Fuel cell Systems Applied in Expedition Cruise Ships

A Comparative Impact Analysis

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by

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Preface

Although hydrogen is the most common element in the universe, it is rarely found in its pure form. Pure hydrogen can be made from different sources and contains an immense amount of energy. In this time where we have to work hard to save the future of our planet, it is important to look into energy generation options that reduce the amount of damage to climate and environment. Fuel cells in combination with hydrogen is such an option.

This document functions as a final report of a graduation project about fuel cells applied on expedition cruise vessels and is part of the Master Marine Technology. The research is a collaboration of DAMEN Cruise and the Delft University of Technology and delivers a contribution to their common goal to support the energy transition. Personally, I am much aligned with this goal and eager to deliver my contribution. This research was executed under supervision of Prof. dr. ir. R.G. Hekkenberg of the TU Delft ship design department, Dr. ir. L. van Biert of the TU Delft marine engineering department and Ir. L. Codiglia of the Damen design & proposal department. Dr. ir. J.W. Haverkort of the TU Delft process and energy department and Dr. B. Atasoy of TU Delft transport engineering logistic filled the roles of independent assessors.

I would like to show my gratitude to the people who supported and criticized my work during this graduation project. Firstly, I want to thank my TU Delft Supervisor who lifted my work to a higher level. Robert Hekkenberg, you gave very constructive feedback and supported me in ship design considerations, reporting skills and interesting discussions. Secondly, I would like to thank my daily supervisor at Damen, Luca Codiglia, who helped me look into the practical design considerations and gave good directions to work towards during the project.

Besides my graduation committee, I want to thank Robin Brouwer who gave me the opportunity to do this graduation project at Damen. As well working at Damen, I want to thank Deniz the Koningh who supported me with ship design methods and Erik-Jan Boonen who was always interested in my work and also gave constructive feedback. Furthermore, my work could not have been reliable without the support of fuel cell experts. Lindert van Biert helped me in understand the complex fuel cell systems and its characteristics and considerations. Jogchem Bruinsma of Nedstack made me able to benchmark my research against the state of the art fuel cell industry.

Most of this research took place during the COVID-19 period. Although this implied no serious difficulties for this research, it has been a different experience than it would have been in a regular period. I would like to thank parents, friends, roommates and my love Yasmijn for the mental support during this unstable period.

B.N. van Veldhuizen
Rotterdam, June 2020

Abstract

With increasing awareness of climate change, global endeavors to reduce emissions in the shipping industry are accelerating the interest in fuel cell systems. Fuel cell systems are an alternative solution for diesel generators and offer high efficiency, low emissions and high redundancy. Currently, fuel cell implementation struggles with high cost, short lifetime and lack of bunker fuel infrastructure. Fuel cells are extra relevant for expedition cruise ships, because they increase comfort (no vibrations and noise) and give a market advantage (compliance to emission regulations). However, it is not known which fuel cell systems are most suitable, how they should be applied and what their impact is on ship design, operability and cost. This knowledge is required to successfully implement fuel cell systems on expedition cruise ships.

The goal of this thesis is to evaluate the impact of the combination of different fuel cell systems and operational profiles on the design of expedition cruise vessels. Impact on design is evaluated in terms of ship size, newbuild price, fuel cost and emissions. LH_2, LNG, $MeOH$ and NH_3 are considered as fuels and LT-PEMFC, HT-PEMFC and SOFC as fuel cell types. Fuel types and fuel cell types are combined to define different fuel cell systems, of which the performance is expressed in terms of power density, energy density (both gravimetric and volumetric), specific capital cost and specific fuel cost. The presented performance includes: fuel storage, fuel reforming, fuel purification, fuel cell power pack, balance of plant components, system efficiency and fuel cell lifetime.

A design tool is developed that compares the impact for different fuel cell systems in the early design phase. The design tool links the presented fuel cell performance to the requirements of expedition cruise ships. Three hybridization options are considered: i) Full fuel cell powered ship (Full FC). ii) Fuel cells only for auxiliary load, including hotel load (Hybrid 1). iii) Diesel generators to support in transit (Hybrid 2). The design tool uses reference expedition cruise ships to determine basic ship parameters based on the requirements. The admiralty formula is used to determine required propulsion power. The required auxiliary power is based on the number of passengers. The sum of the required propulsion and auxiliary power equals the total required power, out of which the (hybrid) fuel cell power plant is dimensioned. The required power is combined with the operational profile and the propeller law to determine the required energy and energy usage for different operations. The former defines the fuel storage and the latter defines the fuel cost. The design tool performs one design iteration to fit the fuel cell system, which increases ship size, required power, energy usage and thus consequently increasing size of fuel cell power plant and fuel storage. The model was verified with: structured walkthrough, balance checks and testing of extreme conditions and validated with: data validation, benchmarks, model output interpretation and sensitivity analysis.

Based on the results of the design tool was concluded: i) The increase in ship size (in GT) ranges from 2% to 25 %, depending on the fuel cell system and hybridization strategy for an average ship (with respect to the reference ships). ii) A full fuel cell powered expedition cruise ship is more expensive in newbuild price and total cost (newbuild price and fuel cost) than a hybrid fuel cell ship for all considered fuel cell systems. iii) Hybrid option 1 (fuel cell for auxiliaries) is inferior to hybrid option 2 (DG to support in transit) in terms of cost, emissions and complying to ECA regulations. iv) Hybrid 2 with $MeOH$ fueled LT-PEMFC offers the lowest percentage increase in newbuild price for expedition cruise ships, which is under 25% for an average ship. v) Hybrid 2 with LNG fueled LT-PEMFC offers to lowest percentage increase in total cost over ship the ship lifetime (including fuel cost) for expedition cruise ships, which is under 5% for an average ship.

For the six best performing combinations of fuel cell system and hybridization option, the range, endurance and capacity requirements are systematically varied. This sensitivity analysis was performed to determine whether the selection of best performing options would be different when the requirements are changed. It was confirmed that conclusion iv) and v) still hold for a large range of endurances and ship sizes. Consequently, it was concluded that the choice of the fuel cell system should not depend on the range requirements and the size of the ship.
Finally, from a newbuild price perspective, hybrid option 2 with $MeOH$ fueled LT-PEMFC is recommended.

This does comply with NO_x, SO_x and PM regulations (including ECA zones) and CO_2 goals for 2030. From a total cost (new build price and fuel cost) perspective, hybrid option 2 with LNG fueled LT-PEMFC is recommended. This does comply with NO_x, SO_x and PM regulations (including ECA zones), but does not meet CO_2 goals for 2030. When it is desired to reach this CO_2 target, hybrid option 2 with $MeOH$ fueled LT-PEMFC is also recommended from a total cost perspective.

Definitions

Fuel:
The bunkered fuel on board to supply the fuel cell with chemical energy.

Hydrogen carrier:
A *fuel* that is not pure hydrogen, like *LNG*.

Syngas:
A mixture of carbon monoxide and hydrogen gas, which is created by reforming hydrogen carriers.

Fuel cell:
A single fuel cell, meaning a membrane electrode assembly (MEA) and two flow-field plates. For all defined fuel cell typology, also refer to figure 1.

Fuel cell stack:
An assembly of several fuel cells to reach higher power.

Fuel cell power pack:
A fuel cell power pack is scoped by how a fuel cell generally is delivered by a fuel cell supplier, including thermal and water management system, flow control etc. Excluding fuel storage equipment, fuel processing equipment and balance of plant components.

Balance of plant components:
Balance of plant components are the supporting components of a power plant. In this research the balance of plant components are defined as the components that ensure a suitable power supply towards the consumers, meaning: batteries and capacitors to satisfy transient loads and electrical converters to generate electricity at right voltage and frequency when required.

Fuel cell power plant:
Fuel cell power plant includes fuel processing equipment, fuel cell power pack and balance of plant components and excludes fuel processing equipment. The power plant as an entirety determines the power density.

Fuel cell system:
A combination of fuel type and fuel cell type, including all required system components: fuel storage, fuel processing (reforming and purification), fuel cell power pack and balance of plant components.

Conventional solution:
When spoken of a conventional solution. The conventional alternative for the fuel cell system is meant, meaning diesel generators fueled by MGO.

Hybrid fuel cell system:
Consists of the whole fuel cell system and conventional system.

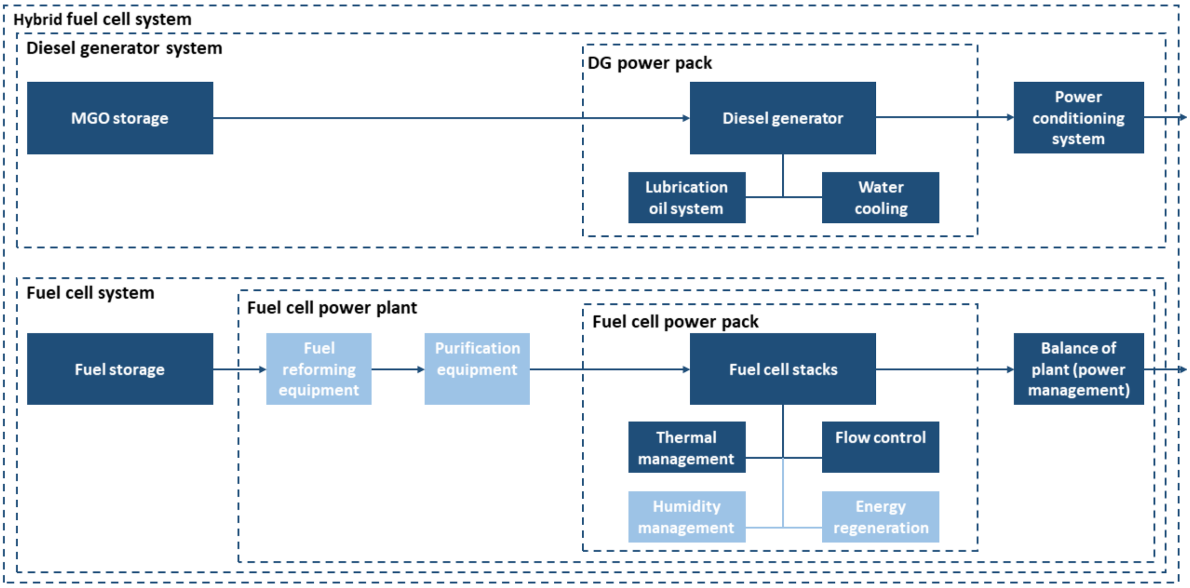

Figure 1: Definitions of on board power generation for simplified DG and FC system.

Nomenclature

Abbreviations

LH_2	-	Liqified Hydrogen
LNG	-	Liqified Natural Gas
$MeOH$	-	Methanol
NH_3	-	Ammonia
NO_x	-	Nitrogen Oxides
SO_x	-	Sulphur Oxides
AFC	-	Alkaline Fuel Cell
CAPEX	-	Capital Expenses
D&P	-	Design & Proposal
DCDF	-	Direct Carbon Fuel Cell
DME	-	Dimethyl Ether
DMFC	-	Direct Methanol Fuel Cell
FC	-	Fuel Cell
GA	-	General Arrangement
GHG	-	Green House Gas
GWP	-	Global Warming Potential
GT	-	Gross Tonnage
HT	-	High Temperature
HVAC	-	Heating Ventilation Air Conditioning
ICE	-	Internal Combustion Engine
IMO	-	International Maritime Organisation
LCA	-	Life Cycle Assesment
LHV	-	Lower Heating Value
LT	-	Low Temperature
MCFC	-	Molton Carbonate Fuel Cell
OPEX	-	Operational Expenses
PAFC	-	Phosphoric Acid Fuel Cell
PAX	-	Number of passengers
PEMFC	-	Proton Exchange Membrane Fuel cell
PM	-	Particulate Matters
PrOx	-	Preferential Oxidation
RFI	-	Request For Information
ROM	-	Rough Order of Magnitude
SOFC	-	Solid Oxide Fuel Cell
SR	-	Steam Reforming
SRtP	-	Safe Return to Port
TRL	-	Technological Readiness Level
VSD	-	Value Sensitive Design
WGS	-	Water Gas Shift reaction

Symbols

Δ	ton	Displacement
$\eta_{FCsystem}$	%	Efficiency of fuel cell system
ρ_{fuel}	ton/m^3	Density of fuel
A	$\frac{ton^{2/3} \cdot kn^3}{kW}$	Admiralty constant
$a_{aux\,demand}$	-	Ratio between average power demand and installed power for auxiliaries
a_{BOP}	-	Ratio of cost increase of FC system due to BOP
$a_{FC\,efficiency}$	-	Ratio of cost increase of FC system due to decrease of FC efficiency over lifetime
$a_{fuel\,processing}$	-	Ratio of cost increase of FC system due to fuel processing plant
$a_{fuel\,utilization}$	-	Ratio between volume for fuel storage and required ship volume
$a_{operation}$	-	Percentage of time in year that certain operation is exectued
$a_{P_{aux}}$	kW/PAX	Amount of auxiliary power per PAX (luxury type dependent)
$a_{P_{fc}}$	-	Ratio between installed FC power and total installed power
a_{ship}	$€/GT$	Extra ship cost per additional GT ship size increase, besides the (hybrid) fuel cell system
$a_{stack\,cost}$	-	Ratio between fuel cell stack cost and fuel cell power pack cost for fuel cell type
$a_{transit}$	-	Fuel margin for operation that requires most energy
B	m	Beam of expedition cruise ship at broadest point
C	$€$	Cost
C_B	-	Block coefficient
$c_{FCplant}$	$€/kW$	Specific capital cost of fuel cell plant
c_{fuel}	$€/ton$	Bunker cost of fuel
$c_{fuelstorage}$	$€/kWh$	Specific capital cost of fuel storage system
D	m	Depth of expedition cruise ship
E	kWh	Energy
e_{grav}	kWh/ton	Gravimetric energy density
e_{vol}	kWh/m^3	Volumetric energy density
$emis_{type}$	$kg/MWhe$	Specific emission of generated electrical energy for certain fuel cell system of
Fn	-	Froude number
GT	GT	Gross tonnage
GV	m^3	Enclosed volume of ship
L_{oa}	m	Length over all
L_{pp}	m	Length between perpendiculars
P	kW	Power
p_{grav}	kW/ton	Gravimetric power density
p_{vol}	kW/m^3	Volumetric power density
PAX	-	Number of passengers is cruise vessel
T	m	Design draught of expedition cruise ships
$t_{operation}$	$days$	The duration of concerned operation
$t_{operational}$	$days$	Number of operational days of ship per year
$t_{lifetime,FCstacks}$	h	The operational lifetime of fuel cell stacks
$t_{lifetime,ship}$	h	The operational lifetime of the expedition cruise ship
t_{start}	s	Start time of fuel cell system
V	m^3	Volume
V_{fuel}	m^3	Storage volume of fuel
$V_{required\,space}$	m^3	The required ship volume to store V_{fuel}
V_s	kn	Maximum ship speed of expedition cruise ship
W	ton	Weight

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1
Introduction

Globally, people are slowly getting aware of the severe possible consequence of climate change. The raising temperature on earth is partly caused by global emissions [77]. The marine industry has a significant environmental footprint. The large amounts of fuel consumed during shipping are converted to greenhouse gasses, particulate matters and hazardous air pollutants (SO_X and NO_X). Miola et al. stated shipping contributes to 3-5% of global carbon dioxide emissions and more than 5% of global SO_X emissions [81]. As a consequence of increasing awareness, in 2015, the Paris agreement was signed with the goal to keep the global average temperature within 2 degrees Celsius above pre-industrial levels [115]. This lead to adoption of ambitious goals and regulations by the International Maritime Organisation (IMO): A CO_2 emission reduction of 50% with respect to 2008 [52] and emission control areas with strict limits to SO_X and NO_X emission [51]. Reduction of emissions in shipping for current solutions can be realised on 3 stages: i) different bunker fuels: LNG [15], bio-diesel [82] and low sulphur diesels [8]. ii) fuel conversion improvements: two stage turbocharging, heat recovery, late miller-timing etc. [11] iii) exhaust treatment: scrubbers and selective catalytic reduction [122]. Currently, diesel engines are used for the majority of power generation on board ships. Although the efficiency has increased significantly throughout the years, it is expected to be reaching its limits [44]. Fuel cells are considered as a promising solution [11, 13]. They have demonstrated lower heating value efficiencies of 60 % [89] (even 70 % with use of combined generator cycles [88]) compared to diesel generator set engines reaching up to 45 % and fuel cells emit very few hazardous compounds [11].

Cruise tourism is one of the most carbon emitting tourism segments, with an average of 160 kg CO_2 per passenger per day [7]. Cruise lines are much interested in the use of fuel cells on their ships. Besides complying to upcoming regulations, cruise lines have extra interests in sustainable power generation. Firstly, several cruise lines report the increasing demand of their customers for 'conscious traveling', meaning customers want their cruise line to reduce their environmental footprint [3, 20]. This makes sustainability a competition aspect between cruise lines. Secondly, cruise lines state that continued access to ports is vital for future business operations [3]. Besides global regulations, local legislation is limiting access to target locations. For instance, the municipality and port of Amsterdam are making attempts to limit the number of incoming cruise tourists and aim on restricted allowance of cruise ships with the lowest environmental footprint [19, 117]. The Norwegian parliament adopted regulations in 2018 to make West Norwegian Fjords a zero emission zone from 2026 [124]. Both Amsterdam and the Norwegian Fjords are much visited by cruise lines, making fuel cells very relevant to them. Fuel cells are not yet implemented on a commercial level on expedition cruise vessels or even on ships in general. It is not yet known which fuel cell systems are most suitable for expedition cruise ships, how they should be applied and how they impact design, cost and operability. In order to successfully implement fuel cells in expedition cruise vessels this knowledge is required.

The goal of this report is to evaluate the impact of the combination of a fuel cell system and the operational profile on the design of expedition cruise vessels. The impact will be evaluated for different fuel cell systems (read fuel type and fuel cell type combinations) and different ship design requirements in order to make a well founded recommendation on what will be the most suitable fuel cell systems for expedition cruise ships.

Outline
For laymen in fuel cell systems, chapter 2.1 starts with background information on fuel cells. This is provided to the reader in order to get an understanding about the working principle of the fuel cell system, different fuel cell types, its advantages and its challenges. Following, current literature and current research project of fuel cells in marine applications are explored. The goal of this chapter is to find out what is and what is not yet covered by literature and research to find the knowledge gap. Out of this knowledge gap, the problem is defined in chapter 3. The problem definition includes a problem statement, research objectives, the research scope and ethical implications of the research. Out of the problem definition, the methodology is formulated in chapter 4.

In chapter 5 the different fuel cell types and possible fuel types are further investigated. Four fuel cell types (LT-PEMFC, HT-PEMFC, MCFC and SOFC) and four fuel types (LH_2, LNG, $MeOH$ and NH_3) are selected for expedition cruise ships with use of existing literature. The performance of the different fuel cell systems in terms of power density, energy density and cost is presented in chapter 6 and the worse performing fuel cell systems are excluded.

Chapter 7 investigates general requirements, trends in ship parameters and operational profiles of existing cruise ships, in order to support the matching process of fuel cell system and expedition cruise ships.

The performance of the fuel cell systems is matched with the requirements of expedition cruise ships in chapter 8, where a design tool is presented. Three hybridization options are considered. The design tool indicates impacts of different fuel cell systems on ship design in terms of ship size, capital cost, operational cost and emissions. The results of the design tool can be found in chapter 9, where also the operational requirements and ship size are varied, to indicate their impact on the design.

In chapter 10, the main conclusions are drawn. Finally, the research is discussed and further research topics are suggested in chapter 11 and 12, respectively.

2
Current state of research

This chapter will help the reader to get an understanding which areas of fuel cells in marine applications are already researched and evenly important, which areas are not. Existing literature and finished research projects are reviewed and their conclusions will be summarized. This chapter is a shortened version, the full overview of existing research in fuel cells (in marine applications) can be found in the literature study report of this graduation project.

First, background information is provided for laymen in fuel cell systems in section 2.1. The current state of research is divided in a literature study (section 2.2) and a review of existing research projects (section 2.3). Their difference being, literature studies are often theoretical, for the research projects concept ships are designed or the fuel cells are even tested on-board. In the end, the gap in existing research is evaluated in section 2.4. The research gap is the foundation of the problem definition of chapter 3.

2.1. Background information of fuel cells

This section gives the reader background information of fuel cells. Their working principle, their advantages and challenges for cruise ship implementation and different fuel cell types are explored. This section is provided to the reader in order to get an understanding of what fuel cell systems can offer and what it lacks for implementation in expedition cruise ships. This section is very valuable for laymen in the area of fuel cells.

Section 2.1.1 describes the working principle of a fuel cell: how is chemical energy translated to electrical energy and what are the losses during the process. Section 2.1.3 and 2.1.4 expose advantages and drawbacks of fuel cell system for (expedition cruise). In 2.1.2 the fundamental difference between different fuel cell types is explained.

2.1.1. Fuel cell working principle

Fuel cells convert chemical energy directly to electrical energy, making it possible to reach high efficiencies. In contrast to diesel generators where chemical energy is converted via thermal and mechanical energy to electrical energy. A fuel cell consists of 2 electrodes (anode and cathode) and an electrolyte in between. The electrochemical reaction differs for different types of fuel cells. The working principle will be explained for a Proton Exchange Membrane Fuel Cell (PEMFC), see figure 2.1. Fuel is fed to the anode where reaction 2.1 takes place. The electrolyte is designed to conduct the created ions and to refuse electrons fuel and oxygen. Thus, the electrons are forced to go from anode to cathode by means of the external circuit, creating a current. At the cathode (reaction 2.2) the ions, the electrons and the oxygen inflow react, creating water. This results in overall reaction 2.3 [66]. Three phase contact is required for the reactions to take place, meaning fuel or oxygen (gas), electrolyte (solid or liquid) and the electrode. Electrodes are often made of a porous material to make the three phase surface area as large as possible. Catalysts are added to the electrodes to accelerate the reaction. Fuel cells are connected in series to create a stack, increasing voltage and thus power.The fundamental difference between a battery and a fuel cell is the constant inflow of fuel and oxygen to pursue the electrochemical reaction.

$$\text{Anode:} \quad 2H_2 \rightarrow 4H^+ + 4e^- \tag{2.1}$$
$$\text{Cathode:} \quad O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \tag{2.2}$$
$$\text{Overall:} \quad 2H_2 + O_2 \rightarrow 2H_2O \tag{2.3}$$

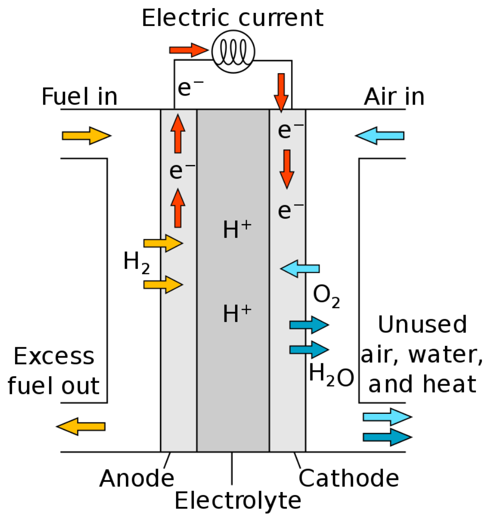


Figure 2.1: Working principle of Proton Exchange Membrane Fuel Cell (PEMFC) [6].

2.1.2. Fuel cell types

The different fuel types are named by their electrolyte. The different fuel cells have big differences in operating temperature, efficiency, cost, system integration and even possible fuels. The operating temperature has big impact on the performance of the fuel cell. Low temperature (LT) fuel cells have very limited tolerance to fuel impurities and often require expensive platinum as catalyst. High temperature (HT) fuel cells don't have these disadvantages, but they are characterized by high start-up times and require expensive materials that can withstand high temperatures. HT fuel cells often have opportunities for high efficiencies by using heat regeneration. An overview of all fuel cell types with their transport ion and temperature can be found in figure 2.2. Different fuel cell types will be further described in section 5.1.

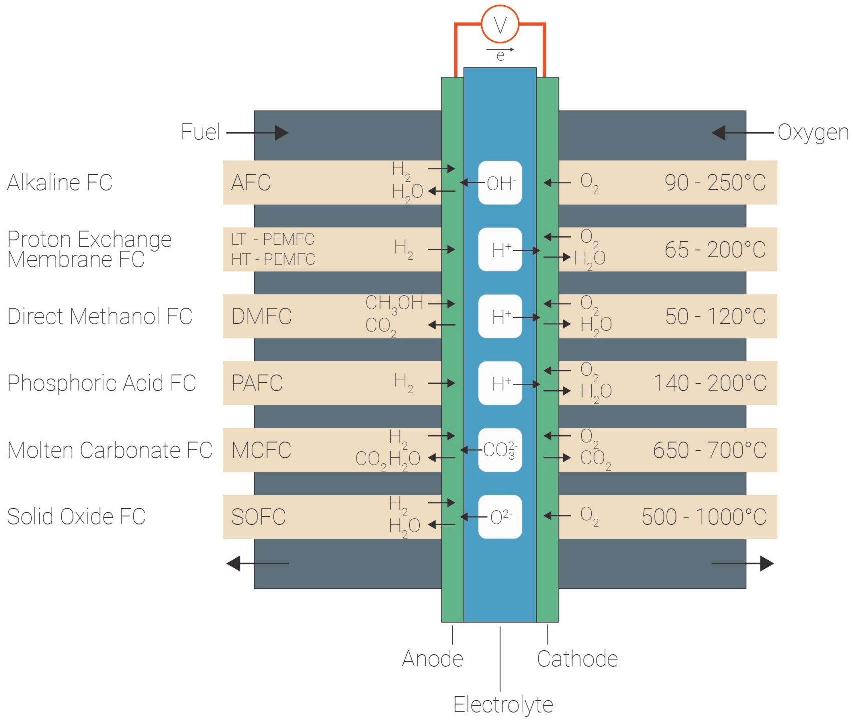


Figure 2.2: Overview of different fuel cell types with their operating temperatures, required fuel and transported ion [own image] [6, 66].

2.1.3. Advantages of fuel cells for expedition cruise vessels

For expedition cruise vessels, fuel cells offer some big advantages compared to internal combustion engines (ICE):

- *No polluting emissions*
  As shown in section 2.1.1, when pure hydrogen is used as fuel, only water and heat are produced at the outlet. There are also other possibilities for fuels (section 5.2), these options produce some emissions but still much less than current solutions.

- *High efficiency*
  Due to the direct conversion of chemical energy to electrical energy, high efficiencies are possible for fuel cells. The efficiency of the fuel cell is very dependent on the type of the fuel cells (section 2.1.2) and its system requirements. Common efficiencies are 50% and for high temperature fuel cells combined with gas turbines efficiencies up to 80% are possible [11, 66, 80, 114]. Compared to ICE where efficiencies range from 35 to 47 % [11], the efficiency potential is higher for fuel cells.

- *Good part load characteristics*
  Out of internal discussion at Damen it is known that most of their operational time, expedition cruise vessels do not utilize their maximum speed and operate much on low speeds. Also, a small overcapacity is often installed for margins between the specifications of the owner and the realized design. Together this results in the vessels seldom utilizing their max installed power and often operating in part-load conditions. Fuel cells perform well over a relative wide range of loads, and the optimal efficiency is on part load [106], see for instance the results of a fuel cell case study 2.3, meaning fuel cells match on this area with operations expedition cruise vessels. On own insight, due to the possibility of modular switch-off of fuel cells there are a lot of efficiency optimization possibilities for part-loading on fuel cells.

- *Highly redundant*
  Similar to batteries, fuel cells are modular, meaning the intrinsic performance of a single cell is not different from a big stack [11]. This leads to a high redundancy level when a lot of fuel cell stacks are used. The modular characteristic also makes it possible to spread energy production throughout the ship (decentral energy production), which decreases electric energy transport losses [97] and weight & installation time of cables. On top of that high redundancy and spread of energy production is very useful with complying to the Safe Return to Port (SRtP) regulation for passenger ships adopted in 2010 [30].

- *Low maintenance*
  Due to few moving parts, fuel cells require very few maintenance [80]. In some studies the maintenance cost is even neglected [97]. However this decision is often not validated, mainly because the amount of required maintenance is not yet known. Of course, it should be investigated whether full neglectance is justified.

- *Silent*
  Silent power generation increases the comfort of the passengers and crew. On own insight, the use of fuel cell also increases the possibilities in the general arrangement. An ICE requires extra space for noise limiting facilities and an ICE is not recommended next to cabins. This is not the case for fuel cells since they do not produce noise. Although it must be noted that safety regulations for placement of fuel cell systems should still be investigated and it might be concluded that fuel cells are still not allowed next to cabins.

- *No vibrations*
  Similar to noise, vibrations lower the comfort of cruise ships, making it an important design aspect. Cruise ships often have diesel-electric propulsion arrangement of which the the pods and the bow thruster are often the limiting vibration sources. ICEs and generators are resiliently damped in cruise ships, since they are not part of the shaft line. Fuel cells have as advantage that the resilient mounting is not necessary, which requires a lot of attention during engineering and construction, according to internal conversations at Damen.

- *Water generation*
  As shown in section 2.1.1, fuel cells produce non-contaminated water. Hristovski et al. studied the potability of produced water of 6 fuel cells and concluded that all contamination levels where lower than the Maximum Contaminant Levels standards (MCLs) for most fuel cells and could easily be filtered for the fuel cells that did not met all MCLs [49]. Cruise ships have a rather large potable water consumption, due to the large amount of people on board. On own insight, there are opportunities to combine the water discharge of the fuel cell system with the on-board potable water plant. In the end this would reduce the required storage for potable water. By combining the water production of a LT-PEMFC system [92] and the water consumption per passenger (300 $L/PAX/d$) it was estimated that the fuel cell system of a full fuel cell powered expedition cruise ship produces 50-70% of the required water consumption during normal coastal operations. It should be noted that Hristovski et al. only investigated PEMFC with pure hydrogen as fuel, meaning this advantage is not proven for all fuel cell systems.

2.1.4. Drawbacks and challenges of fuel cells in expedition cruise vessels

Fuel cells still cope with some challenges that until now are still preventing broad application in the marine industry:

- *High capital expense*
  The price of fuel cell stacks per kW is still very high compared with ICE. Currently, prices are around 1900 €$/kW$ where diesel generators are available for 45 €$/kW$. It is expected that the price of fuel cells will drastically drop to around 250 €$/kW$ due to mass production [11, 114, 121]. For low temperature fuel cells the high cost is mainly caused by the catalyst platinum. For high temperature fuel cells, platinum is not required. Their high cost is mainly due to the electrolyte and extra equipment required for the fuel system [66].

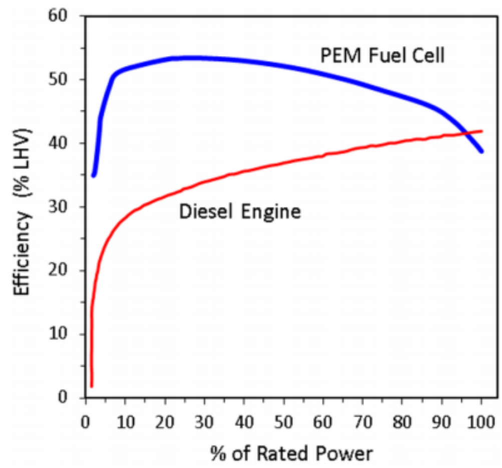


Figure 2.3: Thermal efficiency of a PEM fuel cell (blue line) and a diesel engine (red line) as a function of the partial load [80].

- *Fuel storage*
  Hydrogen has low volumetric energy density compared with conventional shipping fuels. Volume is often a limiting factor in ship design, making fuel storage of hydrogen one of the biggest challenges for fuel cells in marine applications. The introduction of fuel cells in ships has either a big impact on the design or the range and endurance (or both) of the vessel [121]. There are also bunker fuel options with a higher energy density for fuel cells, these will be discussed in section 5.2.

- *Lack of infrastructure*
  Since hydrogen is not widely used as fuel, the required infrastructure for bunkering hydrogen still lacks. Since, the range of vessels is already critical for fuel cell applications, a general availability of hydrogen is required.

- *Short lifetime*
  A fuel cell shows gradual performance degration over its lifetime. The fuel cells show a quite constant fuel cell degration rate, leading to a quite linear power decrease over the lifetime of the fuel cell [103]. Formally the life of a fuel cell is over when it is not able to deliver its rated power [66]. The short lifetime of most fuel cell types (around 5 years), has big impact on the capital expense. For ship application, there are two options to cope with a short lifetime of the fuel cells: i) During the lifetime of a expedition cruise vessels (around 15 years), the fuel cell stacks need to be replaced twice. However on own insight, this could also be an opportunity to keep up with the fast developments of fuel cells in terms of cost and efficiencies, improving the business case for fuel cells. Out of contact with fuel cell suppliers followed that they expect to decrease the cost of their fuel cell systems with 25-50% in the coming 5 years. ii) Install a power overcapacity to artificially increase the operational lifetime of the fuel cells and as a result Option 1 is favourable in terms of cost and fuel cell system size. decrease the number of times the fuel cells need to be replaced, since the fuel cell stacks generally represent half of the cost of the whole system and fuel cell stacks are replaceable separately and since the power decreases approximately. Although not found in literature and regularly not stated by fuel cell suppliers, the efficiency of the fuel cell decreases by the same rate as the power over the lifetime of the fuel cell. Out of discussion with fuel cell suppliers followed that at the end of life the fuel cell efficiency decreased with 10% of the initial fuel cell efficiency. This will have an impact on the fuel consumption of the fuel cell over the lifetime of the fuel cell.

- *Slow transient behavior of some types of fuel cells*
  Some fuel cell types have challenges in their transient performance, meaning their start time and capability to cope with transient loads [11]. Especially the higher temperature fuel cells (MCFC and SOFC) have long startup times (>1.5 hour) and a slower response in operational power [66, 103]. A high number of system components (like fuel processing equipment) and a higher amount of thermal mass also increase start-up and load-response times [11]. In literature, there is consensus that fuel cells are to be combined with components with high transient behavior like batteries [11, 18, 76, 123]. However, this increases the cost, weight and required volume of the total fuel cell system.

- *Low technological readiness level*
  The technological readiness level of all fuel cell types is much lower than conventional solutions (diesel generators). No fuel cell type is yet implemented on a large scale in a ship. Only fuel cells in small ships or small auxiliary power units in large ships are so far realized, see also the overview of fuel cell research projects in section 2.3. A low technological readiness implies: i) Higher uncertainties in the building process of ships (cost, time management, technological risks, performance). ii) Less available expert knowledge. iii) Smaller choice in suppliers and available systems. A lower technological readiness level also goes hand in hand with a smaller available amount of reliable data. Data of maintenance time and transient capabilities for larger scale applications is not yet known.

2.2. Literature

This section reviews existing literature of fuel cell systems in marine applications. The main focus is on design literature, like volume and weight usage, cost and safety. The literature study is limited to the chosen fuel cell types (PEMFC, MCFC and SOFC) and fuel types (LH_2, LNG, $MeOH$ and NH_3).

Ship design literature for fuel cell systems

Van Biert et al. [11] did a very extensive review of fuel cells for marine applications, covering fuel cell types, fuel processing, efficiency, power & energy density, dynamic behavior, environmental impact, safety & reliability and economics. It was concluded that LT-PEMFC with LH_2 as fuel could be a solution for ships with mission requirements up to 12 hours. For sailing times above 100h it is expected the fuel cell system results in a 1.5-5 times larger required volume than current systems. High temperature fuel cell systems in combination with hydrocarbon fuels can provide high efficiency, low emissions solutions for ships with mission requirements of several days [11]. At DAMEN, C. Volger executed a master thesis on alternative fuels for cruise vessels. He concluded that hydrogen as fuel for fuel cells has most impact on the design of a cruise ships, with an increase in GT of 100% for small cruise ships (<500 pax) and a increase of 20% for large cruise ships (>2000 pax). He thus concluded that hydrogen is not feasible for use on board cruise ships. For ammonia as fuel for fuel cells, the increase is 30% and 7% respectively. For methanol as fuel for fuel cells, the increase is 9% and 5% respectively [121]. Geertsma & Krijsgsman executed a case study for the application of fuel cells on board of navy support ships. They proposed a methodology to review alternative power system designs based on: mass & volume, capital & operational expenditure, technological readiness, fuel availability and emissions. They concluded that SOFC is currently insufficiently mature. For these fuel cells to be commercially used, improvements in technological readiness, efficiency and cost of the fuel cell are necessary [44]. Minnehan and Pratt studied the use of fuel cells on board of various ship types. They concluded that available volume of the vessel is the main constraint of the fuel cell system. The total weight of the power train (including fuel storage and distribution equipment) is considerably lower than one powered by liquid fossil fuel [80].

Díaz-de-Baldasano et al. made a conceptual design of a methanol hybrid diesel generator and methanol fueled SOFC for an offshore supply vessel. It was concluded that the hybrid fuel cell power plant does not limit the operational capabilities of the vessel and is technically and economically viable, taking into account the cost of the fuel cell system and the fuel [29]. Although Díaz-de-Baldasano et al. presented a sensible concept model, the writer of this research questions the conclusion that the concept model is economically viable. The used price for SOFC ($1609€/kW$) is much lower than can be found in other literature and supplier information ($7000-10000/kW€$) [11, 44].

EMSA also researched the use of fuel cell in shipping. They mainly focused on standards & regulations regarding installation of fuel cells and performed a safety assessment. They concluded failure mechanisms are very similar for most FC systems. The most critical scenarios (highest combination of probability and severity) are related to: i) leakage, electrical conditioning system, loss of purging system [114].

2.3. Research projects

Over the last 30 years several research project of marine applications of fuel cells emerged. An overview of the most noteworthy projects is given in table 2.1. As can be seen, different ship types, fuels and fuel cell systems are investigated. Most research projects are successfully tested, meaning they operated without significant failure at a reasonable safety level. This does not imply feasibility of the project in terms of cost. First, most research projects focused on diesel as bunkering fuel, due to the low cost and high availability. However, problems emerged in sulphur contamination of the fuel cells and efficiency of the whole system [11]. More recently most project focused on hydrogen and methanol as bunkering fuel. Very recently HT-PEMFC were also successfully tested in marine applications. The overview in table 2.1 also gives insight which fuel and fuel cell combinations are not tested in marine applications. *LNG* fueled HT-PEMFC, hydrogen fueled SOFC, methanol fueled MCFC and ammonia fueled fuel cells are not successfully integrated and tested on board yet. The findings and conclusions of the most relevant research projects will be discussed shortly.

Table 2.1: Overview of research projects of maritime fuel cell applications.

Project	Year	Fuel type	Fuel cell type	Ship type	Power	Capacity [kW]	Succesful	System efficiency	Reference
US SSFC	1997-2003	Diesel	MCFC&PEMFC	Naval	Propulsion	2500	yes	53&35%	[11]
DESIRE	2001-2004	Diesel	LT-PEMFC	Naval	Auxilary	25	no		[64]
FCSHIP	2002-2004	Diesel	LT-PEMFC	Cruise	Auxilary	2000	yes	50%	[5, 11, 114]
FellowSHIP	2003-2011	LNG	MCFC	OSV	Hybrid	320	yes	44.1%	[11, 114]
MC-WAP	2005-2011	Diesel	MCFC	RoPax	Auxilary	500		50.6%	[9, 11]
FELICITAS	2005-2008	LNG	SOFC	Yacht	Auxilary	250			[11, 60, 114]
METHAPU	2006-2009	MeOH	SOFC	RoRo	Auxilary	20			[120]
ZEMSHIP	2006-2013	LH2	LT-PEMFC	Passenger	Propulsion	96	yes		[120]
Nemo H2	2008-2011	LH2	LT-PEMFC	Passenger	Propulsion	60	yes		[11, 114]
schiBZ	2009-2016	Diesel	SOFC	Multipurpose	Auxilary	100	yes	50.0%	[69, 120]
Pa-X-ell	2009-2016	MeOH	HT-PEMFC	Cruise	Auxilary	60	yes		[43, 114, 120]
Rivercell 1	2015-now	LH2	HT-PEMFC	River cruise	Propulsion	250			[114]
SF-BREEZE	2015-now	LH2	LT-PEMFC	Ferry	Propulsion	4920			[93, 114]

2.4. Conclusion

Most literature in fuel cells in marine applications concluded that fuel cell systems are (currently) only usable in ship applications with refuel times under 24 hours. When using hydrogen as bunker fuel a large increase in ship size is anticipated (when the requirements and operational profile are kept constant). Methanol can be stored most energy dense and was concluded as a good option for longer refuel times. In terms of maturity of technology, LT-PEMFC is directly usable for marine applications and there is a wide range of LT-PEMFC suppliers. The cost of a fuel cell powered ship is currently expected to be very high and not economically competitive.

Gap in literature

On own insight, the methods used in research to determine the required ship volume and or weight for the fuel cell system are often not considering the differences in fuel and fuel cell combinations. However fuel processing and balance of plant equipment required for a fuel cell system have a big impact on the power density of the fuel cell system, see also figure 6.1. For instance, the power density of a LT-PEMFC fueled by LH_2 is more than a factor 10 higher than the power density of a LH_2 fueled by methanol, due to the required reforming and purification equipment, see also figure 6.3. Out of the reviewed research, van Biert was the only one taking into account this fundamental difference in fuel cell systems [11]. This research will also take this into account.

Very little studies take into account the cost impact of the different fuel cell systems and compare them. Van Biert only gave some indication values of the cost of the different fuel cell systems [11]. Geertsma and Krijgsman included CAPEX and OPEX impact very briefly for PEM and SO fuel cells and fuels LH_2 and $MeOH$. Díaz-de-Baldasano et al. presented a cost-feasible concept design, but its validity is questioned.

Fuel cells are not investigated for all ship types. Research projects mainly focused on small ship types or small APU units on board of bigger ships. This is a logical choice since this involves smaller risks and lower costs. Literature that explores fuel cell applications on cruise ships is very limited, especially taking into account the fact that fuel cells are so relevant for cruise lines. However, several research projects are performed for passenger vessels, which can be learned from since they have similar standards and rules for safety. Regarding the research projects, *LNG* fueled HT-PEMFC, LH_2 fueled SOFC, methanol fueled MCFC and all ammonia fueled fuel cells are not successfully integrated and tested on board yet.

All in all, it is not known which fuel cell systems perform best for certain type of ships (for instance expedition cruise ships) and what the impact of this implementation is in terms of ship design, operability and cost. For shipping business (for instance cruise lines) this information in necessary to evaluate the business plan of a fuel cell powered ship. Without this knowledge it will not be possible to successfully implement a fuel cell system in an expedition cruise ship. While investigating this, it is important to distinguish in system components for different fuel and fuel cell combinations, since they have big influence on the impact in weight, cost and required space.

3 Problem definition

Literature demonstrates that marine fuel cell implementation is currently in research and development phase. Many studies conclude that fuel cells (especially with hydrogen as fuel) are not economically feasible for a lot of ship types [11, 114, 121]. Even if the costs are not considered, the impact on the size and layout of the ship is still huge. However, both climate change and upcoming regulations stimulate the shipping industry to further investigate and consider the implementation of fuel cells. Fuel cell systems differ substantially and it is not known which systems are most promising, which could also differ per ship type. For expedition cruise ships, the application of fuel cells is even more urgent since it brings a competition advantage in the cruise market. This is summarized in the following problem statement. The problem is explicitly limited to expedition cruise ships, since this is the main focus of Damen Cruise.

Problem statement:
It is not known which fuel cell systems are most suitable for expedition cruise ships, how they should be applied and what their impact is on ship design, operability, cost and emissions. This knowledge is required to successfully implement fuel cell systems on expedition cruise ships.

In this chapter, first the research objectives will be defined (section 3.1), after which the scope of the research objectives is sketched (section 3.2). This chapter ends with discovering the ethical implications of this research, in section 3.3.

3.1. Research objective

Based on the problem statement and a review of existing literature around this topic the main research objective is established. Due to the huge impact of the integration of fuel cells on board it could lead to an economically infeasible ship. It is expected that concessions are necessary in the operational profile. Similar to electric cars, where buyers are slowly adapting to the fact that the range of an electric car is generally shorter than a gasoline car. In literature was also found that very few cost estimations of a fuel cell powered ship were performed.

Main research objective:
Evaluate the impact of the combination of different fuel cell systems and operational profiles on the design of expedition cruise vessels.

The sub research objectives are defined as follows:

i *Analyse relevant performance of fuel cell types and suitable fuel types in terms of efficiency, power and energy density, dynamic behavior, TRL, safety, capital cost and operational cost. Discard worst options.*

ii *Express performance of fuel cell systems for expedition cruise ships in terms of power density, energy density, capital cost and operational cost. Discard worst options.*

iii *Analyse general requirements, ship dimensions, operational profiles and power requirements of existing expedition cruise ships.*

iv *Match the performance of different fuel cell systems for (part of) the power generation to the requirements of expedition cruise ships.*

v *Evaluate the impact (in ship size, capital cost, operational cost and emissions) of the combination of the chosen fuel cell systems and operational profile requirements on the design of expedition cruise ships. Choose the most suitable fuel cell systems for expedition cruise ships.*

3.2. Scope

What is included in the scope:

- *Expedition cruise ships*
  As stated, Damen Cruise mainly focuses on expedition cruise ships. There is no strict boundary between expedition cruise ships and regular cruise ships. Out of internal conversations with Damen employees, it was found that it is mainly a marketing strategy of cruise lines to sell 'off the beaten track', 'non-mainstream' or 'adventurous' experiences. However, for this research the distinction is very important. Expedition cruise trips often contain a high luxury (and thus trip price) level, implying higher area/PAX and GT/PAX. This is why reference ships are strictly limited to expedition cruise ships or luxury cruise ships.

- *Impact on the design*
  The impact will mainly be evaluated for ship parameters (length, beam, draft etc.), volume and weight distribution, and capital cost and operational cost. Or when ship dimensions are kept constant, fuel cells will have influence on the performance of the ship (range and speed). Interaction between design and operational profile is included in the scope. The impact analysis for different fuel cell systems is mainly a tool for engineers to make a well founded decision when applying fuel cell systems in expedition cruise ship. It is not in the scope of this research to optimize a fuel cell powered ship or to choose the best fuel cell system for a certain ship. The decision is with the D&P engineer and the client.

- *Diesel electric parent set*
  When using a parent set of cruise ships, only diesel-electric propulsion plants will be used. This means that the application of fuel cells would only change the power generation part of the propulsion line. Pods are often applied in cruise ships.

- *New building*
  A fuel cell integration method will be proposed for the design of new build expedition cruise ships. Thus, refit or conversion of existing ships is not included in the scope.

- *Safety*
  Safety has very high priority in the design of expedition cruise ships. A short review of current regulations about fuel cells and fuel storage is necessary to determine where parts of the fuel cell system can be placed and what kind of extra equipment is necessary. Extensive safety assessments as FSA or HAZOP studies are not included in the scope.

- *Hybrid power generation solutions*
  In some cases the cruise line could prefer a hybrid solution. For instance when a cruise line wants to access zero-emission zones one day a month, it could be more profitable to only use fuel cells in the zero emission area and use diesel generators for other operations. Hybrid concepts should also be considered to prevent the exclusion of possibly better options. However, it is not in the scope in this research to optimize the hybridization of current solutions and fuel cells. So answers to questions like 'what is the optimal ratio between fuel cell power and diesel generator power?' will not be searched for in this research. The hybrid concept will be implemented in a rather simple manner, for instance by only requiring fuel cells for hotel load or using diesel generators only for an oceanic transit.

- *Innovation of fuel cells*
  Due to innovation, the fuel cell price is expected to decrease over the lifetime of the ship [11]. This means in the coming years, a fuel cell powered ship would become more and more economically competitive with a conventional ship. The prediction of these innovations introduces high uncertainties, but it is possible to sketch conservative and progressive scenarios.

