapesa LNG (sd), which possess much similarities with hydrogen tanks according to S. van Velzen from DEMACO (personal communication, April 14, 2022). With a linear regression line the existing values were extrapolated to the value used for the calculations. This method was also used for the weight and volume of a fuel cell by (Micoli, 2021) in a comparable study. The results of the estimated amount of tanks fitting inside of the existing fuel tanks can be seen in table 8.

Table 8: Hydrogen storage comparison

	Total tanks	Total H2 (kg)	Total weight (ton)	Boil off per day (kg)	Energy amount compared to HFO (100%)
BMW CcH2	8424	54756,0	1010,9*	547,6	6,33%
SAG LH2	1656	66240,0	728,6*	1987,2	7,65%
Gardner 11000 gallon LH2 container	32	85728,0	791,1	0,0	9,91%
NPROXX 40" 500 bar CH2	32	34560,0	860,8	0,0	3,99%
DEMACO Customized	4	126471,1	532,5*	1264,7	14,61%

*The total weight includes the weight of the hydrogen and the tank itself, however the weight for assembling material of the tanks is not added to the weight.

With the comparison between liquid and compressed storage, and also between different sizes of tanks it clarifies the choice for tailored tanks to optimize the space available. For this research, the custom tanks will be used for the lay-out.

Custom tanks can be placed in the fuel tanks 1 and 2 portside (ps) and starboard (sb) side and also in the funnel, which will be redundant if the main engine is removed. The extra weight of the tanks will only positively affect the stability since the weight added for hydrogen storage is not higher than the weight of the full bunker tanks:

$$568{,}07 - 2667{,}6 = -2099{,}5\ ton$$

In appendix 3 the placement of these tanks are shown with the blue rectangles. In table 9 the hydrogen tank overview is displaced.

Table 9: Hydrogen tank overview

Tank name	capacity (kg)	Weight (ton)	Boil off/day (kg)	HFO energy comparison	Volume (m^3)
Tank 1 ps&sb	63235,6	266,2	632,4	7,31%	1099,56
Tank 2 ps&sb	63235,6	266,2	632,4	7,31%	1099,56
Funnel tank	7494,6	35,6	75,0	0,87%	133,60
Total	**133965,68**	**568,07**	**1339,66**	**15,48%**	**2332,71**

The total hydrogen volume was compared with the HFO volume and cross checked with the energy density from table 2. For the calculated fuel, the outcome was 4,47808, while the theoretical outcome 4,47803.

4.3.3 Vessel range

With the determined power, speed and the efficiencies of the electrical motor and it's components taken into account, an estimated fuel consumption can be calculated. Below the calculation for the efficiency of the power from fuel cell to propeller shaft is calculated. The values are provided by Wartsilä, and are indications for the different components mentioned in the one-line diagram in appendix 4. (Per Johannesen, 2021)

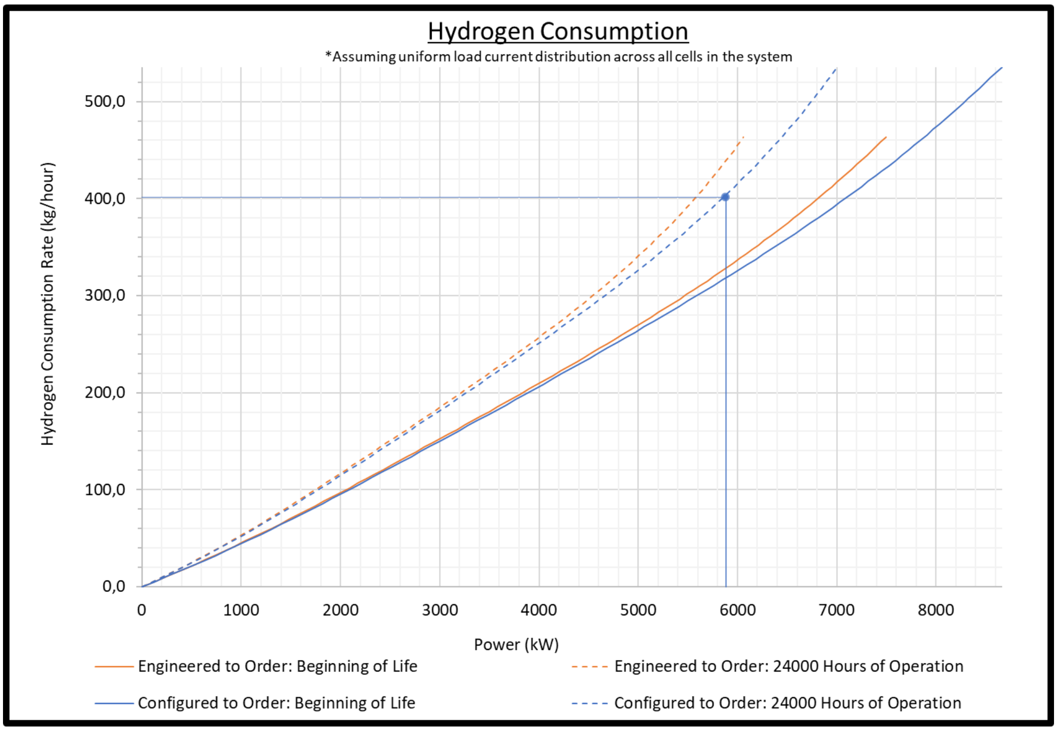
$$power\ efficiency = distr.eff. * conv.eff. * transf.eff. * conv.eff. * e\ motor\ eff.$$