What is not considered in the research:

- *Viability*
  Viability of fuel cells in marine applications is already extensively studied and it can be easily derived that currently fuel cells would not be economically feasible for cruise ships either. For this study it is assumed that fuel cells will be necessary in the future, so a feasibility study will not be performed, merely a study to find out which improvements/changes are necessary to make the application of fuel cells possible. Still, it is very relevant which fuel system performs best on board of a cruise ship.

- *Fuel availability*
  Currently, hydrogen and some other hydrogen carriers are not available at every regular bunkering place. This further complicates the range disadvantage of fuel cells. The (development of) hydrogen and hydrogen carrier infrastructure is only considered in the selection phase of fuel cell systems. Afterwards it is assumed that hydrogen and hydrogen carriers are available at regular bunkering places.

- *Energy saving measures*
  Energy saving measures are even more important for fuel cell powered systems. With the high capital expense and volume usage of fuel cell systems, a small reduction rate in the used energy might suddenly be worth the cost of the energy saving device. However, the implementation of energy saving measures is beyond the scope of this research, meaning this research focuses on the supply side of energy. Actually, another graduation student is investigating the energy demand on board expedition cruise ships simultaneous to this research.

- *Other ship types*
  Although the used methods in this research can be applied on other ship types as well, this research focuses specifically on expedition cruise ships.

3.3. Ethical implications

An emerging technology is often designed to have a certain functionality. In this case, fuel cells system are designed on board of ships to function as an emission reducer. The link of technology and functionality is obvious, but there are also less superficial links. Technology goes hand in hand with ethical implications regardless of whether the technology has been designed with this in mind or not [2]. This section explores the link between fuel cell systems in marine applications and ethics. The reader is stimulated to think about the direct and indirect consequences of implementation of fuel cells. A Value Sensitive Design approach is proposed in section 3.3.1, a stakeholder analysis is performed in section 3.3.2 and Life Cycle Assessments of fuel cell systems in marine applications are reviewed in section 3.3.3. This section is finalized with the ethical consequences of this particular research in section 3.3.4.

3.3.1. Value sensitive design

The fact that technologies are inherently accompanied with ethical implications results in technology being linked to values. Ethic scholars are advocating to integrate ethical values like right to life, privacy and availability in early phases of technology, for instance with self driving cars [27] and information systems [42]. Just like these technologies, fuel cell technology is also linked to (human) values.

A promising method to correctly incorporate ethics in technology design is Value Senstive Design (VSD). "Value Sensitive Design is a theoretically grounded approach to the design of technology that accounts for human values in a principled and comprehensive manner throughout the design process" [40, 41]. Using VSD means that during the design process the following questions are considered: Which values are linked with this technology? Which direct and indirect stakeholders do these values belong to? How should we engage in trade-offs among competing values? VSD is present in the design process from beginning to end and combines conceptual, empirical an technical aspects of the technology. A VSD approach combines functional design with institutional design, the latter meaning government policy and regulations [27]. Values that are linked to the development of fuel cell technology are: transparency, trust, affordability, reliability, physical welfare and preservation of nature. Researchers, engineers, producers and users working with fuel cell systems in marine applications inherently have influence on these values. They are morally obliged to be fair and transparent about the advantages, disadvantages, challenges and risks of fuel cell systems. Since the institutional design of fuel cell systems in marine applications is not in place yet, it is important to focus on this parallel to the functional design of fuel cell systems.

Advocates of fuel cell systems are marketing fuel cells with its positive characteristics. However it should be noted that these advantages might be exaggerated or misleading and the public would get a shifted opinion on fuel cells. Some corrections of false beliefs of fuel cell systems include [32]:

- The fact that hydrogen is very a abundant particle could give a false belief that pure hydrogen is easy to obtain.
- The fact that hydrogen contains much energy per mass goes along with a false belief that hydrogen can be stored very energy dense.
- Since the fact that the fuel cell itself produces very little emissions it is often believed that fuel cells are a much better power generation solution in terms of environmental impact than diesel engines. However this is yet to be validated by taking into account the whole 'well to propeller' chain of the used fuel and 'cradle to grave' chain of the fuel cells. This will be further discussed in 3.3.3

3.3.2. Stakeholders

Different people, institutions or businesses will be affected by the introduction of fuel cells on expedition cruise ships, as described in the following sections. This section is provided to give the reader an indication on who and to what extend (successful) implementation of fuel cell systems in expedition cruise ships would have an impact.

Expedition cruise lines

The development of the aviation industry around 1960 caused a rapid decline in the number of ocean liner passengers. Consequently, ocean lines presented cruises to passengers, in order to find a new business case for their ships. This was the start of the cruise industry [90]. Lately, the cruise industry experienced a rapid growth due to the increasing demand by tourists. Sun et. al. stated that the cruise industry is the fastest growing segment of tourism industry [110]. CLIA reported an increase in cruise passengers of 75% in the past 10 years and an increase from 26.7 to 28.5 million passengers between 2017 and 2018 [21]. The expedition cruise business, a luxury segment of the cruise industry, is a response on tourist trends like: exotic locations, 'total rejuvenation' and 'bucket list achievements over sightseeing' [20]. This segment experiences a similar increase in demand by passengers. Figure 3.1 shows the PAX capacity from 2018 tot 2025, derived from the current order book. An increase from over 50% is visible between 2018 and 2022.

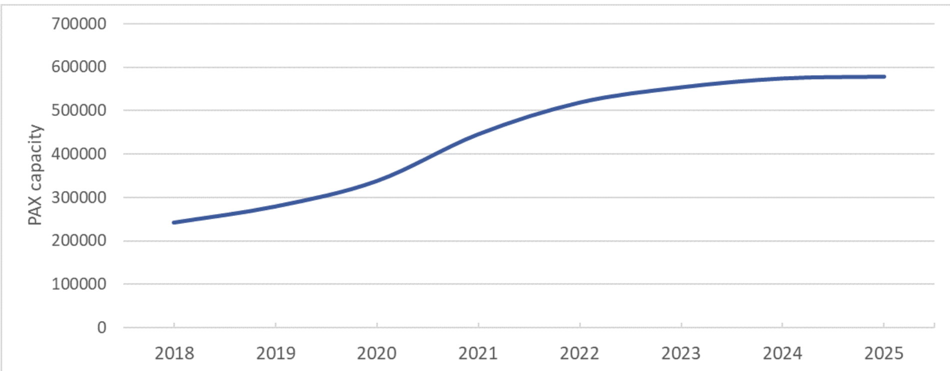


Figure 3.1: Increase in PAX capacity of expedition cruise industry based on current order book of expedition cruise ships [24, 105].

As already stated in the introduction, cruise lines have big interest in environmental friendly ship solutions, since it increases their operability [3] and gives a market advantage [19, 117]. The use of fuel cells has significant impact on the operational side of expedition cruise lines. The use of fuel cells strongly increases the price per PAX [121], so a confident business case is required. Cruise lines have an opportunity to ethically stimulate the use of fuel cells. Regarding operability, expedition cruise lines face a trade-off between a full fuel cell powered ship or a hybrid solution. When target areas like Norwegian Fjords only have to be accessed relative short time frames, they could use fuel cells only for these intervals and sail longer distances on ICE generators. A more ethical way of operating would be to not only use fuel cells where it is strictly forbidden to use diesel generators but also to look for other opportunities to limit their emissions.

Expedition cruise ship builders
The increase in cruise passengers stimulates the demand for expedition cruise ship builders. At the end of 2019 there were 110 cruise ships on order until 2027, of which a considerate part expedition cruise ships [21]. The ships are usually ordered by the cruise lines, who often have a clear view on the operational requirements (operating areas, speed, range, operational profile) and the maximal cost/PAX. According to Damen, cruise lines are more frequently asking for a design proposal with sustainable power generation. However so far, fuel cells were not proposed because the estimated cost/PAX were often too high. So for expedition cruise ship builders, successful implementation of fuel cells also implies strong competitive advantages over other shipbuilders. Ethically, ship builders can have a big and non-reciprocal impact on the right to life of the users of the cruise ship (crew and passengers). When using an emerging technology, some risks can not be quantified (known unknowns) or some risks can not even be known until they occur (unknown unknowns) [95]. Shipbuilders (designers, engineers and production) should keep in mind that their actions can have very big impact on the users of their ship.

Manufacturers
The benefit for fuel cell stack manufacturers is naturally big when fuel cells will be applied on expedition cruise ships. This would make it possible to upscale production and would lead to gradual production cost reduction [11]. Actions of fuel cell manufactures can have large and non-reciprocal impact on the users of the ship, similar to shipbuilders. On the other hand, transition from ICE to fuel cells would have big drawbacks for ICE manufacturers. It would mean a decline in their available work. Especially, since big improvements in efficiency of ICEs are not expected anymore [11].

Expedition cruise tourists
As stated by expedition cruise lines and tourism agencies, sustainable travel is one of the customer trends. Travelers want to minimize the environmental footprint on the locations they visit [20]. If tourists really want to support the use of fuel cells for cruise ships they need to be willing to pay a higher price for their cruise, since the price/PAX for a fuel cell powered cruise ship is much higher.

Classification societies
The classification societies are not fully ready for the implementation of fuel cells on passenger ships. Clear regulations for fuel cells on board are not yet realized, but are in development. End 2019, ABS published a guide for application of fuel cell powered systems for marine and offshore applications, covering fuel storage, reforming equipment, fuel cells, fuel cell stacks, safety systems, testing and certification [1]. The guide is quite extensive and includes arrangement, piping, venting, fire protection, electrical equipment and required monitoring systems. However it is not made specific for passenger ships or even cruise ships, implying even higher safety requirements. DNV assigned an additional class notation to ships with on board fuel cell power installations in 2019 [31]. This section covers required documentation, ventilation, fire safety and electrical systems. The requirements are generic and also the same for all ship types. Classification societies often have the biggest ethical impact on shipbuilding and the shipping industry. The sad reality is that shipbuilders and shipping companies often do not much more in terms of safety or emissions than is strictly required. The parties that guide the requirements thus have most impact and have the largest ethical obligation.

3.3.3. Life cycle assessment of fuel cell systems

Although fuel cells are known for higher efficiency and lower emissions than the conventional solution, it does not have to be true that fuel cells have a smaller environmental impact. For instance, the fuel cell production might require a lot of energy or might use toxic materials. In order to argue whether fuel cell systems will have a lower environmental impact than current solutions several life cycle studies are performed for marine applications. This chapter reviews some of the performed studies.

An environmental Life Cycle Assessment (LCA) takes into account the environmental impact in different stages of a product life. To compare the environmental impact of fuel cell systems to conventional systems it is important to consider all life stages of the fuel cell and the fuel [78], see left and right in figure 3.2 respectively. Alkaner and Zhou compared the MCFC with the diesel engine, including life cycle stages: manufacturing (materials and production), fuel supply, operation and decommissioning. They concluded for MCFC that the manufacturing phase has a big contribution to the environmental impact due to MCFC stack replacement during the MCFC system lifetime [4]. Strazza et al. performed a life cycle assessment for the SOFC, including production of fuel, manufacturing of the fuel cell and on board operation. They noticed that the environmental impacts of the manufacturing and the operational stage are low compared to the environmental impact of the fuel production phase, for all considered fuels (Hydrogen, LNG and methanol). Of the considered fuels bio-methanol and hydrogen are most attractive fuels for a SOFC from a life cycle point of view. Overall, it was concluded that SOFC has a lower environmental impact than conventional diesel generators [109]. Lee at al. did an environmental impact assessment of a SOFC combined heat and power generation concept. They concluded that manufacturing of the fuel cell has a relative small contribution to the total environmental impact (2.1%-9.5%), while operational phase has a large impact (89.9%-97.8%). Within the manufacturing of the SOFC, 72 % of the environmental impact is caused by the SOFC stack, the rest from the BOP components [68]. Apart from just marine applications, Mehmeti et al. extensively studied the performed LCA for SOFC. Out of 46 LCA studies on SOFC was concluded that manufacturing gives a negligible contribution to the total life cycle emissions. Operational phase has by far the biggest contribution, driven by the fuel consumption [78].

All reviewed environmental impact assessments mainly conclude on the relative contribution of life cycle phases (like manufacturing or operation in figure 3.2) to the total environmental impact. A comparison with conventional technology is often not made, making it hard to validate the general believe that fuel cell systems have a smaller environmental impact than conventional systems. However, since it is concluded that the environmental impact is still driven by its fuel consumption, fuel cells are more efficient and emit less hazardous compounds and since manufacturing of fuel cells represents a very small part of the total environmental impact, it can be argued that fuel cells have a smaller environmental impact than conventional systems for shipping. An extensive LCA considering all stages of fuel and fuel cell for all different fuel types is still necessary to confirm this.

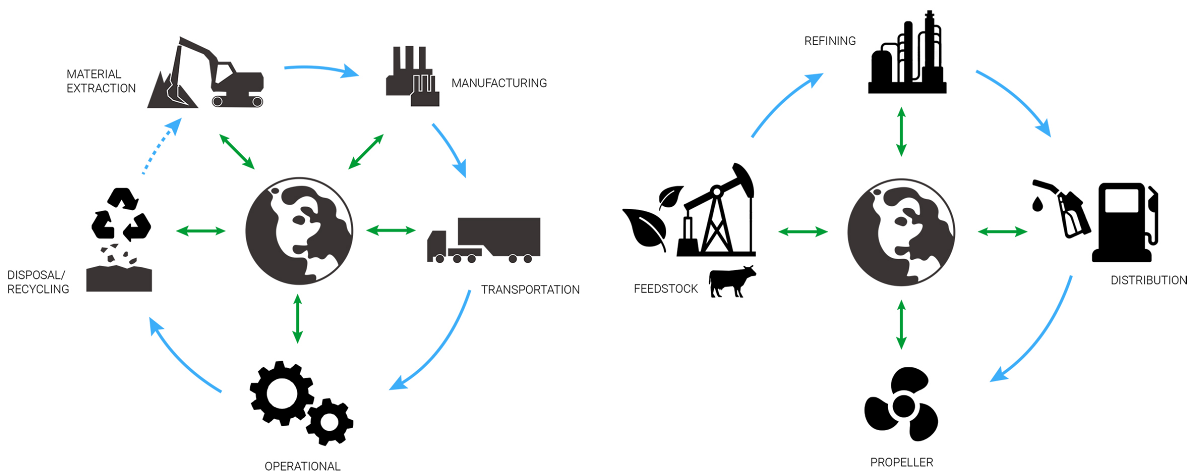


Figure 3.2: Life cycle assessment stages for fuel cell systems. Left: the life cycle stages of the product fuel cell (cradle2grave). Right: the life cycle stages of a fuel (well2propeller) [own image].

3.3.4. Ethical consequences of this research

Similar to fuel cell manufactures and shipbuilders, this research can also have a big impact on the users of the technology. Although the end product is not a ready to use fuel cell concept, this research might be used to achieve such a concept. Thus, the writer of this research is aware that wrong use of data, use of false data, wrong calculations can have serious consequences on the users of a fuel cell technology. Especially since the time and resources of a graduation research are not sufficient to evaluate all aspects of fuel cell systems on board of expedition cruise ships, rough assumptions have to be made. When using the outcome of this research for further research the scope and assumptions should always be kept in mind. This also implies that uncertainties in results should be mentioned to make sure further users of the results of this research will not use the results as fully validated data. When the amount of uncertainty is not known or cannot be determined another option is to express results in ranges denoted by the most conservative and most progressive outcomes, by using ranges of data and assumptions as input. Consequences of mistakes in this research might be: i) when data of fuel cells is wrongly used a fuel cell system might be praised in this research, while in reality another fuel cell system operate more efficiently for this particular application, meaning the environmental impact of the fuel cell system would be higher than necessary. ii) since safety is only briefly evaluated during this research, it could be possible that a fuel cell system is proposed that could not ensure a low enough risk level. If this is discovered very late in the design process, management could take the decision to take the risk and still apply the system on board to prevent major losses in time and cost. This in the end could expose the users of the ship (crew and passengers) to major harm.

4 Methodology

This chapter presents the approach to fulfil the research objectives, for every sub research objective a short methodology is defined. An schematic overview of the methodology is given in figure 4.1, including the distinction between the literature study and the graduation project.

i *Analyse relevant performance of fuel cell types and suitable fuel types in terms of efficiency, power and energy density, dynamic behavior, TRL, safety, capital cost and operational cost. Discard worst options.*
LT-PEMFC, HT-PEMFC, MCFC and SOFC with LH_2, LNG, $MeOH$ and NH_3 are selected as promising candidates for expedition cruise ships in chapter 5, leading to 16 different fuel cell systems.

ii *Express performance of fuel cell systems for expedition cruise ships in terms of power density, energy density, capital cost and operational cost. Discard worst options.*
A system decomposition is performed; the fuel cell system is divided into fuel storage, fuel processing, fuel cell power pack and balance of plant components. The performance of the different fuel cell systems are presented in terms of volumetric and gravimetric power density and volumetric and gravimetric energy density, cost of fuel cell plant, cost of fuel storage system and operational cost of fuel cell system in section 6.3. The efficiency and dynamic behavior are decomposed into the just mentioned indicators. Safety and TRL are treated as binary decision makers. When the safety and TRL are not satisfactory they were already left out during the first selection. Seven different fuel cell systems (combinations of fuel type and fuel cell type) are selected.

iii *Analyse general requirements, ship dimensions, operational profiles and power requirements of existing expedition cruise ships.*
Existing expedition cruise ships and their conceptual design method are examined. The general requirements, relations in main particulars, operational profile and dynamic power demand are investigated for a large parent set of (expedition) cruise ships.

iv *Match the performance of different fuel cell systems for (part of) the power generation to the requirements of expedition cruise ships.*
A design tool is created for early design phase that links the fuel cell system performance to the requirements of the expedition cruise ship. A design tool for the D&P engineer offers several benefits: the impact can be evaluated for different expedition cruise ship designs and it makes the performed work in this research reproducible. The design tool indicates the impact of fuel cell system implementation on increase in ship size, increase in newbuild price and increase in fuel cost. The tool includes 3 hybridization options.

v *Evaluate the impact (in ship size, capital cost, operational cost and emissions) of the combination of the chosen fuel cell systems and operational profile requirements on the design of expedition cruise ships. Choose the most suitable fuel cell systems for expedition cruise ships.*
The results of the design tool are used to fulfil this research objective. The impact is reviewed for all combinations of the seven fuel cell systems and the three hybrid options. Six combinations of hybrid options and fuel cell systems are chosen to be most suitable for expedition cruise ships from newbuild

price, fuel cost and emission regulation compliance perspective. For these six the operational profile requirements and ship size are systematically varied.

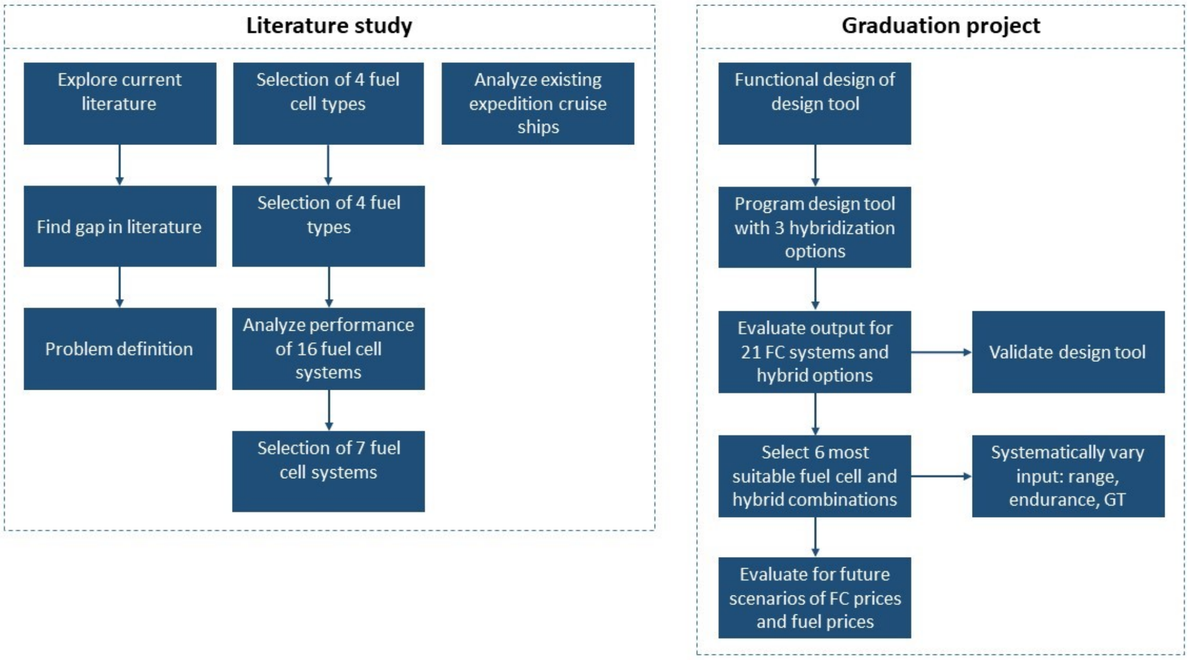


Figure 4.1: Schematic overview of methodology for literature study and graduation project

5

Selection of fuel cell and fuel types

This chapter gives the reader insight in the different fuel cell systems that can be applied in ships. The systems vary strongly, dependent on the used fuel type or fuel cell type. An overview of different fuel cells and different possible fuels for these fuel cells is provided. A first selection of applicable fuel cells and fuels is performed based on literature in sections 5.1 and 5.2 respectively. Fuel cell types LT-PEMFC, HT-PEMFC, MCFC and SOFC will be selected as fuel cell types and LH_2, LNG, $MeOH$ and NH_3 will be selected as fuel types. Sections 5.2.2 and 5.2.3 provide information about storage and fuel processing necessities of the selected fuel types.

This chapter supports the first research objective: *Analyse relevant performance of fuel cell types and suitable fuel types in terms of efficiency, power and energy density, dynamic behavior, TRL, safety, capital cost and operational cost. Discard worst options.*

From this chapter the reader should learn which characteristics of fuel cell systems are important for the implementation in ships and what are good criteria to exclude a fuel or fuel cell for further investigation.

5.1. Fuel cell types

This section describes all fuel cell types, elaborates on advantages and disadvantages. Based on literature a first selection of applicable fuel cell types is made. At the end of this subsection an overview of the different fuel cells is given (table 5.2) and the further considered fuel cell types are stated in table 5.1.

Alkaline fuel cell (AFC)

OH^- travels from the cathode to the anode through an alkaline solution. Its electrolyte and electrode are cheap compared to those of other fuel cell types. The operating temperature of the AFC is between 90 and 250 degrees. [66]. AFC has an efficiency of 50 to 60% and no need for reforming of fuels or heat recovery systems. The main problem of AFC is that the electrolyte reacts with CO_2, resulting in higher activation-, ohmic- and mass transport losses. This means a regenerative system is required for the electrolyte. AFC struggles with CO_2 poisoning and upscaling (only power up to 200 kW is reported [114]).

Proton exchange membrane fuel cell (PEMFC)

PEMFC has been used in many applications, and there is a wide range of companies producing it. The electrolyte transports H^+ ions from anode to cathode. The PEMFC can be categorized in high temperature and low temperature. Due to the relative low temperature of PEMFC, expensive platinum is necessary to catalyse the reaction. Also due to the low temperature, it is very sensitive to fuel impurities, for instance the presence of CO and S.

- *LT-PEMFC*
  The operational temperature of LT-PEMFC ranges from 65-85°C. The membrane requires to be wet, but when too much water is taken in swelling can occur, causing mechanical stresses. A complex water management system is necessary [66]. Efficiency of LT-PEMFC is 50-60% at optimal load (which is at

part load). LT-PEMFC is a mature technology and has been successfully applied in marine applications [100] and demonstrated relative low cost around 2000 €/kW.

- *HT-PEMFC*
  Operates at temperatures from 100-200 °C, resulting in higher impurity tolerance and lower platinum requirements than LT-PEMFC. Due to the higher operation temperature, water is only present in gaseous phase, strongly simplifying the water management system [114]. HT-PEMFC is a newer technology meaning TRL is not as high and so far realised efficiency is slightly lower. However, HT-PEMFC successfully addresses problems of water management system and fuel impurity compared to LT-PEMFC. HT-PEMFC is successfully tested on a cruise ship as support of electrical and heat systems [114].

Direct methanol fuel cell (DMFC)
DMFC is not really a kind of fuel cell, because methanol is used as fuel in an AFC or PEMFC with sleight system modifications. The power density of DMFC is lower, because methanol reacts much slower than hydrogen at the anodes of the fuel cell. Fuel-crossover is high for methanol, decreasing the efficiency [87]. The efficiency of a direct methanol fuel cell is around 20% and CO_2 is created as an exhaust product. However, the storage of methanol has a higher energy density than hydrogen. So, DMFC has low performance but better fuel storage [11, 66].

Phosphoric acid fuel cell (PAFC)
PAFC uses an inorganic acid H_3PO_4 as electrolyte. H^+ ions are transported through the membrane and it operates at temperatures from 140 to 200°C. The higher temperature decreases the required platinum loading and increases CO tolerance. Excess heat can be utilized, making it possible to increase efficiency from 40% up to 80% [114]. PAFC has very limited durability and power density, resulting in a large and heavy system [11, 114].

Molten carbonate fuel cell (MCFC)
In a MCFC CO_3^{2-} travels from cathode to anode through a molten carbonate salt electrolyte. Since CO_2 is required to form CO_3^{2-}, it is often used with carbon-containing fuels like LNG, otherwise extra CO_2 must be supplied to the fuel cell. It operates at high temperatures of 650-700 °C, so no precious metal is needed as catalyst. The electric efficiency of MCFC is 50% and with energy recovery systems it can reach up to 85%. A MCFC requires an additional combustion chamber because not all fuel is converted as well as to keep up the temperature of the fuel cell [66]. Although MCFC is facing high cost and low lifetime, it is rapidly developing.

Solid oxide fuel cell (SOFC)
In a SOFC O^{2-} ions are transported from cathode to anode. This fuel cell operates at a wide range of very high temperatures: 500-1000 °C. SOFC efficiency is around 60% but can be increased to 80% with addition of a gas turbine. Due to the high temperature platinum is not necessary as catalyst [66] and hydrocarbons can be reformed internally. SOFC still struggles with its limited development state, mechanical vulnerability and high cost [11], but is considered one of the most promising fuel cells for shipping due to its high efficiency and relatively high power density [11, 114].

Direct carbonate fuel cell (DCFC)
Similar to a direct methanol fuel cell, a direct carbonate fuel cell is not a specific kind of fuel cell but an application of a fuel cell type with a different kind of fuel. DCFC uses carbon as fuel (for instance coal, coke or graphite) and is applicable on AFC, MCFC and SOFC. DCFC has a very high efficiency (85-90 %) [66]. However, since carbons are combined with oxygen to form CO_2, SO_X and NO_X, polluting emission are very high and thus this type of fuel cell does not fit the purpose of this research.

Conclusion
With use of existing literature, the characteristics of different fuel cell types are reviewed. In this conclusion their most important characteristics are summarized and 4 fuel cell types are selected to use in this research. AFC will not be considered since it struggles with electrolyte poisoning. LT-PEMFC will be considered due to high power density and relative low cost and high TRL. HT-PEMFC will be considered since it requires less platinum than LT-PEMFC and has higher tolerance to fuel impurities. DMFC will not be considered since efficiency and power density are very low due to fuel-cross over in the fuel cell. PAFC is not considered since it struggles with power density and durability. MCFC and SOFC are considered due to high efficiency and

high tolerance to fuel impurity. DCFC emits many hazardous components and thus does not fit this research. An overview of the selection is visible in table 5.1. For all selected fuel cells, data is gathered to use later in this research, see table 5.2.

Table 5.1: Selected fuel cell types from literature.

Fuel cell type
AFC
LT-PEMFC
HT-PEMFC
PAFC
DMFC
MCFC
SOFC
DCFC

Table 5.2: Data of selected fuel cell types. DIR = Direct Internal Reforming.

Fuel cell		LT-PEMFC	HT-PEMFC	MCFC	SOFC
Electrolyte		Nafion™	Various	Molten carbonate	Ceramic oxide
DIR possible		no	no	yes	yes
Temperature	$°C$	50-100	100-150	650-800	500-1000
Vol. P. density	kW/m^3	300-1550	50-150	1.75-20	8-60
Grav. P. density	kW/ton	250-1000	50-100	7.75-25	20-230
FC efficiency	%	40-60	45-50	40-60	45-70
Lifetime	h	25000-40000	20000-30000	10000-30000	25000-40000
Starttime	s	5-20	300-1200	2500-10000	5000-15000
Cost	$€/kW$	2000-2500	2000-3000	3000-5000	5000-8000
Source		[11, 44, 66, 80]	[11, 16, 66, 108, 121]	[11, 28, 66]	[11, 28, 44, 66, 103]

5.2. Fuel types

Depending on the type of fuel cell, different fuels are possible. All considered fuel cells can run on pure hydrogen. Pure hydrogen is often the most practical fuel for a fuel cell: pure hydrogen results in high power density of the fuel cell, due to fast hydrogen oxidation kinetics [61]. However, the energy density of hydrogen storage is low. It is also possible to bunker a more energy dense fuel and reform the fuel on board. In this research, other bunker fuels than hydrogen are defined as hydrogen carriers. In high temperature fuel cells (MCFC and SOFC) it is even possible to internally reform fuels, such as methane and CO, omitting the need for reforming equipment. When considering fuel cells for ships, it is important to cover the combination of fuel and fuel cell, including fuel processing and auxiliary equipment. This has big influence on the power density, energy density and cost of the system. The cost of the fuel is also important: when a certain fuel cell system performs well in cost of fuel cell system cost and space but the fuel itself is really expensive, it might not be a viable concept. In this section only fuels are discussed that are usable for the fuel cells that were selected in the previous section. Firstly, different fuel types will be shortly reviewed and a selection of fuels will be made for the research based on literature in section 5.2.1. LH_2, LNG, $MeOH$ and NH_3 are selected as bunker fuels, see table 5.1. Subsequently, information about storage (section 5.2.2) and on-board processing (section 5.2.3) is provided of the chosen fuels. Information of storage and on-board fuel processing will be used later in the research to define performance of the components of fuel cell system in terms of energy density, power density and cost.

5.2.1. Preliminary fuel selection

This section reviews 8 fuels that can be used for the selected fuel cell types. LH_2, LNG, $MeOH$ and NH_3 are selected as bunker fuels based on literature, see table 5.1.

Hydrogen

Besides its storage, hydrogen is the most convenient fuel for fuel cells. Pure hydrogen can be directly used in all fuel cell types, meaning very few fuel processing equipment is needed when pure hydrogen is bunkered.

Hydrogen is seen as a fuel of the future and its distribution infrastructure is increasing. An example of this is the newly launched project 'Gigawatt electrolysis plant', part of 'Roadmap towards a climate neutral industry 2050' program. [101]. Hydrogen allows fast refuelling and can be produced emission-free if renewable electricity is used as energy source for electrolysis [71]. Pure hydrogen as bunkering fuel also delivers the highest fuel cell system efficiency.

Diesel
Due to the fact that diesel is relatively cheap, energy dense and its highly developed infrastructure, it is the most researched fuel for fuel cells [11]. However, diesel in mobile fuel cell applications is inconvenient since it requires complex fuel processing equipment (except SOFC) lowering the efficiency, contains relatively high sulphur and emissions are still significant [69]. Diesel in combination with ICE generators is mostly used in expedition cruise ships for power generation and thus can also be used as fuel to compare with.

Natural gas
Natural gas is increasingly being used in the marine industry in order to comply with exhaust regulations, meaning its fuel infrastructure is expanding [45]. It is a cost-competitive alternative for diesel with lower emissions of CO_2, PM, SO_X and NO_X [15]. Its main hydrogen carrier is methane CH_4. It contains sulphur, but less than conventional fuels. For shipping, natural gas is usually stored below -162 °C to reduce the required volume, however much energy is required to accomplish this. When stored at this temperature it is called liquefied natural gas (LNG). Natural gas is considered as a transitional solution, since it is mainly produced of fossil fuel stock and polluting emissions are lower but still considerate [8]. On-board hydrogen production from LNG is probably cheaper, more efficient and more dense than producing hydrogen elsewhere and bunkering it [26].

Alcohols
Methanol and ethanol are alcohols that are considered as fuels for shipping. They are colourless, flammable liquids. They do not contain sulphur and particulate matter, meaning a low environmental impact. They are both widely used in the chemical industry and thus have a high availability. Methanol and ethanol dissolve in water, are biodegradable, and do not bioaccumulate. They are rated as non-toxic to aquatic organisms, being a big advantage for fuel spills due to accidents [33].

Methanol (MeOH)

Methanol (CH_3OH) or $MeOH$ can be produced from fossil or renewable feedstock [33]. Compared to hydrogen and natural gas, its advantage is its liquid phase at ambient temperature, due to its boiling point of $64.7°C$. Consequently, methanol is easier to store, leading to higher volumetric power densities. On top of that conventional fuel infrastructure can be used for methanol after sleight adjustments [96]. The main disadvantages are the toxic and corrosive characteristics of methanol.

Ethanol

Ethanol (C_2H_5OH) can be produced from methanol or from syngas and is less toxic than methanol. Production from syngas has not proven to be commercially reliable, very limited data is available of homologation of ethanol and currently there are no prospects of up scaling of production and distribution of the fuel. Ethanol as fuel behaves similar to methanol but due to the much higher prices of ethanol, methanol is a better option [33].

Dimethyl ether (DME)
Dimethyl ether, recently more and more considered as shipping fuel [11, 33, 83], has many promising characteristics: Environmentally friendly and easily stored and transported. It evaporates when spilled, is not absorbed by soil and contains no PM and sulphur. Also, it is non-carcinogenic and non-toxic [102]. DME (C_2H_6O) can be produced by dehydrating methanol, consequently it has a slightly higher power density. Although it is not widely used yet, DME behaves similar to propane, making it possible for propane distributors to adapt their infrastructure to DME [83]. DME is very promising for future use. However, the lack of available information and data regarding storage and on board fuel processing equipment, makes it impossible to do a reliable assessment.

Ammonia
Ammonia (NH_3) is different from the other discussed hydrogen carriers since it uses N to bind to the hydrogen instead of C. Where carbon is hard to extract from the atmosphere, nitrogen is abundant and easy to extract [125]. Since it contains no carbon it can be directly used in LT fuel cells without the risk of CO poisoning, omitting the need for purification equipment. Ammonia is distributed worldwide and is after sulphuric acid the most produced commodity chemical, ensuring high TLR in production and distribution [39]. An important drawback is its severe toxicity to humans and animals and its corrosivity. Ammonia is characterized high TLR of production and distribution combined with moderate volumetric energy density.

Conclusion
From literature, a preliminary selection of applicable fuel types was made. Hydrogen is selected as bunker fuel since very no fuel processing equipment is necessary and its infrastructure is increasing. Diesel is not considered as bunker fuel for fuel cells. Emissions are still significant while efficiency is low due to the extensive fuel reforming equipment. LNG will be considered as bunker fuel. Its availability is increasing and it a more cost-competitive and more energy dense alternative of hydrogen. Of the alcohols, methanol is considered because of high energy density and ethanol is not considered since it performs similar to methanol but is more expensive. DME will not be considered due to lack of available information. Ammonia will be considered since its availability and TLR are high and contains much energy per volume. An overview of the selected bunker fuels for this research is visible in table 5.3.

Table 5.3: Selected fuel types from literature.

Fuel type
Hydrogen
Diesel
Natural gas
Methanol
Ethanol
Dimethyl ether
Ammonia

5.2.2. Fuel Storage of selected fuels
The way fuels are stored has much influence on the energy density of the fuel. For instance cylindrical storage, insulation requirements and minimum fill rate have big influence on the required volume. The considered hydrogen carriers (NG, Methanol and Ammonia) have energy denser storage than hydrogen. How different fuels should be stored is dependent on its ambient phase, flash point, explosivity, toxicity and corrosivity. This section elaborates on the storage of the selected fuels. Knowledge and data about fuel storage are necessary to determine how much ship volume will be required to implement a fuel cell system. Figure 5.1 gives an overview of the explosive ranges of the selected fuels. Table A.1 in appendix A provides an more elaborate overview of the hazardous characteristics of the selected fuels.

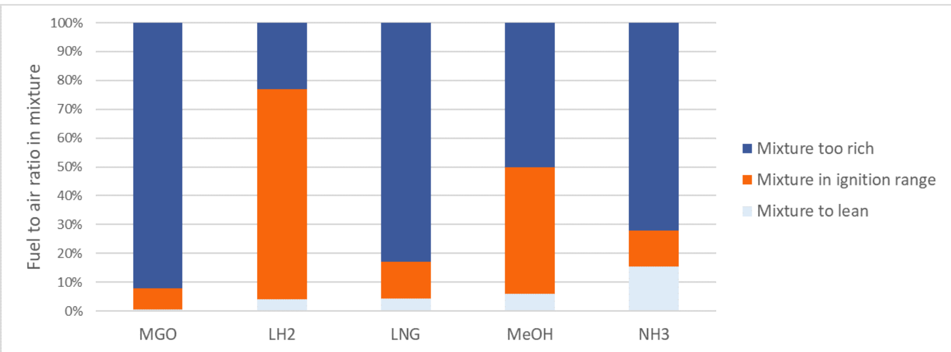


Figure 5.1: Explosive ranges of fuel air mixture.

Hydrogen

There are two options for storing hydrogen: i) in pressurized vessels at either 350 or 700 bar (CH_2). ii) cryogenic storage at a temperature of -253 °C at ambient (or somewhat higher) pressure (LH_2). Cryogenic hydrogen storage is considered to be the most energy dense storage method for marine applications and will only be considered in this study [11]. However, the volumetric energy density of LH_2 is still 4.26 times as small as for MDO. On top of that, there are three factors that further decrease volumetric energy density of hydrogen storage: i) hydrogen can only be stored in spherical, cylindrical or ellipsoid tanks, because these shapes make sure stresses by temperature or pressure change are distributed as equal as possible [121]. Spherical tanks are not easy fitted in ships and ellipsoid tanks require complex and expensive manufacturing techniques. In this research, cylindrical tanks with rounded ends are used to store hydrogen, decreasing the usable volume by a little more than $D^2 - \frac{1}{4}\pi D^2 = 21\%$. ii) several layers of insulation are required to keep hydrogen in liquid state. A radius increase of 15% of the storage radius can be assumed for the tank wall [11]. iii) Not all liquid hydrogen in the tanks is usable as fuel. The tank will deform for high temperature changes, meaning a part of LH_2 should remain in the tank to ensure its low temperature. A minimum fill rate of 10% is assumed [121]. These points combined lead to a maximum utilization ratio of ship volume for hydrogen storage of 51%. This leads to a volumetric energy density of 1207 kWh/m^3, which is verified with storage data of van Biert who estimated 1200 kWh/m^3. For gravimetric energy density of hydrogen, storage data of van Biert is used 2500 kWh/ton) [11]. Hydrogen has a broad explosive range, see figure 5.1. This imposes extra challenges in the safety measurements of hydrogen storage.

Natural gas

Similar to hydrogen, natural gas (NG) is most effectively stored on board of ships in cryogenic conditions at $-162°C$ (LNG) [11]. LNG can be stored more energy dense than hydrogen due to two factors: i) the volumetric energy density of natural gas is higher than of hydrogen. ii) The higher cryogenic temperature of LNG leads to less required insulation. The minimum fill rate of LNG is around 10% (as stated by proposal engineers of Damen). A nitrogen system is required for purging of the pipes. Out of the quotation of a tank supplier followed that natural gas can be stored at 3135 kWh/m^3 (of shipvolume). This is close to the storage density estimated by van Biert [11], namely 3300 kWh/m^3. The same quotation resulted in a gravimetric energy density of 7328 kWh/ton, which was also verified with storage data of van Biert (7400 kWh/ton) [11].

Methanol

Methanol can be stored in any tank shape since it is in liquid phase at ambient temperatures and no insulation is required, leading to a much higher ship volume utilization ratio. It also means irregular volumes can be used more easily for fuel storage. Due to the corrosive characteristics of methanol, it should be stored and transported in stainless steel or carbon steel. With consultation of Damen, a spare/unpumpable ratio of 5% is assumed. Methanol is stored at a volumetric energy density of 3500 kWh/m^3. For gravimetric energy density of methanol, storage data of van Biert is used (3900 kWh/ton) [11]. Methanol has a rather broad explosive range, see figure 5.1. This imposes extra challenges in the safety measurements of methanol storage.

Ammonia

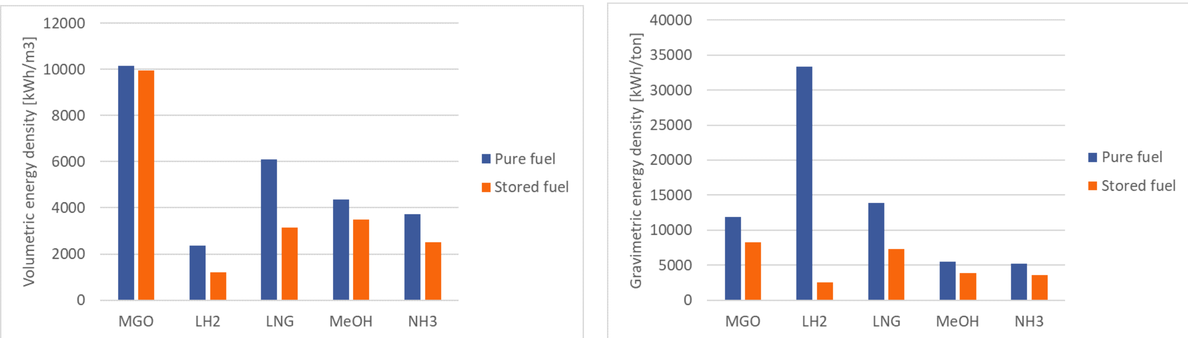
Ammonia is usually stored in liquid form at $-33°C$ and ambient pressure in cylindrical tanks. Tank insulation limits the volumetric energy density, but due to the higher cryogenic temperature much less insulation is required than for LNG and LH_2. 5% reduction in storage radius is assumed for insulation. Also due to the higher cryogenic temperature, a minimum fill rate of 5% is sufficient to limit mechanical stresses. Ammonia tanks have a ship volume utilization ratio of $\frac{1}{4}(1-5\%)^2\pi(1-5\%) = 67.3\%$ leading to a volumetric energy density of 2511 kWh/m^3, which is close to the estimated value of 2300 kWh/m^3 van Biert used. For gravimetric energy density of ammonia, storage data of van Biert is used (3600 kWh/ton) [11]. Due to its corrosivity, stainless steel is required for storage and distribution.

Conclusion

Storage properties of the selected fuel cells were evaluated. The results are summarized in table 5.4 and visualised in figure 5.2 (a) & (b). Methanol can be stored most with most energy per ship volume, followed by LNG and ammonia. Hydrogen is stored at a much lower volumetric energy density. Including the mass of the storage system, LNG contains the most energy per ton. Ammonia and methanol have quite similar gravimetric energy density and LH_2 has the lowest.

Table 5.4: Data of selected fuel types. LHV = Lower Heating Value.

Fuel		LH2	LNG	MeOH	NH3
State		liquid	gas	liquid	gas
Storage temperature	K	20	100	293	293
Density at T	ton/m^3	0.07	0.44	0.79	0.72
LHV	MJ/kg	120.21	50.00	19.90	18.65
Vol. en. density of fuel	kWh/m^3	2363	6097	4372	3729
Grav. en. density of fuel	kWh/ton	33391	13888	5527	5179
Volume utilization	%	51%	-	97%	67%
Vol. en. density for storage in ship	kWh/m^3	1207	3136	3500	2511
Grav. en. density for storage in ship	kWh/ton	2500	7328	3900	3600
Fuel cost	€$/MWh$	75	18	72	164
Sources		[11, 34, 121]	[11, 14, 34, 119]	[11, 33, 34]	[11, 14, 34, 63]



(a) Volumetric energy density.

(b) Gravimetric energy density.

Figure 5.2: Power density of selected fuels and MGO for pure fuel and fuel stored in the ship.

5.2.3. On board fuel processing of selected fuel types

This section explains the required on board fuel processing equipment for different fuels. In general, for cryogenic stored fuels (LH_2, LNG & NH_3) extra equipment is necessary, due to two reasons: i) despite the insulation of cryogenic stored fuels, evaporation of a certain part of the fuel can not be prevented. The part of fuel that evaporates compared to the total volume per unit of time is called the boil-off rate [104]. This can be used for fuel supply towards the fuel cell. However, if the boil-off rate is higher than the fuel consumption at a certain time, the excess fuel is condensed and recirculated to the tank. ii) when the boil-off rate is lower than the fuel consumption, extra fuel must be added from the tank, this fuel must first be heated before it can be used in a fuel cell. However, the latter can be integrated as refrigerator of the HVAC system [125], lowering energy consumption. An assessment of the required fuel processing equipment per fuel cell system will be performed later in section 6.1.

Hydrogen

Pure hydrogen can be directly used in all fuel cell types. Apart from the just stated fuel heating and circulation equipment no extra fuel processing equipment is required.

Natural gas

Natural gas can be converted on board to hydrogen with steam reforming (SR), an endothermic equilibrium reaction (endothermic equation 5.1 with $\Delta H = 206 kJ/mol$). The created mixture of H_2 and CO is called syngas. Heat and steam are constantly required to preserve the reaction, decreasing overall system efficiency compared to pure hydrogen as fuel. The exothermic water gas shift reaction (WGS) usually follows up after the reforming reaction, and lowers the CO concentration of syngas and creating even more H_2, see equation 5.2 (exothermic reaction with $\Delta H = -41 kJ/mol$) [11]. For LT fuel cells SR and WGS takes place in a separate reactor, for HT fuel cells both reactions can take place inside the fuel cell.

$$CH_4 + H_2O \rightleftharpoons CO + H_2 \tag{5.1}$$

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \tag{5.2}$$

As was stated before, LT fuel cells have low CO tolerance, meaning purification equipment is necessary after reformation of NG. A preferential oxidation (PrOx) unit can be used to convert CO to CO_2, where the following exothermic reaction ($\Delta H = -283 kJ/mol$) takes place:

$$2CO + O_2 \rightarrow 2CO_2 \tag{5.3}$$

Membrane separation and pressure swing adsorption can be used when further purification of the fuel cell fuel is needed, for instance for LT-PEMFC [11].

Methanol

Since direct methanol fuel cells are not considered (due to low efficiency and power density), it needs to be reformed to hydrogen. Methanol reforming consists of methanol decomposition (endothermic reaction 5.4 with $\Delta H = 42.9 kJ/mol$) and the WGS reaction 5.2. It takes place at temperatures around 200 °C [87], 100% hydrogen conversion and the CO content of reformate gas is less than 0.2 %, meaning it can be directly used in HT-PEMFC and higher temperature fuel cells. For LT-PEMFC, PrOx and Membrane separation equipment is required, lowering power density and dynamic behavior and increasing the cost.

$$CH_3OH + H_2O \rightleftharpoons CO + 2H_2 \tag{5.4}$$

Ammonia

Ammonia can be used directly in solid oxide fuel cells (SOFC) with similar performance as pure hydrogen [39, 63]. For the other chose fuel cell types, ammonia should be reformed on board with ammonia cracking. Ammonia cracking (endothermic reaction 5.5 with $\Delta H = 383 kJ/mol$) is an easier process than hydrocarbon reformation [65]. Also, there is no CO, CO_2, or S in the fuel, omitting the need for purification equipment. After cracking it can be directly used in the fuel cell.

$$2NH_3 \rightarrow N_2 + 3H_2 \tag{5.5}$$

Conclusion

In this section the fuel processing of the selected fuels was reviewed. The fuel processing equipment mainly has influence on the transient behavior, efficiency and weight and volume usage of the fuel cell system. Hydrogen can be directly used in all fuel cell types. For LNG in combination with LT fuel cells a SR and WGS reactor and purification equipment is required. For LNG in combination with HT fuel cells no fuel processing equipment is needed. Methanol needs to be reformed on board, for LT fuel cells additional purification equipment is required. Ammonia is most suitable for SOFC since it can be directly used, for other fuel cell types an ammonia cracker is needed. Which equipment is needed precisely for which fuel and fuel cell combination will be treated extensively in the next chapter.