$$power\ efficiency = 0.993 * 0.985 * 0.99 * 0.985 * 0.98 = 0.935 = 93{,}5\%$$

With this power efficiency the fuel cell power output can be calculated:

$$\frac{5500}{0.935} = 5882\ kW$$

This 5882 kW is the power needed to create 5500 kW power at the propeller shaft. This value can now be used to calculate the hydrogen consumption of the fuel cells at the end of their lifetime. The results of these calculations can be seen in graph 2. The blue line is used because the set-up is configured of 500 kW units. Because the sea margin and hotel load are included in the 5500 kW, the power efficiency used for the complete value is an added margin in the power determination of 5882 kW.



Graph 2: Hydrogen consumption

The total consumption of the fuel cells is 401 kg/hour. The speed at 5500 kW was determined at 13 knots. The total amount of hydrogen on board was 133965,7 kg. With these values the theoretical vessel range can be determined.

$$vessel\ range = \frac{total\ H2}{H2\ consumption} * \ vessel\ speed$$

$$vessel\ range = \frac{133965.7}{401} * 13 = 4343\ nM$$

This vessel range is sufficient to cover the average trip length of 2091 nM. The hydrogen range covers 86% of the trips. For the same range 412,9 tons HFO is required, which is 421,35 m^3.

With this consumption the boil-off can be completely used in 1340/401 = 3,34 hours. This is for sailing conditions. During port visits the hotel load is applicable. This load is without mooring and cargo equipment. With this load 21 kg hydrogen per hour is consumed. This is a total of 504 kg per day. This is not enough to compensate the boil-off of 1340 kg/day. Linde uses a Low Pressure Extraction to use a part of the boil-off gas to reliquefy the other part of the boil-off gas. If this technique is used on board, no boil off gas has to be vented to the atmosphere. (Linde gas)

Furthermore, the PEM lay-out was compared to the conventional setup for the maximum voyage distance, in weight and volume. In the following calculations the difference is displayed.

$$Weight = \ -129{,}4 + 568 - 412{,}9 = 25{,}7\ ton\ extra$$

$$Volume = \ -2{,}4 + 2332{,}7 - 421{,}35 = 1909\ m^3\ extra$$

When compared to the operational data of the Rotterdam – Baltimore voyage, the required amount of energy for this trip was calculated.

$$Energy\ required = Power * time * 3{,}6 = 4372{,}8 * 380{,}1 * 3{,}6 = \ 5983564{,}6\ MJ$$

With this amount of required energy, the hydrogen needed for this trip was calculated using the lower heating value:

$$Amount\ of\ hydrogen = \frac{5983564{,}6}{120{,}21} = 94{,}776\ ton$$

4.3.4 Emergency generator

The emergency generator equipment on board facilitates 120 kW power for 18 hours, which is required by the International Maritime Organization (IMO) Safety Of Lives At Sea (SOLAS) convention legislation (IMO, 1974). For a zero-emission vessel this cannot be generated by an ICE. Nedstack has a 100 kW unit which can provide this power. For the 18 hours service at full load, 108 kg of hydrogen is required. This hydrogen can be provided from the boil off of the main tanks, or by a secondary source of hydrogen. For the last option a 10 feet 300 bar storage container from NPROXX is used. In this application, compressed hydrogen is used because there is no boil-off and therefore contains the hydrogen without degradation of the amount of stored hydrogen. This container contains 170 kg of hydrogen which is sufficient for the energy required. The containers weights 9,5 tons and the fuel cell unit 2,5 tons which brings the total to 12 tons added weight. J. Bruinsma from Nedstack (personal communication, April 19, 2022). The generator weight is neglectable compared to the weight of the fuel cell solution.

Also, the SOLAS requires 3 start ups from 2 different power sources. For a 100 kW unit, 5 kWh is more than sufficient for 3 start ups. In total, 10 kWh electrical power needs to be provided by batteries. The battery pack used for starting the ICE is 5 kWh. Another 5 kWh battery pack needs to be added, for which space will most likely be available.

In figure 17 the lay-out of the fuel cell and hydrogen storage in the emergency generator room is shown. The emergency fuel cell unit is shown in red, while the hydrogen storage is purple. The complete overview of the lay-out can be found in appendix 3.

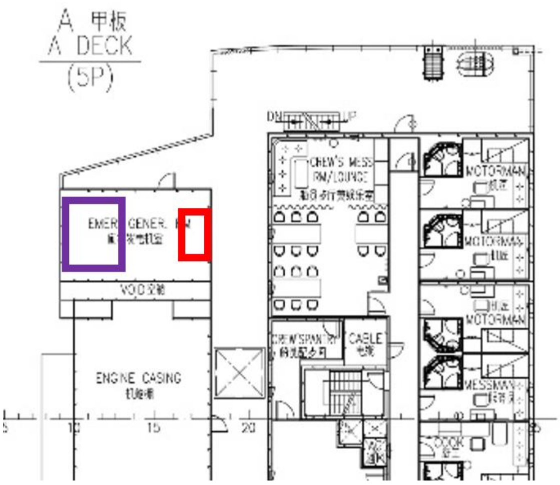


Figure 17: Emergency power facilities

4.4 Comparison with other zero-emission solutions

There are many paths to zero-emission vessels. In this chapter a few different possibilities are being compared to the PEM fuel cell lay-out in this research. This comparison will focus on the weight and volume of the lay-out before and after the maximum voyage length. The reason for this is that the CO_2 storage will be empty at the beginning of the trip (BOT) and full at the end of the trip (EOT). Furthermore the fuel tanks will be empty at the EOT. This is summarized in a table and also indicates the differences between these situations.

4.4.1. Methanol ICE

The first option is using methanol as a fuel for the conventional ICE. To form this option into a zero-emission option, the exhaust gasses need to be stored. The exhaust gasses emitted by methanol fueled engines are mentioned in figure 18.

Compound	Emissions (g/MJ methanol)	Source
CO_2	69	/12/
CH_4	0	/12/
N_2O	0	/12/
NO_x	0.4	/14/
SO_x	0	/12/

Figure 18: GHG emissions methanol fueled ICE (DNV GL, 2016)

When using methanol as a fuel in a conventional diesel, the efficiency is considered the same when using fuel oils (DNV GL, 2016). For 5500 kW the efficiency of the engine is set on 49% when roughly compared to Mrzljak Vedran.(2017) With these values it is possible to calculate the energy input from the methanol. Because the same ICE is used, no other efficiencies come into play.

$$Methanol\ energy = \frac{Power\ output}{efficiency} = \frac{5500}{0.49} = 11224{,}9\ kW$$

For one nautical mile, the power requirement is 11224,9/13 = 863,4 kWh/nM, which equals 3108 MJ/nM. This results in the usage of 3108*4343 = 13499435 MJ energy provided by methanol. This equals 673,2 tons of methanol. The CO_2 released with this amount of energy is 69*13499435 = 931,5 tons.

Also, energy is required for the storage of the CO_2. The used estimate of energy required for the liquefaction of CO_2 is between 1,9 and 7,8 kWh/ton. (Frithjof Engel, 2018) This number depends on the pressure, and the average of 4 kWh/ton was used. To liquify all the CO_2 931,5*4 = 3726 kWh is required. This additional energy requires therefore 1,4 tons extra methanol and emits 1,9 tons CO_2 extra. The energy costs for the liquefaction of this additional CO_2 was deemed negligible.

To store this CO_2 on board, tanks of ASCO CARBON DIOXIDE LTD (2021) are used. One tank of 97,85 ton liquid CO2 is approximately 13,5 x 3 m = 40,5 m^3. 931,5/97,85 = 10 tanks. 10 x 40,5 = **405 m^3** space required for liquid CO_2 storage. The toral weight of the tanks is 10 * 29,5 + 998 = **1228,4 ton**.

673,2 ton methanol can be stored in 673,2/0,786 = **856,5 m^3** storage.

Furthermore, the NO_x gasses need to be captured. This is mostly done by catalytic reduction which has the challenge that with this process not all NO_x gasses are being captured. The NO_x emissions for this setup are 0,4 g/MJ. The total emission is 0.4 * 13499435 = 5,4 ton NO_x. With catalytic reduction this NO_x is reformed to nitrogen and water. However, not all NO_x emissions are converted.

Due to the fact that the lay-out of the engine room only requires minor adjustments, the weight and volume of the equipment in the ER was considered unchanged. Therefore the values from table 7 can be used.

This table mentioned a lower volume **57,6 m^3** extra for the methanol ICE and a added weight of **129,4 tons** compared to the PEM fuel cell lay-out. The volume occupied by the fuel is around 1/3 the volume of the hydrogen. The values from above are summarized in table 10. A remark for this table is that only the weight of the CO_2 is taken into account in comparison to the PEM. This is due to the fact that the maximum amount of CO_2 is present when all fuel is used, and therefore adds no weight.

Table 10: Overview Methanol ICE

Type	Weight (ton)	Volume (m3)	Compared to PEM BOT (ton)	Compared to PEM EOT (ton)	Compared to PEM (m3)
Meth ICE ER	360,0	509,0	129,4	129,4	-57,6
Fuel	673,2	856,5	105,1	-434,1	-1476,3
CO_2	1228,3	405,0	295,0	1228,3	405,0
Total	**2261,5**	**1770,5**	**529,5**	**923,6**	**-1128,9**

4.4.2 SOFC with LNG

SOFC are considered as a promising alternative for conventional propulsion, together with PEM fuel cells. (L. van Biert, 2016) Also Micoli (2021) did a case study of a SOFC on board a cruise ship. The data used in that report was used for this comparison.

The weight and volume of the SOFC are derived from the report of Micoli (2021) which uses a linear regression line of existing units to calculate the weight and volume of multiple MW units. A 6 MW unit according to this method would have the following properties: A weight of **296,5 ton** and a volume of **506,2 m3**. Compared to the PEMFC engine room this adds 296,5-200,6 = **65,9 tons** of weight. For the volume, the difference between the PEM and SOFC is **60,4 m^3**.