6
Fuel cell systems

This chapter gives the reader insight in the relevant performance of fuel cell systems. In this research, a fuel cell system is defined as a combination of fuel type and fuel cell type. Every fuel cell system is characterized by different equipment and requirements and thus different performance. The information of the different fuel cell systems is necessary to determine which fuel cell systems are most applicable for expedition cruise ships later in this report.

This chapter supports the second research objective: *Express performance of fuel cell systems for expedition cruise ships in terms of power density, energy density, capital cost and operational cost. Discard worst options.*

First, a system decomposition of fuel cell systems is provided in section 6.1, it is necessary to know which equipment is required for a fuel cell system to understand how these components influence energy density, power density and cost of the total system. The performance of the fuel cells will be expressed in different criteria. Section 6.2 describes which criteria are used and how they are calculated and also, which ones are not used. Section 6.3 presents the performance of the fuel cell systems on these criteria.

6.1. Fuel cell system decomposition

An on-board fuel cell system is defined by its bunker fuel type and its fuel cell type. The different combinations of fuel type and fuel cell type have big impact on the performance of the system in terms of capital expenses, operational expenses, power density, energy density, efficiency and start-up times. This impact is mainly influenced by the required equipment for the fuel cell system. Figure 6.1 gives insight to the system decomposition of different fuel and fuel cell combinations. The whole fuel cell system is divided in the storage equipment, fuel reforming equipment, purification equipment, the fuel cell power pack (thermal, flow, humidity and energy regeneration equipment) and the balance of plant (BOP) equipment. The balance of plant components are equipment that ensure the required electricity for the energy consumers, meaning batteries and capacitors to satisfy transient loads and electrical converters to supply electricity at the right voltage and frequency. The fuel type influences the fuel storage, the fuel reforming equipment and the purification equipment. The fuel cell type influences the reforming equipment, purification equipment, fuel cell equipment and balance of plant equipment. So reforming and purification equipment are influenced by both fuel type and fuel cell type. This results in some combinations being more inconvenient than others. For instance, LNG in combination with LT-PEMFC requires a lot of fuel processing steps and heat differences, reducing the total system efficiency and power density [11]. For similar reasons, it is inconvenient to use pure hydrogen as bunkering fuel for SOFC, since the strength of SOFC lays in its high tolerance for impurities and SOFC even uses present CO as fuel. The overall efficiency of the fuel cell system is limited by requirements of heat, steam and purification equipment. However, it is not sufficient to reason the performance of the different fuel and fuel cell combinations, in section 6.3 the fuel cell system performance will be quantified.

As is visible in figure 6.1, the required volume and weight to store the required energy is only dependent on the fuel storage equipment, while the required volume and weight to satisfy the required power is depending on reforming, purification, fuel cell and balance of plant equipment.

In order to calculate power density and energy density of the different fuel cell systems it is necessary to know which equipment is necessary for each fuel and fuel cell combination. Table 6.1 shows an overview of the required fuel processing components for all selected fuel and fuel cell combinations. Power densities of components can be found in table A.3 in Appendix A.2. The efficiency per fuel cell system is also showed in the table, since it is very dependent on the required equipment components. The system decomposition and equipment overview will be used to express the performance of the different fuel cell systems, which will be explained in the next section.

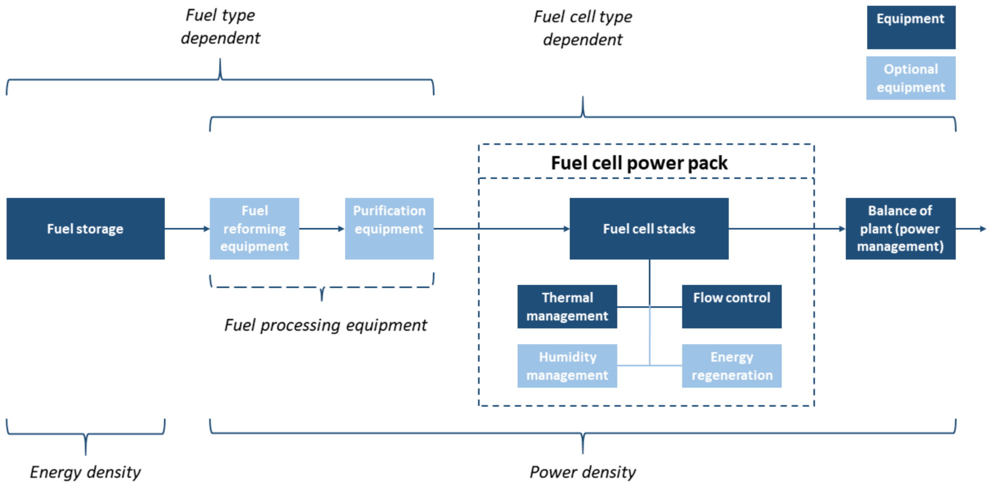


Figure 6.1: Generic overview of fuel cell system on board of a ship [ownimage].

Table 6.1: Required fuel cell equipment and system efficiency per fuel and fuel cell combination. PrOx = preferential oxidation. The mean system efficiency is used as data for the model.

Fuel type	Fuel cell type	Reformer	PrOx unit	Pressure swing adsorption/ Membrane separation	System efficiency		Source
					Peak	*Mean*	
LH2	LT-PEMFC	-	-	-	60%	50%	[11]
LH2	HT-PEMFC	-	-	-	50%	45%	[108]
LH2	MCFC	-	-	-	60%	50%	[11]
LH2	SOFC	-	-	-	60%	50ta%	[11, 36, 91]
LNG	LT-PEMFC	Steam reformer	✓	✓	45%	40%	[11]
LNG	HT-PEMFC	Steam reformer	✓	-	40%	35%	[108]
LNG	MCFC	-	-	-	55%	45%	[11]
LNG	SOFC	-	-	-	65%	60%	[11, 116]
MeOH	LT-PEMFC	Methanol reformer	✓	✓	50%	45%	[11]
MeOH	HT-PEMFC	Methanol reformer	-	-	45%	40%	[87, 108]
MeOH	MCFC	Methanol reformer	-	-	50%	45%	[11]
MeOH	SOFC	Methanol reformer	-	-	65%	55%	[11, 116]
NH3	LT-PEMFC	Ammonia cracker	-	-	50%	45%	[11]
NH3	HT-PEMFC	Ammonia cracker	-	-	45%	40%	[108]
NH3	MCFC	Ammonia cracker	-	-	55%	50%	[11]
NH3	SOFC	-	-	-	65%	60%	[11, 39, 65, 116]

6.2. Selection criteria

To perform a systematic, well founded selection of fuel cell systems later in the research, the fuel cell systems need to be evaluated on different criteria. First, the following criteria were considered:

- Volumetric power density
- Volumetric energy density
- Gravimetric power density
- Gravimetric energy density
- Efficiency
- Lifetime
- Capital cost
- Operational cost
- Safety
- Technological readiness level (TRL)
- Dynamic behavior

During reconsideration of these criteria was found that some of the criteria do not have to be evaluated (separately). Firstly, lifetime of the fuel cell can be decomposed in cost by adding the replacement cost of the the fuel stacks over the operational lifetime of the ship. Fuel cell systems for industry usage are designed such that just the fuel cell stacks can be replaced. Secondly, the efficiency can be decomposed by integrating it into the energy density and the fuel cost (part of operational cost). Thirdly, safety and TRL can better be considered as binary criteria: the fuel cell system can only be used (now) when safety and TRL are sufficient. Since fuel and fuel cell types that performed insufficiently on safety and TRL were already left out during the literature review, these criteria are also not considered anymore. Fourthly, the dynamic behavior (its capability to cope with transient load) of the fuel cell system can always be solved with balance of plant components (electric components like super capacitors or batteries), but it is not known how big the increase in size, weight and price is for large scale systems. Mainly HT fuel cell systems struggle with dynamic behavior [66], but it can be increased with batteries for large transients like cold start-ups and super capacitors for peak shaving. Note that this would increase the capital cost, weight and used volume, so the dynamic behavior will also be dissolved into power density and cost [11, 111].

Consequently, after reconsideration, the following criteria are used and these will be explained in the next subsections:

- Volumetric power density
- Volumetric energy density
- Gravimetric power density
- Gravimetric energy density
- Capital cost
- Operational cost

6.2.1. Power density

The required volume to satisfy the required power is depending on reforming, purification, fuel cell and balance of plant equipment, as can be seen in figure 6.1. The contribution of these different components leads to the power density of the total fuel cell system. The fuel cell power pack is used as a whole component since the separate subsystems (water management system, thermal management system) in this component are often combined to one power pack by the fuel cell supplier.

The accumulated volumetric power density is expressed with equation 6.1. The volumetric power densities of the different components are combined to one power density in the same way as impedances are combined to one system impedance for parallel system components. The same holds for the gravimetric power density, see equation 6.2.

$$p_{vol,FCsystem} = \frac{1}{\left(\frac{1}{p_{vol,reform}} + \frac{1}{p_{vol,purification}}\right)_{fuelprocess} + \frac{1}{p_{vol,FC}} + \frac{1}{p_{vol,BOP}}} \tag{6.1}$$

$$p_{grav,FCsystem} = \frac{1}{\left(\frac{1}{p_{grav,reform}} + \frac{1}{p_{grav,purification}}\right)_{fuelprocess} + \frac{1}{p_{grav,FC}} + \frac{1}{p_{grav,BOP}}} \tag{6.2}$$

where:

$p_{...,reform}$	Power density of reforming equipment
$p_{...,purification}$	Power density of purification equipment
$p_{...,FC}$	Power density of fuel cell power pack
$p_{...,BOP}$	Power density of balance of plant components like batteries and capacitors

6.2.2. Energy density

The required volume to store the required energy is only dependent on the fuel storage equipment, see figure 6.1. The required ship volume for fuel storage is expressed with the volumetric energy density $e_{vol,storage}$. This is calculated with data of suppliers (see equation 6.3) by dividing the stored energy ($V_{fuel}\rho_{fuel}LHV$) by the required space for the storage system. When supplier data was not available, assumptions for volume utilization are used to calculate the volumetric energy density (equation 6.4). The energy density of the fuel ($\rho_{fuel}LHV$) is multiplied with a utilization ratio $a_{fuel\,utilization}$ which describes the difference between fuel volume and required ship volume to store that fuel volume. For both equations, the energy density amount is also multiplied with the efficiency of the whole fuel cell system in order to compare energy densities of different fuel cell systems fairly. This means that $e_{vol,storage}$ represents the amount of electrical energy that can potentially be created with use of the fuel cell system per volume.

$$e_{vol,storage} = V_{fuel}\rho_{fuel}LHV\frac{1}{V_{requiredspace}}\eta_{FCsystem} \tag{6.3}$$

$$e_{vol,storage} = \rho_{fuel}LHV a_{fuel\,utilization}\eta_{FCsystem} \tag{6.4}$$

where:

V_{fuel}	Stored fuel volume in storage equipment
ρ_{fuel}	Density of fuel
LHV	Lower Heating Value of fuel
$V_{requiredspace}$	Required ship volume to fit the storage equipment concerned
$\eta_{FCsystem}$	Efficiency of the whole fuel cell system, from energy available in fuel to delivered electric energy.
$a_{fuel\,utilization}$	Ratio between stored fuel and required ship volume to store that amount of fuel

The gravimetric energy density for storage of different fuels is determined in a similar fashion as the volumetric power density. When supplier data was available, the stored energy ($V_{fuel}\rho_{fuel}LHV$) was divided by the weight of the storage system and multiplied with the efficiency of the fuel cell system, see equation 6.5. When supplier information was not available gravimetric energy densities given by van Biert were used [11] and multiplied with the efficiency of the storage system.

$$e_{grav,storage} = V_{fuel}\rho_{fuel}LHV \cdot \frac{1}{m_{stored\,fuel} + m_{storage\,equipment}} \cdot \eta_{FCsystem} \tag{6.5}$$

where:

$m_{storage\,equipment}$	Mass of the storage equipment to store amount V_{fuel} of the fuel concerned

6.2.3. Capital cost

The cost of the fuel cell system is a big challenge for implementation in marine applications. A high cost per kW of the fuel cell system combined with a relative short lifetime results in high capital costs. The capital cost is divided in cost of fuel cell power plant (€/kW) and cost of fuel storage system (€/kWh), since the first is related to the required power on board and the second to the required energy on board.

Capital cost for fuel cell power plant

The capital cost per kW of the fuel cell plant is different for all fuel and fuel cell type combinations. All system components in figure 6.1 have different cost per kW for different fuel cell systems. For instance, a methanol reformer would have a different cost per kW than an ammonia cracker. However, these cost data per equipment is not generally available and suppliers are not willing to deliver this without signing a NDA. For this reason a percentage increase in cost for the fuel cell power pack is included with $a_{fuel\,processing}$ and a_{BOP}, in consultation with fuel cell experts (values of margins are shown in Appendix A figure A.4). This converts cost of power pack to cost of power plant. $a_{fuel\,processing}$ includes fuel processing and purification equipment. a_{BOP} includes batteries, super capacitors and power conditioning systems. The values of these parameters are different per fuel and fuel cell combination. For instance the increase in cost for fuel processing is 0% for LH_2 fueled LT-PEMFC and highest for LNG fueled LT-PEMFC, since LNG requires a large reforming plant and many purification steps in combination with LT-PEMFC.

The cost data of the fuel cell systems are retrieved from fuel cell suppliers and fuel cell literature. The capital cost per kW for the fuel cell power plant is calculated with equation 6.6. The lifetime of the fuel cell is taken into account in order to compare different fuel cell systems fairly. For a fuel cell system, mainly the fuel cell stacks itself are degrading quickly and have a short lifetime. The lifetime of the rest of the fuel cell system is comparable with the operational lifetime of the ship. Out of discussion with a fuel cell expert followed: fuel cell suppliers who make fuel cell systems for industry usage deliver systems of which just the fuel cell stacks can be replaced. Different fuel cell types are characterized by a different lifetime and different ratio between fuel cell stack cost and fuel cell system cost ($a_{stack\,cost}$). $a_{stack\,cost}$ is very dependent on the platinum loading of the fuel cell stacks and thus dependent on the fuel cell temperature and ranges between 35 and 50 %, as was told by a fuel cell expert. The capital cost of the fuel cell systems are summarized in table 6.2 with and without inclusion of stack replacements.

$$c_{FCplant} = c_{FC} \cdot \left(1 + a_{stack\,cost}\left(\frac{t_{lifetime,ship}}{t_{lifetime,FCstacks}} - 1\right)\right) \cdot (1 + a_{fuel\,processing} + a_{BOP}) \tag{6.6}$$

where:

c_{FC}	Cost of fuel cell power pack per kW, dependent on fuel cell type
$a_{stack\,cost}$	Ratio between fuel cell stack cost and fuel cell system cost, dependent on fuel cell type
$a_{fuel\,processing}$	Rate of cost increase due to fuel processing plant of designated fuel and fuel cell combination, dependent on fuel type and fuel cell type
a_{BOP}	Rate of cost increase due to balance of plant components of designated fuel and fuel cell combination, dependent on fuel type and fuel cell type

Table 6.2: Cost of fuel cell system per kW.

	FC power pack cost	**Lifetime**	**$a_{stack\,cost}$**	**FC power pack cost including stack lifetime**
	€/kW	h	%	€/kW
LT-PEMFC	2000	40000	50%	3300
HT-PEMFC	2500	30000	45%	6100
MCFC	4000	30000	40%	9100
SOFC	7000	40000	35%	14000

Cost of fuel storage

The capital cost per kWh of the installed fuel storage system is dependent on the stored fuel type and the fuel cell type, see equation 6.7. The fuel cell efficiency is again included to compare the cost of fuel storage for different fuel cell systems fairly. The cost data is retrieved from suppliers and literature about fuel storage [67]. The cost of the storage system is viewed in table 6.3.

$$c_{fuel\,storage} = \frac{C_{fuel\,tank}}{V_{fuel}\rho_{fuel}LHV} \cdot \frac{1}{\eta_{FCsystem}} \tag{6.7}$$

where:

$C_{fuel\ tank}$	cost of the fuel tank to store amount of fuel V_{fuel}

Table 6.3: Cost of fuel storage system system per kWh chemical energy in fuel

	Fuel storage cost €/kWh
LH_2	5
LNG	1.44
$MeOH$	0.04
NH_3	0.31
MGO	0.02

6.2.4. Operational cost

A different power generation system can have a big effect on the operational expenses (vessel operating expenses and voyage costs). Although these costs are not paid by the shipbuilder (Damen), it is very relevant for their client (cruise line). Most of the time, cruise lines are owning and are operating cruise ships, which was concluded from the Shippax database (see figure 6.2). In that case the operational expenses consist of: fuel, crew wages, maintenance, lubricants, passenger-handling port fees, towage fees, management fees, agent fees, insurance and certifications. Out of internal discussion with Damen, implementation of a fuel cell system mainly influences expenses of fuel, maintenance and lubricants. The maintenance cost of fuel cell systems is very low due to few moving parts and studies often neglect its cost [80, 97]. The total difference in maintenance cost for different fuel cell system would thus be very low and is neglected while selecting fuel cell systems. Choice of fuel and or fuel cell might also influence expenses of insurance and certifications, however quantifying these costs is outside the scope of this research. Other cost items (crew wages, passenger-handling, port, towage, management and agent) are assumed not to change to the implementation of a fuel cell system on board compared with a diesel electric system. All together, the difference in operational cost with a diesel electric power plant mainly consist of the fuel cost.

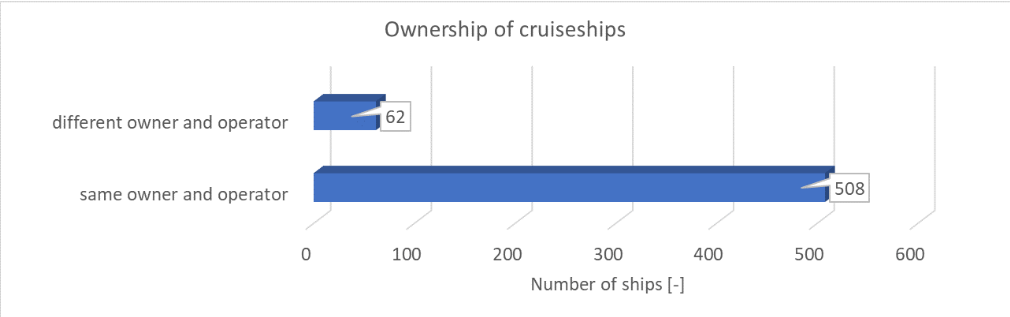


Figure 6.2: Quantification of ownership of cruise ships, established from Shippax © database [105].

The fuel cost per MWh (equation 6.8) is calculated with the mean global bunker price of the fuel, LHV of the fuel and the efficiency of the fuel cell system concerned. The used values of these parameters were already presented in table 5.4.

$$OPEX_{fuel} = \frac{c_{fuel}}{LHV} \cdot \frac{1}{\eta_{FCsystem}} \tag{6.8}$$

where:

c_{fuel}	Cost of concerned fuel per mass
LHV	Lower heating value
$\eta_{FCsystem}$	Efficiency of fuel cell system concerned

6.3. Performance

This section shows the performance of different fuel and fuel cell combinations in terms of power density, energy density, capital cost and fuel cost, see table 6.3. The performance is expressed in the criteria explained in section 6.2. For each column a color scale is added to indicate the order of performance for the concerned criterion. When calculating the performance, priority was given to supplier data and when not available, data from literature was used. Once the relevant context is available, this data can be used to select the best performing systems. The presented data in this chapter and data of Appendix A of fuels, fuel cells and other system components are used to calculate this performance.

Fuel cell system *bunker fuel*	 *fuel cell*	*Fuel cell plant* **volumetric power density** kW/m^3	*Fuel storage (inc. efficiency)* **volumetric energy density** kWh/m^3	*Fuel cell plant* **gravimetric power density** kW/ton	*Fuel storage (inc. efficiency)* **gravimetric energy density** kWh/ton	*for 15 years* **FC plant** €/kW	*inc. efficiency* **Fuel storage** €/kWh	*inc. efficiency* **Fuel cost** €/MWhe
LH2	LT-PEMFC	250	604	408	1250	€ 4,213	€ 10.00	€ 898
LH2	HT-PEMFC	99	543	74	1125	€ 6,256	€ 11.11	€ 998
LH2	MCFC	11	604	16	1250	€ 9,532	€ 10.00	€ 898
LH2	SOFC	32	604	119	1250	€ 13,043	€ 10.00	€ 898
LNG	LT-PEMFC	90	1254	272	2931	€ 5,393	€ 3.61	€ 51
LNG	HT-PEMFC	58	1098	74	2565	€ 7,681	€ 4.12	€ 58
LNG	MCFC	11	1411	16	3298	€ 10,735	€ 3.21	€ 45
LNG	SOFC	32	1882	119	4397	€ 14,658	€ 2.41	€ 34
MeOH	LT-PEMFC	41	1575	83	1755	€ 4,929	€ 0.09	€ 159
MeOH	HT-PEMFC	31	1400	74	1560	€ 7,000	€ 0.10	€ 179
MeOH	MCFC	8	1575	16	1755	€ 10,643	€ 0.09	€ 159
MeOH	SOFC	18	1925	119	2145	€ 14,534	€ 0.07	€ 130
NH3	LT-PEMFC	102	1130	155	1620	€ 4,466	€ 0.73	€ 365
NH3	HT-PEMFC	53	1004	74	1440	€ 6,628	€ 0.82	€ 410
NH3	MCFC	10	1256	16	1800	€ 10,087	€ 0.65	€ 328
NH3	SOFC	32	1507	119	2160	€ 13,167	€ 0.54	€ 274
MGO	DG	67	3985	79	3320	€ 425	€ 0.05	€ 121

Figure 6.3: Performance of different fuel cell and fuel combinations on energy density, power density and costs.

From figure 6.3 the following can be noted on the performance:

- *Power density and energy density*
  MCFC performs very poorly in terms of volumetric and gravimetric power density, also shown in figure 6.4. LH_2 fueled fuel cells perform worst in terms of volumetric and gravimetric energy density, see also figure 6.5. SOFC performs best in terms of volumetric energy density due to its high efficiency, see also figure 6.5. LNG fueled fuel cells perform best in terms of gravimetric energy density, see also figure 6.5.

- *Capital cost*
  LT-PEMFC is characterized by relative low cost per kW and SOFC by high cost per kW, see figure 6.6. Methanol and ammonia are relatively cheap in its fuel storage equipment, see figure 6.7.

- *Fuel cost*
  LNG fueled fuel cells are generally cheap in operation due to the lowest fuel cost of the 4 considered fuels, where NH_3 and especially LH_2 are relatively expensive to operate, see figure 6.8.

To really decide which options are best for expedition cruise ships, impact estimations on ship dimensions, ship performance (range and speed) and cost for expedition cruise ships are necessary. This will be evaluated with the design tool in chapter 8.

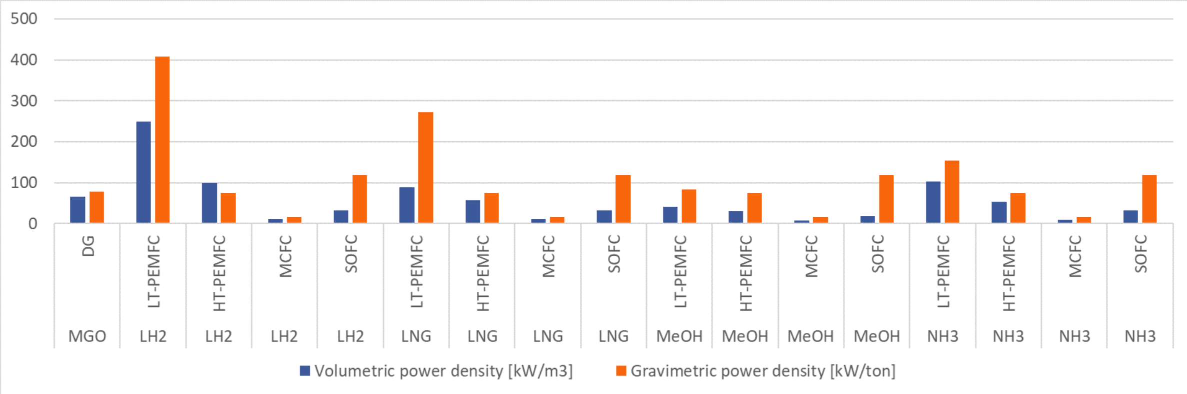


Figure 6.4: Performance in terms of power density of different fuel cell systems.

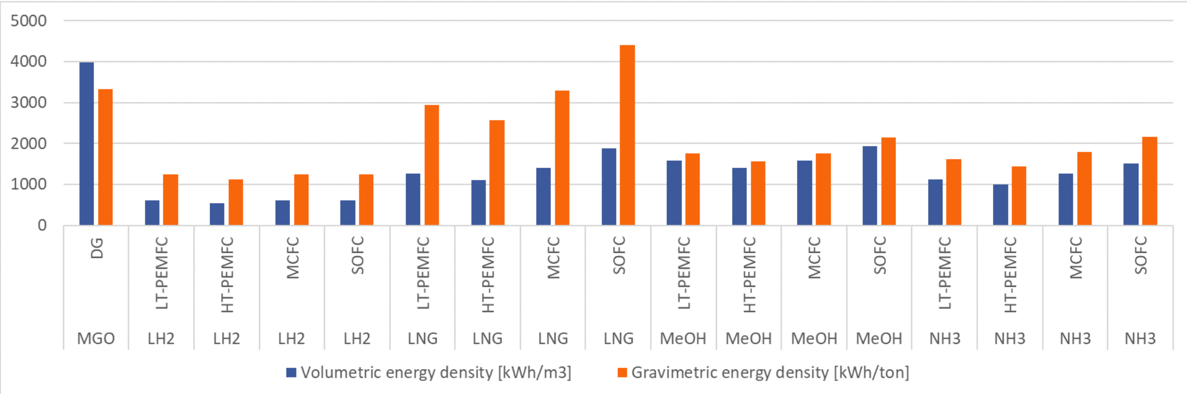


Figure 6.5: Performance in terms of energy density of different fuel cell systems.

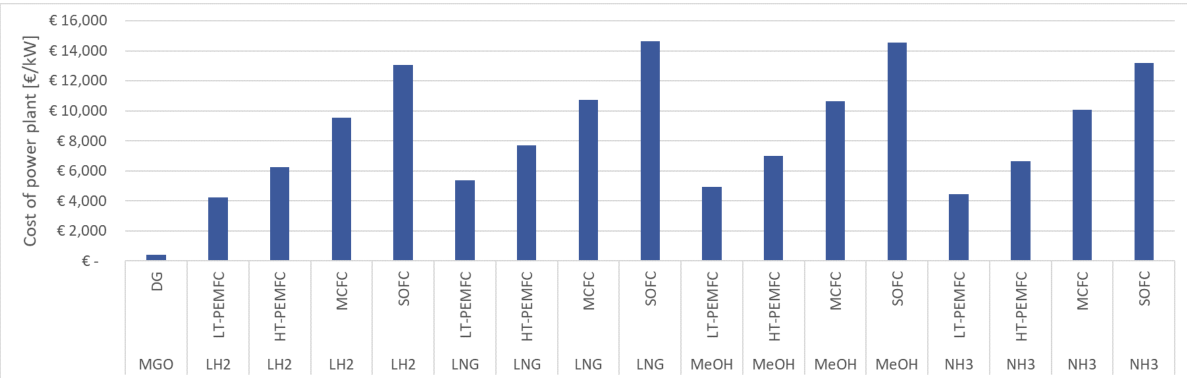


Figure 6.6: Capital cost of fuel cell system per kW.

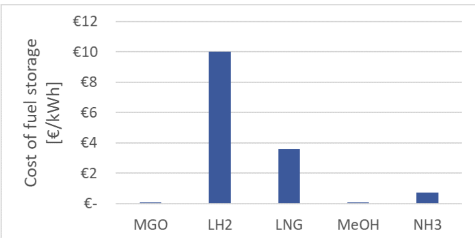


Figure 6.7: Capital cost of fuel storage system per kWh.

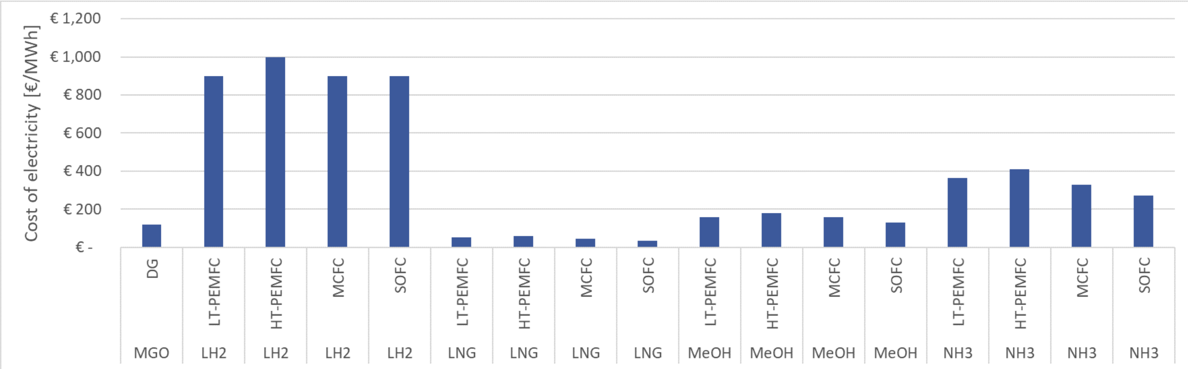


Figure 6.8: Performance in terms of cost of electricity of different fuel cell systems. This is cost is uncoupled from the capital cost of the fuel cell power plant and thus just dependent on the fuel cost and the efficiency of the system..

6.3.1. Discard lowest performing fuel cell systems

Based on the presented performance of 16 fuel cell systems, it is already possible to exclude some of the worst performing fuel and fuel cell combinations from the research. MCFC performs very badly on volumetric and gravimetric power density and does not perform better on any areas than all the other fuel cell types. Thus MCFC will not be further considered in this research. For all fuel types LT-PEMFC outperforms HT-PEMFC on all criteria. Only for methanol fueled LT-PEMFC and methanol fueled HT-PEMFC the differences are small. This is the case due to the similar temperature of the methanol reforming process and the HT-PEMFC, resulting in a high efficiency [11]. For the other fuels the LT-PEMFC outperforms HT-PEMFC significantly. For this reason only methanol combined with HT-PEMFC is considered out of the HT-PEMFC fuel cell systems. Out of the fuel cell systems fueled by liquid hydrogen, LT-PEMFC outperforms the other fuel cell types on all criteria, see table 6.3. For this reason only hydrogen fueled LT-PEMFC is selected from the fuel cell systems with LH_2 as bunker fuel. NH_3 fueled LT-PEMFC performs much worse on all criteria than LNG fueled LT-PEMFC, except capital cost of fuel storage. For this reason NH_3 fueled LT-PEMFC is also not further considered in this research.

Crossing out the fuel cell systems that perform worse on all criteria than others, leads to a selection of seven different fuel cell systems. An overview of the selected fuel cell systems out of the presented performance is shown in table 6.4. The selected fuel cell systems perform very differently on different criteria, see also the overview in table 6.5. Which fuel cell system is best applicable is also very dependent on the ship design and the requirements, wishes and budget of the customer. Therefore it cannot be concluded now which fuel cell system performs best or is best applicable for expedition cruise ships. The performance will be matched to the relevant requirements with the design tool in chapter 8 , where the fuel cell systems will be evaluated for expedition cruise ship design.

Table 6.4: Selected fuel cell systems out of performance in power density, energy density, capital cost and fuel cost.

Fuel cell system							
LH_2	LT-PEMFC	LNG	LT-PEMFC	$MeOH$	LT-PEMFC	NH_3	LT-PEMFC
LH_2	HT-PEMFC	LNG	HT-PEMFC	$MeOH$	HT-PEMFC	NH_3	HT-PEMFC
LH_2	MCFC	LNG	MCFC	$MeOH$	MCFC	NH_3	MCFC
LH_2	SOFC	LNG	SOFC	$MeOH$	SOFC	NH_3	SOFC

Table 6.5: Overview of performance of selected fuel cell systems. Denoted in contribution to performance, so ++ for cost means the lowest cost out of the different fuel cell systems.

Fuel type	**FC type**	**Power density**		**Energy density**		**Power plant cost**	**Fuel storage system cost**	**Fuel cost**
		vol.	grav.	vol.	grav.			
LH_2	LT-PEMFC	++	++	- -	- -	++	- -	- -
LNG	LT-PEMFC	+	+	+-	+	++	-	++
LNG	SOFC	-	+-	++	++	- -	-	++
$MeOH$	LT-PEMFC	+-	-	+	-	++	++	+-
$MeOH$	HT-PEMFC	-	-	+-	-	+-	++	+-
$MeOH$	SOFC	- -	+-	++	+-	- -	++	+
NH_3	SOFC	-	+-	+-	+-	- -	+	-

6.4. Conclusion

In this chapter a method was proposed to express the performance of different fuel cell systems, based on a system decomposition. The fuel cell system is decomposed in fuel storage, fuel processing (reforming and purification), fuel cell power pack and balance of plant components (batteries, super capacitors and transformers). For these different components, the power density and energy density (volumetric and gravimetric) are determined and added as impedances to determine the total power and energy density of the the fuel cell system. It was concluded that the fuel storage only has influence on the energy density of the fuel cell system. Fuel processing, fuel cell power pack and balance of plant components have influence on the power density of the fuel cell system. It was also concluded that the fuel storage component is dependent only on fuel type, the fuel processing component is dependent on fuel and fuel cell type and the fuel cell power pack and balance of plant components are only dependent on the fuel cell type.

The performance of the different fuel cell systems is expressed in volumetric power density, volumetric energy density, gravimetric power density, gravimetric energy density, capital cost of FC power plant, capital cost of fuel storage system and cost of generated electricity (related to fuel cost) and presented in figure 6.3. The fuel cell system efficiency and fuel cell lifetime is included in the performance. For calculations, preference was given to supplier data and when not available, data from literature was used. The following main assumptions were used when determining the fuel cell system performance:

- Due to lack of cost data on fuel processing and BOP components, in the presented performance the capital cost of the fuel cell system is only dependent on the fuel cell type, so cost differences in the fuel processing plant for different fuel types are not taken into account. This will be adjusted later in the research (section 8.2.4).
- The stack cost of the fuel cell are 35-50% of the capital cost of the fuel cell system, dependent on the fuel cell type.
- Change in operational cost with respect to a conventional ship is mainly dependent on change in fuel cost.

The worst performing options were discarded, leading to a selection of seven combinations of fuel type and fuel cell type, see table 6.4.

7 Expedition cruise ships

In order to link the different performance indicators to the design of expedition cruise ships, the general requirements, ship dimensions, operational profile and power demand of expedition cruise ships are investigated in this chapter. Data and knowledge of this chapter form the foundation of the design tool which will be presented in chapter 8. This chapter is mainly based on experience of Damen engineers and reference expedition cruise ships.

This chapter is focused on the third research objective: *Analyse general requirements, ship dimensions, operational profiles and power requirements of existing expedition cruise ships.*

Section 7.1 investigates common requirements for expedition cruise ships. Section 7.2 looks into correlations in ship parameters of existing expedition cruise ships. Next, different operational profiles of existing expedition cruise ships are compared in section 7.3 and the on board power demand is investigated in section 7.4.

7.1. General requirements expedition cruise ships

Of course, the requirements of expedition cruise ships differ per client and per operational area. However, some requirements and design focuses are similar for all expedition cruise ships.

7.1.1. Comfort

During the design of expedition cruise ships a lot of attention is given to the comfort of the passenger. During design, measurements are taken for noise and vibrations [25]. Out of discussion with Damen D&P engineers followed that vibrations (high frequency) are often local and can most of the time be solved with fortification of the steel structure to adjust the natural frequency. Often, noise can be solved with insulation, meaning extra volume should be reserved in early design. Fuel cell systems offer an advantage here, since they do not produce noise and vibrations, leading to savings in fortifications and insulation volume.

7.1.2. Range, endurance and speed

The range, endurance and speed are all related and have major influence on the design, especially when taking into account the low volumetric energy density of a fuel cell system. Out of internal discussions at Damen followed that expedition cruise ships often operate at cruises of minimal 12 days and require a range of 6000 nautical miles to cross the Atlantic ocean at a service speed of around 15 knots.

A first estimation of the required installed auxiliary power of expedition cruise ships is usually performed by expressing hotel power as half of the propulsion power (1/3 - 2/3 rule) [48]. Lowering the service speed of the vessel drastically lowers required propulsion power while sailing (third power relation [62]). However, it does not reduce hotel consumption and increases sail duration when a certain distance is desired, so a trade-off emerges between range, endurance and speed. The interaction between range, endurance and speed will be included in the design tool (see chapter 8).

7.1.3. Volume, weight and stability

Design of expedition cruise ships is more limited by volume than by weight. Their freight (passengers) has low density and requires lots of volume for different kinds of spaces. Although the ships have rather high superstructures, heavy parts like generators can be mostly placed low in the ship, meaning stability is often not very critical during the design, but should of course always be evaluated. In short, between volume, weight and stability, design of expedition cruise ships is mostly volume critical (in contrast with for instance crane vessels where stability is very critical). The volume usage of the fuel cell system becomes for this reason the main focus in this research and thus also in the design tool.

7.2. Trends in parameters of existing cruise ships

To investigate how a fuel cell powered expedition cruise ship relates to existing expedition cruise ships, a parent set of cruise ships is used. In this section, ship parameters are evaluated by looking for trends in the ship parameters. Later in the research, ship parameters of a fuel cell powered ship can be plotted in these graphs to see whether these ship parameters would approximate parameters of existing ships. This will be valuable later in order to judge whether the fuel cell powered expedition cruise ship would be a viable concept or that it would differ so much from existing designs that it would not be viable at all. In section 7.2.1 a cruise ship database will be scoped to the relevant ships for this research. In section 7.2.2 the parent set is analysed. A parent set of 373 cruise ships is used.

7.2.1. Scoping parent set

Expedition cruise ships are among the luxury segment of cruise ships. The parent set of cruise ships is adapted to these luxury classes. Luxury is measured in GT/PAX. Three luxury classes are defined [70]:

- Budget (<30 GT/PAX)
- Premium (30-50 GT/PAX)
- Luxury (>50 GT/PAX)

Out of discussion with D&P engineers followed: other possibilities to measure luxury are $crew\ members/PAX$, $build\ price/PAX$, or $PAX\ accommodation\ area/PAX$. The first two options are also plotted as function of the used budget, premium and luxury classes, see figure 7.2 and 7.3. From analysing figure 7.2 it can be concluded that GT/PAX and $crew\ members/PAX$ give a very similar luxury division. In figure 7.3, the luxury divisions are much more spread. However, $build\ price/PAX$ might be an inferior luxury indicator, since it is also related to the state of economy and country the ship was build in. For $PAX\ accommodation\ area/\ PAX$, data was only available for a very small number of ships, making a less representative parent set more probable, so this luxury indicator was not considered. All expedition cruise ships are considered as luxury cruise ships and only the parent data of this luxury class will be used. This luxury division will exclude data of ships that deviate much from the expedition cruise ship type.

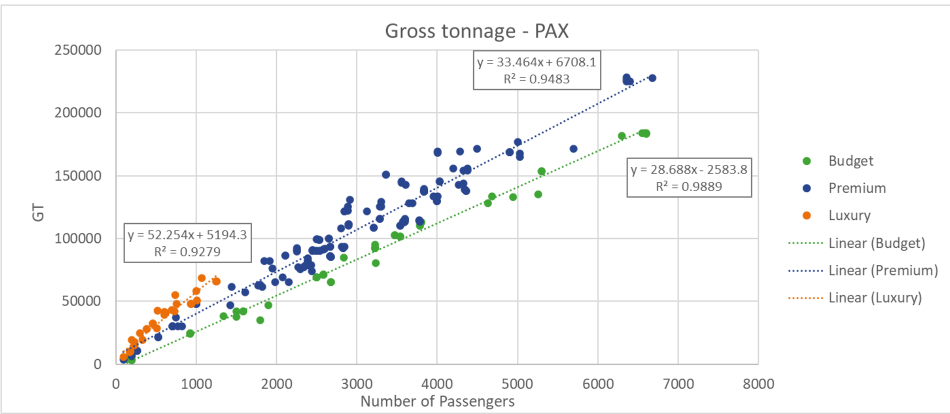


Figure 7.1: Luxury classes of cruise ships, based on differences in GT/PAX

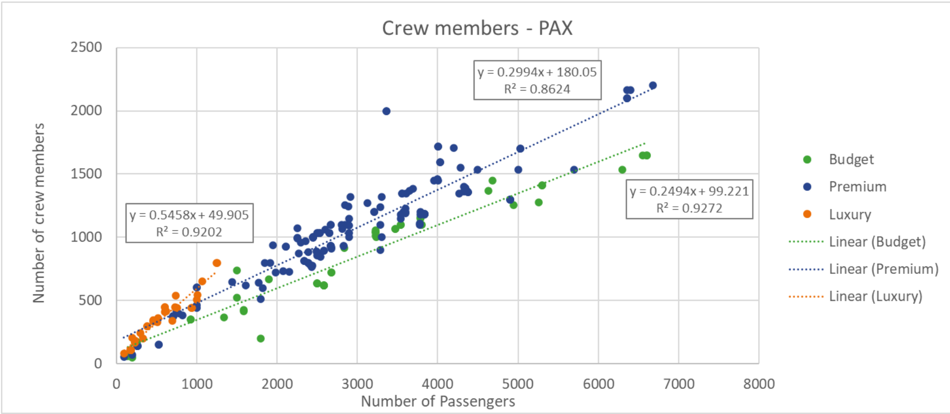


Figure 7.2: The number of crew members plotted as function of the number of passengers for the parent set, divided in 3 classes based on GT/PAX

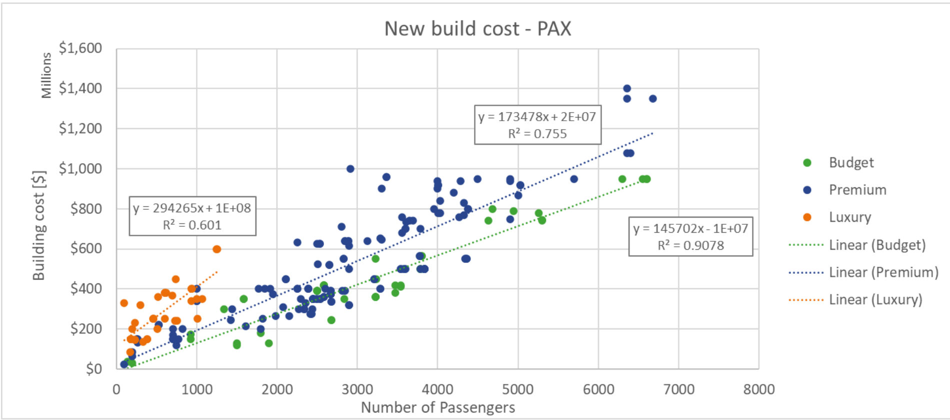


Figure 7.3: The new build cost plotted as function of the number of passengers for the parent set, divided in 3 classes based on GT/PAX

7.2.2. Parent set analysis

Ship parameters are expressed as function of other ship parameters to find correlations between different ship designs. All regression charts are showed in appendix B. Some of them will be highlighted in this section. In all regression charts the expedition cruise (luxury segment) and the three segments combined (all) are shown, to visualize differences in correlations between expedition cruise ships and all cruise ships.

Figure 7.4 shows the length overall and length between perpendiculars expressed as function of GT. The trend lines show that the relation between length and GT is very similar for cruise ships and luxury cruise ships, especially for the overall length. High R^2 values indicate a strong relationship.

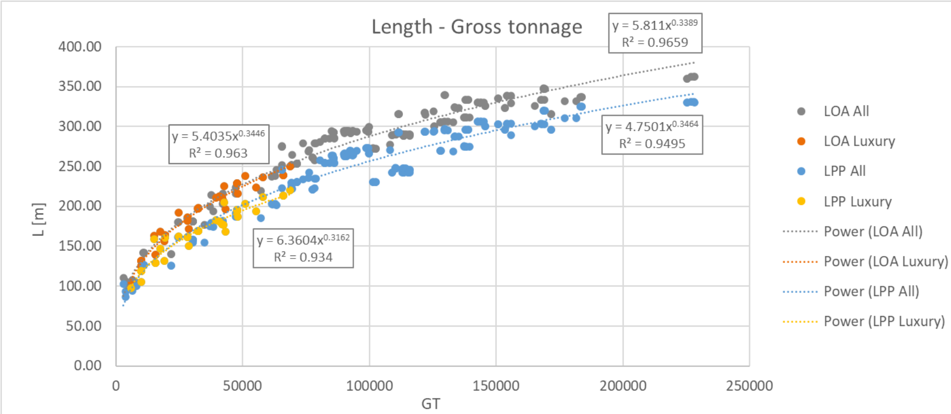


Figure 7.4: Length overall and length between perpendiculars as function of gross tonnage for luxury cruise ships and all cruise ships

Figure 7.5 shows the overall length as function of the number of passengers. In this relationship expedition cruise ships vary much from regular cruise ships (see difference in trend line in figure 7.5). This is due to the fact that luxury cruises often offer more space per passenger on board.

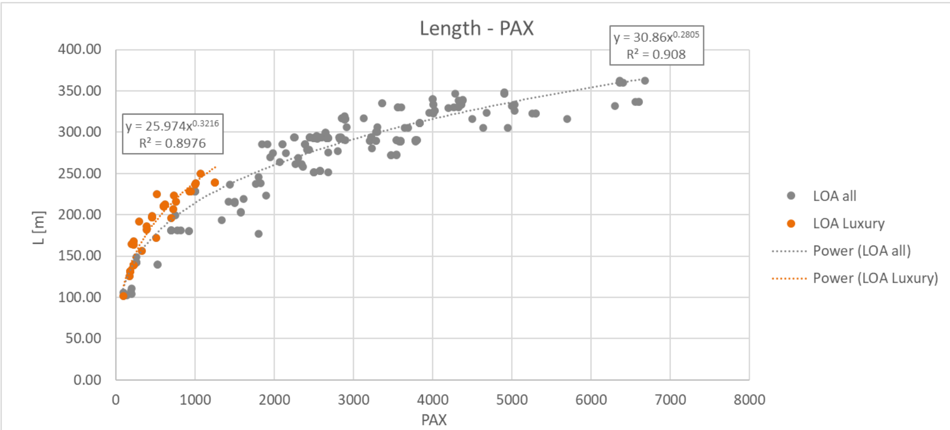


Figure 7.5: Length overall as function of number of passengers for luxury cruise ships and all cruise ships

Figure 7.6 shows a strong power correlation between the beam and the gross tonnage of all cruise ships. A strong stagnation in data points is visible at $B = 32\ m$, representing the limitations of the original locks of the Panama Canal.

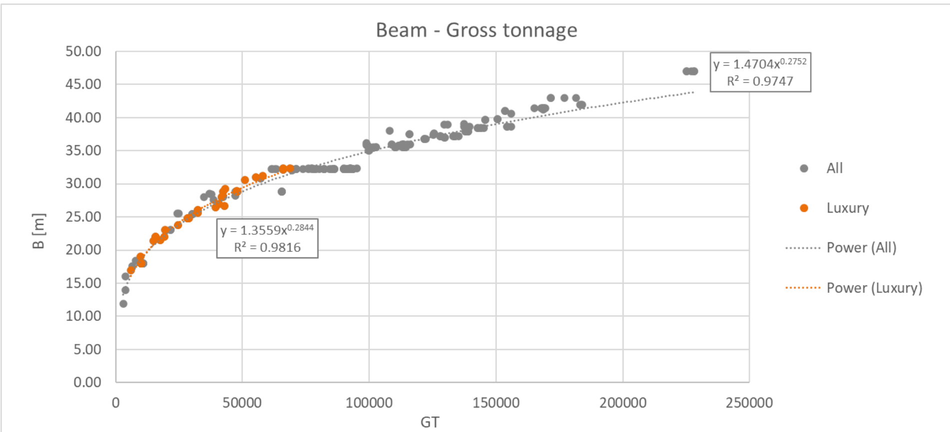


Figure 7.6: Beam as function of GT for luxury cruise ships and all cruise ships

In figure 7.7 the propulsion power is plotted linearly as function of $\Delta^{\frac{2}{3}}V^3$. The slope of the trend line shows the admiralty constant, see also equation 7.1 [74]. The admiral constant can be used for very rough estimations of propulsion power.

$$A = \frac{\Delta^{\frac{2}{3}}V^3}{P_{propulsion}} \tag{7.1}$$

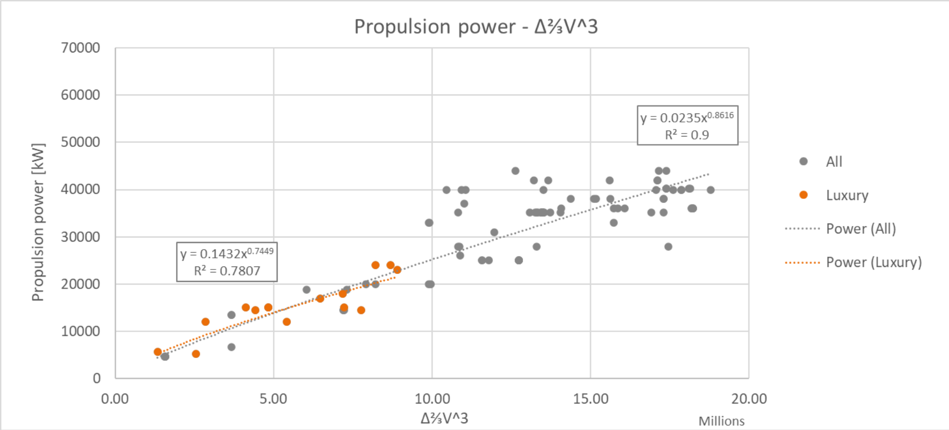


Figure 7.7: Propulsion power as function of $\Delta^{\frac{2}{3}}Vs^3$ for luxury cruise ships and all cruise ships

For the build cost of cruise ships no close correlation was found with any ship parameter. The strongest relation was found in build cost and gross tonnage, see figure 7.8. However, especially for the luxury segment the relation with cost and GT was not very strong (low R^2).

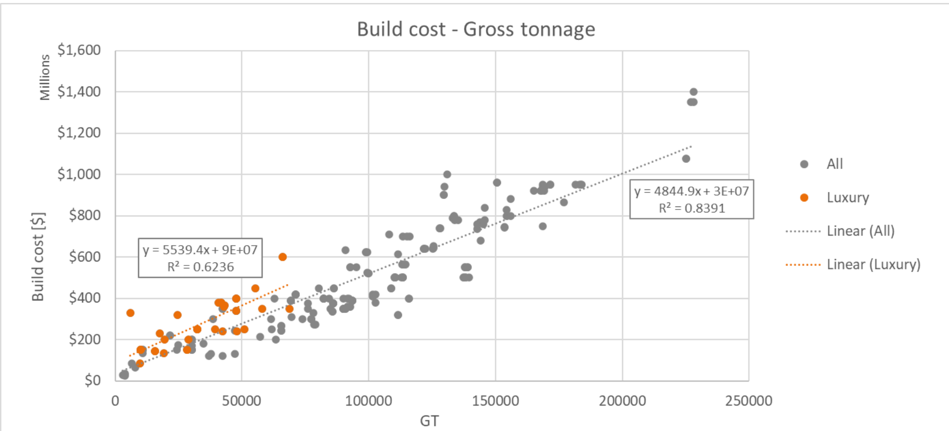
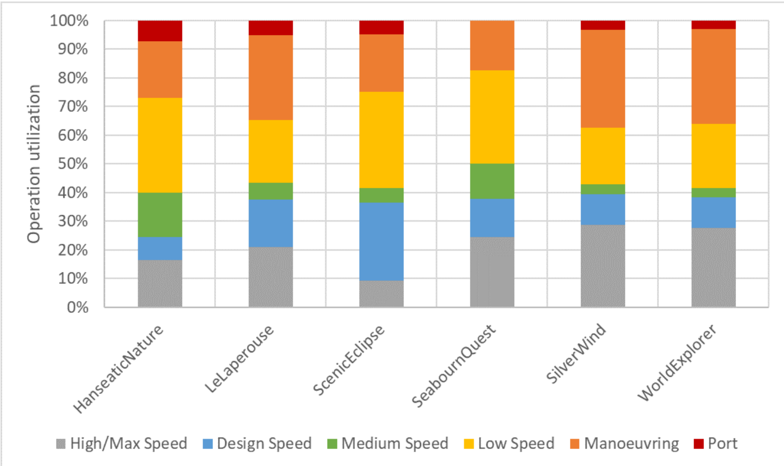


Figure 7.8: New build cost as function of GT for luxury cruise ships and all cruise ships

Many ship parameters were compared for a large parent set of cruise ships. It was found that the expedition cruise ship segment can be represented with the luxury segment of cruise ships with >50 GT/PAX. For the luxury segment, $GT - PAX$, $L_{OA} - PAX$, $L_{OA} - GT$, $L_{pp} - GT$, $B - GT$, $\Delta - GT$, $DWT - GT$, $N_{crew} - PAX$ and $P_{propulsion} - GT$ all showed regression relations with a R^2 of 0.9 or higher. Consequently, the reader can learn that the reference database is a suitable foundation for the design tool that will be presented in chapter 8.

7.3. Operational profile

Cruise lines often have clear data on their operational profile, which is based on standard itineraries and market research on traveler demand. This data can be used to calculate energy usage for propulsion in different operations (cruising, slow cruising, manoeuvring, harbour) for different operational areas (Atlantic crossing, coastal areas, Antarctic areas). Figure 7.9 shows the mean operations of six ice class expedition cruise ships in September 2019 and January 2020. This graph is retrieved from real time AIS data. Two ships (Europa 2 and Seadream) were not included, since their operational profiles were very divergent due to docking. From these data can be learned that high speeds are barely used and the ships mostly sail at medium speed (lower than the design speed). Here lays an opportunity to use the fuel cell system for most of the operation and use diesel generators to boost power when necessary. This results in a high reduction of emissions and this is a good option in terms of cost, since the fuel cell system is very expensive per kW.



(a) Operations per ship

	mean speed [kn]	rate
High/Max Speed	20.17	4%
Design Speed	17.14	26%
Medium Speed	14.12	27%
Low Speed	8.07	7%
Manoeuvring	0.92	14%
Port	-	21%

(b) Mean operations

Figure 7.9: Operations of 7 ice class expedition cruise ships between 09-2019 and 01-2020. This figure has been partially supported by MarineTraffic.

Expedition cruise ships are often required to go to arctic/antarctic areas, meaning they often require a high ice class. When it is the goal to disembark in these areas, it implies extra regulations. For instance for Antarctica: i) cruise vessels carrying more than 500 passengers cannot disembark passengers. ii) organizers of vessels that make landings can not have over 100 visitors ashore at any site at the same time and have a limited time at one site [84]. This makes it convenient to design expedition cruise ships for a multiple of 100 PAX. This is relevant to this research for the following reason: a way to fit the fuel cell system in the ship is to reduce the number of passengers (when requirements and size are kept equal) to make extra space for the fuel cell system. With this procedure it is convenient to design the ship for a multiple of 100 persons.

7.4. Power demand of expedition cruise ships

This section identifies the gradual and sudden changes in power demand on board of expedition cruise ships. This is relevant because the power demand of the ship must be satisfied by the fuel cell system. The fuel cell system should not only deliver enough power, but should also make sure the power plant can cope with the dynamic loads. This section is performed in collaboration with Damen mechanical engineers and Clemens Boertz, who was simultaneously researching the dynamic power consumption in expedition cruise ships.

For expedition cruise ships, in early design phase the required hotel power is usually estimated as one third of the required propulsion power and when including all auxiliary systems, 40% of propulsion power [48]. In early design this power is usually assumed constant while operating the ship (for instance while determining required size of MGO tanks). However, it is still an unanswered question how much the power demand is varying in actual operation of the ship. This is extra relevant when considering a fuel cell system, because fuel cells (especially HT-FC) are characterized by a lower dynamic capability than diesel generators [66]. The analysis presented in this section is used to identify the most critical power consumers in terms of dynamic load and to conclude that the propulsion load has more stringent dynamic power requirement than the auxiliary load. In chapter 8, this conclusion will be used to define a hybrid option where the fuel cell systems are only used to supply power to the auxiliary consumers.

7.4.1. Gradual load change

Figure 7.10 shows the power demand for propulsion and auxiliaries (including hotel) for a typical day in a coastal itinerary. The propulsion demand is composed of main propulsion, bow thrusters and propulsion support systems. In this typical day the ship is sailing at high speed in the night and gradually reducing its speed during the day, in order to go ashore at one of the cruise destinations. The auxiliary demand is composed of HVAC (fans, heating and cooling), lighting, galley and laundry (see also Appendix C). The used time step is half an hour. Over the time of the day the auxiliary power demand varies much less than the propulsion power demand.

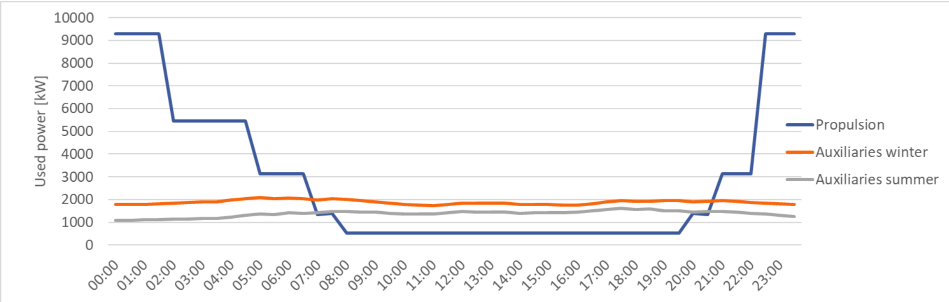


Figure 7.10: Power demand for auxiliaries (including hotel) and propulsion for typical operational day of coastal itinerary for winter and summer condition. Retrieved from research into power demand on board of expedition cruise ships (Appendix C)

7.4.2. Sudden load changes

The presented power demand in the past section is predicted over time steps of half an hour. However some consumers demand power instantaneously, this can cause issues for fuel cell systems, since the power delivered by the fuel cell must change rapidly to meet this changing demand. This section identifies some of the systems that demand rapid change in power supply, subdivided in propulsion systems and auxiliary systems.

Propulsion systems

The main propulsion system is the largest power consumer on board of expedition cruise ships. Although the increase in power could be adjusted generally while traveling, often the ship is rather quickly driven to its desired speed. So the main propulsion system is a large consumer that requires a significantly changing power supply. The bow thruster is a much smaller consumer than the main propulsion (see also appendix C), but the demand is instantaneous while manoeuvring, meaning the bow thruster is also a critical changing load for fuel cell systems. The bow thruster could even be a more critical part in matching the dynamic power demand to the dynamic power supply; it is not disastrous if the vessel accelerates slower than desired to cruise speed, but it is crucial that the bow thruster can deliver instantaneous power when manoeuvring. The propulsion support systems are constantly running in the background and power demand is low compared with the main propulsion, meaning the required change in power is low for this consumer.

Auxiliary systems

The heating and cooling of the HVAC system are the biggest consumers of the auxiliary systems. Although the whole power demand of these systems will not be instantaneously, since it is always (partly) running, some components in these systems might require instantaneous power demand, for instance when an extra chilled water unit is turned on. The fans of the HVAC system (ventilation) are driven with variable motors, meaning no sudden change in load will occur for these consumers. The galley is a system that is more intensively used at some points during the day (breakfast, lunch, dinner), meaning it will also be characterized by changing loads. Since lighting and laundry systems are composed of many different components with small power demand that generally will not be switched on or off all at the same time, these systems are not expected to cause any troubles in changing power demands.

7.5. Conclusion

Out of the past sections of this chapter, the following conclusions are drawn:

- Expedition cruise ship design is mostly volume critical.
- Expedition cruise ships resembles with the luxury segment of cruise ships, scoped at >50 GT/PAX. Existing expedition cruise ships demonstrate strong regression relations. $GT-PAX$, $L_{OA}-PAX$, $L_{OA}-GT$, $L_{pp}-GT$, $B-GT$, $\Delta-GT$, $DWT-GT$, $N_{crew}-PAX$ and $P_{propulsion}-GT$ all showed regression relations with a R^2 of 0.9 or higher. Consequently, reference expedition cruise ships can be used to suggest suitable ship parameters.
- The maximum speed of expedition cruise ships is barely used, they mostly operate at medium and design speed. Here lays an opportunity to use the fuel cell system for most of the operation and use diesel generators to boost power when necessary. This results in a high reduction of emissions and this is a good option in terms of cost, since the fuel cell system is very expensive per kW.
- For the gradual load change, the auxiliary power demand is much more constant (smaller increment in power over a time step of half an hour) than the power demand of the propulsion systems. For sudden load changes, the bow thruster is indicated as the most critical system, and also significant but less critical, components in the HVAC system. So the auxiliary power is characterized with lower dynamic load changes than the propulsion power. For fuel cell systems, rapidly changing loads are generally solved by adding balance of plants components (batteries, super capacitors). Consequently, when fuel cell systems are applied for the auxiliaries, less balance of plant capacity is required to satisfy the required dynamic capability than for applying fuel cell systems for propulsion power.

8
Design tool

This chapter presents the design tool that was made during the research. A design tool is produced to make the work of this research easy applicable on different cases. This chapter is provided to the reader to understand how the writer produced his results, to know which assumptions are made and to make the writer's work reproducible.

The design tool is produced to realize the fourth research objective: *Match the performance of different fuel cell systems for (part of) the power generation to the requirements of expedition cruise ships.*

A functional design is provided to the reader in section 8.1. Following, a more elaborate description of the model is given in section 8.2. By reading this chapter, the reader can understand the steps, mathematics and logic between the input and the output. The model is verified in section 8.3. This chapter is ended with a conclusion where a concise description of the design tool and the used assumptions can be found.

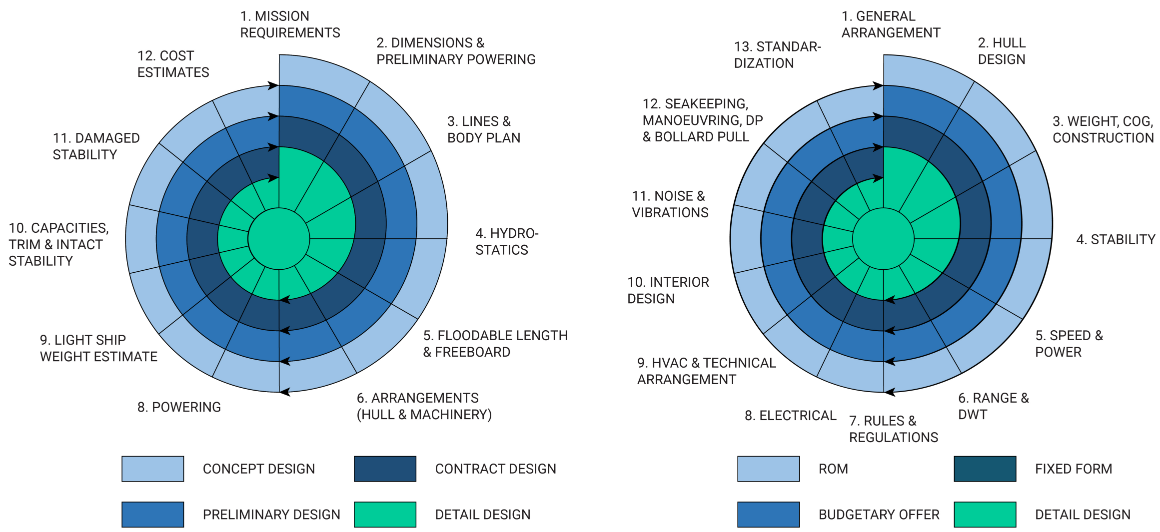
8.1. Functional design

The design tool is adapted to the needs and workflow of the design & proposal team of Damen to make the design tool effective and applicable. In order to judge in which design phase the design tool should be fitted, the Damen design process is mapped (section 8.1.1). The design tool is fitted in the Damen process in section 8.1.2 where it is defined that the design tool should be applicable for a Rough Order of Magnitude and that the design & proposal engineer is the user of the tool. Out of the use case, the goal of the design tool is presented in section 8.1.3. This section ends with a more elaborate description of the design tool, where the workflow of the design tool is explained (section 8.1.4). The workflow describes which parameters have to be known to use the design tool, which data is used for the design tool and what the desired output of the design tool is. At the end of this section the reader should have an idea on how the design tool should be applied, but not yet how it functions. The latter will be explained in section 8.2.

8.1.1. Design process of Damen CRO

Damen CRO makes the distinction between the design phase (all steps before contract signature) and the engineering phase (after contract signature). The design & proposal team covers the design phase and this is the phase where most dynamism and creativity is asked. Since the goal of this research is to give an early estimate of the impact of fuel cell implementation, the design phase will be elaborated and it will be determined where in the design phase a fuel cell system impact design tool would be most necessary.

When a cruise line (or other customer) would like to build a ship they approach the sales department of Damen Cruise or the sales department approaches them. From this point, there are several phases in the design process which will be explained in this section. Figure 8.2 shows the different steps of this design process. For every phase except the RFI (most of) the different areas of the design spiral (see figure 8.1 (b)) will be covered at least one time. Note the differences and similarities between the ship design spiral from literature (figure 8.1 (a)) and the cruise ship design spiral by Damen CRO (figure 8.1 (b)).



(a) Original ship design spiral from literature [own image, derived from [75]]. (b) Design spiral for cruise ships at Damen CRO [own image].

Figure 8.1: Ship design spirals.

Request for information

A project starts with a Request for Information (RFI). The client approaches several potential shipyards to build his ship. In an RFI the client asks the shipyard about its track record, competences and processes with building similar vessels. In an RFI, the particular design is not yet evaluated and the main goal of the shipyard is to convince the client that the shipyard is able to execute the project. After assessing the different shipyards, the client draws up a Longlist (approximately 10 candidates) with the most competent shipyards.

Rough order of magnitude

The shipyards on the Longlist get the conceptual design and general requirements of the vessel. This conceptual design is often made by the cruise line or a third party and is generally focused on use aspects and aesthetics. Often cruise lines have a clear view on their requirements in terms of operational profile, capacity, spaces and maximum cost/PAX. The shipyards use this information to make a rough order of magnitude (ROM), which is a rough cost estimate of the vessel with a maximum deviation of 10 %. The cost estimate is mainly based on reference ships. Also, very rough calculations of resistance, required power and maximum speed are performed. The preliminary GA is checked on irregularities in order to asses in an early stage whether the design by the cruise line is technically feasible or that major changes are necessary. This phase usually takes two to four weeks. The ROMs of the shipyards are assessed by the client and the best candidates are placed on the Shortlist (four to five candidates).

Budgetary offer

After the rough order of magnitude, the shipyard receives responsibility over the design. The shipyard receives all functional requirements and it is their task to come up with a design that fits the requirements. The budgetary offer must lead to a 'proven ship' in terms of stability, safety, speed, range, regulations, system integration and noise & vibrations. In this phase supplier information of the important components (power generation, HVAC, PODS, cabins) is retrieved to make more accurate estimates of weights, volume usage and prices. This phase generally takes two to three months. At the end the shipyard makes a price offer with a maximum deviation of 5%.

Fixed form

After assessing the budgetary offers of the shortlist, the client continues to work with one shipyard towards a contract. A Letter of Intent is used to formally agree the commitment of the client and the shipyard towards each other. During this phase the design gets iterated and elaborated until it is sufficiently accurate to formulate the contract. The shipbuilding contract gets signed at the end of the fixed form and generally from this point the cost cannot change anymore. When the contract is signed, the design phase is finished and the engineering phase starts.

Note that not every project follows these exact steps. For instance, some clients are already known with Damen and do not require an RFI. Other clients perform design steps by themselves or with a design bureau. A table is set-up to indicate which activities for the design spiral (figure 8.1 (b)) are done for the Rough Order of Magnitude, Budgetary offer and Fixed & Firm, see table D.1 in appendix D.

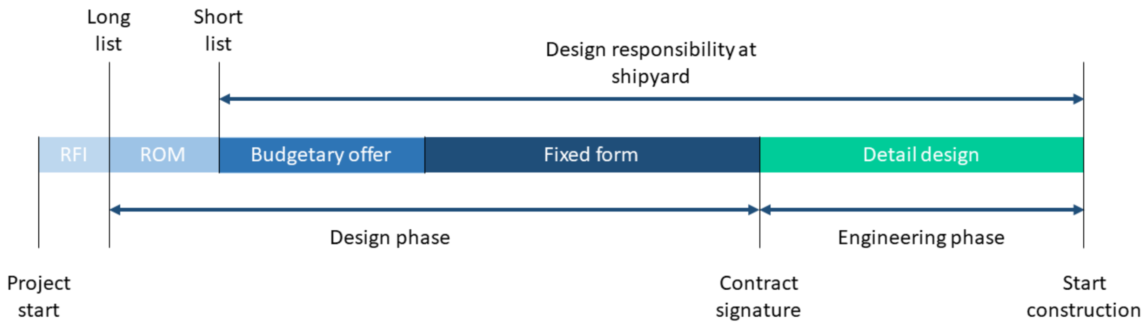


Figure 8.2: Design process for Damen CRO projects

8.1.2. Use case of design tool

Damen CRO prefers a design tool that is applicable on the first phase of design & proposal and gives a quick impression on the cost impact of a fuel cell system and what a possible reduction in performance would be (less passengers, lower speed, lower range) . This is mainly information to communicate to the client. They can use this information to make a choice between MDO, LNG, fuel cells etc. This means the design tool should give a quick analysis of the impact of implementation of fuel cells in the design, mainly in terms of volume and cost. This matches with the Rough Order of Magnitude phase, described in section 8.1.1. This means the design tool should be adapted to the available information in that stage of the design, which is still very conceptual and much based on reference ships. The design & proposal engineer will be the user of the design tool. The available information in ROM phase usually consists of: general requirements (PAX, speed, range, size), a conceptual general arrangement and occasionally the operational profile of the ship. For all design activities that are usually performed in the ROM phase, refer to Appendix D table D.1.

8.1.3. Goal of design tool

Out of the preferences and use case, a goal for the design tool has been set-up.

Goal of design tool:
The design tool should deliver a cost estimation for a fuel cell powered expedition cruise ship based on the general requirements and information available in the Rough Order of Magnitude design phase.

The design tool should support the D&P engineer and the client in making a well-founded decision on questions like: do we want to implement a fuel cell system in the ship design? Which fuel cell system would we implement? This means that the purpose of the design tool is to support the D&P engineer in making decisions regarding fuel cell system implementation. The aim of the design tool is not to deliver an optimized fuel cell powered ship design.

8.1.4. Workflow of design tool

In the workflow of the design tool is defined which data is necessary for the model, which user input is required, the outline of the model is given is defined which output is provided to the user. This section gives a brief overview of the functionalities of the design tool. An in depth explanation of calculations and assumptions can be found in section 8.2.

An overview of the design tool is visible in figure 8.3. Based on expedition cruise reference ships, fuel cell performance data and the user input, the model calculates the dimensions and cost of the fuel cell power plant and the fuel storage. This impacts the size, capital cost, operational cost and emissions of the total ship, which is also provided by the design tool. The design tool can be used to quantitatively compare different fuel types, fuel cell types and hybridization strategies.

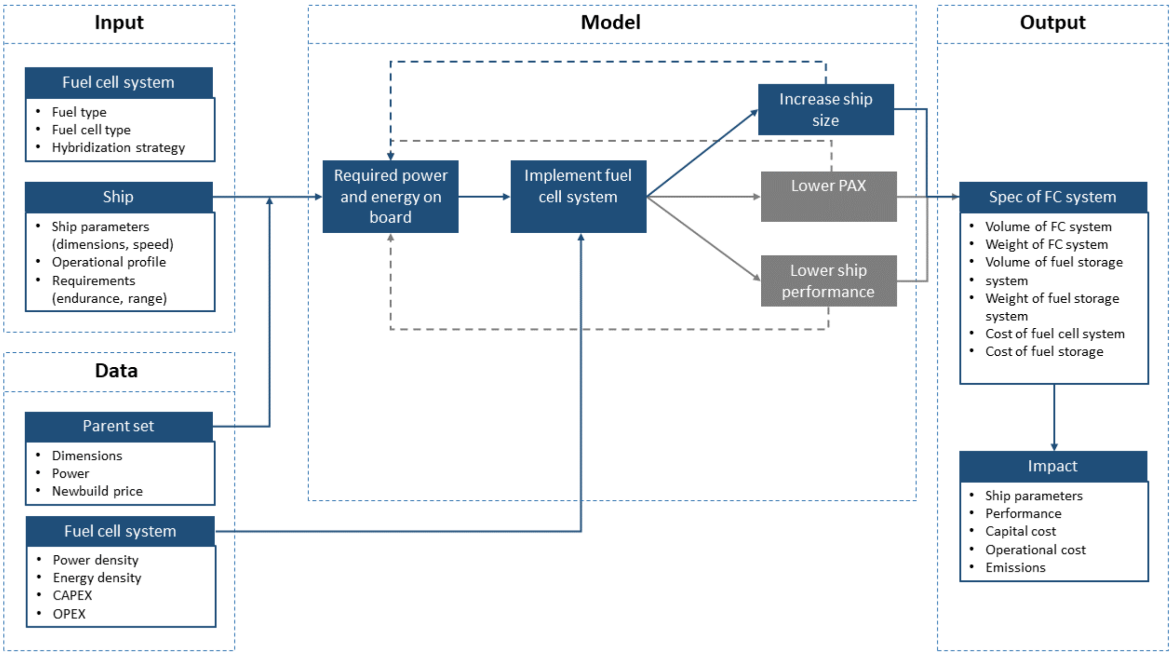


Figure 8.3: Schematic overview of the workflow of the design tool

Input

A cruise line usually has an initial design, meaning main ship parameters (L_{OA}, L_{PP}, B, T and D) are used as input. In line with how the cruise line operates their cruises, the cruise line usually has strict requirements in range, endurance and speed. In most cases the cruise line also delivers an operational profile in the ROM phase, meaning a more precise estimation of energy usage is possible. Both range endurance as operational profile as input are made possible in the model, but the operational profile as input is emphasized in this research since this input makes it possible to compare capital cost of the fuel cell system with the fuel cost and realized emissions of the ship for different fuel cell systems.

The preferred fuel cell system (fuel type and fuel cell type combination) is also used as input together with the hybridization strategy of the fuel cell system. For the hybridization strategy, a functional approach is used: meaning the hybridization options are functional options in the configuration of the power generation system, instead of fixed ratios between fuel cell power and diesel power. The hybridization options are:

1. *Full fuel cell powered ship*
   All energy on board is generated by fuel cells. Its main advantage is that no extra machine room is required for diesel generators. However, large fuel storage and an expensive power generation system are expected with this option.

2. *Hybrid 1: Fuel cell power generation for auxiliary load*
   All power for auxiliary systems (including hotel) is provided by the fuel cell system. All power for propulsion is provided by the diesel generator set. The advantage of this option is that less balance of plant components are required for high temperature fuel cells to ensure dynamic power capabilities, since the auxiliary load is much more constant (smaller changes in power demand per time) than the propulsion load, which was concluded in section 7.5. This means that less space, weight and cost is required per kW of fuel cell system, compared to an option where fuel cells are also used to generate power for propulsion. The disadvantage of this option is that zero emission operation is not possible.

3. *Hybrid 2: Diesel generators for the transit*
   For this hybrid configuration the operation which requires the most stored energy and installed power (transit) is supported with diesel generators running on MGO. Since fuel storage is critical for a fuel cell powered ship, this option gives a way to cope with long ranges and huge storage tanks for fuel for the fuel cells, while still operating most of its operations on fuel cells. The DG system is used to

boost the ship speed that can be acquired with just the fuel cell system, to the desired speed for transit, while also fulfilling the range requirements for the transit. In discussion with D&P engineers, there are extra advantages of this option: (i) The most harmful emissions are mainly emitted outside sensitive areas, which is in line with meeting ECA requirements [54, 55]. (ii) This option offers more redundancy than hybrid option 1, meaning applying this option makes it easier to comply to Safe Return to Port regulations.

The operational profile as input for the design tool is based on the travel itinerary of the cruise line, see figure 8.4. The operational input is defined from a functional approach: three operations are defined (transit, coastal, (ant)arctic). These operations are separate itineraries. It is also defined how much each operation is used yearly. This division in operations is important for hybrid option 2: diesel generators are used for the transit. Although the transit requires much energy on board, because regularly it is the longest travel distance on the highest speed, the transit is usually the least used operation over the year. When using a fuel cell system for the non-transit operations, large savings are still possible for emissions and fuel cost over the whole year. For the defined operations, time and distance is defined for different sail modes (harbour, manoeuvring, slow cruising and cruising). This leads to a desired ship speed for all sail modes in all ship operations.

Operational profile				
	Distance	**Days**	**Time**	**Speed**
	nm	-	%	kn
Transit			10%	
Harbour	-	4	20%	-
Manouvring	5	0.5	2%	0.4
Slow cruising	100	1	5%	4.2
Cruising	4500	15	73%	12.5
Total	4,605	21	100%	9.4
Coastal operation			50%	
Harbour	-	2.5	19%	-
Manouvring	5	0.5	4%	0.4
Slow cruising	0	0	0%	-
Cruising	2000	10	77%	8.3
Total	2,005	13	100%	6.4
Antartic operation			40%	
Harbour	-	4	23%	-
Manouvring	5	0.5	3%	0.4
Slow cruising	100	1	6%	4.2
Cruising	2500	12	69%	8.7
Total	2,605	18	100%	6.2
Cruise speed	12.5	kn		
Max speed	15.6	kn		

Figure 8.4: Example of input for the operational profile

Data

The relations in the expedition cruise parent set, presented in section 7.2 are used to derive some of the key parameters of the ship like GT, displacement and new build cost. The used reference ships (luxury segment as defined in section 7.2) range from 5000 to 70000 GT, meaning the design tool is not valid for ships outside this range. Extrapolating the used relations too much would give large uncertainties.

The fuel cell system performance, which was presented in section 6.3 is used as data for the implementation of the fuel cell system on board. Meaning the power density, energy density and specific cost for the different fuel cell systems are used to determine the volume, weight and cost of the required fuel cell system on board.

Model

The input parameters combined with the parent set are used to estimate the required propulsion power by means of the admiralty formula. With the propulsion power the total installed power will be estimated, from which the volume, weight and cost of the fuel cell power pack can be calculated with the performance data of figure 6.3. The required power and operational requirements can be used to determine the required electrical energy on board in order to estimate the volume, weight and cost of the fuel storage. If the operational profile is known the fuel usage can also be determined for a fuel cost estimation.

The (hybrid) fuel cell system is much larger than a conventional solution, mainly due to the large volume of the fuel storage system. Consequently, a design iteration is necessary to fit the required fuel cell system in the preliminary design. Looking at the model (figure 8.3) there are three possibilities to fit the (hybrid) fuel cell system. All options include a feedback in the design (see also dotted line) and start an iterative cycle:

1. *Increase ship size*
   Increasing the ship size to fit the fuel cell system increases the ship resistance and thus installed power and required energy on board, consequently increasing the volume, weight and capital cost of the fuel cell system.

2. *Lower number of passengers*
   With lowering the number of passengers, extra space becomes available to fit the fuel cell system. Lowering the number of passengers also decreases the required hotel power, thus decreases installed power, required energy on board and consequently decreases the required volume for the fuel cell system. Out of internal discussion with D&P engineers followed that decreasing PAX to make extra space is usually not preferable. Firstly, because the passenger spaces are usually and desired to be separated from the technical spaces, making a rearrangement in the conceptual design necessary for this option. Secondly, because PAX is usually fixed by the cruise line. It is based on market research and how the cruise line operates.

3. *Lower ship performance*
   For lowering the ship performance there are several options, because the operational profile input exists of distance and time. Firstly, just reducing the distance decreases the operational speed and thus decreases the required installed power and required energy on board, consequently reducing the required volume for the fuel cell system. Secondly, just decreasing the duration decreases the consumed hotel energy consequently decreasing the required volume of the fuel storage but increases the desired ship speed and thus increases the required power and required energy on board, consequently increasing the volume of the fuel cell system. Cruise itineraries commonly have quite fixed durations (Saturday to Saturday for instance). For this reason, the best option to vary operational input is to decrease the distance. Practically this would mean skipping a visit destination in the itinerary. This keeps itinerary durations the same, while reducing the distance and thus decreasing the operational speed during the itinerary.

For the model it is decided to increase the ship size (option i) to fit the fuel cell system since decreasing PAX (option ii) needs rearrangements in the design and is generally not desired by the cruise line. At the same time lowering the ship performance (option iii) will not be implemented as method to fit the fuel cell system in the ship, but will be used as varying input for the model in order to see the effect of varying the itinerary requirements on the ship size, build cost and fuel cost of the ship.

Output
The specifications (volume, weight and cost) of the fuel cell system will be provided as output. The implementation of the fuel cell system also has an impact on the ship design. This impact will also be provided as output to the D&P engineer. Figure 8.5 shows an example of the model output.

In this research, the model output will be systematically varied for different inputs (fuel cell systems, hybridization degrees and ship designs). The different outputs will be compared making it possible to give recommendations for a fuel cell powered expedition cruise ship.

Main ship dimension					
Length OA	192	m	Gross Tonnage	31693	GT
Length PP	169	m	Displacement	19045	ton
Beam	26	m	Deadweight	3590	ton
Draught	6	m	Total volume	105597	m³
Depth	10	m	Block coefficient	0.66	-

Main ship performance					
Design speed	14	kn	PAX	500	-
Maximum speed	15	kn	Crew	323	-
Range	4105	nm	POB	823	-
Endurance	17	days	Luxury class	Luxury	-

Machinery					
Required			Installed		
Propulsion power	6890	kW	Fuel cell power	14990	kW
Auxilary power	8100	kW			
Total required power	14990	kW	Total installed power	14990	kW

Fuel cell system					
Fuel type	LNG	-			
Fuel cell type	SOFC	-			
FC installed power ratio	100%	-	0%: fully DG powered	100%: fully FC powered	
Fuel cell system efficiency	70%				
Volume of FC fuel	1020	m³	Weight of FC fuel	448	ton
Volume fuel cell system	2448	m³	Weight fuel cell system	975	ton
Fuel cell power pack	464	m³	Fuel cell power pack	126	ton
Fuel cell storage	1984	m³	Fuel cell storage	849	ton

Capital cost of fuel cell system					
Absolute			Relative to conventional solution		
Cost fuel cell system	264.3	M€	Cost fuel cell system	257.8	M€
Cost fuel cells	255.4	M€			
Cost FC fuel storage	9.0	M€			

Comparison with operational cost (for cruise line)					
Absolute			Relative to conventional solution		
Build cost of total ship	555.9	M€	Build cost of total ship	298.3	M€
			Increase in build cost of total ship	116%	-
Fuel cost over lifetime	26.7	M€	Fuel cost over lifetime	-82.1	M€
			Increase in fuel cost	-75%	
Total cost	582.6	M€	Increase in total cost	216.3	M€
			Increase in total cost	59%	-

Figure 8.5: Example of model output. 'Relative to conventional solution' means the difference with the cost of a ship with the same requirements but with conventional power generation. Consequently, for the last 2 section the right column equals the left column minus the concerned cost of a conventional ship.

8.2. Model explanation

This section describes and explains the just presented design tool. This section is provided to the reader to understand how the model functions, on which assumptions it is based and which methods are used. In section 8.2.1, the reference ship database is applied to determine the main ship parameters. To determine the displacement, the Townsin method and a regression method are considered, of which the regression method is selected. The required power for propulsion and auxiliaries are determined in section 8.2.2, based on the displacement (Admiral method) and the number of passengers (regression method) respectively. Since hybrid options are also considered, the required power is divided over the fuel cell system and the diesel generator system. With the required power and the operational profile, the required energy on board (to satisfy the required range) and the yearly energy consumption are determined is section 8.2.3. The installed power, required energy on board, and energy consumption are combined with the performance data in section 8.2.4 to find the weight, volume, capital cost and operational of the seven selected fuel cell systems for three hybridization options. Section 8.2.6 describes how the fuel cell powered ship can be related to a conventional ship to indicate the impact of the fuel cell system on ship dimensions and cost. Lastly, because the overarching goal of this research is to reduce emissions, section 8.2.7 describes how emissions of the fuel cell powered ships are determined.

8.2.1. Ship parameters

The ship dimensions and the required speed will be used to estimate how much propulsion power is required on board of the ship. This section describes how the relevant ship parameters are determined. Two methods are proposed to determine the displacement of the ship: the Townsin Method and a regression method.

Displacement estimation method 1: Townsin method
Using the Townsin method, the Froude number (equation 8.2) is used to suggest a suitable block coefficient (equation 8.3) [113]. The trend line of the Townsin method is shown in Appendix E figure E.1. Out of discussion with Marin was concluded that the Townsin method is reliable for expedition cruise ships until a Froude number of 0.4 [121]. As shown in Appendix E figure E.2, all expedition cruise ships used in the parent set range from Froude number 0.18 to 0.28, so the Townsin method is applicable for expedition cruise ships. The block coefficient is used to determine the displacement (equation 8.4). Using the Townsin method, the displacement is dependent on the main dimensions and the ship speed. Displacements estimations by using the Townsin method are compared with the reference ships (of which displacement data is known), see figure 8.6 and table 8.1. It was found that the Townsin method estimates the displacement averagely 8% higher than the real displacement of the parent ships with a standard deviation of 0.09.

$$L_{WL} = 1.02 L_{PP} \tag{8.1}$$

$$Fn = \frac{V_s}{\sqrt{g L_{WL}}} \tag{8.2}$$

$$C_B = 0.7 + 0.125 \arctan\left(\frac{23 - 100Fn}{4}\right) \tag{8.3}$$

$$\nabla = \rho_{sw} C_B L_{WL} B_{WL} T \tag{8.4}$$

Displacement estimation method 2: regression data
The gross tonnage has a strong relation with the number of passengers for the used reference ships, see equation 8.5. This relation is expected to change after fuel cell implementation, so it is only used to determine initial GT. Also using the reference ships, the displacement can be calculated out of the just calculated GT, see equation 8.6. The deadweight is also based on the GT, see equation 8.7. Using method 2, the displacement is dependent on the number of passengers. Displacements estimations by using the regression method are compared with the reference ships (of which displacement data is known), see figure 8.6 and table 8.1. The regression method estimates the displacement averagely 2% lower than the real displacement of the parent ships with a standard deviation of 0.1.

$$GT = 52.25 PAX + 5194 \quad \text{(Regression formula, } R^2 = 0.93\text{)} \tag{8.5}$$

$$\Delta = 0.5014 GT + 3154 \quad \text{(Regression formula, } R^2 = 0.99\text{)} \tag{8.6}$$

$$DWT = 0.181 GT^{0.955} \quad \text{(Regression formula, } R^2 = 0.93\text{)} \tag{8.7}$$

Selection displacement estimation method
Using the regression data to estimate the displacement leads to a lower error with a comparable standard deviation compared to the Townsin method. For this reason the regression method is chosen to estimate the displacement. The displacement is consequently required to estimate the propulsion power with the Admiralty constant, see also section 8.2.2. To make sure there is no mismatch with the C_B and the desired speed, the C_B is calculated and compared in the model with the C_B of reference ships with a comparable desired speed.

Main dimensions
As stated before, the main dimensions are often known before hand, since a preliminary design is often provided in early design phase by the cruise line. These will be used as input of the model. In the case the main parameters are not known or are uncertain, they are based on the GT with regression formulas (equations 8.8 - 8.11). This gives an indication on suitable dimensions for a ship with the required PAX capacity and a certain luxury class, but this should not define the main parameters in the design process.

$$L_{OA} = 5.404 GT^{0.345} \quad \text{(Regression formula, } R^2 = 0.96\text{)} \tag{8.8}$$

$$L_{pp} = 6.360 GT^{0.316} \quad \text{(Regression formula, } R^2 = 0.93\text{)} \tag{8.9}$$

$$B = 1.356 GT^{0.284} \quad \text{(Regression formula, } R^2 = 0.98\text{)} \tag{8.10}$$

$$T = 0.476 GT^{0.250} \quad \text{(Regression formula, } R^2 = 0.90\text{)} \tag{8.11}$$

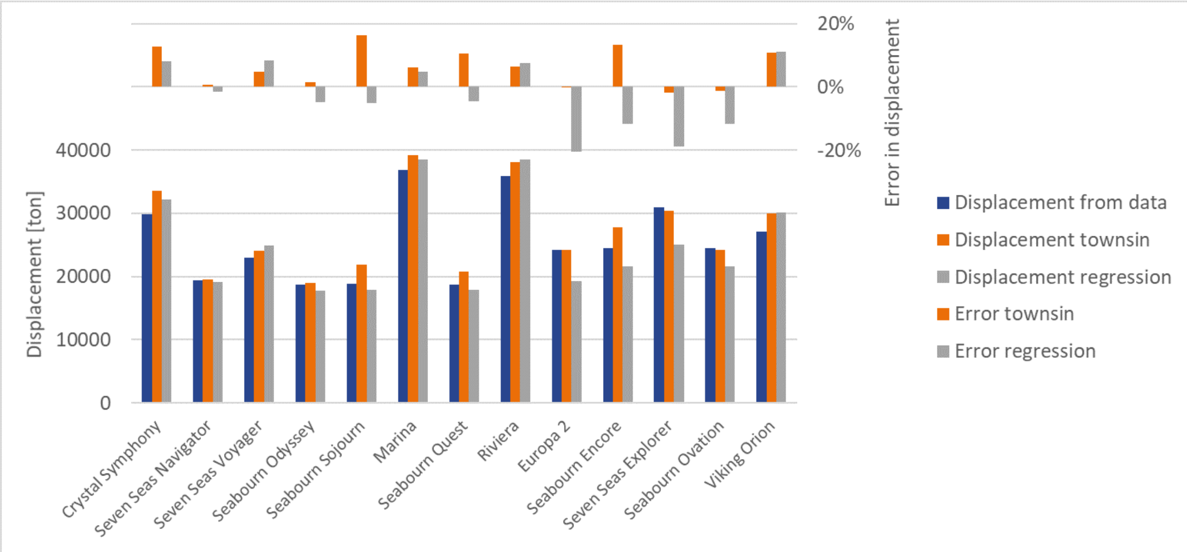


Figure 8.6: Displacement estimations of method 1 and method 2 compared with displacement data of part of the reference ships.

Table 8.1: Error and standard deviation of displacement methods

			Mean error displacement	SD Dispplacement
Townsin method			8%	0.09
	Mean error GT	SD GT	Mean error displacement	SD Displacement
Regression method	7%	0.23	-2%	0.10

Passengers on board

The number of crew members is strongly related with the number of passengers for this luxury level (equation 8.12), together defining the number of persons on board (equation 8.13).

$$N_{crew} = 0.546PAX^{49.905} \qquad \text{(Regression formula, } R^2 = 0.92\text{)} \tag{8.12}$$

$$POB = PAX + N_{crew} \tag{8.13}$$

8.2.2. Power estimation

The required power exist of the propulsion power and the auxiliary power (including hotel). Dependent on the hybridization option the installed power is divided over the fuel cell plant and the diesel plant.

Propulsion power

Most methods to estimate propulsion power mainly involve calculating the resistance of the ship (such as Holtrop & Mennen [47]) and combining this with the speed and losses along the propulsion chain [62]. However for these kinds of predictions more information is required than available at this stage, such as area of waterline and the wetted area of hull and of underwater structures. For this reason the admiralty formula is used to estimate the required propulsion power (equation 8.14) [62]. The admiralty constant A is derived out of the reference ships. It must be noted that A is only constant for relative small changes in Δ and V [10]. The evaluated ship must not deviate much from the reference ship, so this tool will not be suitable for evaluating an expedition cruise ship with unique design requirements, like a high speed or double-ended design. Also, the admiralty formula is only applicable for the first design stage, meaning it is suitable for this tool, but a more precise method should definitely be applied in the next design phase. The regression formula for propulsion power is shown in equation 8.15.

$$A = \frac{\Delta^{\frac{2}{3}} V^3}{P_{propulsion}} \tag{8.14}$$

$$P_{propulsion} = 0.00271\Delta^{2/3} V_{s,max}^3 \qquad \text{(Regression formula, } R^2 = 0.93\text{)} \tag{8.15}$$

Auxiliary power
The auxiliary power is defined in this research as all required power besides the propulsion. For expedition cruise ships the auxiliary power is dominated by the hotel power. A first estimation of the required installed auxiliary power of expedition cruise ships is usually performed by expressing hotel power as half of the propulsion power (1/3 - 2/3 rule) or auxiliary power (including hotel) as 40% of total installed power [48]. As can be seen in the third column of table 8.2, especially the last assumption is much in line with the reference ships. When comparing this to the power demand of auxiliary and propulsion during a typical day, 40% seems like an overestimation (in the data presented in section 7.4, the auxiliary power demand was approximately 20% of the propulsion power demand). However, the auxiliary power demand for a typical day is logically lower than the total required installed power that must be available at extreme conditions.

For this tool, using a fixed rate between hotel and propulsion power would not make sense; when the input speed would be lowered much, the required propulsion power would decrease much, consequently decreasing the auxiliary power. However, for expedition cruise ships that would mean that not enough power remains for the auxiliary load, since this is very dependent on the number of passengers. For this reason the auxiliary power is defined as function of PAX, see equation 8.16. The amount of auxiliary power per PAX ($a_{P_{aux}}$) is also very dependent on the luxury level. For luxury ships the HVAC needs to cover more volume per passenger and luxury equipment also requires power. Table 8.2 shows how much auxiliary power is on average installed per PAX for different luxury levels.

$$P_{aux} = a_{P_{aux}} \cdot PAX \tag{8.16}$$

Table 8.2: Average auxiliary power (including hotel power) per passenger for different luxury classes, based on reference ships.