The efficiency of the SOFC is stated at 60%. Furthermore, the efficiency from fuel cell to shaft which was calculated was used for the calculation below. For 5500 kW, the required energy in the fuel is:

$$LNG\ energy = \frac{Power\ output}{efficiency} = \frac{5500}{0.6*0.935} = 9803{,}9\ kW$$

To sail one nM, the power requirement is 2714,9 MJ. When multiplied by the range of 4343 nM, the total energy need is 1,18*10^7 MJ. This resulted in a total weight of **250,7 ton** LNG, which **is 571,2 m^3**. These calculations were made with the values in table 2.

Since LNG also consists of carbon elements, the CO_2 also needs to be captured. The amount of CO_2 emitted by the SOFC is 343g/kWh. The total amount of CO_2 emitted is **1201 ton**. For the storage of this CO_2 in liquid form, 4*1201 = 4804 kWh is required. This results in 0,6 ton extra LNG and 10 tons extra CO_2. The energy for the liquification of this additional CO_2 is neglectable.

The CO_2 will be stored in the same tanks as mentioned in 4.4.1. To store the CO_2 in these tanks 1211/97,85 = 13 tanks are required. The space taken by these tanks is 40,5*13 = **526,5 m^3**.
The total weight of the CO_2 and the tanks is **1486,7 ton.**

For the storage of the LNG the same tanks are used as in the PEM retrofit, due to the many similarities between LH2 storage and LNG storage. Both of these fuels are stored cryogenic. This storage requires at least 2 tanks (ps/sb) for redundancy and weight balance. These tanks are 305,4 m^3 each, and use the same diameter of 5m. The length of each tank is therefore 18 m. With vacuum insulation this will results in 352,6 m^3 and 86,6 ton per tank.
The total space taken by LNG storage is **705 m^3** and the total weight is **423,9 tons**. This is significant less volume than the storage of liquid hydrogen.

The overview of these values can be found in table 11.

Table 11: Overview LNG SOFC

Type	Weight (ton)	Volume (m^3)	Compared to PEM BOT (ton)	Compared to PEM EOT (ton)	Compared to PEM (m^3)
SOFC ER	296,5	506,2	65,9	65,9	-60,4
Fuel	423,9	705,2	-144,2	-260,9	-1627,5
CO_2	1486,7	486,0	354,0	1486,7	486,0
Total	**2207,0**	**1697,4**	**275,7**	**1291,6**	**-1201,9**

With LNG used in a SOFC, NO_x and CO emissions are present. To capture these emissions, extensive exhaust gas treatment is necessary. Also it is not possible to reduce these emissions to 0%. Compared to the CO_2 emissions, NO_x and CO emissions are only a small part of the total emissions.

4.4.3 PEM fuel cell with ammonia through reformation

For the ammonia fueled PEM fuel cell the lay-out explained earlier in this chapter can be used. An ammonia fueled fuel cell differs in two ways from a hydrogen fueled fuel cell. The ammonia used needs to be reformed to acquire the pure hydrogen required in a PEMFC. The nitrogen that is released during this reforming needs to be captured. The last part is difficult, and not 100% achievable so for absolute zero-emission this option is not suited. However the use of ammonia as a fuel is a high potential alternative fuel and therefore considered in this comparison.

The efficiency of the reformer and purifier is set at 80% and 90% respectively. This combines to a total efficiency of 0,8*0,9 = 72%. Due to this process, the amount of energy needed is divided by this efficiency. (Kyunghwa Kim, 2020)

$$Ammonia\ energy = \frac{Power\ H2}{efficiency} = \frac{16104014{,}26}{0{,}72} = 22366686{,}47\ MJ$$

The amount of power required resulted in 1204 tons and 1768 m^3 of ammonia. Ammonia is mostly stored as a liquid under pressure or cryogenic at ambient pressure. For this application cryogenic tanks are used as the boil off can be used for direct power generation. These tanks can contain 238,8 m^3 ammonia and are 28,8 m long with a diameter 3,66 m. These dimensions are comparable with those of the liquid hydrogen tanks. (Tatsa)

Furthermore weight is added to the engine room due to the reforming of the ammonia. Also the capturing of the NO_x emissions adds weight. These weights are mentioned by Kyunghwa Kim (2020) and are taken into the comparison in table 12.

Table 12: Ammonia comparison

Type	Weight (ton)	Volume (m3)	Compared to PEM BOT (ton)	Compared to PEM EOT (ton)	Compared to PEM (m3)
PEM ER	255,6	616,1	25	25	49,5
Fuel	2023,0	2121,7	1045,4	-24,6	-211,0
Total	**2278,6**	**2737,8**	**1070,4**	**0,4**	**-161,5**

As for almost all hydrogen carriers, ammonia also has added emissions which cannot be reduced completely. Therefore as a zero-emission solution this faces a lot of challenges.

In table 13, all comparisons are summarized in one table. In this table all options are compared to the liquid hydrogen PEM retrofit regarding weight and volume.

Table 13: Summary comparison

Options	Compared to PEM BOT (ton)	Compared to PEM EOT (ton)	Compared to PEM (m3)
Methanol ICE	529,5	923,6	-1128,9
SOFC with LNG	275,7	1291,6	-1201,9
PEM with ammonia	1070,4	0,4	-161,5

If the values from table 13 are converted to a percentage deadweight of the vessel this results in the values displayed in table 14.

Table 14: Comparison in percentage of deadweight

Options	Compared to PEM BOT (ton)	Compared to PEM EOT (ton)
Methanol ICE	1,04%	1,81%
SOFC with LNG	0,54%	2,53%
PEM with ammonia	2,10%	0,00%

5. Discussion

In this paragraph the different aspects of the results presented in chapter 4 will be discussed. The hotel load was derived from a power calculation, but was not verified with actual data from the vessel itself. Also the heating system on board was only shortly covered.
For the vessel profile determination AIS data was used. This data was retrieved from the website Marinetraffic.com, and not directly from the vessel itself. Therefore this data could deviate from the actual data on board the vessel. In this research, the scope was a feasibility study and therefore only an estimate with little data was determined with the Holtrop-Mennen method, this method is used for a design prediction of the vessel resistance.
Furthermore the propeller efficiency in this research is considered constant while in practice, this is dependent on the vessel resistance. Also the weather conditions were not taken into account, while weather can have significant impact on the vessels power demand, as could be seen in table 6. However the fact that AIS data was used, caused the missing weather influence. To verify the method, one voyage was used as comparison. This increases the chance that the comparison is not representative for the rest of the voyages.
Moreover, a dataset of one year was used due to the fact that the Marinetraffic information did not cover a larger period. Finally for the power determination it is necessary to validate if the installed power is sufficient to comply with the IMO legislation. The minimum power using the minimum power lines of the IMO results in a power of 8217,9 kW. However, using the simplified assessment this power will likely be less. In research from F. C. Gerhardt, (2020) the power determined via the minimum power lines was 25,5 MW, while the power with the simplified assessment was 12 MW. This assessment was not conducted in this research due to the scope of this research.

For the retrofit, many assumptions had to be made:
Because fuel cells have been used in only a few large projects, most of the information relies on experience with smaller projects and researches.
Moreover, this report was made in cooperation with Nedstack, so no other manufacturers of fuel cells were contacted.
Furthermore, for the storage of the fuel, contact was made with one specialized company to acquire information for a fitting assumption. This also applies to the electric propulsion train, which was derived from one company, General Electric.
Also the specifications and exact lay-out for the electric propulsion were not covered in this report. To contribute to the feasibility of a retrofit, more research into this specific component is necessary.

The comparison between the PEM lay-out and the other options is not complete. There are numerous options for zero-emission energy conversion, and to contain all these options in this report would require more research. The most promising options were chosen, but for a conclusive comparison, all alternatives should be considered. Also the comparisons are on a superficial level in contrast to the PEM fuel cell retrofit. This was due to the fact that the scope of this research focusses on the PEM fuel cell. For the most optimal comparison, all options should be reviewed on an even level regarding the feasibility on board of a vessel. Furthermore the storage for the different kinds of fuel was composed of information available to the researchers.

Finally, all used parameters were acquired to be as accurate as possible, but are nonetheless estimates. For a realistic retrofit, all components from this retrofit need additional research.

6. Conclusion & recommendations

In this paragraph, the answers to the research sub-questions are given. All these answers combined will result in a solution for the main question. Finally, recommendations were made for further research.

6.1 Conclusion

To create the retro fit, the operational profile of the vessel regarding the sailing profile and the performance on board was examined. At first, the hotel load was specified. The hotel load was calculated and set on 289 kW. The total power delivered by the ME on board was determined with the Holtrop-Mennen method for a year of voyage data. With this method a power demand including sea margin and hotel load was determined. For 86% of the voyages 5500 kW was sufficient. The average trip length was 2091 nM. This was considered an acceptable profile because the Falcon Triumph is a bulk carrier which does not require a high speed for cargo transportation. The method was compared with on board data of one trip, and was considered accurate enough for this research with a accuracy of 48%, however this was due to severe weather conditions which decreased the speed over ground drastically. When the calculated speed was used, the used method was 96% accurate.

With the above mentioned vessel profile the feasible lay-out is researched. Using this profile the fuel cells required on board were set on 12 units of 500 kW. An electric motor was added for propulsion of the propeller. This 6 MW e-motor is provided by General Electric. With the removal of the old engine this resulted in a weight balance of -159,4 ton in the engine room. Due to this weight loss, the stability will change. However, the decreased weight in the bunker tanks will counteract this challenge. Furthermore the new vessel range was determined at 4343 nM, using close to 124 ton hydrogen. With this range, 86% of the voyages made in the past year could be sailed. For this vessel range only the space on board for fuel storage and the redundant funnel were used. As a result this retrofit requires a minimum amount of structural changes to the vessel. In figure 19 the retrofit of the ER is pictured. This is a cut out from the lay-out in appendix 3.