	Auxiliary power kW/PAX	**Standard deviation** kW/PAX	**Auxiliary power** % of installed power	**Standard deviation** % of installed power
Budget	5.9	1.8	38%	6%
Premium	8.3	2.9	39%	8%
Luxury	16.2	5.7	41%	9%

The required power is defined by the required propulsion and the required auxiliary power, see equation 8.17. As was already seen in section 7.4 figure 7.10 both $P_{propulsion}$ and P_{aux} are varying during the day.

$$P_{required} = P_{propulsion} + P_{aux} \tag{8.17}$$

Installed power
The installed power should satisfy the required power. Since the propulsion power calculated out of the reference ships is also based on installed power, no additional margins (like sea margin or losses along propulsion chain) are added and are assumed not to change much for a fuel cell powered ship. These margins are already involved in the power data. This means that the installed power is more or less equal to the required power. In reality, the installed power also depends on the nominal power of available diesel generators, so installed power would usually be a step function. However, since fuel cells have a modular orientation and since not all diesel generator options can be reviewed, the installed power is equated to the maximum required power (equation 8.18).

$$P_{installed} = \max\left[P_{required}\right] \tag{8.18}$$

For a full fuel cell powered ship, equation 8.18 holds and the installed fuel cell power is equal to the required power (equation 8.19). For the first hybrid option (FC for auxiliaries) equation 8.18 holds as well, since the installed FC power is equal to the required power for auxiliaries (equation 8.20) and the installed DG power is equal to the required power for propulsion (equation 8.21). However for the second hybrid option (DG for transit), 8.18 does not hold, since more power might be installed than the required power. Enough fuel cell power must be installed for all sail modes in coastal and antarctic operation to run independently, see equation 8.22. The DG system is used to support the fuel cell system in supplying enough energy to fulfil the transit and to boost the speed to the desired transit speed by adding more power. Consequently, the installed power of the DG system can be dominated by how much energy it needs to add to the energy the fuel cell system can deliver (equation 8.25) or it can be dominated by the power it needs to reach the maximum speed (equation 8.26). For this reason an IF logic is used to determine the installed power of the diesel generator system, see equation 8.24. The energy dominated installed DG power is based on the amount of installed fuel cell power that is used during the transit; the fuel cell is running on part load during transit to make sure the fuel cell fuel does not run out when the transit is not yet completed, see equation 8.23. Consequently, running the fuel cell system on part load increases the required installed power of the DG system to fulfil the required power in transit, see equation 8.25. Essentially, this means that the power usage in transit of the fuel cell system and the diesel system are adjusted to the point where their fuel is consumed at an equal percentage rate, to ensure their total power can be supplied during the whole transit. This is added as constraint to the model. Since this concept is hard to understand, it is further explained by means of an example calculation in the grey box on page 59. The power dominated installed power (equation 8.26) is equal to the total required power to reach the maximum speed (including auxiliaries) minus the already installed fuel cell power. The highest required installed power out of the two is chosen as installed power with the IF logic (equation 8.24) to make sure both requirements are met.

$$(P_{FC})_{Full\,FC} = P_{propulsion} + P_{aux} \tag{8.19}$$

$$(P_{FC})_{Hybrid\,1} = P_{aux} \tag{8.20}$$

$$(P_{DG})_{Hybrid\,1} = P_{propulsion} \tag{8.21}$$

$$(P_{FC})_{Hybrid\,2} = \max\left[(P_{propulsion} + P_{aux})_{coastal}, (P_{propulsion} + P_{aux})_{antarctic}\right] \tag{8.22}$$

$$(P_{FC})_{Hybrid\,2,\,transit} = \frac{\max\left[E_{coastal}, E_{antarctic}\right]}{t_{transit}} \tag{8.23}$$

$$(P_{DG})_{Hybrid\,2} = \begin{cases} (P_{DG})_{Hybrid\,2,\,energy\,based} & \text{if}(P_{DG})_{Hybrid\,2,\,energy\,based} > (P_{DG})_{Hybrid\,2,\,power\,based} \\ (P_{DG})_{Hybrid\,2,\,power\,based} & \text{otherwise} \end{cases} \tag{8.24}$$

with:

$$(P_{DG})_{Hybrid\,2,\,energy\,based} = (P_{max})_{transit} - (P_{FC})_{Hybrid\,2,\,transit} \tag{8.25}$$

$$(P_{DG})_{Hybrid\,2,\,power\,based} = P_{required} - (P_{FC})_{Hybrid\,2} \tag{8.26}$$

where:

$E_{operation}$	The amount of energy that is required on board (stored in the fuel) to execute an operation, in this case coastal or antarctic. This will also be explained in section 8.2.3, see equation 8.38.
$(P_{max})_{transit}$	The maximum required power in transit out of the different sail modes (including propulsion and auxiliaries)
$(P_{FC})_{Hybrid\,2,\,transit}$	The partial power supply that is used during transit to make the fuel cell fuel does not deplete before the end of the transit
$P_{required}$	The total required power at max speed and max auxiliary load

A fuel cell power factor $a_{P_{FC}}$ is defined to indicate the ratio between installed fuel cell power and total installed power. For a full fuel cell powered ship this is obviously one. For hybrid option 1 (FC for auxiliary load), the fuel cell power factor is dependent on the propulsion power and the auxiliary power, see equation 8.28. For hybrid option 2, it depends on the required power in transit, coastal and antarctic operations, see equation 8.29 of which the formula variables were presented above.

$$(a_{P_{FC}})_{Full\,FC} = 1 \tag{8.27}$$

$$(a_{P_{FC}})_{Hybrid\,1} = \frac{P_{aux}}{P_{aux} + P_{prop}} \tag{8.28}$$

$$(a_{P_{FC}})_{Hybrid\,2} = \frac{(P_{FC})_{Hybrid\,2}}{(P_{FC})_{Hybrid\,2} + (P_{DG})_{Hybrid\,2}} \tag{8.29}$$

Installed power example - hybrid option 2

This example gives deeper insight in the estimation of installed power for hybrid option 2.
Table 8.3 gives requirements for two different operations (transit and coastal). The transit operation is characterized by a longer distance and longer duration at a higher speed. As stated earlier, for hybrid option 2, diesel generators are used for the transit in order to reduce the required volume of the expensive and not energy dense storage tanks of fuel cell fuel (like LH_2). The example is performed for a ship with an average auxiliary power demand of 3000 kW and a demand of electric power for propulsion of 4000 kW at 17 knots.
For both operations, the electric power demand for propulsion for the desired speed is calculated with the propeller law (equation 8.30 and 8.31). The electric power demand for auxiliary is equal, leading to a total electric power demand for both operations. Based on the duration and the average required power, the required electric energy for both operations are calculated, see last column of table 8.3.

$$(P_{propulsion})_{transit} = \left(\frac{15}{17}\right)^3 \cdot 4000 = 2748\ kW \tag{8.30}$$

$$(P_{propulsion})_{coastal} = \left(\frac{12}{17}\right)^3 \cdot 4000 = 1407\ kW \tag{8.31}$$

Table 8.3: Used operational data, required power and energy for example of hybrid option 2 (DG for transit)

	Distance	**Duration**	**Speed**	**Power demand for propulsion**	**Power demand for aux**	**Total Power demand**	**Required elec. energy**
	nm	days	kn	kW	kW	kW	MWh
Transit operation	4320	12	15	2748	3000	5748	1655
Coastal operation	2016	7	12	1407	3000	4407	740

Since the fuel cell system should be able to independently perform the coastal operation, the installed power of the fuel cell system is 4407 kW (table 8.4). With the fuel cell efficiency and the required electric energy in coastal operation the required energy in the stored FC fuel can be determined. Margins in power and fuel are not included in this example.
Following, the installed power of the DG system must be determined. In transit the DG system supports the FC system and can be used to boost the speed to the desired transit speed. The required electric power to boost up the speed is 2748-1407=1341 kW. However, transit generally takes longer than coastal operation. Meaning, if the fuel cell system is operated at full power, the fuel for the fuel cell system would run out after 7 days. From that point the DG system should still be able to supply all required power in transit. For this reason, the used power of the fuel cell system in transit operation must be lowered to make sure the fuel cell system can deliver power of the full duration of the transit, see equation 8.32. At the same time the installed power of the DG system increases, to still fulfil the required electric power demand of 5748 kW, see equation 8.33. The required energy in the stored MGO is calculated with equation 8.34.

$$(P_{FC,used})_{transit} = \frac{E_{FC,fuel} \cdot \eta_{FC}}{t_{transit}} = P_{FC,installed} \cdot \frac{t_{coastal}}{t_{transit}} = 4407 \cdot \frac{7}{12} = 2571\ kW \tag{8.32}$$

$$P_{DG,installed} = (P_{total})_{transit} - (P_{FC,used})_{transit} = 5748 - 2571 = 3177\ kW \tag{8.33}$$

$$E_{MGO} = \frac{P_{DG,installed}}{\eta_{DG}} \cdot t_{transit} = \frac{E_{required,transit} - E_{required,coastal}}{\eta_{DG}} = 2128\ MWh \tag{8.34}$$

At the same time the total installed power by DG and FC system must ensure that the required maximum speed can be reached, so in this example it is checked whether $P_{FC,installed}$ and $P_{DG,installed}$ is higher than 7000 kW, which is the case (4407+3177). Table 8.4 shows the results.

Table 8.4: Example installed power of FC system and DG system for hybrid option 2.

FC power and fuel storage based on coastal operation		
Installed power FC	4407	kW
FC efficiency	55%	-
Required energy in stored FC fuel	1346	MWh

DG power and fuel storage based on transit operation		
Power to boost to transit speed	1341	kW
Used power in transit of FC	2571	kW
Installed power of DG	3177	kW
DG efficiency	43%	-
Required energy in DG fuel	2128	MWh

8.2.3. Energy estimation

With the operational profile as input it is possible to determine the required energy on board (defining the fuel storage size) and the energy usage (defining the fuel cost and emissions). For every sail mode in every defined ship operation is calculated with the propeller law and the desired speed how much propulsion power is required. For harbour operation, no propulsion power is needed. For slow cruising and cruising the required propulsion power is calculated with the propeller law [62] and the desired speed, see equation 8.37. For manoeuvring the propeller law does not hold, since much power is consumed during accelerating and decelerating. A rate of the total propulsion power ($a_{manoeuvring}$) is defined to take this into account, see equation 8.36.

$$(P_{propulsion})_{harbour} = 0 \tag{8.35}$$

$$(P_{propulsion})_{manoeuvring} = a_{manoeuvring} P_{propulsion} \tag{8.36}$$

$$(P_{propulsion})_{cruising} = \left(\frac{V_{s,desired}}{V_{s,max}}\right)^3 \cdot P_{propulsion} \tag{8.37}$$

For the auxiliary power demand an average is used, based on the conclusion of section 7.5, where it was found that the auxiliary power demand does not fluctuate heavily over a typical day. One might object to this assumption for two reasons: i) For auxiliaries, in harbour no fuel might be consumed since a grid connection might be used. However, the prices of grid energy in harbours are not easily available. ii) One might state that arctic areas require more energy for heating. However, by reviewing several load balances for different ships it was concluded that the HVAC system requires similar installed power for heating in Arctic areas as cooling in warmer areas, making this assumption justifiable. Although the auxiliary power demand is assumed constant, the average auxiliary power demand is not the same as the installed auxiliary power. With consultation of Damen electrical engineers a ratio $a_{aux\,demand}$ is defined between the average demanded auxiliary power and the installed power for auxiliaries. $a_{aux\,demand}$ is considered constant for the different sail modes in the different operations, except for the harbour sail mode. In this sail mode few passengers are on board and the the power demand will decrease significantly.

With the required propulsion power, auxiliary power and the time for every sail mode, the necessary energy for a transit, a coastal itinerary and an (ant)arctic itinerary can be calculated. This is expressed in equation 8.38, where the four sail modes are represented with m. The just defined ratio for demand of auxiliary power is also used in this equation.

$$E_{operation} = \sum_{m=1}^{4} ((P_{propulsion})_m + a_{aux\,demand} \cdot P_{aux}) \cdot t_m \tag{8.38}$$

where:

$(P_{propulsion})_m$	Required propulsion power in sail mode m
P_{aux}	Installed auxiliary power (including hotel)
$a_{aux\,demand}$	Ratio between average power demand for auxiliaries and installed power for auxiliaries
t_m	Duration of sail mode m

Required energy on board

The required energy on board defines the weight, volume and cost for the storage of the different fuels. The required energy on board differs for the different hybrid systems. A fuel margin $a_{transit}$ is defined to make sure delays in the operational profile are possible or to enable the option to sail a little faster when behind schedule, both increasing the fuel consumption. For the DG system a 10% fuel margin ($a_{transit,DG}$) is used out of advice of Damen D&P engineers. For the FC system a higher fuel margin is needed, due to the decrease in efficiency over the lifetime of the fuel cell stacks. A decrease of fuel cell stack efficiency of 10% over the lifetime of the stack resulted in the use of fuel margin of 20% for the FC system ($a_{transit,FC}$) to make sure the range requirements can still be met during the end of the lifetime of the fuel cell stacks.

For the full fuel cell powered ship the required energy on board is the maximum out of the different operations (maximum because the operations are different itineraries), see equation 8.39.

For hybrid option 1 (FC for auxiliary) the required energy on board for the fuel cell system is the maximum energy required for auxiliaries for the different operations, see equation 8.40. The required energy for the diesel generator system is the maximum energy required for propulsion for the different operations, see equation 8.41. Note that total maximum energy on board for hybrid option 1 could be higher than the maximum energy on board for the full FC powered option. For instance when the coastal operation has a low speed but a high duration and the transit operation has a high speed and a low duration, the maximum required auxiliary energy and the maximum required propulsion energy could not be in the same operation, resulting in a higher required total energy on board.

For hybrid option 2 (DG for transit) the required energy on board for the fuel cell system is dependent on the required energy for coastal and antarctic operations, see equation 8.42. The fuel cell system is also used to support the diesel generators in transit, otherwise extra space for MGO tanks is necessary in the ship for just the transit. It was investigated how much extra space would be required when just the diesel generators would be used during a transit, which resulted in 10% to 30% higher volume of MGO tanks, dependent on the operational profile. On top of that more power has to be installed for the DG system since the DG system would supply all power for the transit. This resulted in the decision to also use the fuel cell system to generate power during transit. For this reason the required energy for the fuel cell system is subtracted from the required energy for the diesel generators in transit, see equation 8.43.

$$(E_{required})_{Full\,FC} = (1 + a_{transit,FC}) \cdot \max\left[E_{transit}, E_{coastal}, E_{antarctic}\right] \tag{8.39}$$

$$(E_{required,FC})_{Hybrid\,1} = (1 + a_{transit,FC}) \cdot \max\left[(E_{transit})_{aux}, (E_{coastal})_{aux}, (E_{antarctic})_{aux}\right] \tag{8.40}$$

$$(E_{required,DG})_{Hybrid\,1} = (1 + a_{transit,DG}) \cdot \max\left[(E_{transit})_{propulsion}, (E_{coastal})_{propulsion}, (E_{antarctic})_{propulsion}\right] \tag{8.41}$$

$$(E_{required,FC})_{Hybrid\,2} = (1 + a_{transit,FC}) \cdot \max\left[E_{coastal}, E_{antarctic}\right] \tag{8.42}$$

$$(E_{required,DG})_{Hybrid\,2} = (1 + a_{transit,DG}) \cdot (E_{transit} - \max\left[E_{coastal}, E_{antarctic}\right]) \tag{8.43}$$

where:

$a_{transit,DG}$	Fuel margin for DG system (10%)
$a_{transit,FC}$	Fuel margin for FC system (20%), higher for FC due to decrease in efficiency over lifetime

Energy usage

The energy usage is calculated in this section, which is mainly important for the fuel consumption, which in turn has big impact on the operational cost of the ship. The energy required for an operation (equation 8.38) is combined with the usage rate of the operations to determine how much energy is used yearly for every operation, see equation 8.44. The usage rate of the different operations is defined as the percentage time the cruise line executes a certain operation yearly, for instance 10% transit, 50% coastal operation and 40% arctic operation. This especially matters for the yearly fuel consumption of hybrid option 2 where MGO is consumed in transit and alternative fuel is consumed in other operations. The yearly energy usage equals the sum for the different operations, see equation 8.45. Equation 8.46 to 8.50 describe of which components the yearly energy consumption exist for the different hybrid options.

$$(E_{operation})_{yearly} = E_{operation} \cdot \frac{t_{operational}}{t_{operation}} \cdot a_{operation} \tag{8.44}$$

$$E_{yearly} = (E_{yearly})_{transit} + (E_{yearly})_{coastal} + (E_{yearly})_{antarctic} \tag{8.45}$$

where:

$t_{operational}$	Number of operational days of ship per year
$t_{operation}$	Duration in days of concerned operation
$a_{operation}$	Percentage of time in year that cruise line executes certain operation (transit, coastal, antarctic)

$$(E_{yearly})_{Full\,FC} = (E_{transit})_{yearly} + (E_{coastal})_{yearly} + (E_{antarctic})_{yearly} \tag{8.46}$$

$$(E_{yearly,FC})_{Hybrid\,1} = (E_{aux})_{yearly} \tag{8.47}$$
$$(E_{yearly,DG})_{Hybrid\,1} = (E_{propulsion})_{yearly} \tag{8.48}$$

$$(E_{yearly,FC})_{Hybrid\,2} = (E_{coastal})_{yearly} + (E_{antarctic})_{yearly} \tag{8.49}$$
$$(E_{yearly,DG})_{Hybrid\,2} = (E_{transit})_{yearly} \tag{8.50}$$

8.2.4. Implementation of fuel cell system

At this point in the model the required power, required energy and energy consumption of the (hybrid) fuel cell system are known. This is combined with the fuel cell system performance (presented in section 6.3) to calculate the volume, weight, capital cost and fuel cost of the fuel cell system.

The required ship volume for the fuel cell system (and of the diesel generator system for a hybrid system) consists out of the volume of the power plant (including space for maintenance and other systems) and the ship volume to store the concerning fuel, see equation 8.51 and 8.53. The ship volume of the power plant equals the required power divided by the volumetric power density and the ship volume of the stored fuel equals the required energy on board divided by the volumetric energy density. Power and energy densities were already presented in section 6.3 and the energy density already includes the efficiency of the fuel cell system. The weight of the fuel cell system is determined analogously, see equation 8.52 and 8.54.

$$V_{FC\,system} = V_{FC\,plant} + V_{fuelstorage,FC} = \frac{P_{FC}}{p_{vol,FCsystem}} + \frac{E_{required,FC}}{e_{vol,FCsystem}} \tag{8.51}$$
$$W_{FC\,system} = W_{FC\,plant} + W_{fuelstorage,FC} = \frac{P_{FC}}{p_{grav,FCsystem}} + \frac{E_{required,FC}}{e_{grav,FCsystem}} \tag{8.52}$$
$$V_{DG\,system} = V_{DG\,plant} + V_{fuelstorage,DG} = \frac{P_{DG}}{p_{vol,DGsystem}} + \frac{E_{required,DG}}{e_{vol,DGsystem}} \tag{8.53}$$
$$W_{DG\,system} = W_{DG\,plant} + W_{fuelstorage,DG} = \frac{P_{DG}}{p_{grav,DGsystem}} + \frac{E_{required,DG}}{e_{grav,DGsystem}} \tag{8.54}$$

The cost of the fuel cell system (and of the diesel generator system for a hybrid system) is also dependent on the power pack and the fuel storage, see equation 8.55 and 8.56. The cost of the power pack is equal to the required power times the cost per kW. The cost of the fuel storage is equal to the required energy on board times the cost per kWh for fuel storage, see equation 8.55 and 8.56.

$$\begin{aligned} C_{FC\,system} &= C_{FC} + C_{fuelstorage\,FC} \\ &= P_{FC} \cdot c_{FCplant} + E_{required,FC} \cdot c_{fuel\,storage} \end{aligned} \tag{8.55}$$
$$\begin{aligned} C_{DG\,system} &= C_{DG} + C_{fuelstorage\,DG} \\ &= P_{DG} \cdot c_{DGplant} + E_{required,DG} \cdot c_{fuel\,storage} \end{aligned} \tag{8.56}$$

The fuel cost of the (hybrid) fuel cell system depends on the yearly energy consumption, the operational years of the ship and the cost of generated electrical energy, the latter depending on the fuel cost and the efficiency of the system. Although not often stated in fuel cell literature or fuel cell specifications, out of discussion with fuel cell suppliers followed that the efficiency of the fuel cell system decreases with 10% over the lifetime of the fuel cell stacks. This implies an increase in fuel consumption over the lifetime of the fuel cell stacks, until it is replaced. Since the efficiency decreases linear, a 5% increase in fuel cost is added to take this effect into account, see $a_{FC\,efficiency}$ in equation 8.57.

$$C_{fuel,FC\,system} = E_{yearly,FC} \cdot t_{lifetime,ship} \cdot c_{generated\,energy,FC} \cdot (1 + a_{FC\,efficiency}) \tag{8.57}$$
$$C_{fuel,DG\,system} = E_{yearly,DG} \cdot t_{lifetime,ship} \cdot c_{generated\,energy,DG} \tag{8.58}$$

8.2.5. Fitting the fuel cell system in the ship

To fit the fuel cell system the ship size is increased, consequently increasing a lot of other ship parameters like installed power and energy consumption. Figure 8.7 shows on which parameters the increase in ship size has an impact. This impact is iterative: when the ship size increases, the required power increases, increasing the size of the power plant and fuel storage further increasing the ship size. Figure 8.7 shows one iteration in ship size increase. All steps in the design iteration will be explained in the following subsections. In the last subsection will be explained how many iterations are necessary.

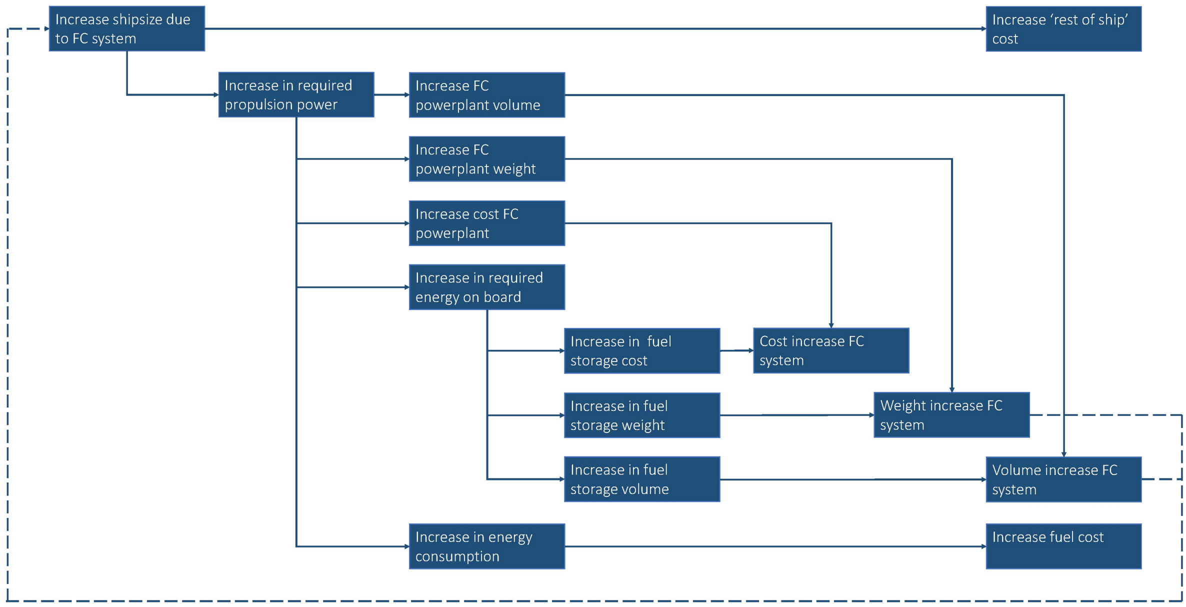


Figure 8.7: Consequences of increasing ship size to fit fuel cell system. Scheme shows one iteration in design.

Increase in ship size

The increase in ship size due to fuel cell system implementation is expressed in GT because a ship cost per GT will be defined to take into account the increase in ship cost (besides the fuel cell system) when increasing the ship size. While increasing the ship size it should be checked whether the increase in ship size is driven by the volume of the fuel cell system or by the weight of the fuel cell system. For example, when introducing a fuel cell system that is slightly larger in volume and much heavier than the conventional system and the ship size would only slightly be increased proportional to the size of the fuel cell system, the draft of the ship would increase until the weight is in balance with the buoyant force of the body under the surface (Law of Archimedes). Such an increase in draft is generally not desired, since it increases ship resistance and draft is often restricted by the water depth of the operational areas. To counter this, the displacement can be further increased by increasing L, B, T and/or C_B. Vice versa, when the increase in weight of the fuel cell system is relatively lower than the volume increase due to fuel cell implementation, the draft would become smaller. This is often less of a problem, since it generally reduces ship resistance and it can be solved more easily by adding weight when a reduction of draft is not desirable (for instance when this would cause surfacing of the propeller). Actually, whether the increase in ship size is volume driven or weight driven is a density problem.

In the model, an IF logic determines whether the increase in displacement is volume driven or weight driven, see equation 8.59. Volume based displacement is determined with a regression formula out of the increase in GT, which follows out of the increase in GV due to the relative volume increase for a fuel cell system compared to a conventional solution (see equation 8.60 and 8.62). The weight based displacement is determined out of the increase in weight of the fuel cell system compared to the weight of a conventional system, see equation 8.61. Whether the increase in ship size is volume driven or weight driven is different per fuel cell system, per hybrid option and dependent on the operational requirements.

$$\Delta\Delta = \begin{cases} \Delta\Delta_{volume\ based} & \text{if } \Delta\Delta_{volume\ based} > \Delta\Delta_{weight\ based} \\ \Delta\Delta_{weight\ based} & \text{otherwise} \end{cases} \tag{8.59}$$

$$\Delta_{volume\,based} = a_{\Delta-GT} \cdot \Delta GT_{GV} \tag{8.60}$$

$$\Delta_{weight\,based} = W_{FC,system} - W_{conventional} \tag{8.61}$$

$$\Delta GT_{GV} = (0.2 + 0.02\log(GV + \Delta GV)) \cdot (GV + \Delta GV) - (0.2 + 0.02\log(GV)) \cdot GV \tag{8.62}$$

where:

$a_{\Delta-GT}$	Linear regression factor between Δ and GT
ΔGT_{GV}	Difference in GT, driven by volume due to increase in GV
$W_{conventional}$	The weight of the MGO and diesel generator system that would normally be installed
ΔGV	Enclosed volume is derived of the difference of the volume of the (hybrid) fuel cell system and the same performing power generation for a conventional solution (MGO fueled DG)

Following, the actual increase in GT is determined out of the increase in displacement using regression data, see equation 8.63.

$$\Delta GT = a_{GT-\Delta} \cdot \Delta\Delta \tag{8.63}$$

The increase in ship size implies an increase in the cost of the ship. A larger ship means more structural steel usage, larger systems, longer cables etc. A cost per additional GT (c_{ship}) is defined to take into account the increase in ship size, see equation 8.64. c_{ship} is derived from the reference ships. $\Delta C_{rest\,of\,ship}$ does not include extra cost for the power plant, fuel storage and fuel consumption, due to the increase in ship size. These will be taken into account separately in the following sections.

$$\Delta C_{rest\,of\,ship} = c_{ship} \cdot \Delta GT \tag{8.64}$$

Increase of power plant

The increase in ship size results in a higher required propulsion power, due to an increase in ship resistance. The increase in propulsion power is again calculated with the Admiral constant of the reference ships (equation 8.65), via the increase in displacement (equation 8.59).

$$\Delta P_{propulsion} = a_{P_{propulsion}-A} \cdot V_{s,max}^3 (\Delta + \Delta\Delta)^{2/3} - a_{P_{propulsion}-A} \cdot V_{s,max}^3 (\Delta)^{2/3} \tag{8.65}$$

where:

$a_{P_{propulsion}-A}$	Regression factor between propulsion power and admiral constant

For the full fuel cell powered option, $\Delta P_{propulsion}$ is covered by an increase in the installed fuel cell power. For hybrid option 1, $\Delta P_{propulsion}$ is fully covered by an increase in installed diesel generator power, because in this hybrid option the diesel plant delivers all power for propulsion (equation 8.67 and 8.69). For hybrid option 2, the $\Delta P_{propulsion}$ is covered by an increase in installed FC power and an increase in installed DG power using the earlier defined fuel cell power factor $a_{P_{FC}}$, while taking into account that the installed power of this hybrid option can be larger than the required power for auxiliaries and propulsion (equation 8.69 and 8.70).

$$\Delta(P_{FC})_{Full\,FC} = \Delta P_{propulsion} \tag{8.66}$$

$$\Delta(P_{FC})_{Hybrid\,1} = 0 \tag{8.67}$$

$$\Delta(P_{FC})_{Hybrid\,1} = \Delta P_{propulsion} \tag{8.68}$$

$$\Delta(P_{FC})_{Hybrid\,2} = \Delta P_{propulsion} \cdot \frac{(P_{FC})_{Hybrid2} + (P_{DG})_{Hybrid2}}{P_{propulsion} + P_{aux}} \cdot (a_{P_{FC}})_{Hybrid\,2} \tag{8.69}$$

$$\Delta(P_{DG})_{Hybrid\,2} = \Delta P_{propulsion} \cdot \frac{(P_{FC})_{Hybrid2} + (P_{DG})_{Hybrid2}}{P_{propulsion} + P_{aux}} \cdot \left(1 - (a_{P_{FC}})_{Hybrid\,2}\right) \tag{8.70}$$

An increase in the installed power of the FC and/or DG system consequently increases the volume, weight and cost of the power plant, see equation 8.71 to 8.73.

$$\Delta V_{power\ plant} = \frac{\Delta P_{FC}}{p_{vol,FCsystem}} + \frac{\Delta P_{DG}}{p_{vol,DGsystem}} \tag{8.71}$$

$$\Delta W_{power\ plant} = \frac{\Delta P_{FC}}{p_{grav,FCsystem}} + \frac{\Delta P_{DG}}{p_{grav,DGsystem}} \tag{8.72}$$

$$\Delta C_{power\ plant} = \Delta P_{FC} \cdot c_{FCplant} + \Delta P_{DG} \cdot c_{DGplant} \tag{8.73}$$

Increase in required energy

When the required propulsion power increases, the required energy on board increases (when range and speed remain constant), see equation 8.74 and 8.75. $E_{required,FC}$ and $E_{required,DG}$ already include a percentage fuel margin, meaning this margin is also included in the increase in required energy. An increase in the required energy consequently increases the volume, weight and cost of the fuel storage system (equation 8.76 to 8.78).

$$\Delta E_{required,FC} = \frac{\Delta P_{FC}}{P_{FC}} \cdot E_{required,FC} \tag{8.74}$$

$$\Delta E_{required,DG} = \frac{\Delta P_{DG}}{P_{DG}} \cdot E_{required,DG} \tag{8.75}$$

$$\Delta V_{fuel\ storage} = \frac{\Delta E_{required,FC}}{e_{vol,FCsystem}} + \frac{\Delta E_{required,DG}}{e_{vol,DGsystem}} \tag{8.76}$$

$$\Delta W_{fuel\ storage} = \frac{E_{required,FC}}{e_{grav,FCsystem}} + \frac{\Delta E_{required,DG}}{e_{grav,DGsystem}} \tag{8.77}$$

$$\Delta C_{fuel\ storage} = \Delta E_{required,FC} \cdot c_{fuel\ storage,FC} + \Delta E_{required,DG} \cdot c_{fuel\ storage,DG} \tag{8.78}$$

Increase in energy consumption

When the required propulsion power increases, the energy consumption also increases (when operational profile remains constant), see equation 8.79 and 8.80. This has a direct impact on the fuel cost, see equation 8.81 and 8.82. In equation 8.81 the factor that compensates for the decrease in efficiency over the lifetime of the fuel cell stack is again added.

$$\Delta E_{yearly,FC} = \frac{\Delta P_{FC}}{P_{FC}} \cdot E_{yearly,FC} \tag{8.79}$$

$$\Delta E_{yearly,DG} = \frac{\Delta P_{DG}}{P_{DG}} \cdot E_{yearly,DG} \tag{8.80}$$

$$\Delta C_{fuel,FC} = \Delta E_{yearly,FC} \cdot t_{lifetime,ship} \cdot c_{generated\ energy,FC} \cdot (1 + a_{FC\ efficiency}) \tag{8.81}$$

$$\Delta C_{fuel,DG} = \Delta E_{yearly,DG} \cdot t_{lifetime,ship} \cdot c_{generated\ energy,DG} \tag{8.82}$$

Iteration process

At the end of one iteration the ship design does not converge: extra volume is calculated for the fuel cell system, but it is not yet fitted into the ship. When iterating infinitely the extra required space approaches zero and thus the increase in ship size approaches zero, see equation 8.83. This is the case because ΔGT becomes smaller every iteration. For the model, infinite iteration is not possible. The iteration should be repeated until the consequences for the end result are limited. Several iterations were performed and it was found that after one iteration ΔGT is smaller than 0.5 % of the total GT for all combinations of fuel cell system and hybridization options. Consequently, one iteration is sufficient to exclude significant mutations from the end result.

$$\Delta GT_i = \lim_{i\to\infty} \big(0.2 + 0.02\log(GV_i + \Delta GV_i \cdot (GV_i + \Delta GV_i) - 0.2 + 0.02\log(GV_i) \cdot GV_i\big) = 0 \tag{8.83}$$

8.2.6. Comparison with the conventional solution

To indicate the impact of the concerning fuel cell system on the ship design, the (hybrid) fuel cell powered ship design is compared with the design of a conventional solution, meaning a full diesel generator powered plant, fueled with MGO. All calculated parameters of past 2 sections can be calculated as well for a conventional solution. The conventional solution is subtracted (or divided by for a percentage impact) to find the impact in the design.

For the cruise line, it is interesting to see how much the newbuild price increases for a fuel cell powered ship compared to a ship with the same requirements using a conventional solution. This is calculated with equation 8.84. The cost of the fuel cell system cannot simply be added to the original new build price to define the new build price. For the shipbuilder, a larger fuel cell powered ship implies a higher risk and a longer project duration. To the increase in cost of the newbuild ship a margin (a_{profit}) is added consisting of risk margin, overhead margin and profit margin. The used margins are not given in this research since they are confidential. ΔC_{ship} represents the increase in cost from the perspective of the ship owner. It is needed to convert the building cost to new build price to compare it with the fuel cost, which are both paid by the cruise line. In reality in the shipping market, the new build price paid by the customer cannot just be determined by the cost and a margin. The new build price would also be dependent on supply and demand forces of new vessels. For instance, when the demand is low, a shipbuilder might sell his ship at lower margins just to prevent big losses. This phenomenon is not included in the model.

$$\Delta C_{ship}[\%] = \frac{C_{ship,conv.} + \Delta C_{rest\,of\,ship} + a_{profit} \cdot \left(C_{FCsystem} + \Delta C_{FCsystem} - C_{conv.\,system}\right)}{C_{ship,conv.}} \tag{8.84}$$

where:

$C_{ship,conv.}$	New build price of ship with conventional solution, retrieved from expedition cruise reference ships
$\Delta C_{rest\,of\,ship}$	Increase in new build price due to increase in ship size, besides fuel storage system and power plant
a_{profit}	Profit margin of shipbuilder, including risk, overhead and profit
$C_{FCsystem}$	Cost of (hybrid) fuel cell power plant and fuel storage system for shipbuilder
$\Delta C_{FCsystem}$	Extra cost for shipbuilder of (hybrid) fuel cell power plant and fuel storage system due to increase in ship size
$C_{conv.\,system}$	Cost for shipbuilder of a conventional system

8.2.7. Emissions

The main purpose of fuel cell implementation in shipping is to reduce emissions. So, it is relevant to indicate the fuel cell system emissions compared with a conventional solution. This shows the effectiveness of implementing such a system. Although fuel cell emissions are drastically lower than emissions of a conventional solution [11, 66], it should be noted that for some fuel and fuel cell combinations some emissions remain [12, 22, 44, 68, 109]. Literature and supplier specifications often lack emission data. This section is executed in collaboration with a fuel cell expert; when references are missing this can be assumed to be the source of information. The chemical processes for all selected fuel cell systems are explained in this section for the reader to understand where certain emissions originate.

The emissions in the scope are CO, CO_2, NO_x, SO_x and particulate matter (PM). At the outlet of the fuel cell system other emissions can be measured as well (N_2, Ar, He, CH_4) [109]. Air is normally used to supply oxygen to the fuel cells and air contains all these elements [112]. Since the non-oxygen air is just circulated trough the fuel cell (with SOFC as exception), the net emission of these elements is zero and are therefore not included in the scope. So, for emissions to arise, their main chemical element (not H or O) must exist in the inlet fuel, contradicting to combustion engines where N_2 of the air is combusted into NO_x under very high temperatures, as was told by a fuel cell expert. The used system boundary of the emissions includes the whole fuel cell system on board. It is important to not just take into account the emission of the fuel cell itself but to the whole fuel cell system. For instance for LNG fueled LT-PEMFC, CO_2 is formed during the reforming process and not emitted by the fuel cell itself.

Fuel cells have very low sulfide tolerance (ppm range), meaning sulfides (in H_2S form) are already extracted from the fuel before reforming [66]. Zinc oxide is used to subtract the H_2S from the fuel. The absorbent is regenerated and H_2S is stored separately [103]. For all considered fuel cell systems the SO_x emissions are basically zero. So SO_x emissions will not be discussed in the following subsections, where the origin of the remaining four emissions will be explained.

LH2 fueled LT-PEMFC

Liquefied hydrogen only contains H_2. All hydrogen is converted to water, see figure 8.8 [66, 103]. Moreover, the temperature in this fuel cell type is not high enough to convert any N_2 of the air inflow into NO_x, meaning the emissions of a LH_2 fueled LT-PEMFC are zero.

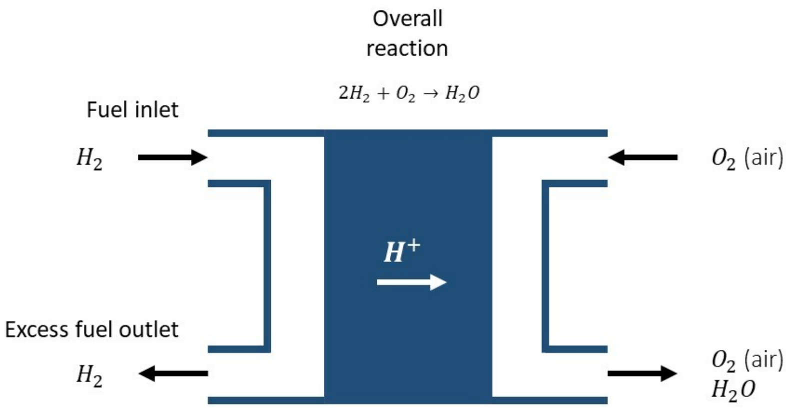


Figure 8.8: Fuel input, processing and fuel cell output for LH_2 fueled LT-PEMFC [own image]

LNG fueled LT-PEMFC

LNG mainly consists of methane (CH_4), some other hydrocarbons and a small proportion of N_2. During steam reforming (equation 8.85), syngas is formed out of LNG, consisting out of H_2 and CO. Most CO is turned into CO_2 with the water gas shift reaction (equation 8.86) [11, 66].

$$CH_4 + H_2O \rightleftharpoons CO + H_2 \tag{8.85}$$

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \tag{8.86}$$

Most of the remaining CO is taken out with purification equipment to meet the stringent impurity requirements of LT-PEMFC, see figure 8.9 [11, 66]. Also, the temperature of the LT-PEMFC is not high enough to form any NO_x. At the outlet of the reformer, a burner converts remaining H_2 and CO and resupplies heat to the reformer. In case of incomplete combustion, traces of CO, NO_x and H_2 can remain in the outlet of the reformer, but these are very low (figure 8.9). The fuel that enters the fuel cell consists mainly of hydrogen. To conclude, for LNG fueled LT-PEMFC the emissions consist of CO_2 and traces of CO and NO_x. These substances are emitted at the reformer.

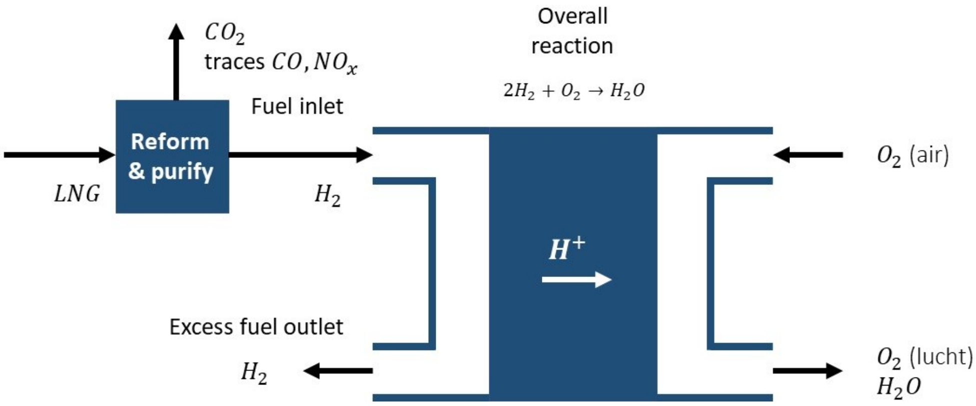


Figure 8.9: Fuel input, processing and fuel cell output for LNG fueled LT-PEMFC [own image]

LNG fueled SOFC

For SOFC, internal reforming omits the need for an external reformer, meaning LNG can be directly used as input for SOFC , see figure 8.10. SOFC makes use of an afterburner which is fueled by the excess fuel and the air outlet of the fuel cell. The after burner heats the high temperature fuel cell to increase efficiency of the fuel cell system [66]. Although the temperature of SOFC is very high, it is not high enough to form NO_x out of the present N_2. However, in the afterburner some N_2 is converted to NO_x due to combination of high temperature and catalytic burning. The afterburner emits CO_2 and traces of NO_x, CO and PM.

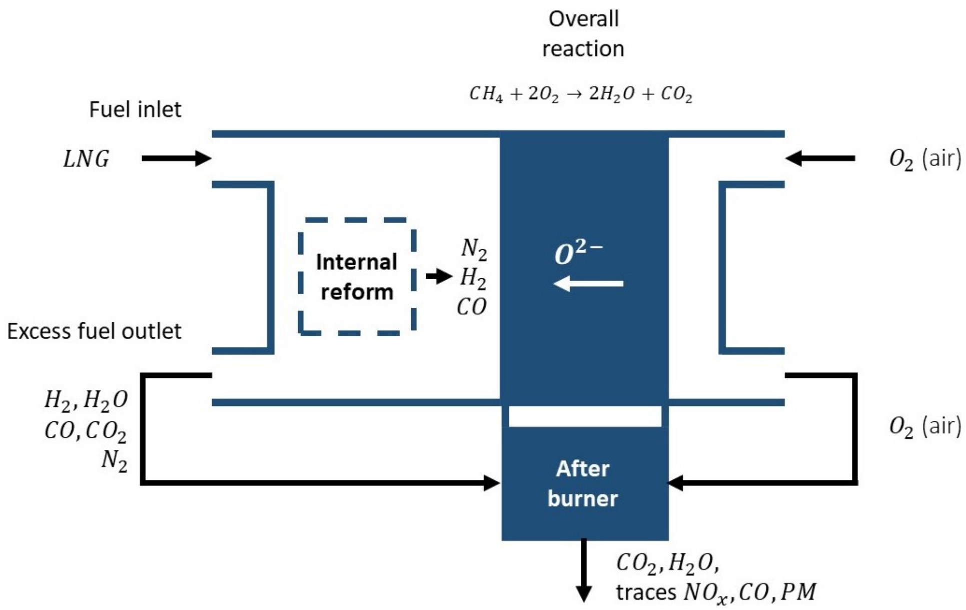


Figure 8.10: Fuel input, processing and fuel cell output for LNG fueled SOFC [own image]

MeOH fueled PEMFC

In terms of emissions, the methanol fueled PEMFC is analogous to LNG fueled LT-PEMFC, with the only fundamental difference that methanol does not contain N_2, meaning no NO_x is formed at the reformer. Methanol is converted to CO, CO_2 and H_2 in the methanol reformer and most of the CO is subtracted from the fuel during purification [66]. Figure 8.11 is the same for LT-PEMFC and HT-PEMFC, the only difference is that for LT-PEMFC more purification is necessary. To conclude, for $MeOH$ fueled PEMFC main emissions are CO_2 with traces of CO and are emitted at the reformer.

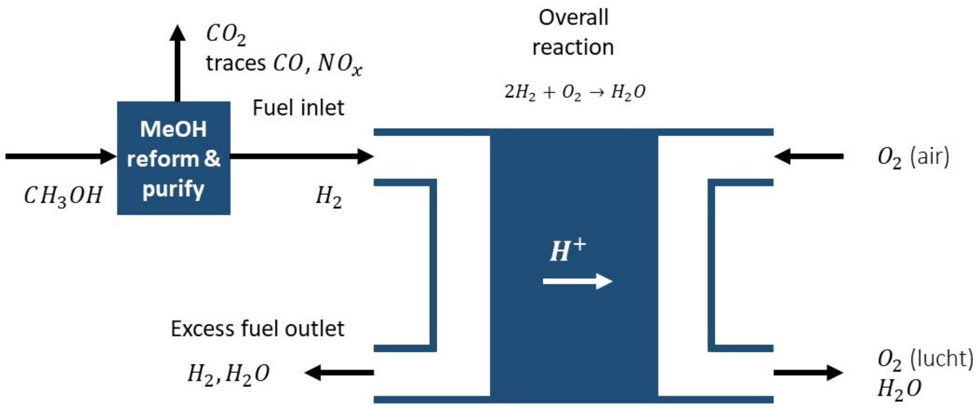


Figure 8.11: Fuel input, processing and fuel cell output for $MeOH$ fueled LT-PEMFC and $MeOH$ fueled HT-PEMFC [own image]

MeOH fueled SOFC

Methanol is reformed in the methanol reformer to syngas (H_2 and CO). No purification is needed because the SOFC has high CO tolerance. The CO and excess H_2 are redirected to the afterburner [66]. The main emission at the afterburner is CO_2 and in case of incomplete combustion some traces of CO can be emitted. Although methanol does not contain N_2, the air used for the combustion does, meaning some of the N_2 will be converted to NO_x in the afterburner as well due to combination of high temperature and catalytic burning.

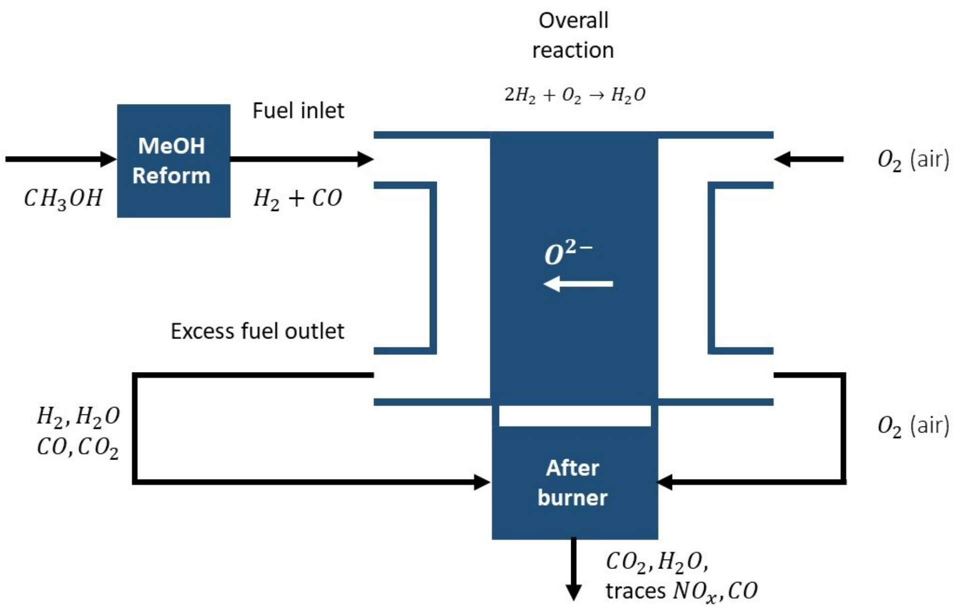


Figure 8.12: Fuel input, processing and fuel cell output for $MeOH$ fueled SOFC [own image]

NH3 fueled SOFC

Ammonia is a carbon free fuel, meaning this option does not emit any CO or CO_2, see figure 8.13. Sulfides are also not existing in Ammonia. Ammonia can directly be used in SOFC, since it is internally reformed to N_2 and H_2 [116]. High amounts of N_2 are redirected to the afterburner, meaning a considerable amount of N_2 will be converted to NO_x in the afterburner as well due to combination of high temperature and catalytic burning. However for the $NH3$ fueled SOFC this is the only considerable emission.