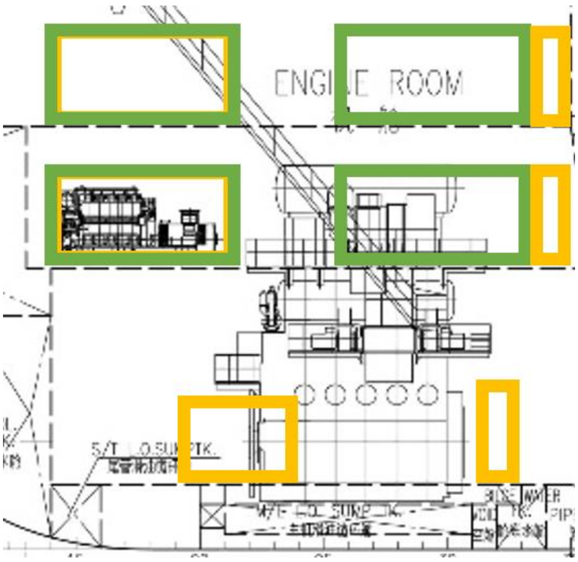
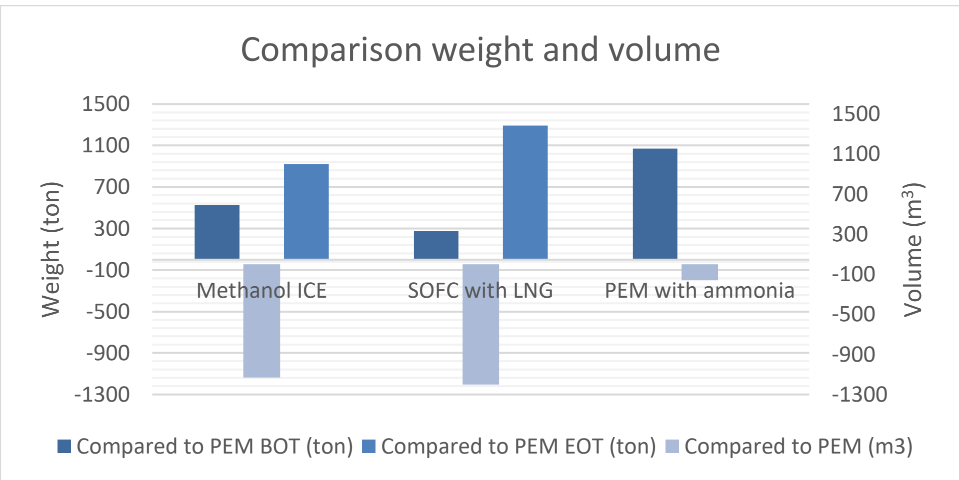


Figure 19: Retrofit engine room Zero-emission vessel Falcon Triumph

In this figure the main components of the retrofit are drawn into the general plan of the Falcon Triumph. Because of the large 2 stroke engine, the engine room retrofit is feasible. There is sufficient space for the fuel cells and also the emergency generator can be replaced with a 100 kW fuel cell unit. However, this emergency fuel cell will impact stability due to the added weight relatively high in the accommodation.

As a last sub-question, the comparison between the PEM zero-emission lay-out was made with other zero-emission solutions, to research the feasibility of the PEM lay-out. In general, all the fuel used occupied less space than the liquid hydrogen however the added weight is a problem for most options.
When compared to the methanol ICE, a lot of weight was added mostly due to the storage of the CO_2. However, for the same vessel range as with the PEM, only 915,9 m^3 of storage space was required. When compared to the liquid hydrogen, the vessel range can be expanded due to the fact that more fuel can be taken in. However, the extra CO2 storage space and weight has to be taken into account. Furthermore the weight of the storage of methanol and CO2 is at the EOT 923,6 tons more then the PEM lay-out. Finally, to use a methanol ICE as a zero-emission solution requires a lot of exhaust gas processing techniques and even then zero-emission will be a difficult to reach.
The SOFC configuration is a promising fuel cell technique, but with the LNG fuel the emissions are still present. The engine room lay-out in terms of space is comparable with the PEM retrofit and with the weight comparable to the conventional lay-out. The fuel needed for the vessel range is less then that for the PEM lay-out, which results in a smaller storage of fuel. Also, the emissions of NO_x and CO are difficult to reduce to 0%. Like the methanol ICE this requires a lot of exhaust gas treatment. Furthermore the SOFC is not capable of absorbing fluctuating power demands. Therefore it is less suitable for bad weather conditions, where fluctuations quite often happen.
As the last comparison the ammonia option looks promising, however the NO_x emissions are, as mentioned above, difficult to solve. However, there are no carbon emissions. When comparing the ammonia PEM solution at the EOT, the ammonia lay-out is in favor. In opposite, at the BOT, the ammonia weighs 1070 tons more than the LH_2 PEM lay-out.
Finally looking at all options, the PEM fuel cell fed with liquid hydrogen is the best option, with the PEM on ammonia as a second option. This is mostly due to the fact of the weight of the CO_2 captured.



Graph 3: Comparison weight and volume

With these conclusions to the various sections of this research, the final conclusion in this report can be concluded. The question was:

What are the possibilities to create a feasible retrofit with PEM fuel cells for a conventional deep-sea cargo vessel to a zero-emission vessel?

The possibilities for a retrofit with PEM fuel cells are feasible, however the vessel range will be compromised due to the reduced energy density of liquid hydrogen. To ensure this feasibility, other options for a zero-emission vessel are compared to this PEM retrofit. However, these options were not complete zero-emission or not (yet) suitable for implementation on board a conventional deep sea cargo vessel. Therefore the PEM fuel cell retrofit is the most suitable possibility for a zero-emission vessel.