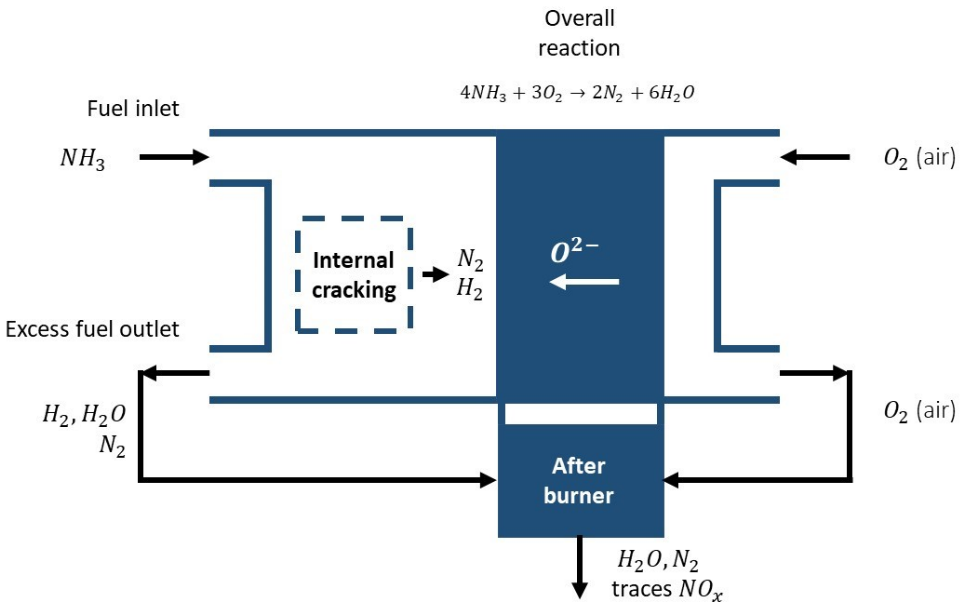


Figure 8.13: Fuel input, processing and fuel cell output for NH_3 fueled SOFC [own image]

Overview of emissions of all selected systems

The amount of emissions per MWh generated electricity is shown in table 8.5. This includes the efficiency of the fuel cell system. The emissions of CO, CO_2, NO_x, SO_x and particulate matter (PM) are provided. Other emissions that are measurable at the exhaust (Ar, He) originate out of the used air and are not included in the emission scope. This data is used as input for the model to calculate the emissions over the operational lifetime of the ship and compared it to the emissions of a conventional solution. Equations 8.87 and 8.88 show that the emissions are defined per different operation. This is because the impact of the emissions on the environment is dependent on where they are emitted. For instance Antarctic areas are more sensitive to emissions than the middle of the Atlantic ocean. This will also be used in discussion section 11.3 while determining the environmental damage of the emissions.

$$EMIS_{type,FCsystem} = E_{yearly,FC,operation} \cdot emis_{type,FCsystem} \tag{8.87}$$

$$EMIS_{type,DGsystem} = E_{yearly,DG,operation} \cdot emis_{type,DGsystem} \tag{8.88}$$

where:

E_{yearly}	Yearly energy consumption, including non-operative days for a certain operation (transit, coastal, antarctic)
$emis_{type}$	Specific emission of generated electrical energy including efficiency of fuel cell system [$kg/MWhe$], see table 8.5 for used data

Table 8.5: Specific emissions per generated MWhe for selected FC systems and conventional solution (including system efficiency). The emissions for MGO fueled diesel generator is derived with Damen mechanical engineers. As can be seen in the table, the NO_x, SO_x and PM emissions are not significant compared to those of a conventional system.

		CO kg/MWhe	**CO_2** kg/MWhe	**NO_x** kg/MWhe	**SO_x** kg/MWhe	**PM** kg/MWhe	**Source**
LH2	LT-PEMFC	-	-	-	-	-	[5, 11]
LNG	LT-PEMFC	0.0225	514	-	-	-	[5, 11]
LNG	SOFC	0.0150	343	0.0008	-	0.0001	[5, 11, 12, 22, 106]
MeOH	LT-PEMFC	0.0111	349	0.0005	-	-	[11, 46, 57, 107]
MeOH	HT-PEMFC	0.0125	466	0.0006	-	-	[11, 46, 57, 107]
MeOH	SOFC	0.0091	524	0.0008	-	0.0001	[11, 12, 46, 57, 107]
NH3	SOFC	-	-	0.0031	-	-	[11, 12]
MGO	DG	1.56	661	11.99	2	1.60	[5]

8.3. Model verification

A vast number of steps and calculations were presented in section 8.2, where the model was explained. There is a significant chance on typing and programming errors, so model verification is required. This section is dedicated to ensuring the reader that the presented model is implemented correctly [99].

First the verification approach is stated in 8.3.1. Following, the results of the verification process is presented per verification method. Not all performed verification calculations are shown, since that would be too extensive to show in this report.

8.3.1. Verification approach

Since the full model cannot be compared with benchmark models (as far as known there are no comparable calculation models for this subject with the same scope), partial verification is applied. With partial verification parts of the model for which the output is known for a certain input, are isolated and tested. When this is performed systematically for the whole model, it is possible to verify the model. The following verification methods of Sargent [99] are used to verify the model:

- *Structured walk through of the model*
  The model is thoroughly inspected by redoing all calculations steps and by doing simplified versions of the calculations and comparing them.
- *Balance checks of sums, averages and or combinations of parameters*
  For instance, is the installed power of the FC system divided by the FC system volume equal to the used power density of the concerned FC system?
- *Testing extreme conditions*
  For instance operating at a very high speed or excluding the transit operation from the model.

8.3.2. Balance checks

The results of the performed balance checks are shown in table 8.6. To systematically check the model, verification is divided in: ship design, fuel cell system and cost. These checks are performed for all fuel cell systems and all hybrid options. In the third column the maximum error (positive or negative) is viewed for these different fuel cell systems and hybrid options. The inquiries that resulted in an error will be explained shortly.

The GT output was checked by comparing it with the GT that belongs to the GV output (according to the GT equation). A small error was found here, this is due to the fact that only one iteration is performed and the GV does not fully converge to the GT, as explained in section 8.2.5 with equation 8.83. The small error acknowledges the statement that one iteration is sufficient.

For the range check, a small error was found. The error originates out of a linearization in the increase in energy consumption calculation during the design iteration. The increase in energy consumption was linearized by multiplying the energy consumption with the ratio between increase in installed power due to the increase in ship size and the original installed power. This was presented in equation 8.79 and 8.80. Although the used energy for a transit is slightly higher than the stored energy on board, the error is sufficiently small to be compensated by the included fuel margin for the FC system.

For the fuel cell power ratio there is a significant maximum error with the ratio between the installed FC and DG power. This error is only present for hybrid option 1. The error originates from the fact that in the design iteration only the required propulsion power (and not the required auxiliary power) increases and the fuel cell power ratio is calculated before the feedback step. Since in hybrid option 1 all propulsion power is delivered by the DG system, the increase in ship size only increases the DG power, resulting in a shift of the fuel cell power factor. Since the power factor is not used to calculate any other parameters (like required energy or energy usage), this has no effect on the results of the model. Thus, the error is acceptable.

The density of the fuel has a small error compared to the stored volume and weight of the fuel cell fuel. The error has the same origin and the same magnitude as the error in the range check. It originates from a linearization in the increase in energy consumption. The error is sufficiently small. All other checks did not result in any error. An example calculation of the error of the range check is provided on the next page.

Table 8.6: Model verification: balance checks to verificate output and intermediate values of the model.

Balance check	**Description**	**Max error**	**Verified**
Ship design			
Displacement	Does displacement output match with $L_{wl} \cdot B \cdot T \cdot C_B$	0.0%	✓
GT-GV	Does GT output match with GV output	-0.1%	✓
Cb-speed	Does the block coefficient align with the desired speed	-	✓
Installed power	Is there enough power installed to reach maximum speed	0.0%	✓
Range check	Does total stored fuel satisfy range and endurance requirement	-0.3%	✓
Fuel cell system			
FC power factor	Does a_{FC} match with installed power	2.7%	✓
Density of fuel	Does weight and volume of stored fuel match with density	-0.3%	✓
Volumetric power density	Does installed FC power and FC volume match with used $p_{FC,vol}$	0.0%	✓
Gravimetric power density	Does installed FC power and FC weight match with used $p_{FC,grav}$	0.0%	✓
Cost			
Specific cost FC plant	Does cost of FC system and installed FC power match with c_{FC}	0.0%	✓
Cost of FC system	Does cost of FC system match with sum of cost components	0.0%	✓
Shipbuilding cost	Does shipbuilding cost match with sum of cost components	0.0%	✓

Verification example - Range check

This example is provided to the reader to show how verification is performed and how the error is derived. Other balance checks are performed in a similar way. This verification example evaluates whether enough fuel cell fuel is stored on board to satisfy range requirements. In this example intermediate results of the model are shown for input of an average ship.
The output of the fuel tanks is used to calculate how much energy can be stored on board, see equation 8.89 and column 4 of table 8.7. This is compared with the used energy during the most energy consuming operation, see 8.90 and column 5. The error is calculated out of these values, see equation 8.91 and column 5. For the full fuel cell powered ship and hybrid option 1 the error is 0%. For hybrid option 2, the used energy is slightly higher than the energy in the stored fuel. However, in the used fuel a 20% fuel margin is taken into account, so this error is easily compensated. The error originates from a linearization in the increase in energy consumption calculation during the design iteration. Consequently, the calculation that determines the amount of required fuel is verified.

$$E_{stored\,fuel} = W_{stored\,fuel} \cdot LHV \tag{8.89}$$

$$E_{used,FC} = \frac{E_{used,FC} + \Delta E_{used})}{\eta_{FCsystem}} \tag{8.90}$$

$$Error = \frac{E_{Stored\,fuel} - E_{Used\,energy}}{E_{Used\,energy}} \tag{8.91}$$

Table 8.7: Verification example: compare stored fuel with range requirements.

Fuel	Fuel cell	Hybrid	Energy in stored FC fuel	Energy used FC	Error
			kWh	kWh	-
LH2	LT-PEMFC	Full_FC	6,500,685	6,500,685	0.0%
LNG	LT-PEMFC	Full_FC	8,498,203	8,498,203	0.0%
LNG	SOFC	Full_FC	5,454,032	5,454,032	0.0%
MeOH	LT-PEMFC	Full_FC	7,736,848	7,736,848	0.0%
MeOH	HT-PEMFC	Full_FC	8,636,806	8,636,806	0.0%
MeOH	SOFC	Full_FC	5,896,485	5,896,485	0.0%
NH3	SOFC	Full_FC	5,910,529	5,910,529	0.0%
LH2	LT-PEMFC	Hybrid1	3,551,688	3,551,688	0.0%
LNG	LT-PEMFC	Hybrid1	4,735,584	4,735,584	0.0%
LNG	SOFC	Hybrid1	3,044,304	3,044,304	0.0%
MeOH	LT-PEMFC	Hybrid1	4,262,026	4,262,026	0.0%
MeOH	HT-PEMFC	Hybrid1	4,735,584	4,735,584	0.0%
MeOH	SOFC	Hybrid1	3,278,481	3,278,481	0.0%
NH3	SOFC	Hybrid1	3,278,481	3,278,481	0.0%
LH2	LT-PEMFC	Hybrid2	3,408,614	3,417,375	-0.3%
LNG	LT-PEMFC	Hybrid2	4,505,528	4,507,851	-0.1%
LNG	SOFC	Hybrid2	2,893,949	2,894,856	0.0%
MeOH	LT-PEMFC	Hybrid2	4,074,202	4,080,872	-0.2%
MeOH	HT-PEMFC	Hybrid2	4,536,434	4,546,119	-0.2%
MeOH	SOFC	Hybrid2	3,120,705	3,122,668	-0.1%
NH3	SOFC	Hybrid2	3,124,096	3,126,867	-0.1%
				MAX	-0.3%

8.3.3. Testing of extreme conditions

In this section different extreme conditions are defined for which the model is not designed, but should be able to handle accordingly. The results of the tests are summarized in table 8.8. The following extreme conditions are investigated:

1. No antarctic operation
2. No transit

The following extreme conditions are considered but not investigated:

- Very high transit speed. Although it would be interesting to see how the model would behave for using a very high speed, it is already known that some of the used assumptions and formulas do not hold for high speeds, like the Admiralty constant. So the model should not be applied for these conditions.

Table 8.8: Verification of model: testing extreme conditions.

Extreme condition	Discription	Result	Confirmed
No Antarctic operation	Antarctic similar to coastal in terms of requirements and fuel usage	Similar build cost and fuel cost	✓
No transit operation	Lower range, endurance and speed requirements and no DG for hybrid 2	Smaller ship and lower shipbuilding cost	✓

Test case 1: No antarctic operation
Although expedition cruise ships regularly operate partly in antarctic areas and partly in temperate coastal areas, a cruise line might choose to only operate in coastal areas and not perform any antarctic itineraries (or vice versa). Since antarctic and coastal operations are quite similar, no big differences in output are expected. The build cost of the ship is mainly dependent on the requirements for transit, so build cost is expected to be equal. The fuel consumption in coastal and antarctic operation is similar but not the same, so a small deviation in fuel cost is expected. The hypothesis for how the model would behave for only coastal operation is:

When excluding the antarctic operation the model will result in almost equal build cost and similar fuel cost.

When antarctic operation execution is set to 0%, the model averagely results in a 0.11% decrease in shipbuilding cost and a 0.7% increase in fuel cost, meaning the hypothesis is confirmed. Although the behavior of the model is as expected, it should be noted that in reality, when (ant)arctic requirements are not needed the build cost would decrease. For instance, no ice class would be needed and the HVAC system would have lower heating capacity requirements. However, these design considerations are not included in the model.

Test case 2: No transit
When the cruise line determines that a long transit is not required, for instance when antarctic operations are started from the south of Chili and coastal operations are executed at the Argentinian coast. This means that the power plant is purely based on the requirements of the coastal and antarctic operations. This will lead to lower range, endurance and speed requirements. The hypothesis for how the model would behave for no transit is:

When excluding transit the model will result a smaller and cheaper ship. Also, hybrid option 2 (DG for transit) should now be the same as full FC option.

When transit usage is set to 0%, the model averagely results in a 2% smaller ship and a decrease in shipbuilding cost of 20% compared to a design that can fulfil a transit. Consequently, the first part of the hypothesis is confirmed. For the second part of the hypothesis it was expected that the results of hybrid option 2 are the same as for the full fuel cell option, since no transit is used so no diesel system is needed. However, for hybrid option 2 the power required for the coastal and antarctic operation is complemented with DG power to fulfil the speed requirements, meaning DG was still installed is this option. Nevertheless, since no transit is used in this test case it could be stated that hybrid option 2 (DG for transit) is not applicable.

8.4. Model validation

After model verification confirmed that the presented model is correctly programmed, the reader should also get the confidence that the programmed model has sufficient accuracy for the model's intended purpose over the application range of the model [99]. That is the goal of this section.

Full scale validation by comparing the model results with similar models or real life examples is not possible. Similar models were not found and there are no ships on which fuel cell systems are implemented on a large scale, let alone for expedition cruise ships.

The validation methods that were executed for this model are [99]:

- *Data validation*
  The calculated performance data is presented to fuel cell experts and checked versus their knowledge of the systems.

- *Benchmarks*
  Intermediate results of the model were benchmarked using research results and knowledge of suppliers and fuel cell experts. Examples of executed benchmark validations are: i) size of LNG reforming plant is approximately 3 times the size of the power pack for LNG fueled LT-PEMFC. ii) size of a 2 MW LT-PEMFC plant.

- *Logical interpretation of results*
  The results were interpreted and reasoned whether these model outputs would match expectations from reality. Result interpretation is done in the next section where the results will also be presented.

- *Sensitivity analysis*
  The input and/or internal parameters of the model were systematically changed to determine the impact on the model output. Input was varied in section 9.2 in terms of range, endurance and GT. Internal parameters were varied in section 11.4 in terms of fuel cell prices and fuel prices.

8.5. Conclusion

A design tool was developed to estimate impact on ship design in terms of ship size, capital cost and fuel cost. The design tool is meant for design & proposal engineers and is applicable for the very first design phase. The purpose of the design tool is to support the engineer in making well-funded decision on the implementation of a fuel cell system. The goal of the design tool was: "The design tool should deliver a cost estimate for a fuel cell powered expedition cruise ship based on the general requirements and information available in the Rough Order of Magnitude design phase."

The design tool evaluates seven different fuel cell systems for a ship design based on general ship requirements (dimensions and PAX) and the operational profile of the ship. Three different energy generation options are evaluated:

- *Full fuel cell powered ship*
  All energy on board is generated by fuel cells. No extra machine room is required for diesel generators.

- *Hybrid 1: Fuel cell power generation for auxiliary load*
  All power for auxiliary systems (including hotel) is provided by the fuel cell system. All power for propulsion is provided by the diesel generator set. For this option the fuel cell system fits well with hotel systems due the smaller changes in power demand (compared to the propulsion system).

- *Hybrid 2: Diesel generators for the transit*
  For this hybrid configuration the operation which requires most fuel storage and power (transit) is supported with diesel generators running on MGO. The DG system is used to boost the ship speed to the desired speed for transit, while also fulfilling the range requirements for the transit.

The fuel cell system performance data (section 6.3) and expedition cruise reference ships (section 7.2) are used as data for the design tool. Reference ships are used to determine ship parameters. Townsin and regression method are considered to determine displacement, of which the regression method was selected. Following, propulsion power is determined with the admiralty formula and auxiliary power is based on PAX, leading to the required power. From here, the power plant is dimensioned. By combining power with operational profile and using propeller law, the required energy and energy usage are determined for different operations. Required energy is used to dimension fuel storage and energy usage is used to determine fuel cost. One design iteration is performed to fit the fuel cell system, consequently increasing ship size and required power. This in turn further increases the size and cost of the fuel cell system and the fuel cost. In the design iteration, the increase in displacement can be weight driven or volume driven. Finally, the CO, CO_2, NO_x, SO_x and PM emissions are determined. The model was verified with: structured walkthrough, balance checks and testing extreme conditions. An overview of the most important assumptions for the design tool is viewed in table 8.9.

Table 8.9: Most important assumptions for the design tool.

Assumptions	**Amount**	**Unit**	**Source**
Fuel cell system data			
Constant FC system efficiency over load			
Volume and weight of FC system scale linearly with installed power			
Operations			
Operational days	357	days	
Lifetime ship	15	years	Damen
Density seawater	1.025	ton/m3	
High fuel availability			
Power			
Admiralty formula - ships with similar C_B, F_n			[62]
Installed power for auxiliaries per PAX	16.2	kW/PAX	Reference ships
Propulsion power demand for operations determined with propeller law			[62]
- Propulsive efficiency remains constant in off-design conditions			[62]
- Shaft speed is linearly proportional to translating speed			[62]
Average auxiliary power demand	70%	-	Damen electrical engineers
Average auxiliary power demand in harbour	35%	-	Damen electrical engineers
Required energy			
Fuel margin FC system	20%	-	Fuel cell expert
Fuel margin DG system	10%	-	Damen D&P engineers
Energy usage			
Electrical- and mechanical transmission losses same for FC and DG system			
Financial			
Constant fuel prices over lifetime			
Constant fuel cell prices over lifetime			
Increase in cost of FC system for fuel processing (not included in data)			
Increase in cost of FC system for BOP (not included in data)			
Operational cost besides fuel cost are constant (crew wages, port, towage)			
Increase in fuel cost due to decrease in fuel cell efficiency over lifetime	5%		
Profit margin	confidential	-	Damen
Risk margin	confidential	-	Damen
Overhead margin	confidential	-	Damen
Design iteration			
Increase in ship cost per increase in GT apart from FC system	5000	€/GT	Reference ships

9
Results

This chapter presents the results of the design tool. It aims to achieve the fifth research objective: *Evaluate the impact (in ship size, capital cost, operational cost and emissions) of the combination of the chosen fuel cell systems and operational profile requirements on the design of expedition cruise ships. Choose the most suitable fuel cell systems for expedition cruise ships.*

The general results are shown in section 9.1, where an average ship (compared with the reference ships) is evaluated. In section 9.2, the operational and capacity requirements of the ship are systematically varied.

In all results, the model output is presented. This means for instance, when the volume of the fuel cell system is presented, it already includes the extra volume of the system that is necessary because the required power and required energy increased when the ship size increased during the design iteration.

9.1. General results

The results are characterized by a different order of accuracy. The required volume, weight and cost of the fuel cell system are accurately calculated. However, for the percentage increase in newbuild price, the cost of the fuel cell system is related to the expected shipbuilding cost for a conventional ship with the same requirements. The expected shipbuilding cost is based on reference ships and the spread for build cost per GT is significant. Following, the fuel cost over the lifetime can have even higher deviations, since the fuel price could vary much over the lifetime of the ship. In this section, the results are broken down and presented to the reader in decreasing order of accuracy. They are generated for an average ship (compared to the reference ships). The main particulars of this average ship are shown in table 9.1. The requirements for which the results are generated are shown in table 9.2.

Table 9.1: Main particulars of average ship (average with respect to reference ships) for which the results are generated. The model uses PAX and luxury level as starting point, of which the other parameters are derived.

Dimension	Amount	Unit	Quantity	Amount	Unit
Length OA	191	m	Gross Tonnage	31321	GT
Length PP	168	m	Displacement	18858	ton
Beam	26	m	PAX	500	-
Draught	6.3	m	Crew	323	-
Depth	9.8	m	POB	823	-

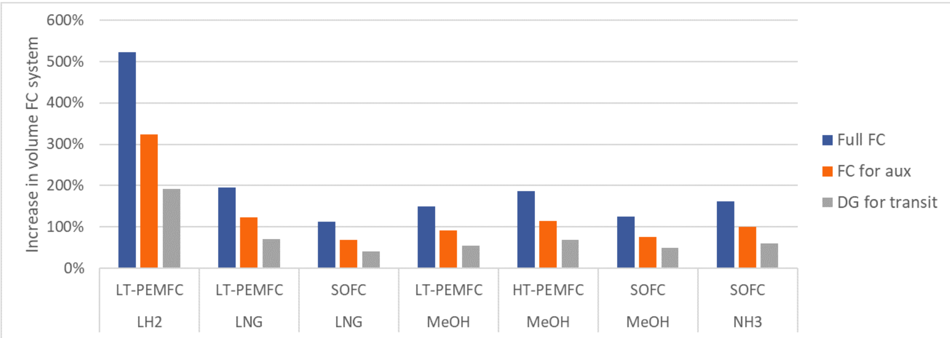
Table 9.2: Requirements of evaluated fuel cell powered ship. Derived from operational profiles and requirements of several expedition cruise ships.

Requirement		Unit	Requirement		Unit
Design speed	12	kn	Range	3600	nm
Max speed	14	kn	Endurance	17	days

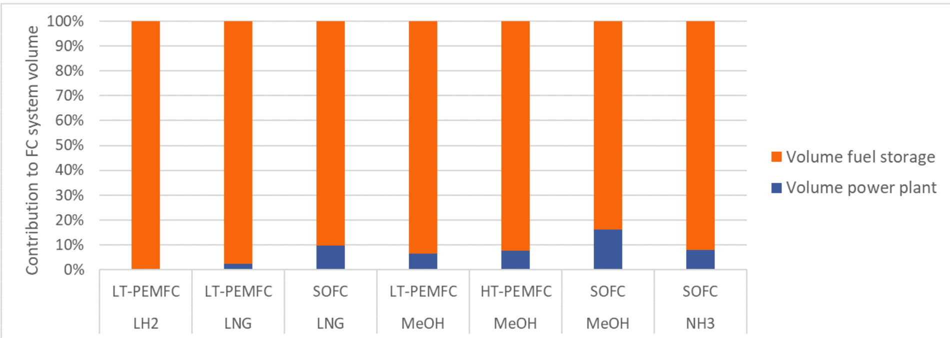
9.1.1. Fuel cell implementation

In this section, the characteristics of the fuel cell implementation are compared with the diesel generator system that would be necessary for a ship with the same requirements. Fuel cell implementation has influence on the volume, weight and cost with respect to the conventional system.

Figure 9.1 (a) shows the increase in volume of the (hybrid) fuel cell system compared to the conventional system. The volume increase is by far the largest for the *LH2* fueled LT-PEMFC system. *LNG* fueled SOFC offers the lowest increase in volume for all hybrid strategies of which hybrid option 2 (DG for transit) results in the smallest volume increase of all 21 options. Between the hybridization strategies, the full fuel cell powered ship requires most volume for the fuel cell system; the diesel for transit option requires the lowest volume for all different fuel cell systems. This was expected, since for hybrid option 2, the long range requirements are solved by using diesel generators for support. With this method the very large alternative fuel tanks are not necessary. Figure 9.1 (b) shows the contribution of the fuel storage and the fuel cell power plant to the volume of the FC system. From this figure can be derived, that the volume of all considered fuel cell systems is mainly driven by fuel storage.



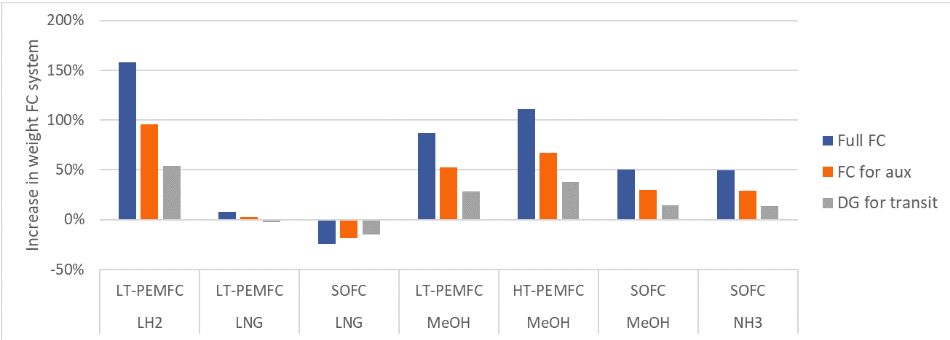
(a) Increase in volume of (hybrid) fuel cell system with respect to the volume of the DG system that would be necessary for a conventional ship. This graph includes power plant and fuel storage.



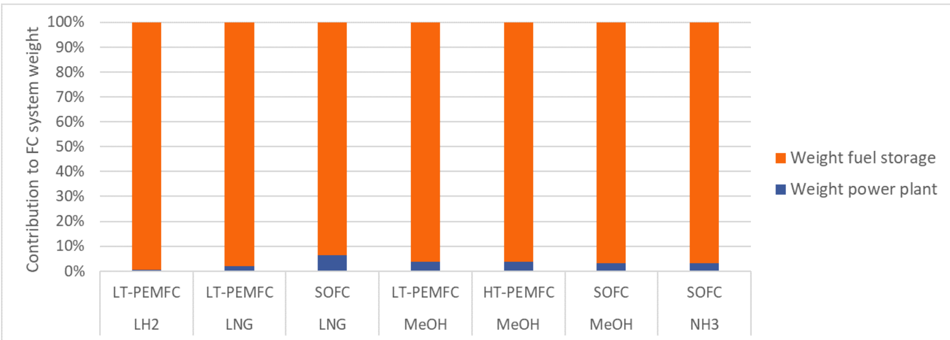
(b) Contribution of fuel storage system and power plant to volume increase of figure (a) for the full FC option. This graph is not by definition the same for the hybrid options, but they are similar and are thus for practical reasons not shown.

Figure 9.1: Increase in volume.

Figure 9.2 (a) shows the increase in weight of the (hybrid) fuel cell system compared to the conventional system. The weight increase is the largest for the *LH*2 fueled LT-PEMFC system. This can be explained by the high weight of the hydrogen storage tanks. For all considered fuel cell systems, the weight increase is mainly driven by the weight of the fuel storage (figure 9.2 (b)). For fuel cell systems fueled with LNG, there are options where the required fuel cell system is less heavy than the conventional system. This implies that for these options, the increase in ship size to fit the fuel cell system is definitely volume driven. Hybrid option 2 (DG for transit) often causes the smallest increase in weight. *LNG* fueled SOFC used for a full fuel cell powered ship causes the largest decrease in weight compared to the conventional system.



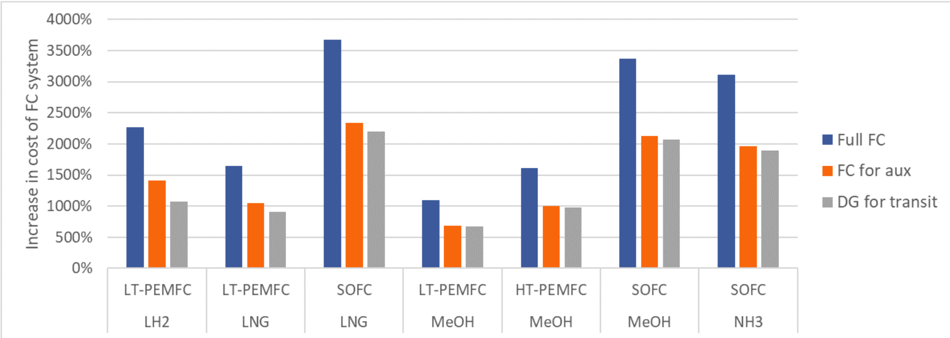
(a) Increase in weight of (hybrid) fuel cell system with respect to the weight of the DG system for a conventional ship. This graph includes power plant and fuel storage.



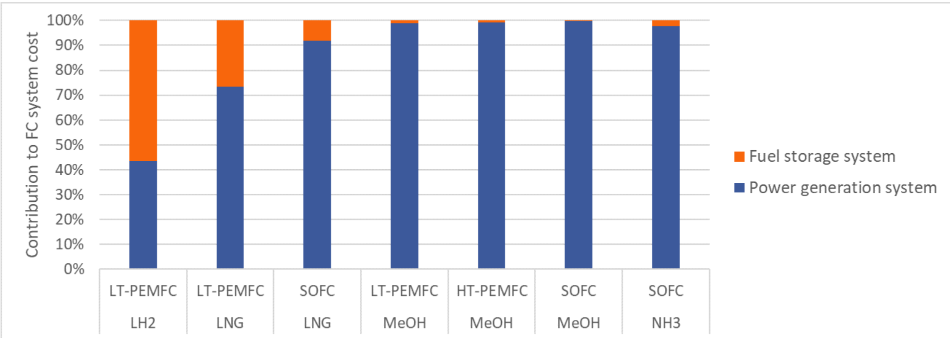
(b) Contribution of fuel storage system and power plant to weight increase of figure (a) for the full FC option. This graph is not by definition the same for the hybrid options, but they are similar and are thus for practical reasons not shown.

Figure 9.2: Increase in weight.

Figure 9.3 (a) shows the increase in cost of the whole fuel cell system compared to the conventional system. This represents the increase in cost from the perspective of the ship builder. Very large cost increases are found, especially for SOFC systems. This is due to the very high cost of SOFC stacks. Where volume and weight were mostly driven by the fuel storage system, the power generation system dominates in driving the cost (with exception of LH_2 fueled LT-PEMFC), see figure 9.3 (b). $MeOH$ fueled LT-PEMFC combined with one of the hybrid options results in the lowest increase of the power plant. For every fuel cell system, the highest increase in cost occurs for the full fuel cell powered ship. This is due to the fact that, for the hybrid options less fuel cell power is installed. From figure 9.3 (a) can be expected that the fuel cell power ratio $a_{P_{FC}}$ (explained in section 8.2.2) was very similar for both hybrid options, since the cost of their fuel cell power plant is very similar. This can be affirmed since the $a_{P_{FC}} = 0.64$ for hybrid option 1 and $a_{P_{FC}} = 0.62$ for hybrid option 2. These values also explain why the increase in cost is slightly higher for hybrid option 1 for most of the considered fuel cell systems.



(a) Increase in cost of (hybrid) fuel cell system with respect to the cost of the DG system for a conventional ship. This graph includes power plant and fuel storage.



(b) Contribution of fuel storage system and power plant to increase in cost of figure (a) for the full FC option. This graph is not by definition the same for the hybrid options, but they are similar and are thus for practical reasons not shown.

Figure 9.3: Increase in cost.

9.1.2. Increase in ship size

Since the (hybrid) fuel cell system is bigger than the conventional system, the ship size was increased in the model to fit the fuel cell system. Consequently, this increases: ship resistance, required power, required energy, energy consumption, and thus the cost of the fuel cell system. Figure 8.63 shows the increase in GT for the different fuel cell systems and hybrid options. The figure shows that the increase in ship size is very different per fuel cell system and hybrid option. Hybrid option 2 (DG for transit) consistently leads to the lowest increase in ship size. Overall, LNG fueled SOFC in combination with hybrid option 2 leads to the lowest increase in ship size. This was expected due to the high power density of LNG and high efficiency of SOFC. LH_2 fueled LT-PEMFC results in the largest increase in ship size. This was also expected due to the low energy density of the storage of hydrogen.

In the model, the increase in required propulsion power and the increase in rest of ship cost, do not scale with the same percentage as the increase in GT. They do scale with the same mutual ratios between the different options. So the graphs of these increases look identical to figure 8.63 with different percentages on the y axis.

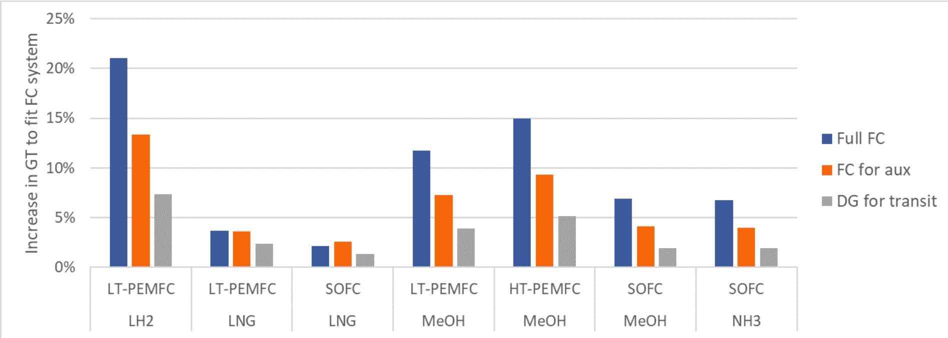


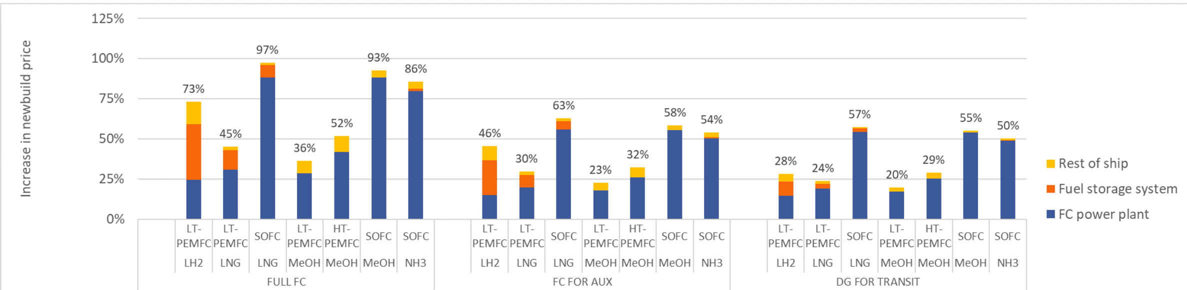
Figure 9.4: Increase in GT during the design iteration with respect to GT of conventional ship (in order to fit FC system in the ship).

9.1.3. Increase in cost

This section presents the increase in cost of the total ship. It is relevant to relate the cost of the fuel cell system to the newbuild price; when the newbuild price is combined with the fuel cost over the lifetime, a conclusion can be drawn about the impact of the fuel cell system on the total cost from the perspective of the cruise line. This means that profit, risk and overhead margins of the shipbuilder are added to the ship building cost of the fuel cell implementation to result in the newbuild price. Financing cost for the cruise line are not included, since it is very dependent on the country and risk of the project.

Increase in newbuild price

Figure 9.5 shows the increase in newbuild price for the different fuel cell systems and hybrid options compared to the same ship with conventional power generation. The total increase in newbuild price is provided with data labels, while the contributions by fuel storage, power plant and rest of ship are viewed with stacked columns (contributions also showed in table under graph). As was also reported for figure 9.3, the cost is still dominated by the cost of the power plant (expect for LH_2 fueled LT-PEMFC). The 'rest of ship cost' scales linearly with figure 9.4, since a constant cost increase per GT was defined for the design iteration. Fuel cell systems that use SOFC cause the highest increase in newbuild price, due to the high cost of SOFC per kW. For every hybridization strategy, $MeOH$ fueled LT-PEMFC results in the lowest increase in newbuild price. LNG fueled LT-PEMFC also offers a low increase in newbuild price for hybrid option 1 and 2, followed by LH_2 fueled LT-PEMFC for hybrid 2. When the different hybridization options are compared, it can be noted that for both hybrid options the contribution by the FC power plant (blue) is very similar, however hybrid option 2 performs better on contribution of fuel storage system and 'rest of ship'. This makes sense since the approach of hybrid option 2 was to let the diesel generator system support during longer trips, leading to smaller alternative fuel tanks and thus a smaller increase in ship size. Consequently, hybrid option 2 results in a lower increase in newbuild price for all considered fuel cell systems.



	FULL FC							FC FOR AUX							DG FOR TRANSIT						
	LT-PEMFC LH2	LT-PEMFC LNG	SOFC LNG	LT-PEMFC MeOH	HT-PEMFC MeOH	SOFC MeOH	SOFC NH3	LT-PEMFC LH2	LT-PEMFC LNG	SOFC LNG	LT-PEMFC MeOH	HT-PEMFC MeOH	SOFC MeOH	SOFC NH3	LT-PEMFC LH2	LT-PEMFC LNG	SOFC LNG	LT-PEMFC MeOH	HT-PEMFC MeOH	SOFC MeOH	SOFC NH3
Total increase	73%	45%	97%	36%	52%	93%	86%	46%	30%	63%	23%	32%	58%	54%	28%	24%	57%	20%	29%	55%	50%
Rest of ship	14%	2%	1%	8%	10%	5%	4%	9%	2%	2%	5%	6%	3%	3%	5%	2%	1%	3%	3%	1%	1%
Fuel storage system	35%	12%	8%	0%	0%	0%	2%	22%	8%	5%	0%	0%	0%	1%	9%	3%	2%	0%	0%	0%	0%
FC power plant	24%	31%	88%	28%	42%	88%	80%	15%	20%	56%	18%	26%	56%	50%	15%	19%	54%	17%	25%	54%	49%

Figure 9.5: Increase in newbuild price with respect to the newbuild price of a conventional ship with equal requirements. The data labels indicate the total increase in newbuild price.

Increase in fuel cost

To really judge which option is more effective, the fuel cost over the lifetime should also be reviewed; a higher newbuild price might be worthwhile for a cruise line when it is accompanied by savings in fuel cost. Figure 9.6 shows the increase in fuel cost compared to the fuel cost over the lifetime of the operation of a conventional ship. This figure shows that all solutions consuming ammonia and especially hydrogen imply severe increases in fuel cost. This is due to the high prices of these fuels. $MeOH$ fueled fuel cell systems increase the fuel price over the lifetime with a smaller, but significant amount (up to 55% for the different options). All options using LNG actually decrease the fuel cost over the lifetime of the ship. This can be explained by the relative low price of LNG accompanied with the higher efficiency of fuel cell systems compared with DG systems. LNG fueled SOFC combined with a full FC powered ship results in the largest decrease of fuel cost, since SOFC has the highest efficiency of the different fuel cell systems. In the next section the fuel cost data will be combined with the newbuild price data.

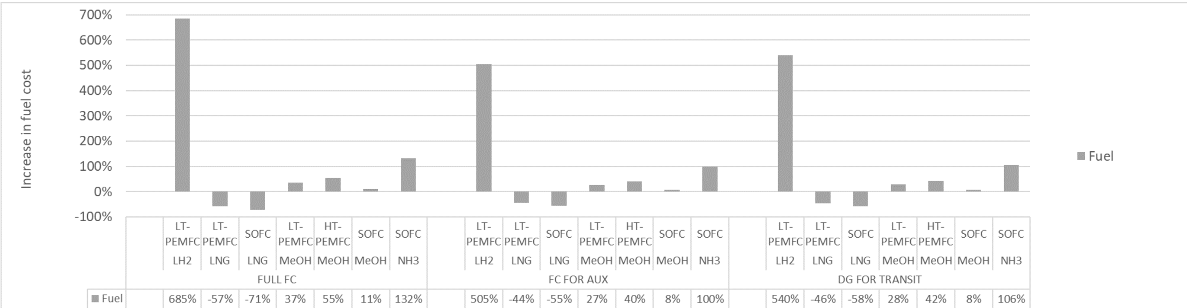


Figure 9.6: Increase in fuel cost over ship lifetime (15 years) with respect to the fuel cost for a conventional ship with equal requirements.

Total cost

This section combines the increase in newbuild price with the increase in fuel cost in order to give a well-founded recommendation on the financial impact of different fuel cell systems and hybrid options. Figure 9.7 shows the total increase in cost compared to the newbuild price plus the fuel cost of a conventional ship with equal requirements. The data labels show the total increase in cost while the stacked columns show the contribution to this total increase (contributions are shown in table under graph). Note that the data label (total increase in cost), does not correspond with the height of the bar, since the bars do not stack for negative values. As becomes clear from this figure, the fuel cost has a big impact on the economic viability of the option, especially for the LH_2 and NH_3 fueled fuel cell systems. It can be concluded that a ship equipped with LNG fueled LT-PEMFC is the best option for all hybridization strategies from a total cost perspective (perspective of the cruise line). This can be explained by the decrease in fuel cost by LNG. The next best performing options from this perspective are $MeOH$ fueled LT-PEMFC and LNG fueled SOFC for hybrid option 1 and 2. Between the different hybridization strategies, the increase in total cost is slightly lower for hybrid option 2 for most considered fuel cell systems.

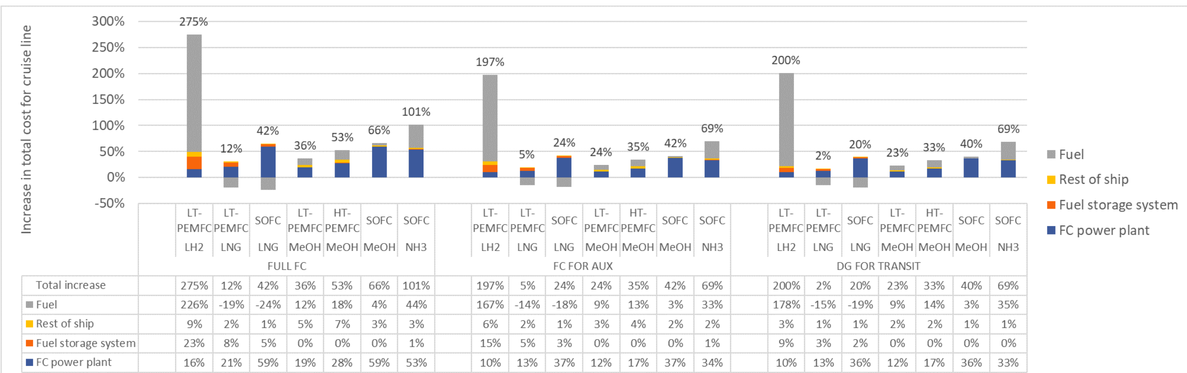


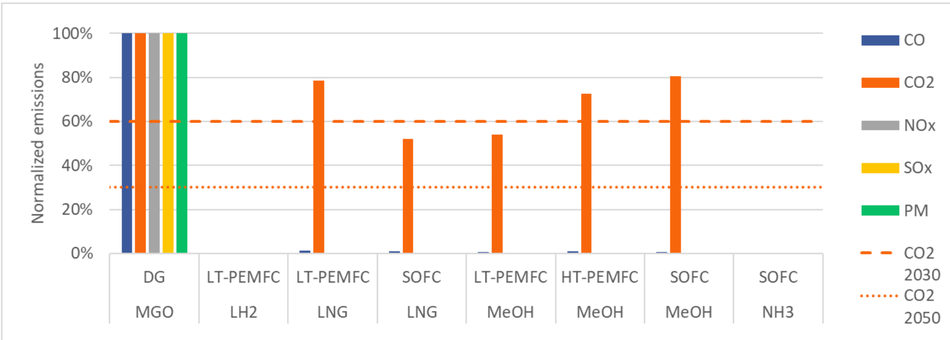
Figure 9.7: Increase in total cost over ship lifetime (15 years) with respect to the newbuild price and fuel cost over ship lifetime for a conventional ship with equal requirements. Note that the data label (total increase in cost) does not correspond with the height of the bar, since the bars do not stack for negative values.

9.1.4. Emissions

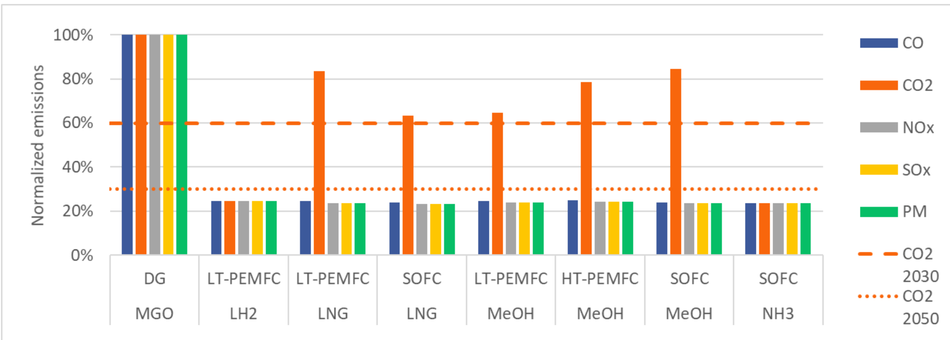
While interpreting results, the reader should keep in mind that the main driver for implementing fuel cell systems is the reduction of emissions. The reduction in emissions are the gain that oppose the higher cost. The consequential gain is compliance with upcoming regulations.

Figure 9.8 (a) - (c) show the gain in emissions for the full fuel cell powered ship, hybrid option 1 and hybrid option 2 respectively. The emissions are normalized, meaning they are represented as a ratio of the emission of a conventional ship. This is done to reasonably show emissions that have very different orders of magnitudes, like % for CO_2 and ppm for PM. The emissions include all emissions on board by the fuel cell system, by the reforming process and any by DG systems in case of a hybrid configuration.

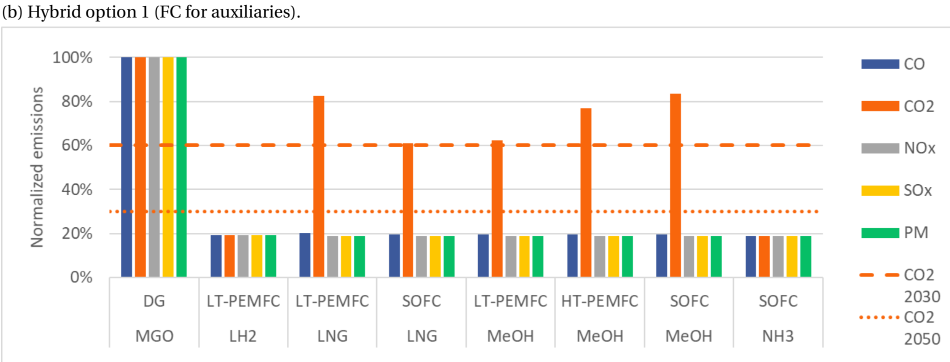
When no DG system is used, CO, CO_x, SO_x and PM on-board emissions are neglectable when compared to a conventional ship (see figure 9.8 (a)). CO_2 emissions are still significant for most fuel cell systems, excluding LH_2 fueled LT-PEMFC and NH_3 fueled SOFC. The emissions besides CO_2, are for the hybrid configurations, mainly dependent on how much the DG system is used, see figure 9.8 (b) and (c).