6.2 Recommendations

In following research the operational profile of the vessel can be determined more accurate by changing the method from AIS data to operational data. An other option is to conduct measurements on board. This also applies to the determination of the hotel load. Furthermore, the propeller efficiency which depends on the speed can be implemented. When using operational data, the weather conditions need to be taken into account. With the comparison of the operational data this became very clear. If the same method is used in following research, the accuracy can be increased by using data of a larger timespan. To validate the method, other types of vessels can be used for this type of research to conclude that this method is also suitable for other types of ships. Also the comparison of operational data with the calculated value can be done with multiple trips. Adding to this, the heating system on board was only discussed briefly. This could be researched to examine if the heat generated by the fuel cells is sufficient for the regasification and heating of the different systems on board. For a legitimate propulsion power, a minimum power assessment as defined per IMO legislation should be completed.

The effect of the retrofit on the stability of the vessel should be calculated in further research to ensure the stability of the vessel will comply with applicable legislation. For the storage and the energy converters more alternatives could be examined. The research would be more conclusive if multiple companies were contacted. This would result in a small feasibility study of the various options for the electric propulsion, storage and fuel cells.

It is advisable to explore the options of hydrogen carriers in combination with a reformer and PEM fuel cells. Furthermore the comparison with other options can be expanded and compared at a higher level of detail.

Finally, this report is a first glance at the possibilities of zero-emission operations on board deep-sea cargo vessels with the aid of fuel cells or other zero-emission types of energy converters. This research reveals that PEM fuel cells are a viable option for zero-emission shipping. However further research into the different aspects is necessary for a detailed and elaborate option for hydrogen fuel cells on board.

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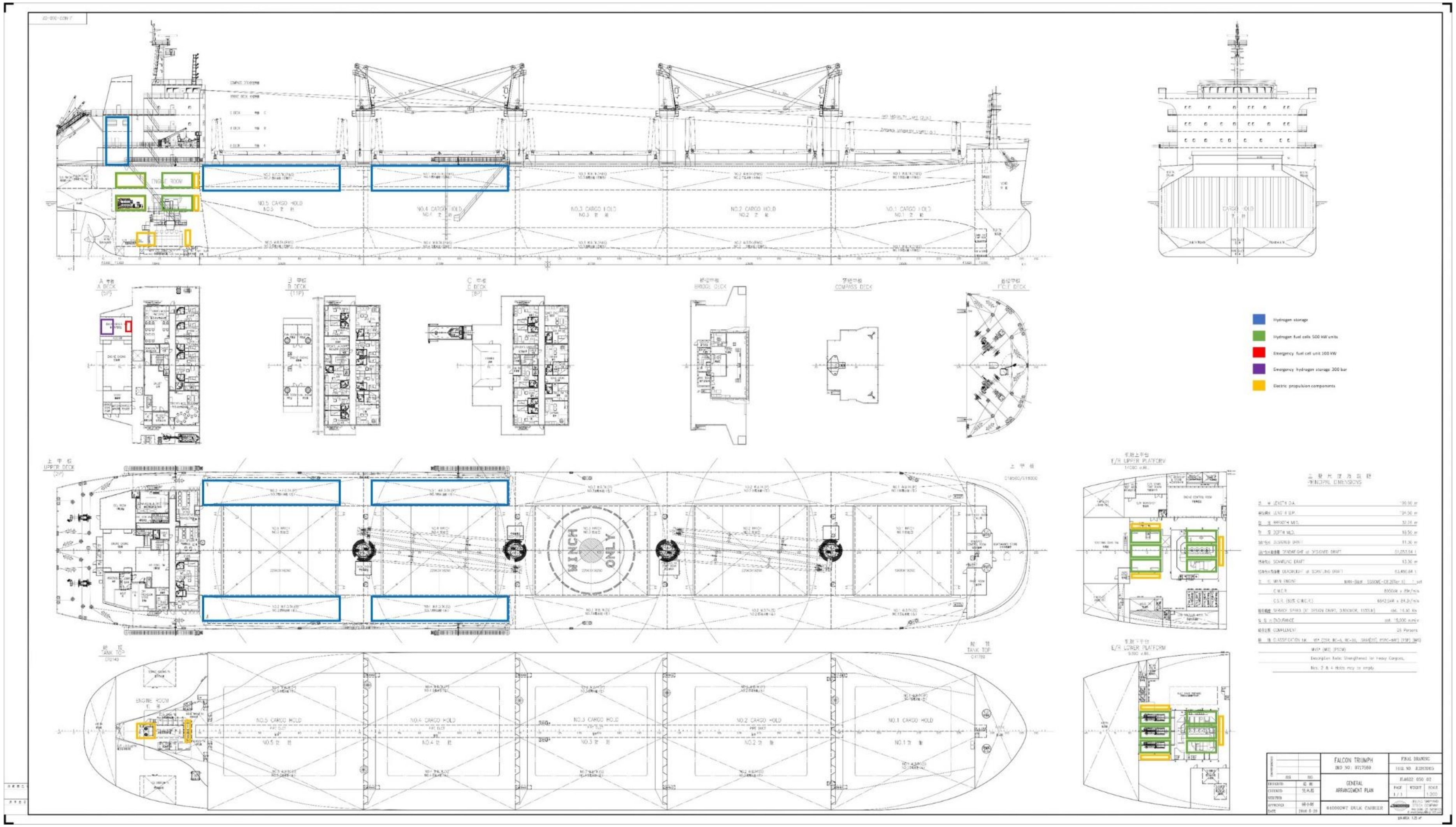
Appendix 1: Nomenclature parameters used