(a) Full FC powered ship.



(b) Hybrid option 1 (FC for auxiliaries).

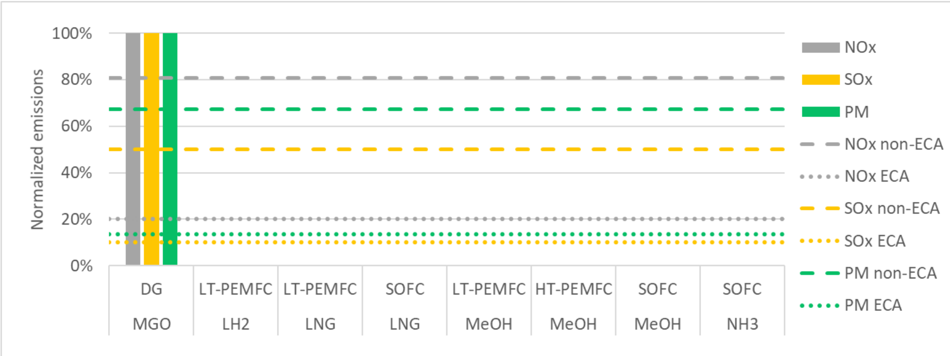


(c) Hybrid option 2 (DG for transit).

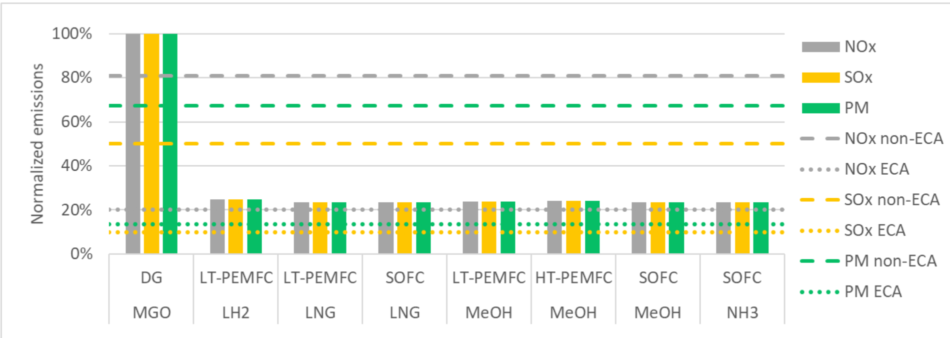
Figure 9.8: Normalized on-board emissions for CO, CO_2, NO_x, SO_x and PM over lifetime of the average ship with a conventional system and with the selected fuel cell systems. CO_2 ambition levels for 2030 and 2050 by IMO are also shown in the figures [53].

When selecting a fuel cell system and or hybrid option, the emission regulations should be considered. It might not be worthwile to take the cheapest solution now, when the ship would not be able to operate anymore or needs a refit in 2030 due to regulations. The 'levels of ambition' for CO_2 defined in the IMO Strategy on reduction of GHG emissions are also plotted in the emission graphs with dotted lines [52]. Although these levels are currently no stringent regulations, they might be in the future. The LNG fueled LT-PEMFC, $MeOH$ fueled HT-PEMFC and $MeOH$ fueled SOFC exceed the 2030 CO_2 target for all hybridization strategies. Only the LH_2 fueled LT-PEMFC and NH_3 fueled SOFC do not exceed the 2050 goals (for all hybridization strategies).

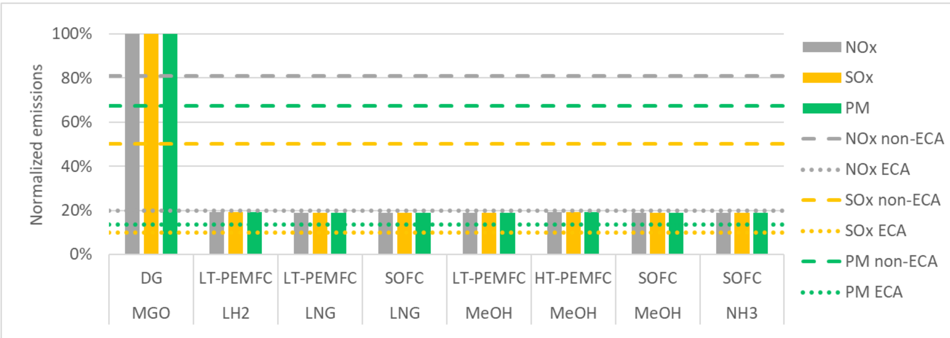
The other emission regulations (CO, NO_x, SO_x and PM) were also checked versus the normalized emissions (see figure 9.9). For the full fuel cell powered solutions, all upcoming regulations (inside and outside ECA zones) are easily met, since PM, NO_x and SO_x emissions are not significant. For both hybrid options, only the SOx and PM emissions within ECA zones are not met, due to emissions of the diesel generator system (no emissions abatement system is applied). For hybrid option 2 this is easily solvable, since the ship can run solely on fuel cells in these zones. For hybrid option 1 this is not the case.



(a) Full FC powered ship.



(b) Hybrid option 1 (FC for auxiliaries).



(c) Hybrid option 2 (DG for transit).

Figure 9.9: Normalized on-board emissions for NO_x, SO_x and PM over lifetime of ship for conventional system and selected fuel cell systems. Compared with NO_x, SO_x and PM regulations inside and outside ECA zones [54, 55].

Finally, figure 9.10 combines the increase in total cost (compared to a conventional ship) with the reduction in emissions (compared to a conventional ship) to express the cost per ton emission reduction. Although, some emissions are more harmful than others per emitted ton (this will be elaborately discussed in section 11.3), for this graph the masses of the different emissions are summed without adjusting the different emissions towards their harm potential.

Although it was found that LNG fueled LT-PEMFC is the option with the most emissions, its cost per ton of emission reduction is the lowest. The LH_2 fueled and $MeOH$ fueled options lead to substantially higher cost per ton emission reduction than the other options. For all considered fuel cell systems, hybrid option 2 leads to the lowest cost per ton emission reduction.

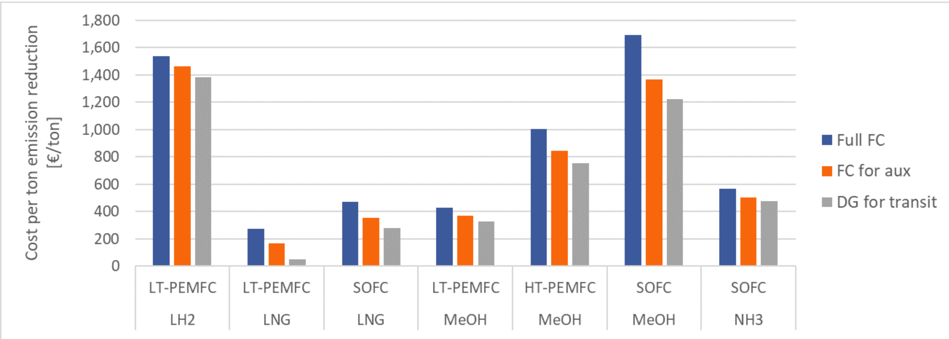


Figure 9.10: The cost per ton emission reduction (compared to a conventional ship). Includes CO, CO_2, NO_x, SO_x and PM.

9.1.5. Conclusion

The results show that the best option can vary per case and can even be dependent on the used perspective (shipyard or cruise line). From the perspective of the shipyard, a low newbuild price is important; cruise lines generally do not have enough knowledge about fuel cell systems in order to know which option would be better for their operational cost, so during the early stages in the tender (ROM) they might choose for the shipyard that can offer the lowest newbuild price. However, if a shipyard can prove to the client that a higher newbuild price can drastically reduce the fuel cost, the shipyard can get a serious advantage over the other candidates in the tender process.

When looking to the hybrid options in terms of newbuild price and fuel cost, hybrid option 2 performed always slightly better than hybrid option 1. The normalized emissions of hybrid option 2 are also lower. On top of that, hybrid option 2 has as extra advantages that it can operate solely on fuel cells in ECA zones. For this reason hybrid option 1 is discarded for the remaining part of the research (also from the remaining part of this conclusion). Full FC options are not yet discarded, since are the the only possibility for a zero emission ship.

In terms of newbuild price, $MeOH$ fueled LT-PEMFC, LNG fueled LT-PEMFC, LH_2 fueled LT-PEMFC and $MeOH$ fueled HT-PEMFC (all with hybrid option 2) are the four best performing options; all cause an increase in build cost lower than 30%.

In terms of total cost, LNG fueled LT-PEMFC, LNG fueled SOFC and $MeOH$ fueled LT-PEMFC are the best performing options for hybrid option 2. LNG fueled LT-PEMFC is the best performing option for a full fuel cell powered ship. These four options all result in an increase in total cost under 25%.

In terms of emissions, LNG fueled LT-PEMFC, $MeOH$ fueled HT-PEMFC and $MeOH$ fueled SOFC do not reduce the CO_2 emissions sufficiently to reach the 2030 goals for both a full fuel cell powered ship and hybrid option 2. NO_x, SO_x and PM regulations (as well in ECA zones) can be satisfied for all fuel cell systems for a full fuel cell powered ship and for hybrid option 2.

The results of the past sections are combined to recommend the best performing combinations of fuel cell system and hybridization option. The six best performing options are selected and viewed in table 9.3. Although a ranking is provided, the most recommended option is very case dependent. For a zero emission vessel, a recommendation is done as well, see table 9.4. However, these options are much more expensive (especially in terms of total cost, due to high fuel cost). The six presented options in table 9.3 will be further reviewed in the next section, where the input of the model is systematically varied.

Table 9.3: Recommendation for fuel cell powered ships.

Rank	Fuel type	FC type	Hybridization	Based on	Compliance		
					CO2 2030	CO2 2050	ECA
1	LNG	LT-PEMFC	Hybrid 2	Total cost			✓
2	LNG	LT-PEMFC	Full FC	Total cost			✓
3	MeOH	LT-PEMFC	Hybrid 2	Total cost and shipbuilding cost	✓		✓
4	LNG	SOFC	Hybrid 2	Total cost	✓		✓
5	MeOH	LT-PEMFC	Full FC	Total cost and shipbuilding cost	✓		✓
6	MeOH	HT-PEMFC	Hybrid 2	Total cost and shipbuilding cost			✓

Table 9.4: Recommendation for zero emission ships.

Rank	Fuel type	FC type	Hybridization	Based on	Compliance		
					CO2 2030	CO2 2050	ECA
1	NH3	SOFC	Full FC	Zero emission and total cost	✓	✓	✓
2	LH2	LT-PEMFC	Full FC	Zero emission and shipbuilding cost	✓	✓	✓

9.2. Systematical variation of requirements

In this section, the requirements of the design are systematically varied for model validation. This corresponds to a type of sensitivity analysis where the input values are changed to determine the model's behavior [99]. Only the six best performing options (table 9.3) are considered in this section.

The varying requirements are divided in operational requirements (endurance and range in section 9.2.1) and capacity requirements (number of passengers in section 9.2.2). The cost is represented from the perspective of the cruise line. Financing cost for the cruise line is not included, since it is very dependent on the risk profile.

9.2.1. Variation of transit endurance

The endurance of the transit operation is varied. The design speed is kept constant, meaning the variation influences the size of the fuel storage but not the size of the power plant, since the latter is related to the required power. The speed during transit operation is also kept constant. Consequently, the transit range scales proportionally with the endurance (denoted with dotted black line in the upcoming figures).

Newbuild price

Figure 9.11 shows the increase in newbuild price compared to a conventional solution, varied over the transit endurance. It can be derived that, hybrid option 2 with *MeOH* fueled LT-PEMFC leads to the lowest increase in newbuild price over the whole endurance variation, followed by hybrid option 2 with *LNG* fueled LT-PEMFC. The increase in newbuild price compared with the conventional ship increases slightly for the full FC options (orange and green) with higher transit endurance. For the 4 hybrid options the increase in newbuild price is fairly constant, this can be explained due to the fact that for hybrid option 2 a longer transit endurance is mainly covered by a larger MGO tank, meaning the ship cost increase does not increase significantly for high endurance. As can be expected from the high price of SOFC, LNG fueled SOFC leads to the highest increase in newbuild price. Overall, for all considered endurances the same results are found as for the general case in section 9.1.3. Selecting between the proposed options should not depend on the endurance; in the considered endurance span none of the lines cross.

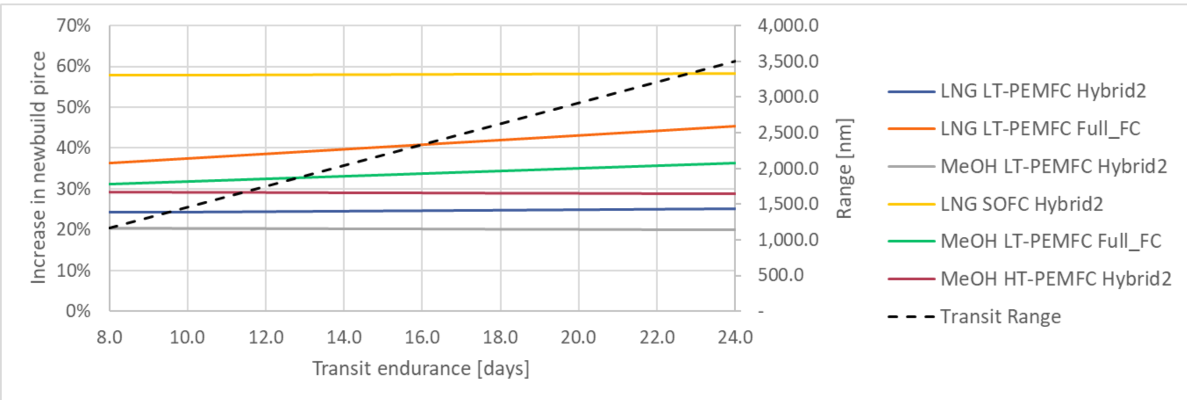


Figure 9.11: The increase in newbuild price (compared with a conventional ship with equal requirements) for different endurance requirements of the transit operation.

Fuel cost

In figure 9.12, the increase in fuel cost is varied over the transit endurance. Hybrid option 2 with *LNG* fueled SOFC always offers the highest decrease in fuel cost for all considered endurances, due to the low price of *LNG* and the high efficiency of *SOFC*. All *LNG* fueled options cause a decrease in fuel cost and all *MeOH* results in an increase in fuel cost. The increase in fuel cost is only slightly dependent on the transit endurance requirement. This can be explained from the fact that the range requirement has only little influence on the energy consumption, but mainly on the energy that is required to be stored on board.

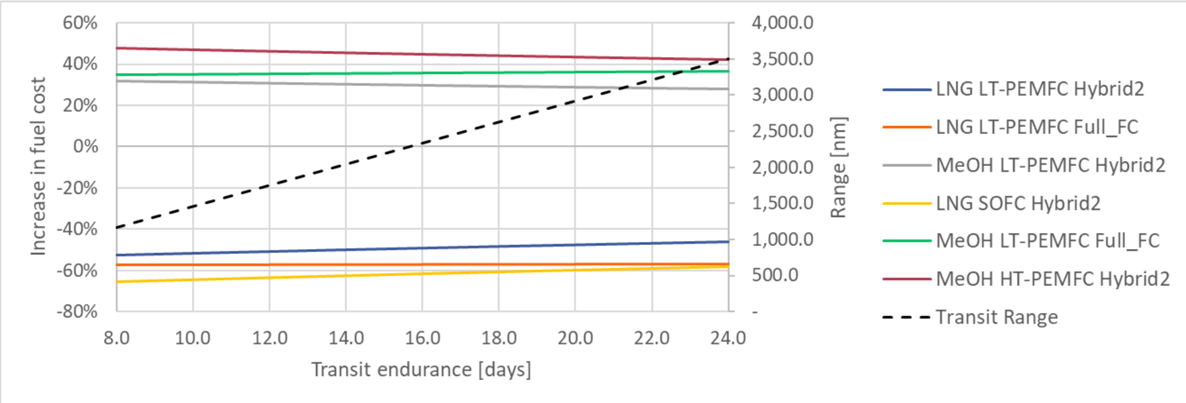


Figure 9.12: The increase in fuel cost (compared with a conventional ship with equal requirements) for different endurance requirements of the transit operation.

Total cost

In figure 9.13 the past two figures are combined into the increase in total cost, varied over the transit endurance. The total increase in cost is composed of the new build price of the ship and the fuel cost, so the total cost is from the perspective of the cruise line. Time value of money is not taken into account in this cost, so the operational cost is not discounted (refer to discussion section 11.1). Ship finance costs for the cruise line are also not included since these are very country and risk dependent. It can be observed that hybrid option 2 with *LNG* fueled LT-PEMFC always offers the lowest increase in total cost. The green line and purple line cross, meaning between these option, the best performer on total increase in cost is dependent on the transit endurance. For the other options there is no interdependence for different endurance requirements. For all considered endurances the same conclusion is found regarding the best performing options as in the general results that were presented in section 9.1.3.

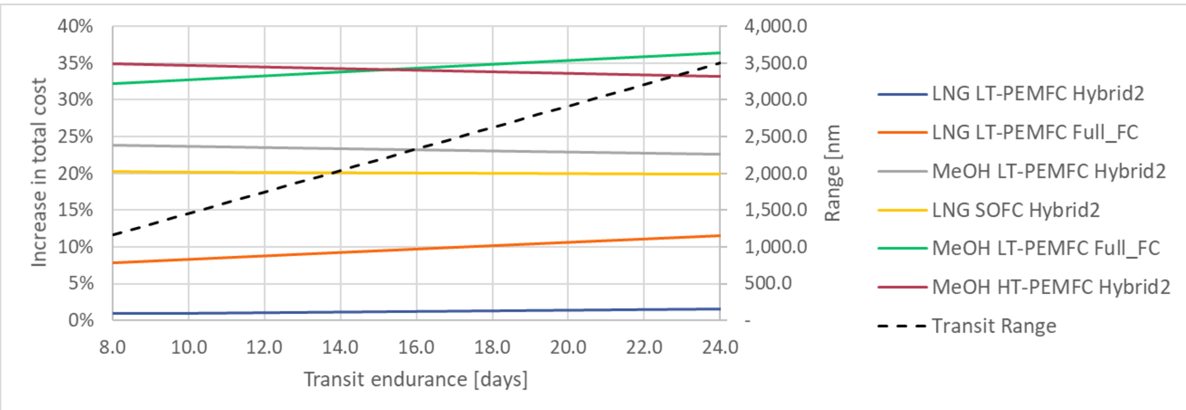


Figure 9.13: The increase in total cost (compared with a conventional ship with equal requirements) for different endurance requirements of the transit operation.

Increase in GT

Finally, figure 9.14 shows the increase in ship size varied over the transit endurance. Hybrid option 2 with *LNG* fueled SOFC leads to the smallest increase in ship size for all examined transit endurances. This is due to the relatively high energy density of LNG and high efficiency of SOFC. Full FC with *MeOH* fueled LT-PEMFC results in a high increase in ship size for high endurance requirements. At first sight it seems not realistic that full FC with *MeOH* fueled LT-PEMFC (green) increases much quicker for higher endurance than full FC with *LNG* fueled LT-PEMFC (orange), since their volumetric energy density is quite similar (see table 6.3). By reviewing the calculation data it was found that the quick increase can be explained by the fact that the increase in ship size for *MeOH* fueled LT-PEMFC is not volume driven, but weight driven (the IF logic was explained in section 8.2.5), due to the lower gravimetric energy density.

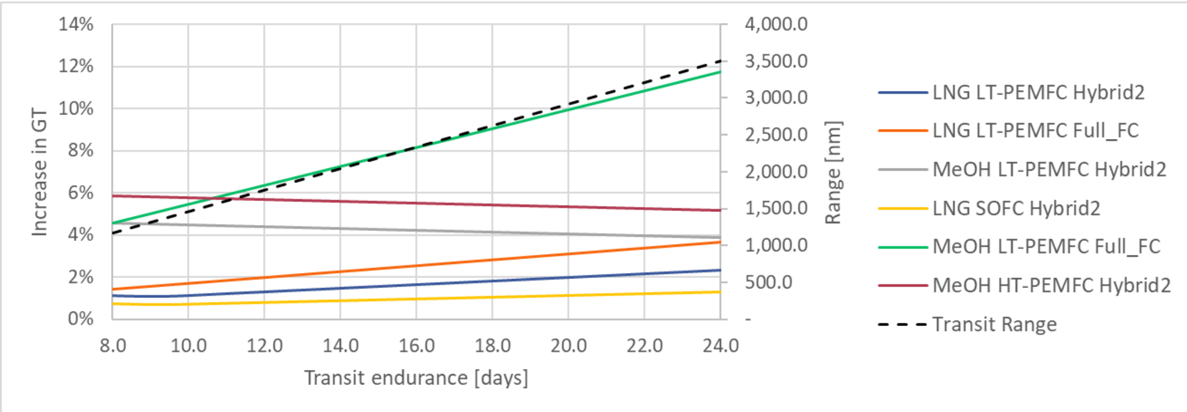


Figure 9.14: The increase in GT (compared with a conventional ship with equal requirements) for different endurance requirements of the transit operation.

9.2.2. Variation of capacity requirements

In this section the size of the conventional ship (in GT) is varied in order to see whether some fuel cell systems and hybrid options perform better for different ship sizes than other options. The size of the ship (GT) is driven by the capacity of the ship (PAX) and they were linearly linked in the model since the luxury level is kept constant. In all graphs, the capacity (PAX) is also shown as function of the GT of the fuel cell powered ship with a black dotted line.

Newbuild price

Figure 9.15 represents the increase in newbuild price as a result of varying the GT. It can be observed that for all options the increase in newbuild price increases for a larger ship, but the mutual ratios do not change much. This means that for all ship sizes the performance in terms of newbuild price of the different options is comparable in relation to each other. *MeOH* fueled LT-PEMFC in combination with hybrid option 2 results in the lowest newbuild price for all considered ship sizes, followed by *LNG* fueled LT-PEMFC with hybrid option 2. Hybrid option 2 with *LNG* fueled SOFC leads to a high increase in newbuild price, especially for larger ships. In reality this effect will be smaller, since there would be scale effects for larger ships. For instance, systems like fuel processing equipment would cost less per kW for a 30 MW system than for a 5 MW system. However, in the model such components are scaled linearly with the amount of required power or required stored energy. Nevertheless, it must be noted that this scale effect is not present for all components. For instance for *LNG* tanks, a very large ship would not have one big *LNG* tank, but several smaller ones. For all considered ship sizes the same order of best performing options was found as in the results presented in section 9.1.3.

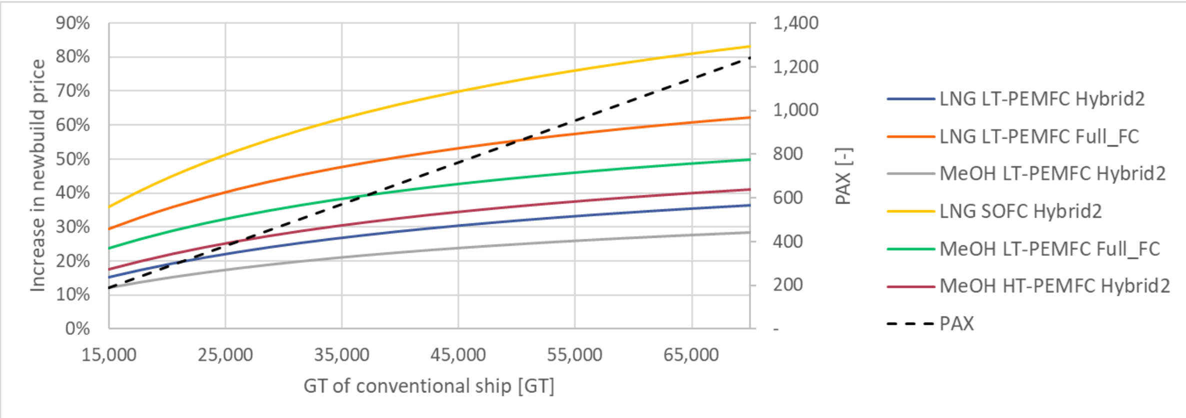


Figure 9.15: The increase in newbuild price (compared with a conventional ship with equal requirements) for different capacity requirements.

Fuel cost

The increase in fuel cost is varied over the ship size in figure 9.16. For all options the increase in fuel cost is relatively constant. Meaning the increase in fuel cost compared with the a conventional ship does not depend much on the size of the ship. *LNG* fueled SOFC with hybrid 2 offers the lowest increase in fuel cost, directly followed by *LNG* fueled LT-PEMFC with full FC. This is obviously to the relative low price of *LNG*.

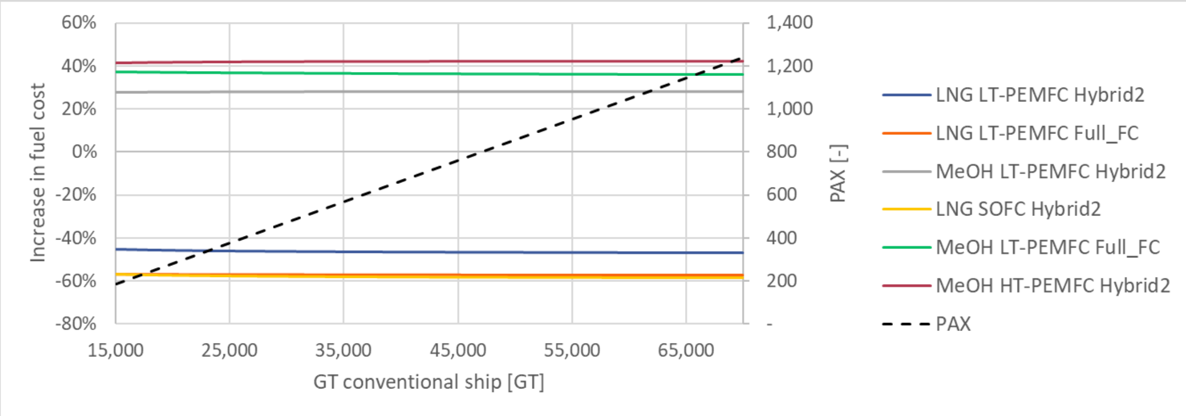


Figure 9.16: The increase in fuel cost (compared with a conventional ship with equal requirements) for different capacity requirements.

Total cost

In figure 9.17 the resulting total increase in cost is showed for varying GT. This is composed of the new build price of the ship and the fuel cost, so the total cost is in perspective from the cruise line. Time value of money is not taken into account in this cost, so the operational cost is not discounted (refer to discussion section 11.1). *LNG* fueled LT-PEMFC offers the lowest increase in total cost. In general the increase in total cost is higher for larger ships. For all considered GT the same order of performance was found as presented in section 9.1.3. None of the lines cross, meaning the best fuel cell and hybrid strategy for a certain ship in terms of total cost is not dependent on the ship size.

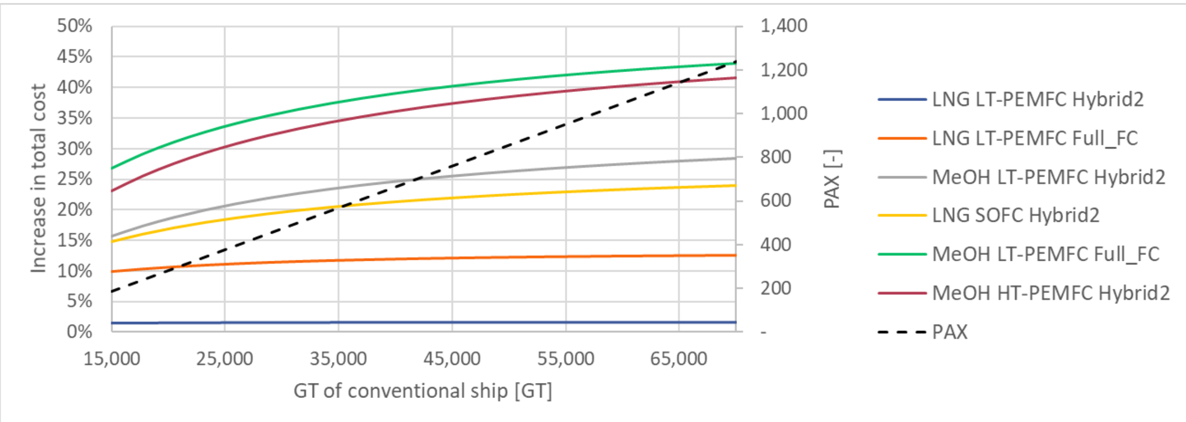


Figure 9.17: The increase in total cost (compared with a conventional ship with equal requirements) for different capacity requirements.

Increase in GT
Figure 9.18 shows the increase in GT that is necessary to fit the fuel cell system (compared to the conventional ship) as a results of varying the GT of the conventional ship. In other words, this shows whether a larger ship requires a larger percentage increase in ship size to fit the fuel cell system. Whether it does, is different per option, as can be observed from the figure; some lines incline and some decline. However, for all options, no large changes are visible over the considered range of GT. *LNG* fueled SOFC with hybrid option 2 offers the lowest increase in GT for all considered ship sizes, due to high energy density of *LNG* and high efficiency of SOFC.

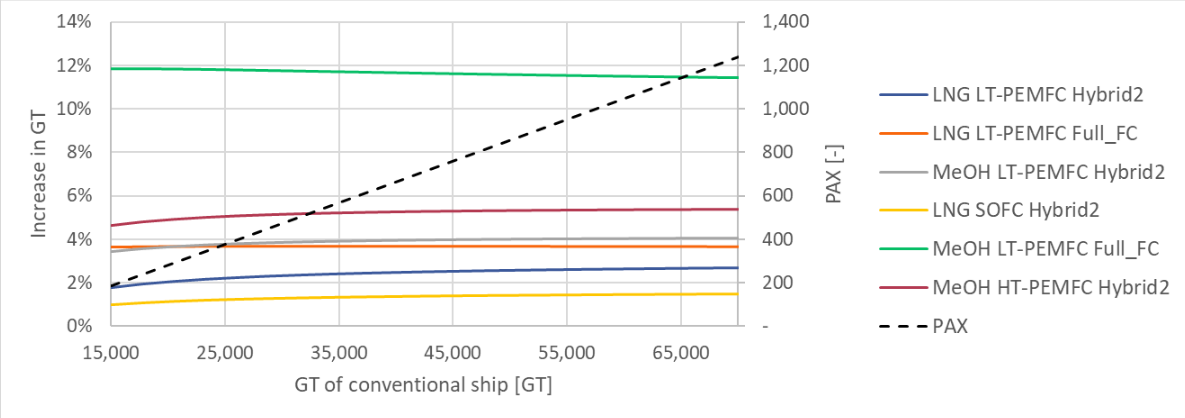


Figure 9.18: The increase in GT (compared with a conventional ship with equal requirements) for different capacity requirements.

9.2.3. Conclusion

In this section the influence of operational requirements and capacity requirements (ship size) on the output of the model was investigated. This was performed for the selected options (combination of hybrid option and fuel cell system) in the previous section.

The following can be concluded out of varying the endurance requirements of the transit:

- Hybrid option 2 with *MeOH* fueled LT-PEMFC offers the lowest increase in newbuild price for all considered endurance requirements.
- Hybrid option 2 with *LNG* fueled SOFC offers the lowest increase in fuel cost for all considered endurance requirements.
- Hybrid option 2 with *LNG* fueled LT-PEMFC offers the lowest increase in total cost for all considered endurance requirements.
- The choice of the fuel cell system and hybridization strategy should not depend on the the transit requirement from ship building cost perspective and total cost perspective, since the best options from these perspectives are the same for all considered endurances.
- The endurance requirement influences the percentage increase in ship size to fit the fuel cell system.

The following can be concluded out of varying the ship size:

- The ship size has an impact on the increase in newbuild price (and thus increase in total cost), but not much influence on the mutual ratios between the different options. This means that the choice of the fuel cell system and hybrid option should not be based on the size/capacity of the ship.
- The ship size has very little influence on the increase in fuel cost.

10 Conclusion

This chapter presents the conclusions that are drawn from the work of this research. This research aimed to achieve the following main research objective:

Evaluate the impact of the combination of different fuel cell systems and operational profiles on the design of expedition cruise vessels.

A design tool is developed that compares the impact for different fuel cell systems and hybridization strategies in the early design phase. The design tool evaluates the impact in terms of increase in ship size, newbuild cost, fuel cost and emissions.

In this chapter, the sub research objectives are treated one by one.

First research objective
Analyse relevant performance of fuel cell types and suitable fuel types in terms of efficiency, power and energy density, dynamic behavior, TRL, safety, capital cost and operational cost. Discard worst options.

After analysing the different fuel cell types and fuel types on efficiency, power and energy density, dynamic behavior, TRL, safety, capital cost and operational cost it was concluded that the green colored fuel cell types (table 10.1) and and fuel types (table 10.2) should be considered for expedition cruise ships.

When reflecting on this decision with the current knowledge after the research, the MCFC (orange) would not have been selected anymore to evaluate, due to low performance in power density and capital price.

Table 10.1: Selected fuel cell types from literature.

Fuel cell type
AFC
LT-PEMFC
HT-PEMFC
PAFC
DMFC
MCFC
SOFC
DCFC

Table 10.2: Selected fuel types from literature.

Fuel type
Hydrogen
Diesel
Natural gas
Methanol
Ethanol
Dimethyl ether
Ammonia

Second research objective
Express performance of fuel cell systems for expedition cruise ships in terms of power density, energy density, capital cost and operational cost. Discard worst options.

A system decomposition method was proposed to express the performance of the fuel cell systems. The fuel cell system is divided in fuel storage, fuel processing, fuel cell power pack and balance of plant components. For all these different components their performance in energy density, power density and specific cost can be added as impedances to express the performance of the total system. Lifetime and efficiency of the fuel cell is also taken into account. By discarding options that are outperformed on all criteria, the selection in table 10.3 was made.

When reflecting this on decision with the current knowledge after the research, $MeOH$ fueled HT-PEMFC and $MeOH$ fueled SOFC (orange) would not have been selected for the design tool to evaluate. These options do not perform well in terms of newbuild price or fuel cost while they are not reaching IMO CO_2 targets for 2030.

Table 10.3: Selected fuel cell systems out of performance in power density, energy density, capital cost and fuel cost.

Fuel cell system							
LH_2	LT-PEMFC	LNG	LT-PEMFC	$MeOH$	LT-PEMFC	NH_3	LT-PEMFC
LH_2	HT-PEMFC	LNG	HT-PEMFC	$MeOH$	HT-PEMFC	NH_3	HT-PEMFC
LH_2	MCFC	LNG	MCFC	$MeOH$	MCFC	NH_3	MCFC
LH_2	SOFC	LNG	SOFC	$MeOH$	SOFC	NH_3	SOFC

From the fuel cell system performance the following is concluded:

- LT-PEMFC outperforms HT-PEMFC on all criteria, except when HT-PEMFC is combined with $MeOH$.
- LT-PEMFC performs best in terms of capital cost of the fuel cell system.
- MCFC performs poorly on volumetric and gravimetric power density.
- SOFC performs best in terms of volumetric energy density, this is due to the high efficiency of SOFC.
- LH_2 performs best in combination with LT-PEMFC.
- LNG fueled fuel cell systems perform best in terms of gravimetric energy density and fuel cost.
- NH_3 performs best in combination with SOFC.

Third research objective
Analyse general requirements, ship dimensions, operational profiles and power requirements of existing expedition cruise ships.

For this research objective a large number of existing (expedition) cruise ships was examined. The following is concluded:

- Expedition cruise ship design is mostly volume critical.
- Expedition cruise ships resemble the luxury segment of cruise ships, scoped at >50 GT/PAX. Existing expedition cruise ships demonstrate strong regression relations. $GT-PAX$, $L_{OA}-PAX$, $L_{OA}-GT$, $L_{pp}-GT$, $B-GT$, $\Delta-GT$, $DWT-GT$, $N_{crew}-PAX$ and $P_{propulsion}-GT$ all showed regression relations with a R^2 of 0.9 or higher. Consequently, reference expedition cruise ships can be used to suggest suitable ship parameters.
- The maximum speed of expedition cruise ships is barely used; they mostly operate at medium and design speed. Here lays an opportunity to use the fuel cell system for most of the operation and use diesel generators to boost power when necessary. This results in a high reduction of emissions and it is a good option in terms of cost, since the fuel cell system is very expensive per kW. In this research, hybrid option 2 (DG for transit) is based on this finding.
- Auxiliary power demand is characterized with lower changes in power demand than the propulsion power demand. Consequently, fuel cell systems require less batteries and capacitors to fullfil the dynamic power demand when implemented as auxiliary power supply than when implemented as propulsion power supply. So, for auxiliaries the size, weight and cost per kW of the fuel cell system is lower. In this research, hybrid option 1 (FC for aux) is based on this finding.

Fourth research objective
Match the performance of different fuel cell systems for (part of) the power generation to the requirements of expedition cruise ships.

For this research objective, a design tool is created for the early design phase that links the fuel cell system performance to the requirements of the expedition cruise ship. A design tool for the D&P engineer offers several benefits: the impact can be evaluated for different expedition cruise ship designs and it makes the performed work in this research reproducible. Three hybridization strategies were added to the model:

- Full fuel cell powered ship (Full FC).
- Fuel cell power generation only for auxiliary load (hybrid option 1).
- Diesel generators only for transit (hybrid option 2).

The design tool indicates the impact of fuel cell system implementation on increase in ship size, increase in newbuild price, increase in fuel cost and decrease in emissions. The model performs one design iteration to fit the fuel cell system in the reference ship. The design tool was verified with structured walk through, balance checks and testing extreme conditions. The model was validated with data validation, benchmarks, interpretation of results and sensitivity analysis.

Fifth research objective
Evaluate the impact (in ship size, capital cost, operational cost and emissions) of the combination of the chosen fuel cell systems and operational profile requirements on the design of expedition cruise ships. Choose the most suitable fuel cell systems for expedition cruise ships.

For the last research objective the output of the design tool is used. First the impact of 21 options (7 fuel cell systems and 3 hybridization options) is compared for an average ship design (compared to the reference ships). Out of these 21 options, the 6 best performing options in terms of percentage increase in newbuild price, percentage increase in total cost (newbuild price and fuel cost) and percentage decrease in emissions are selected (table 10.4). The following conclusions are drawn regarding the research objective:

- The increase in ship size (in GT) ranges from 2% to 22 % for an average ship (with respect to the reference ships), depending on the fuel cell system and hybridization strategy.
- A full fuel cell powered ship is always the most expensive option in terms of newbuild price and total cost (newbuild price combined with fuel cost), compared to the examined hybrid options.
- Hybrid option 1 (fuel cells for auxiliary load) is for most fuel cell systems inferior to hybrid option 2 (diesel generators for transit) in terms of increase in newbuild price and increase in total cost. On top of that hybrid option 2 offers the extra advantages that it can comply to all ECA regulations. For that reason hybrid option 1 is discarded.
- In terms of newbuild price, $MeOH$ fueled LT-PEMFC, LNG fueled LT-PEMFC, LH_2 fueled LT-PEMFC and $MeOH$ fueled HT-PEMFC (all with hybrid option 2) are the four best performing options and all result in an increase in build cost under 30%.
- In terms of total cost, LNG fueled LT-PEMFC, LNG fueled SOFC and $MeOH$ fueled LT-PEMFC are the best performing options for hybrid option 2. LNG fueled LT-PEMFC is the best performing option for full a full fuel cell powered ship. These four options all result in an increase in total cost under 25%.
- In terms of emissions, LNG fueled LT-PEMFC, $MeOH$ fueled HT-PEMFC and $MeOH$ fueled SOFC do not reduce the CO_2 emissions sufficiently to reach the 2030 goals for full FC ship and hybrid option 1. NO_x, SO_x and PM regulations (including ECA zones) are satisfied for all considered fuel cell systems (for full FC and hybrid option 2).

As stated in the research objective, the impact of the operational profile on expedition cruise ships was also investigated. For the options of table 10.4, different inputs (range, endurance and GT) are systematically varied to observe the response behavior of the model. The following is concluded:

- Hybrid option 2 with $MeOH$ fueled LT-PEMFC offers the lowest increase in newbuild price for all considered endurance requirements and ship sizes.
- Hybrid option 2 with LNG fueled SOFC offers the lowest increase in fuel cost for all considered endurance requirements and ship sizes.
- Hybrid option 2 with LNG fueled LT-PEMFC offers the lowest increase in total cost for all considered endurance requirements and ship sizes.
- The choice of the fuel cell system and hybridization strategy should not depend on the endurance requirements and the ship size.

Table 10.4: Recommendation for fuel cell powered ships.

Rank	**Fuel type**	**FC type**	**Hybridization**	**Ship cost**	**Total cost**	**Compliance**		
						CO2 2030	CO2 2050	ECA
1	LNG	LT-PEMFC	Hybrid 2	++	++			✓
2	LNG	LT-PEMFC	Full FC	-	+			✓
3	MeOH	LT-PEMFC	Hybrid 2	++	+-	✓		✓
4	LNG	SOFC	Hybrid 2	- -	-	✓		✓
5	MeOH	LT-PEMFC	Full FC	+-	-	✓		✓
6	MeOH	HT-PEMFC	Hybrid 2	+-	- -			✓

Final recommendation
Bases on the presented conclusions a final recommendation is given and shown in table 10.4.

From a newbuild price perspective the cheapest option for a fuel cell powered ship is to implement a $MeOH$ fueled LT-PEMFC system with diesel generators to support in long ranges and high speeds. This does comply with NO_x,SO_x and PM regulations (including ECA zones) and CO_2 reduction goals.

From a total cost perspective the cheapest option for a fuel cell powered ship is to implement a LNG fueled LT-PEMFC system with diesel generators to support in long ranges and high speeds. This does comply with NO_x, SO_x and PM regulations including ECA zones. However, this cheapest option does not meet 2030 CO_2 reduction goals. When these reduction goals are required, $MeOH$ fueled LT-PEMFC is recommended, also with diesel generators to support in transit.

11 Discussion

This chapter further discusses the implications of the results and conclusions of the main research. Firstly, the implications of a shift from operational cost to capital cost is explained in section 11.1. Following, section 11.2 discusses the addition of subsidies to the model, since they often drive sustainable technologies. In section 11.3, the gain in emissions will be related to the increase in cost by expressing emissions in damage cost. Finally, in section 11.4, different future scenarios are sketched for change in fuel cell price and fuel price.

11.1. Financial perspective

From the financial perspective of the cruise line, increasing the build cost and decreasing the operational cost (when total cost would stay equal) is generally not desirable. Firstly, when the ship cost increases it will be harder to finance the building of the ship. A larger loan is harder to acquire and more equity is needed when the equity ratio is kept constant (equation 11.1). Secondly, the future value FV of money is higher than the present value of money (PV), see equation 11.2. If a higher proportion of the total cost needs to be payed at the start of the lifetime of the ship (compared to high operational expenses of the ship which are payed during the lifetime of the ship), this money cannot be used for other investments, resulting in higher opportunity cost. An example is shown on the next page.

$$Equity\,ratio = \frac{Equity}{Liability} \tag{11.1}$$

$$PV = \frac{FV}{(1+d)^y} \tag{11.2}$$

where:

d	Discount rate: intends to compensate an investor for the time waiting for future payment and for the risk that payment might not occur. Discount rate is dependent on the risk level of the investment.
t_y	Difference in years between future and present

However the decision on fuel cell implementation is also very dependent on the required emissions in 2030. Even when a certain combination of fuel cell and hybrid option has lower total cost now, if it does not satisfy the required emission limitations of 2030, a refit would be necessary. This would justify the selecting a more expensive ship (in capital and operational cost).

Investment example - present value of cost

From an investment perspective it is usually not preferable that a large proportion of the cost is payed upfront of the project (investment). This is showed here by example of a DG powered ship and a FC powered ship. It is assumed that the total cost of the ship and its operation are the same and the FC powered ship requires a higher investment and needs lower yearly operational cost, see table 11.1. The present value (calculated with equation 11.2) of the cost for every year is showed in table 11.2.

Table 11.1: Simplified example of purchase and operational cost for DG powered ship and FC powered ship.

		DG powered ship	FC powered ship
Cost of ship	[m€]	240	320
Fuel cost in lifetime	[m€]	160	80
Total	[m€]	400	400
Discount rate	[-]	0.8	

Table 11.2: Investment example: cost and present cost per year for DG powered ship and FC powered ship (uneven years are removed to fit the table).

DG powered ship	*year*	*0*	*2*	*4*	*6*	*8*	*10*	*12*	*14*
Cost per year	[m€]	250.7	10.7	10.7	10.7	10.7	10.7	10.7	10.7
Present cost value per year	[m€]	250.7	9.1	7.8	6.7	5.8	4.9	4.2	3.6
Present cost value until year	[m€]	250.7	269.7	286.0	300.0	312.0	322.2	331.1	338.6

FC powered ship	*year*	*0*	*2*	*4*	*6*	*8*	*10*	*12*	*14*
Cost per year	[m€]	325.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3
Present cost value	[m€]	325.3	4.6	3.9	3.4	2.9	2.5	2.1	1.8
Present cost value until year	[m€]	325.3	334.8	343.0	350.0	356.0	361.1	365.5	369.3

The present cost value over the years is showed in figure 11.1. It can be seen that the present value of the cost of the FC powered ship over the lifetime of the ship is higher because a larger investment is required. This is even without taking into account that the investment to build the ship is usually financed with loans. A higher loan results in a higher cost of finances.

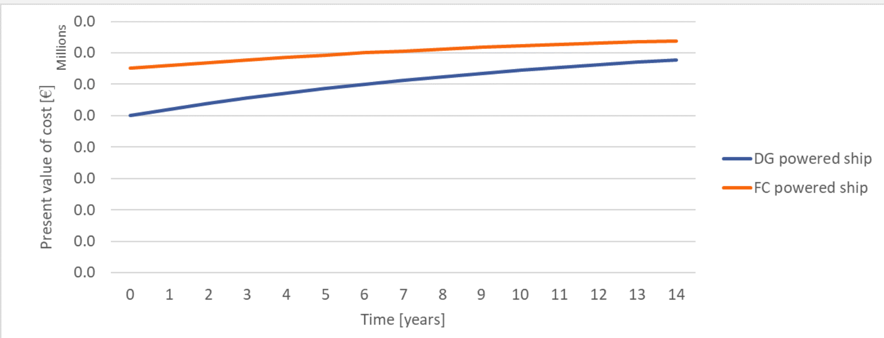


Figure 11.1: Example: present value of cost for DG powered ship and FC powered ship

11.2. Subsidies

To really get fuel cell systems in marine applications off the ground, it is expected that subsidies are required, analogously to the emergence of the solar panel and offshore wind energy market. When information about subsidies would be added to the model, the fuel cell powered ship increases its economic feasibility with respect to the the current conventional solutions. However, current subsidy programs that can be applied for fuel cell systems (FCH2 JU under Horizon 2020 [37], Interreg [98]) are still much focused on R&D and gained subsidies are very dependent on the approach of the project (for instance is it demonstrational, adding valuable research or really producing energy). For renewable energy subsidies, indication of the realizable reduction in emissions is very relevant; subsidy programs for renewable energy are determined on energy output or installation capacity [86]. However, fuel cell system subsidies are not yet in the stage that an amount of money can be tied to the amount of generated energy or the power of the system. For this reason, no subsidies were considered in the model to further judge the economic feasibility of a fuel cell powered ship.