g	Gravitational force, stated at 9,8 m/s^2 (Hoon Kim, 2020)
ρ_{sea}	Density of the seawater, stated at 1,025 ton/m^3 (Hoon Kim, 2020)
ρ_{air}	Density of the air, stated at 0,0012 ton/m^3 (Hoon Kim, 2020)
$v_{kin\ sea}$	Kinematic viscosity, stated at 0.00000118 m^2/s (Hoon Kim, 2020)
v_{ship}	Speed of the ship
v_{design}	Design speed of the ship
T_{ship}	Draft of the ship
L_{bl}	Length between load lines
B	Breadth of the ship
T_{design}	Design draft of the ship
MCR	Maximum Continuous Rating (MCR) the maximum safe power output of an engine
N_{mcr}	Rounds Per Minute (RPM) at MCR power
L_{wl}	Length on the waterline
C_b	Block coefficient
C_m	Midship section area coefficient
C_{wp}	Waterplane area coefficient
A_{bt}	cross-sectional area at the fore perpendicular
A_t	Transom area under the waterline
R_t	Total ship resistance
R_f	Frictional resistance
R_{app}	Appendage resistance
R_w	Wave resistance
R_b	Additional pressure resistance of bulbous bow near the water surface
R_{tr}	Additional pressure resistance due to immersed transom immersion
R_a	Model ship correlation resistance
η_h	Hull efficiency
η_r	Relative rotative efficiency
$v_{average}$	Average speed during the voyage

Appendix 2: Voyage data

POD	POA	Start voyage	End voyage	Voyage time (days)	Draft (m)	Voyage distance (nM)	Average speed (kn)	Average power by fuel cells
MORMUGAO ANCH	SINGAPORE ANCH	14-04-21 3:52	22-04-21 10:40	8.283333333	13.3	2278	11.45875252	4249.890624
SINGAPORE ANCH	LIANYUNGANG ANCH	22-04-21 18:27	1-05-21 22:52	9.184027778	13.3	2380	10.79773157	3572.798226
LIANYUNGANG	SKARDON RIVER ANCH	5-05-21 7:24	19-05-21 2:41	13.80347222	7.2	3367	10.16350556	2442.097121
NINGBO ANCH	PEMANCINGAN ANCH	20-06-21 14:49	28-06-21 10:10	7.80625	7.4	2157	11.51321057	3560.280906
PEMANCINGAN ANCH	CHANGJIANGKOU	2-07-21 19:14	11-07-21 8:40	8.559722222	11.5	2277	11.08388772	3608.507937
CHANGJIANGKOU	NANTONG	17-07-21 18:49	18-07-21 5:08	0.429861111	11.5	96	9.305331179	2177.894369
SHANGHAI	KOAHSIUNG ANCH	3-09-21 8:23	5-09-21 9:40	2.053472222	7.3	652	13.22962462	5259.514267
KOAHSIUNG	SINGAPORE ANCH	23-09-21 13:03	28-09-21 18:29	5.226388889	10.3	1617	12.89131012	5710.670912
SINGAPORE ANCH	SUEZ SOUTH ANCH	29-09-21 6:41	17-10-21 7:31	18.03472222	10.5	5082	11.74123989	4288.580896
SUEZ CANAL NORTH	MALTA POL ANCH	18-10-21 18:24	22-10-21 8:03	3.56875	10.5	940	10.97489784	3519.513427
MALTA POL ANCH	ANTWERP	22-10-21 23:14	31-10-21 14:34	8.638888889	10.8	2406	11.60450161	4117.078374
ANTWERP	SKAGEN ANCH	6-11-21 12:58	8-11-21 22:21	2.390972222	7.1	556	9.689224514	2113.773985
SKAGEN ANCH	ST PETERSBURG ANCH	8-11-21 22:21	11-11-21 14:26	2.670138889	7.5	843	13.15474642	5320.196199
ST PETERSBURG	SKAGEN ANCH	15-11-21 17:50	19-11-21 4:35	3.447916667	10.7	983	11.87915408	4418.91207
SKAGEN ANCH	PARANAGUA ANCH	20-11-21 6:41	10-12-21 0:00	19.72152778	10.8	6043	12.76735096	5482.225889
PARANAGUA	RECALADA	12-01-22 11:31	15-01-22 0:51	2.555555556	7.1	766	12.48913043	4311.402484
CAMPANA	LAS PALMAS ANCH	22-01-22 16:00	6-02-22 5:51	14.57708333	9.1	4827	13.79734172	7256.326047
LAS PALMAS ANCH	CORK ANCH/RINGASKIDDY	6-02-22 17:30	11-02-22 15:44	4.926388889	9.1	1451	12.27234282	5116.887349
CORK ANCH/RINGASKIDDY	BELFAST	15-02-22 20:55	16-02-22 16:00	0.795138889	7.1	265	13.88646288	5950.907215
BELFAST	MURMANSK	22-02-22 15:56	1-03-22 2:52	6.455555556	9	1729	11.15963855	3879.66867
MURMANSK	ROTTERDAM	9-03-22 5:53	17-03-22 3:14	7.889583333	13.1	1699	8.97280169	2079.940135
ROTTERDAM	BALTIMORE	22-03-22 16:21	7-04-22 6:54	15.60625	7.2	3583	9.566146042	2069.972973

Appendix 3: Retrofit lay-out



Appendix 4: One-line diagram