11.3. Damage cost of emissions

Expressing the emissions in terms of damage cost enables the comparison between increase in cost and emission reduction. The 'Handbook on External Costs of Transport' by the European Commission provides a method and data to convert emissions to damage cost [35]. This does not improve the business case of the fuel cell powered ship, because these are not real cost that can be cut by the shipyard or the cruise line. However, they can be used to convince subsidy providers. The damage cost of emissions are divided in air pollution cost and climate change cost [35].

11.3.1. Air pollution damage cost

Of the scoped emissions, SO_x, NO_x and PM are contributing to air pollution. The cost per emitted ton of the different particles are viewed in table 11.3. The damage cost of air pollution is based on health effects, crop loss, biodiversity loss, material damage and is different for marine and land-based operations. The latter applies to the different operations of this research and the following is defined for air pollution:

- *Transit*
  In this research, the transit operation is considered as crossing a large ocean, like the Atlantic Ocean. For this reason the pollution damage data of the Atlantic ocean of table 11.3 is used for this operation.

- *Coastal*
  The coastal operation is defined as an itinerary where places along a coast are visited (for instance Caribbean, Mediterranean or Scandinavian itinerary). Meaning this operation is partly marine based and partly land based. For this reason, the average of the land based pollution cost and the marine based pollution cost (excluding Atlantic ocean) is used for this operation, see table 11.3.

- *Antarctic*
  Although most of the antarctic itinerary is marine based or close to land, the (Ant)arctics are seen as a vulnerable zone regarding air pollution. Some sources even argue that the (Ant)arctic areas are even more sensitive to pollution since natural processes that remove hydrocarbons and other pollution are slowly due to the low temperatures [23, 79]. For this reason, the same pollution cost of land-based operations are applied to the Antarctic operation, see table 11.3.

Table 11.3: Damage cost of air pollution for marine operations and on-land operations, derived in 2016. Including: health effects, crop loss, biodiversity loss, material damage. The land-based pollution is the average of 28 EU countries. [35]

Marine-based	**NH_3** €/kg	**NMVOC** €/kg	**NO_x** €/kg	**SO_x** €/kg	**PM 10** €/kg
Atlantic	-	0.4	3.8	3.5	4.1
Baltic	-	1.0	7.9	6.9	10.4
Black Sea	-	0.2	7.8	11.1	17.1
Mediterranean	-	0.5	3.0	9.2	14.0
North Sea	-	2.3	10.7	10.5	19.7
Average	-	0.9	6.6	8.2	13.1
Average without Atlantic	-	1.0	7.4	9.4	15.3

Land-based	**NH_3** €/kg	**NMVOC** €/kg	**NO_x** (rural) €/kg	**SO_x** €/kg	**PM 10** €/kg
Average (EU28)	17.5	1.2	12.6	10.9	22.3

11.3.2. Climate change damage cost

Of the scoped emissions, CO_2 contributes to the climate change cost. The climate change cost can be monetised using a damage cost approach or an avoidance cost approach. An avoidance cost approach has the advantage that it can include potential catastrophic effects, like melting of ice caps [35]. For that reason an avoidance cost approach is used. Table 11.4 shows the avoidance cost per ton of equivalent CO_2 emission. Equivalent CO_2 emission is regularly used to express green house gasses (GHG). Since GHG differ in lifetime and potency, the Global Warming Potential (GWP) can be used to combine the impact of different emissions on global warming. GWP compares the amount of heat that is trapped by a gas mass to the amount of heat trapped by the same mass of CO_2 [35], see also appendix A.3 table A.5. The GWP is not location dependent, meaning it is the same for the defined operations in this research. The handbook recommends using the central value (low, central and high are based on the variety in global warming cost estimations in existing literature). The long run value is used since the emissions have impact over a long time.

Table 11.4: Avoidance cost of global warming per emitted CO_2 equivalent. Data is presented as low central and high estimations and over short run and long run [35].

	Low €/t CO_2 eq.	**Central** €/t CO_2 eq.	**High** €/t $CO2$ eq.
Short run (up to 2030)	60	100	189
Lon run (up to 2060)	156	269	498

11.3.3. Emission damage cost

The damage cost of pollution and the avoidance cost of climate change are combined to define the cost of emission for the different operations defined in this research, see table 11.5.

Table 11.5: Damage cost of scoped emissions, consisting of pollution cost and global warming avoidance cost, established with "Handbook on External Costs of Transport" [35].

	CO €/kg	**CO_2** €/kg	**NO_x** €/kg	**SOx** €/kg	**PM** €/kg
Transit operation	0.00	0.27	3.80	3.50	4.10
Coastal operation	0.00	0.27	10.25	8.90	16.35
Antarctic operation	0.00	0.27	12.60	10.90	22.30

Figure 11.2 shows the damage cost of the ship of which the general results were presented in section 9.1. It becomes clear that de damage cost for most (hybrid) fuel cell powered ships is still significant. This is due to the high CO_2 emissions for most fuel cell systems. Only the NH_3 and LH_2 fueled options result in a low damage cost, due to the absence of carbon in the fuel. In figure 11.3 the saving in damage cost (damage cost of conventional ship minus damage cost of concerned fuel cell powered ship) is compared with the increase in total cost (newbuild price and fuel cost) over the lifetime of the ship. The options where the savings in damage cost (green) are higher than the increase in total cost (red) are economically justifiable from a societal perspective. From this perspective, LNG fueled LT-PEMFC would be most justifiable to invest in.

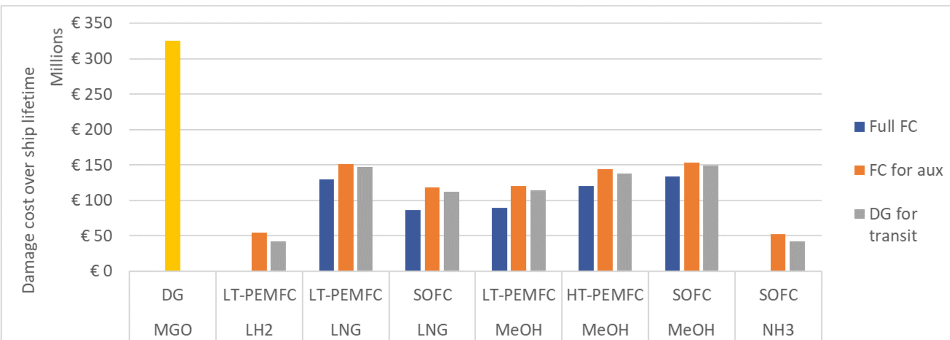


Figure 11.2: Damage cost of emission over ship lifetime. Includes pollution damage cost and climate change damage cost.

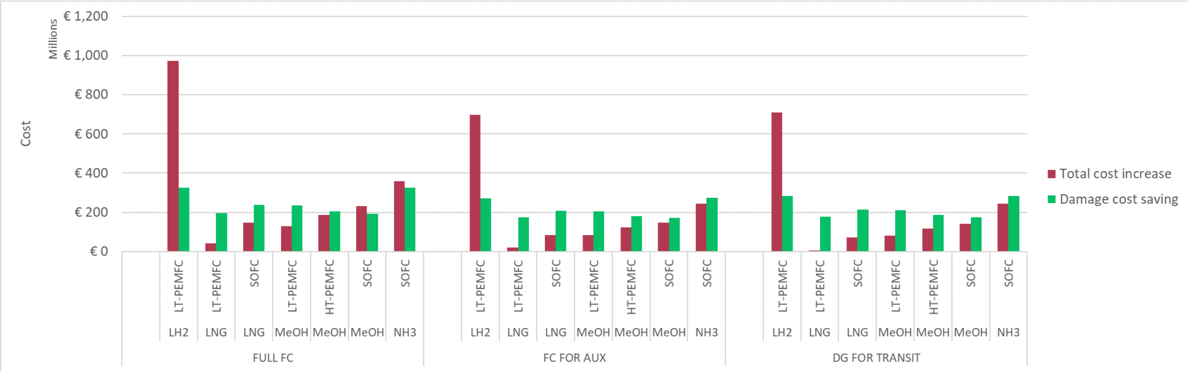


Figure 11.3: In red: absolute increase in total cost (newbuild price and fuel cost) over ship lifetime compared with total cost of conventional ship with equal requirements. In green: absolute savings in emission damage cost over lifetime compared to the emission damage cost of conventional ship with equal requirements. If green is higher than red, that option is economically better from a societal perspective.

11.4. Scenarios

Some of the used data for the model is very subjective to change. Cost of fuel cell systems is expected to decrease due to technological advance and expectancy of mass production [11, 17, 28, 85] and fuel prices of the different fuels are fluctuating [14] due to market force and regulations. Different scenarios are defined to review this change in key parameters. This section corresponds to a type of sensitivity analysis where the values of internal parameters are changed to determine the model's behavior, which is a type of model validation [99].

11.4.1. Decrease in cost of fuel cell system

The decrease in cost of the selected fuel cell systems is estimated from literature and opinion of fuel cell experts. The expected cost of the fuel cell power pack over the next 10 years is shown in figure 11.4. Predicting reduction in cost of technology in the future is a speculative effort. For this reason pessimistic (upper boundary), typical and optimistic (lower boundary) situations are defined, see the colored areas in figure 11.4.

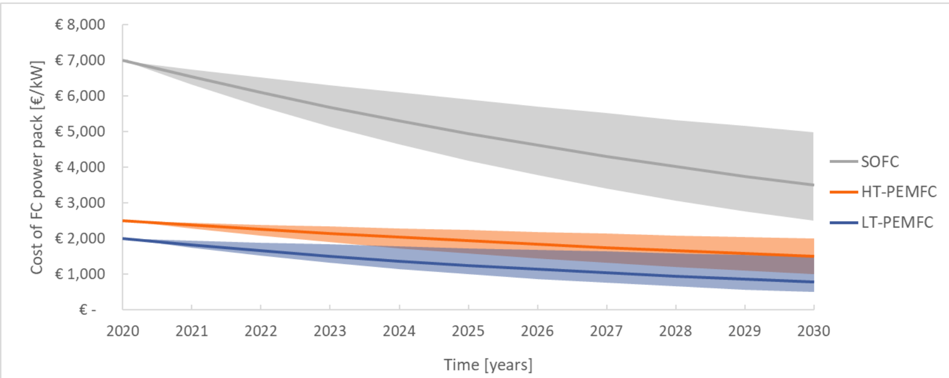
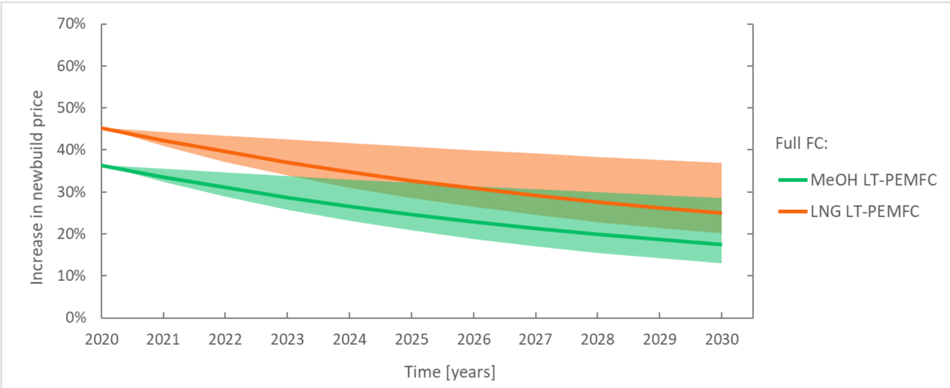


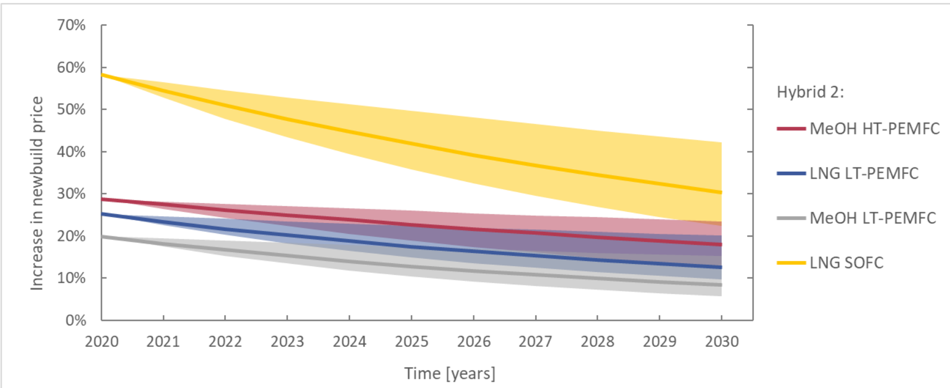
Figure 11.4: Expected decrease in cost for selected fuel cell systems in coming 10 years. Including pessimistic, normal and optimistic scenarios.

Increase in newbuild price

The expected decrease in cost of the fuel cell systems over the coming 10 years is used as input for the model. The increase in newbuild price for the selected fuel cell system and hybrid options can be found in figure 11.5 (a) and (b). Since many shaded areas are overlapping the following can be observed: which combination of fuel cell system and hybrid option performs the best in terms of newbuild price over 10 years is much dependent on how fuel cell prices are going to develop. *MeOH* fueled LT-PEMFC and *LNG* fueled LT-PEMFC for hybrid option 2 most likely results in the lowest increase in build cost over 10 years. Although *LNG* fueled SOFC decreases in price the fastest it is still very likely to be the most expensive option in terms of newbuild price in 10 years.



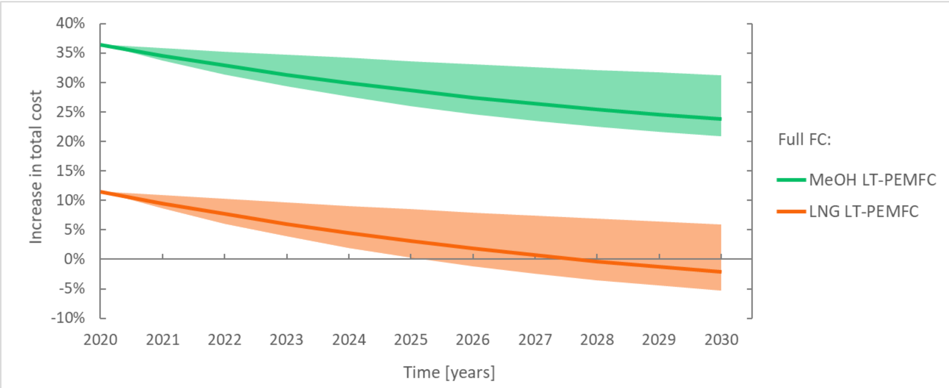
(a) Full FC options.



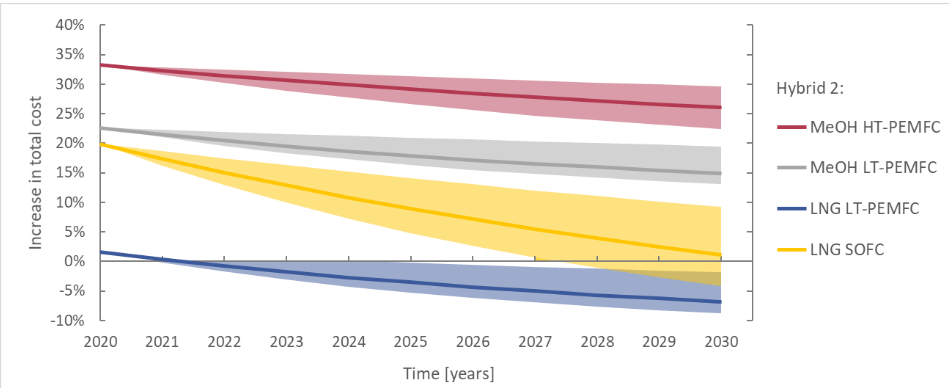
(b) Hyrbid 2 options.

Figure 11.5: Increase in newbuild price compared to newbuild price of a conventional ship, when using expected decrease in cost of fuel cell systems in coming 10 years as input for the model.

Increase in total cost
The expected decrease in cost of the fuel cell systems over the coming 10 years is used as input for the model. The increase in total cost (newbuild price and fuel cost) for the selected combinations of fuel cell system and hybrid option can be found in figure 11.6 (a) and (b). It is visible that all six options become more cost effective in the future, however some quicker than others. For instance in 10 years for hybrid option 2, *LNG* fueled SOFC might be a better option than *LNG* fueled LT-PEMFC when SOFC develops rapidly and LT-PEMFC prices do not decrease much. It must be noted that variations in fuel prices are not included in this prediction.



(a) Full FC options.



(b) Hyrbid 2 options.

Figure 11.6: Increase in total cost (newbuild price and fuel cost) of ship compared to total cost of a conventional ship, when using expected decrease in cost of fuel cell systems in coming 10 years as input for the model.

Overview
Table 11.6 shows an overview of figures 11.5 and 11.6. From this table can be retrieved which options are favoured in 2030, dependent on the scenario. For instance the total cost for a pessimistic scenario for *LNG* fueled SOFC with hybrid option 2 is in 2030 still lower than the total cost of an optimistic scenario for *MeOH* fueled LT-PEMFC with hybrid option 2. This is in accordance with figure 11.6 (b).

Table 11.6: Summary of figures 11.5 and 11.6

			Increase in ship cost			Increase in total cost		
			2020	2030		2020	2030	
				Pess.	Opt.		Pess.	Opt.
LNG	LT-PEMFC	Full FC	45%	37%	20%	12%	6%	-5%
MeOH	LT-PEMFC	Full FC	36%	29%	13%	36%	31%	21%
LNG	LT-PEMFC	Hybrid 2	25%	20%	10%	2%	-2%	-9%
LNG	SOFC	Hybrid 2	58%	42%	22%	20%	9%	-4%
MeOH	LT-PEMFC	Hybrid 2	20%	15%	6%	23%	19%	13%
MeOH	HT-PEMFC	Hybrid 2	18%	23%	13%	26%	30%	22%

11.4.2. Fluctuation in fuel prices

The conclusions drawn in this research are very dependent on the fuel price of the conventional fuel (MGO) as well as of the alternative fuels. For that reason fuel prices are varied in this section to indicate the effect on the results.

The International Energy Agency expects MGO to play a significant role in the fuel mix for shipping [56], see figure 11.7. The price of this MGO is very dependent on supply and demand of MGO. The economic feasibility of a fuel cell powered ship is dependent on the price of MGO: when MGO prices are very high, a cruise line is more willing to invest in a power generation system for a different fuel and vice versa for low MGO prices.

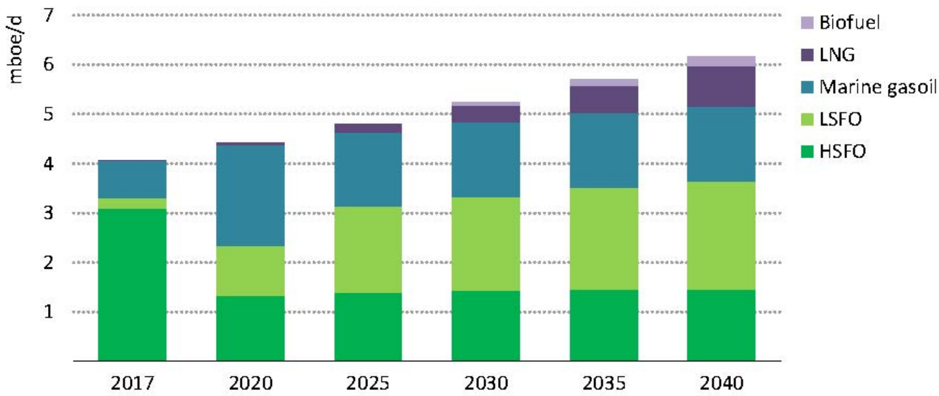


Figure 11.7: Fuel mix for the international shipping sector in the New Policies Scenario (low sulphur compliant fuels). mboe/d = million barrels of oil equivalent per day; HSFO = high sulfur fuel oil; LSFO = low sulfur fuel oil. LSFO includes both straight-run LSFO and LSFO produced by blending HSFO and gasoil [56].

Predicting fuel prices is very speculative, for that reason different scenarios for MGO prices are defined (see below). The development of MGO for the different scenarios is sketched in figure 11.8 with use of the World Energy Outlook 2018 [56]. Other fuel prices are assumed constant, since not enough data is available to predict the prices of LH_2, LNG, $MeOH$ and NH_3. This is a conservative assumption since all these fuels are expected to drop in price due to increase in supply and fuel infrastructure [72]. For instance, the price of hydrogen is expected to drop in the coming decade due to declining costs of renewable electricity generation and upscaling of electrolyser manufacturing [50].

1. *Low MGO price*
   External factors can lead to low MGO prices, for instance at the moment of writing, an over supply of oil by Russia and Saudi Arabia and a low demand of oil due to the Corona crisis has lead to a very low oil price, directly leading to a low MGO price.

2. *Medium MGO price*
   While MGO will stay a key fuel in the coming years, more and more ship owners might transfer to other fuels (LNG, Biofuel, Methanol etc.), consequently also decreasing the demand for MGO. Since this transition happens gradually and slowly due to large investments and long operational lifetimes of ships, this situation is defined as a medium MGO price scenario.

3. *High MGO price*
   The expected increase in demand for MGO in the coming years (figure 11.7) due to the decrease in demand for high polluting fuels because of stricter regulations might lead to an increase in the fuel price of MGO. This situation is used to define a high MGO price scenario.

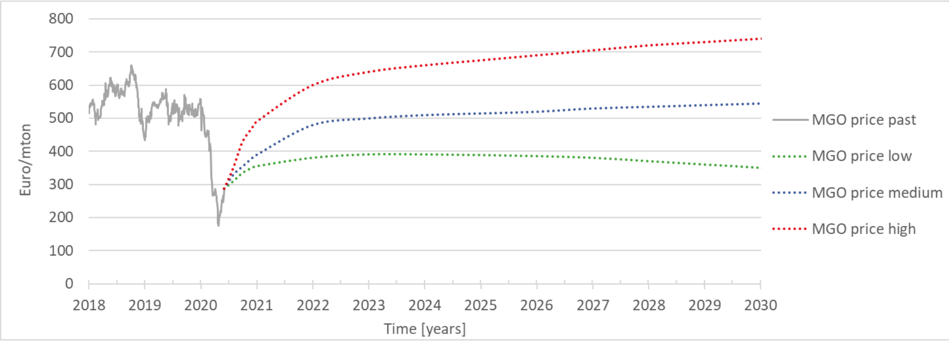
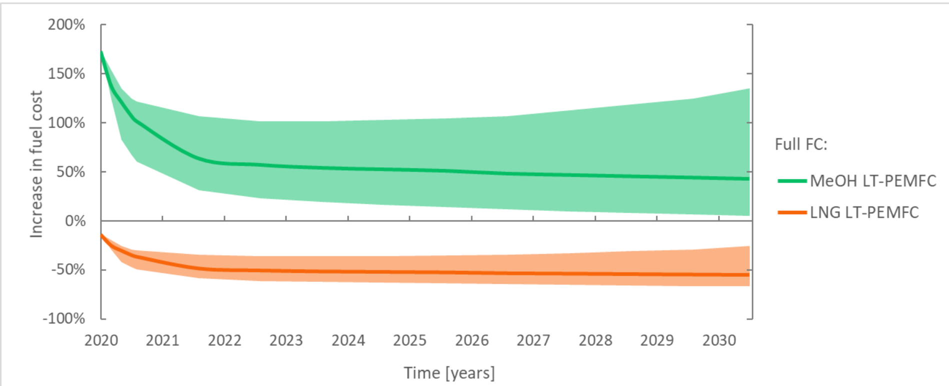


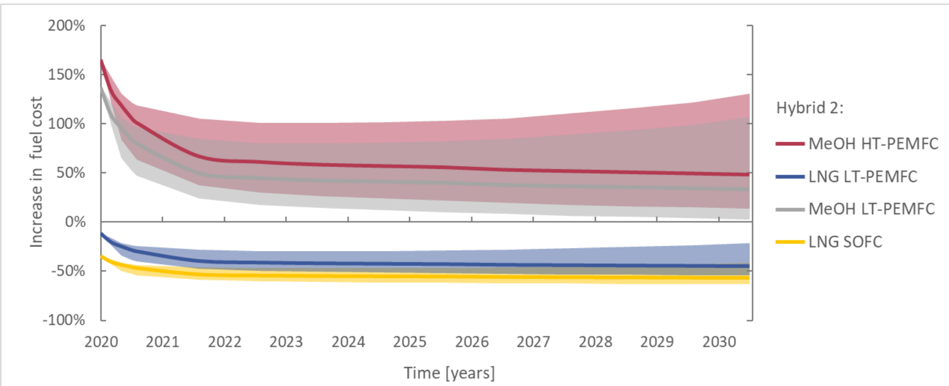
Figure 11.8: Development of MGO price for three different scenarios. Established with World Energy Outlook 2018 by International Energy Agency [56]

Increase in fuel cost

The different MGO pricing scenarios are used as input for the model. Figures 11.9 (a) and (b) show the increase in fuel cost compared to the fuel cost of a conventional ship. The upper bounds of the shaded areas correspond with the low MGO pricing scenario; a lower MGO price with an equal alternative fuel price leads to a higher increase in fuel cost of the fuel cell powered option with respect to the conventional option. Vice versa, the lower bound of the increase in fuel price correspond with a high MGO price. So, a high MGO price, is favorable for a fuel cell powered ship. For a hybrid option the impact is smaller, since it still uses some MGO. *LNG* fueled LT-PEMFC and hybrid option 2 with *LNG* fueled SOFC most probably lead to the lowest increase in fuel cost over the next 10 years. The increase in newbuild price is not presented, since the MGO price has no influence on this.



(a) Full FC options.

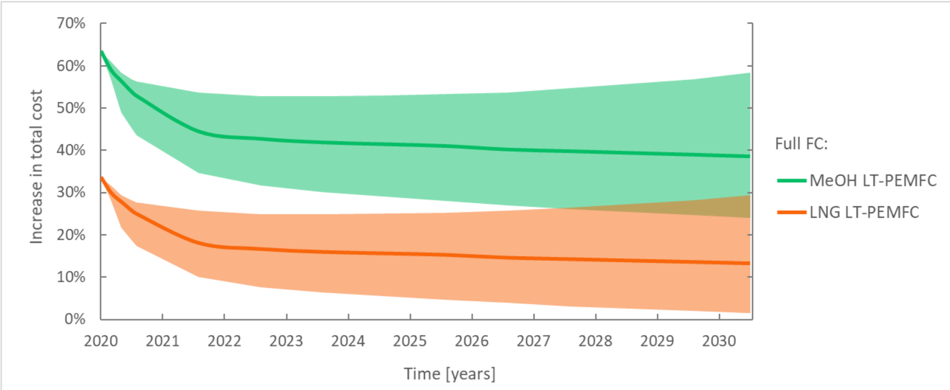


(b) Hyrbid 2 options.

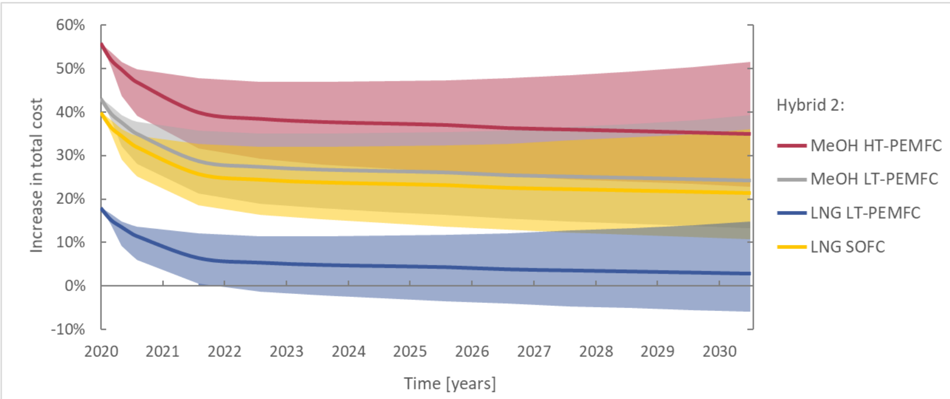
Figure 11.9: Increase in fuel cost compared to fuel cost of a conventional ship, when using different MGO pricing scenarios for the next 10 years as input for the model.

Increase in total cost

The increase in fuel cost over the ship lifetime is combined with the increase in newbuild price (which is in this case constant over the years) into the total increase in cost, see figure 11.10 (a) and (b). Even for a high MGO price scenario, hybrid option 2 with *LNG* fueled LT-PEMFC offers the lowest increase in total cost, despite the fact that expensive MGO is in that case consumed during the transit operation.



(a) Full FC options.



(b) Hyrbid 2 options.

Figure 11.10: Increase in total cost (over ship lifetime) compared to total cost of a conventional ship, when using different MGO pricing scenarios for the next 10 years as input for the model.

Overview

Table 11.7 shows an overview of figures 11.9 and 11.10. From this table can be retrieved which options are favoured in 2030, dependent on the MGO price. For instance that a high MGO price in combination with *LNG* fueled LT-PEMFC using hybrid option 2 leads to the most favourable scenario in terms of increase in total cost with respect to a conventional solution.

Table 11.7: Summary of figures 11.9 and 11.10. High = high MGO price scenario, Low = low MGO price scenario.

			Increase in fuel cost			Increase in total cost		
			2020	2030		2020	2030	
				High	Low		High	Low
LNG	LT-PEMFC	Full FC	-14%	-67%	-26%	34%	1%	29%
MeOH	LT-PEMFC	Full FC	173%	5%	135%	63%	24%	58%
LNG	LT-PEMFC	Hybrid 2	-11%	-41%	-21%	18%	-6%	15%
LNG	SOFC	Hybrid 2	-35%	-63%	-50%	40%	11%	36%
MeOH	LT-PEMFC	Hybrid 2	137%	3%	107%	43%	13%	39%
MeOH	HT-PEMFC	Hybrid 2	165%	14%	131%	56%	23%	52%

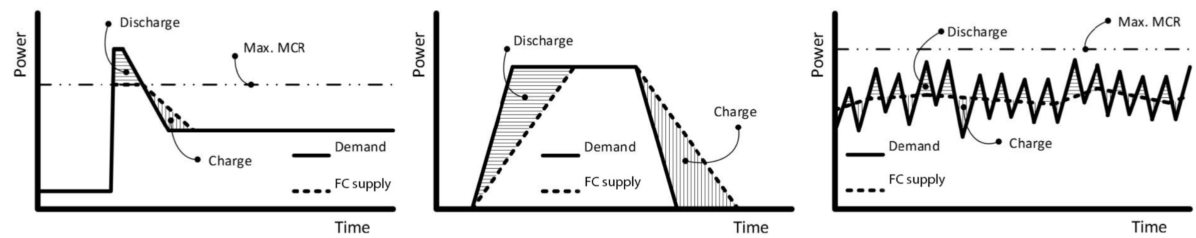
12
Further research

In this chapter, suggestions for further research are presented. The first two suggestions aim at making the current model more accurate and the third and fourth suggestion aim at broadening the scope of the research.

12.1. Matching dynamic power supply and demand

To more precisely estimate the size, weight and cost of the balance of plant components, the dynamic power supply should be matched with the dynamic power demand. The balance of plant components (batteries and super capacitors) can support the fuel cell system on three different functionalities: peak shaving, ramp support and load smoothing (figure 12.1). In the operation of a fuel cell power plant on a ship, a combination of these three would be necessary. Dynamic power supply and demand can be matched with the following method:

1. Investigating the transient power demand of the power consumers. The required change in power should be derived from studying the required electrical consumers of expedition cruise ships.
2. Investigating the transient capability of the fuel cell systems. Although data is available of start-up times, no data is available of the ability of the fuel cell system to change its power supply. The lack of data is especially present for HT-PEMFC and SOFC, for which the transient power behavior matters the most.
3. Investigating the transient capability of balance of plant components. The required volume, weight and price of the balance of plant components for a certain transient power performance must be defined.
4. Comparing the required change in power to the available change in power of the fuel cell system. The deficit between the required and the available change in power must be repleted with balance of plant components. With the defined volume, weight and cost for transient behavior performance (point 3), the balance of plant components can be more accurately dimensioned.



(a) Peak shaving. (b) Ramp support. (c) Load smoothing.

Figure 12.1: Different functionalities of balance of plant components.

12.2. Cost of fuel processing system and balance of plant components

Since no cost data of the fuel processing systems and balance of plant components was available, the cost sof these systems are added by using extra margins on the cost of the fuel cell system, in consultation with fuel cell experts. To more accurately incorporate the cost of the fuel cell power plant, cost data of these systems is necessary. Cost data of course is available at suppliers of these systems, but suppliers are reluctant to share this data. Getting in closer contact with suppliers (under Non-Disclosure Agreement) to obtain cost data would be necessary to more accurately determine the cost of the fuel cell power plant. For this research this was not necessary (in the Rough Order of Magnitude phase budgetary quotations are usually not retrieved) and not possible (a graduation project infringes with the arrangements of an NDA). But for the next design phase (Budgetary offer) more precise information on these components would be necessary.

12.3. Life Cycle Assessment

To completely assess the environmental impact of the different fuel cell systems, it is necessary to take into account the environmental impact during all stages of the fuel cell (cradle to grave) and the fuel (well to propeller), see also figure 3.2 in section 3.3.3. A complete Life Cycle Assessment (LCA) assesses the fuel cell and fuel on Global warming (GWP100), Ozone layer depletion (ODP), Photo chemical oxidation (POCP), Acidification (AP) and Eutrophication (EP) [109]. When this is performed a well-grounded conclusion can be drawn on which fuel cell system would be most environmental friendly. With this study ISO 14040 and 14044 should be followed, which are introduced in 2006 for LCAs [38]. Doing a complete LCA according to these standards would make it possible to compare with other LCA research.

12.4. Fuel prices

As was stated in section 11.4.2, the drawn conclusions of this research are very dependent on the price of conventional and alternative fuels. Although a varying MGO price was used as input for the model to sketch different scenarios, alternative fuel prices were kept constant, since no reliable data for predicting these fuels were found. To further investigate the effect of the alternative fuel prices on the cost performance of the different fuel cell systems applied in ships, scenarios for fuel alternative fuel prices should be sketched as well.

An alternative method to map the effect of different fuel price, is using a statistical method to include uncertainty in fuel prices. Several studies use such methods (Markov chain or Monte Carlo simulation) to take into account uncertainty in fuel price when analyzing decisions over converting a ship to LNG power [58, 59] or when analyzing decisions on energy saving devices [118]. It should be investigated whether the model can be extended with such methods to include uncertainty in the different alternative fuel prices. Such methods can also be used to include fuel supply chain risks and uncertainty in upcoming regulations.

Bibliography

[1] ABS. Guide for fuel cell power systems for marine and offshore applications. Technical report, American Bureau of Shipping, New York, 2019.

[2] A. Albrechtslund. Ethics and technology design. *Ethics and Information Technology*, 9(1):63–72, mar 2007. ISSN 13881957. doi: 10.1007/s10676-006-9129-8.

[3] M. Alessandro. Imagine - The Future of Cruise Ship Design. Technical report, RINA, 2019.

[4] S. Alkaner and P. Zhou. A comparative study on life cycle analysis of molten carbon fuel cells and diesel engines for marine application. *Journal of Power Sources*, 158(1):188–199, jul 2006. ISSN 03787753. doi: 10.1016/j.jpowsour.2005.07.076.

[5] M. Altmann, W. Weindorf, R. Wurster, M. Weinberger, and G. Filip. FCSHIP: Environmental Impacts and Costs of Hydrogen, Natural Gas and Conventional Fuels for Fuel Cell Ships. In *15th World Hydrogen Energy Conference*, Yokohama, 2004.

[6] P. V. Aravind and T. Woudstra. Fuel cell course at delft university of technology, 2019.

[7] F. Baldi, F. Ahlgren, T. Nguyen, M. Thern, and K. Andersson. Energy and Exergy Analysis of a Cruise Ship. *Energies*, 11(10):2508, sep 2018. ISSN 1996-1073. doi: 10.3390/en11102508. URL `http://www.mdpi.com/1996-1073/11/10/2508`.

[8] S. Bengtsson, K. Andersson, and E. Fridell. A comparative life cycle assessment of marine fuels liquefied natural gas and three other fossil fuels. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 225(2):97–110, may 2011. ISSN 1475-0902. doi: 10.1177/1475090211402136. URL `http://journals.sagepub.com/doi/10.1177/1475090211402136`.

[9] S. Bensaid, S. Specchia, F. Federici, G. Saracco, and V. Specchia. MCFC-based marine APU: Comparison between conventional ATR and cracking coupled with SR integrated inside the stack pressurized vessel. *International Journal of Hydrogen Energy*, 34(4):2026–2042, feb 2009. ISSN 03603199. doi: 10.1016/j.ijhydene.2008.11.092.

[10] V. Bertram. *Practical Ship Hydrodynamics*. Elsevier, 2012.

[11] L. van Biert, M. Godjevac, K. Visser, and P. V. Aravind. A review of fuel cell systems for maritime applications Review article A review of fuel cell systems for maritime applications. *Journal of Power Sources*, 327(February 2018):345–364, 2016. ISSN 0378-7753. doi: 10.1016/j.jpowsour.2016.07.007. URL `http://dx.doi.org/10.1016/j.jpowsour.2016.07.007`.

[12] Bloom Energy. Energy Server 5 Product Datasheet. Technical report, 2019. URL `www.bloomenergy.com`.

[13] A. Boudghene Stambouli and E. Traversa. Fuel cells, an alternative to standard sources of energy, 2002. ISSN 13640321.

[14] Ship & Bunker. World Bunker Prices - Ship & Bunker, 2019. URL `https://shipandbunker.com/prices`.

[15] F. Burel, R. Taccani, and N. Zuliani. Improving sustainability of maritime transport through utilization of Liquefied Natural Gas (LNG) for propulsion. *Energy*, 57:412–420, aug 2013. ISSN 03605442. doi: 10.1016/j.energy.2013.05.002. URL `https://linkinghub.elsevier.com/retrieve/pii/S0360544213003861`.

[16] A. Chandan, M. Hattenberger, A. El-Kharouf, S. Du, A. Dhir, V. Self, B. G. Pollet, A. Ingram, and W. Bujalski. High temperature (HT) polymer electrolyte membrane fuel cells (PEMFC)-A review. *Journal of Power Sources*, 231:264–278, jun 2013. ISSN 03787753. doi: 10.1016/j.jpowsour.2012.11.126.

[17] H. Chen, P. Pei, and M. Song. Lifetime prediction and the economic lifetime of proton exchange membrane fuel cells. *Applied Energy*, 142:154–163, mar 2015. ISSN 03062619. doi: 10.1016/j.apenergy.2014.12.062.

[18] C. H. Choi, S. Yu, I. S. Han, B. K. Kho, D. G. Kang, H. Y. Lee, M. S. Seo, J. W. Kong, G. Kim, J. W. Ahn, S. K. Park, D. W. Jang, J. H. Lee, and M. Kim. Development and demonstration of PEM fuel-cell-battery hybrid system for propulsion of tourist boat. *International Journal of Hydrogen Energy*, 41(5):3591–3599, feb 2016. ISSN 03603199. doi: 10.1016/j.ijhydene.2015.12.186.

[19] S. Claus. Steeds meer cruiseschepen mijden Amsterdam, de sector baalt, 2019. URL `https://www.trouw.nl/economie/steeds-meer-cruiseschepen-mijden-amsterdam-de-sector-baalt{~}b0fdb7f1/`.

[20] CLIA. 2019 Cruise Trends & Industry Outlook. Technical report, Cruise Line Internation Association, 2019.

[21] CLIA. STATE OF THE CRUISE INDUSTRY OUTLOOK 2020. Technical report, CLIA, 2019.

[22] Convion. Products, 2019. URL `http://convion.fi/products/`.

[23] Cool Antartica. Pollution in Antarctica, Human Impacts on Antarctica and Threats to the Environment - Pollution, 2020. URL `https://www.coolantarctica.com/Antarcticafactfile/science/threats{_}pollution.php`.

[24] Cruise Industry News. Cruise Ship Orderbook, 2020. URL `https://www.cruiseindustrynews.com/cruise-news/cruise-ship-orderbook.html`.

[25] R. P. Dallinga and J. E. Bos. Cruise Ship Seakeeping and Passenger Comfort. 2010.

[26] S. K. Das and K. K. Gadde. Computational fluid dynamics modeling of a catalytic flat plate fuel reformer for on-board hydrogen generation. *Journal of Fuel Cell Science and Technology*, 10(6), 2013. ISSN 1550624X. doi: 10.1115/1.4025056.

[27] S. De Sio. Ethics and Self-driving Cars: A White Paper on Responsible Innovation in Automated Driving Systems. Technical report, 2016.

[28] J. J. De-Troya, C. Álvarez, C. Fernández-Garrido, and L. Carral. Analysing the possibilities of using fuel cells in ships, 2016. ISSN 03603199.

[29] M. C. Díaz-de Baldasano, F. J. Mateos, L. R. Núñez-Rivas, and T. J. Leo. Conceptual design of offshore platform supply vessel based on hybrid diesel generator-fuel cell power plant. *Applied Energy*, 116:91–100, mar 2014. ISSN 03062619. doi: 10.1016/j.apenergy.2013.11.049.

[30] DNV GL. Guidance for safe return to port projects. Technical report, 2016.

[31] DNV GL. Fuel Cell Installations. In *DNVGL Rules for Classification of Ships*, chapter Part 6, pages 78–97. 2019.

[32] K. C. Elliott. Hydrogen fuel-cell vehicles, energy policy, and the ethics of expertise. *Journal of Applied Philosophy*, 27(4):376–393, nov 2010. ISSN 14685930. doi: 10.1111/j.1468-5930.2010.00502.x. URL `http://doi.wiley.com/10.1111/j.1468-5930.2010.00502.x`.

[33] J. Ellis and K. Tanneberger. Study on the use of ethyl and methyl alcohol as alternative fuels in shipping. Technical report, EMSA, 2016. URL `http://www.emsa.europa.eu/news-a-press-centre/external-news/item/2726-study-on-the-use-of-ethyl-and-methyl-alcohol-as-alternative-fuels-in-shipping.html`.

[34] The engineering toolbox. Fuels - Higher and Lower Calorific Values, 2019. URL `https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d{_}169.html`.

[35] European Commission. *Handbook on External Costs of Transport*. Publications Office of the European Union, luxembourg edition, 2019. ISBN 9789279969171. doi: 10.2832/27212.

[36] R. A. Evrin and I. Dincer. Thermodynamic analysis and assessment of an integrated hydrogen fuel cell system for ships. *International Journal of Hydrogen Energy*, 44(13):6919–6928, mar 2019. ISSN 03603199. doi: 10.1016/j.ijhydene.2019.01.097.

[37] FCH. Fuel cells and Hydrogen - Joint undertaking, 2020. URL `https://www.fch.europa.eu/`.

[38] M. Finkbeiner, A. Inaba, R. Tan, K. Christiansesn, and H. Klüppel. The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044. *The International Journal of Lice Cycle Assessment*, 11:80–85, 2006. ISSN 0004640X. doi: 10.1007/BF00648130.

[39] G. G. M. Fournier, I. W. Cumming, and K. Hellgardt. High performance direct ammonia solid oxide fuel cell. *Journal of Power Sources*, 162(1):198–206, nov 2006. ISSN 03787753. doi: 10.1016/j.jpowsour.2006.06.047.

[40] B. Friedman. Value-Sensitive Design. Technical report, Colby College, 1996.

[41] B. Friedman, P. H. Kahn, and A. Borning. Value Sensitive Design: Theory and Methods. Technical report, University of Washington, 2002.

[42] B. Friedman, P. H. Kahn, A. Borning, and A. Huldtgren. Value Sensitive Design and Information Systems. pages 55–95. Springer, Dordrecht, 2013. doi: 10.1007/978-94-007-7844-3_4.

[43] Fuel Cells Bulletin. Sunfire 50 kW SOFC for ship-integrated fuel cell project in Germany, nov 2015. ISSN 14642859.

[44] R. Geertsma and M. Krijgsman. Alternative fuels and power systems to reduce environmental impact of support vessels. 2019.

[45] M. M. F. Hasan, A. M. Zheng, and I. A. Karimi. Minimizing boil-off losses in liquefied natural gas transportation. *Industrial and Engineering Chemistry Research*, 48(21):9571–9580, 2009. ISSN 08885885. doi: 10.1021/ie801975q.

[46] B. Höhlein, M. Boe, J. Bøgild-Hansen, P. Bröckerhoff, G. Colsman, B. Emonts, R. Menzer, and E. Riedel. Hydrogen from methanol for fuel cells in mobile systems: Development of a compact reformer. *Journal of Power Sources*, 61(1-2):143–147, jul 1996. ISSN 03787753. doi: 10.1016/S0378-7753(96)02357-9.

[47] J. Holtrop and G. G. J. Mennen. An aproximate power prediction method. 1982.

[48] O. J. A. Howitt, V. G. N. Revol, Inga J. Smith, and Craig J. Rodger. Carbon emissions from international cruise ship passengers' travel to and from New Zealand. *Energy Policy*, 2010. ISSN 03014215. doi: 10.1016/j.enpol.2009.12.050.

[49] K. D. Hristovski, B. Dhanasekaran, J. E. Tibaquirá, J. D. Posner, and P. K. Westerhoff. Producing drinking water from hydrogen fuel cells. *Journal of Water Supply: Research and Technology - AQUA*, 58(5):327–335, 2009. ISSN 00037214. doi: 10.2166/aqua.2009.103.

[50] Hydrogen Council. Path to hydrogen competitiveness - A cost perspective. Technical report, 2020. URL `www.hydrogencouncil.com`.

[51] IMO. MARPOL ANNEX VI AND NTC 2008 WITH GUIDELINES FOR IMPLEMENTATION. Technical report, 2013.

[52] IMO. UN body adopts climate change strategy for shipping, 2018. URL `http://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx`.

[53] IMO. GHG Emissions, 2018. URL `http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/GHG-Emissions.aspx`.

[54] IMO. Nitrogen oxides (NOx) – Regulation 13, 2020. URL `http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Nitrogen-oxides-(NOx)-\T1\textendash-Regulation-13.aspx`.

[55] IMO. Sulphur oxides (SOx) – Regulation 14, 2020. URL http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Sulphur-oxides-(SOx)-\T1\textendash-Regulation-14.aspx.

[56] International Energy Agency. World Energy Outlook 2018: Highlights. Technical report, 2018. URL https://www.oecd-ilibrary.org/energy/world-energy-outlook-2018/executive-summary{_}weo-2018-2-en.

[57] R. K. Isaacs, N. Palfreeman, and R. Robert. Achieving Ultra-Low NOx Emissions in Methanol Downfired Reformer Applications. In *International Combustion Symposium*. American Flam Research Committee, 2013. URL https://collections.lib.utah.edu/details?id=14363.

[58] A. Kana, J. T. Knight, M. J. Sypniewski, and D. J. Singer. A Markov Decision Process Framework for Analyzing LNG as Fuel in the Face of Uncertainty. *International Marine Design Conference*, 2:297–308, 2015. doi: 10.13140/RG.2.1.2189.5525.

[59] A. A. Kana and B. M. Harrison. A Monte Carlo approach to the ship-centric Markov decision process for analyzing decisions over converting a containership to LNG power. *Ocean Engineering*, 130:40–48, jan 2017. ISSN 00298018. doi: 10.1016/j.oceaneng.2016.11.042.

[60] L. Kar Chung Tse, S. Wilkins, N. McGlashan, B. Urban, and R. Martinez-Botas. Solid oxide fuel cell/gas turbine trigeneration system for marine applications. *Journal of Power Sources*, 196(6):3149–3162, mar 2011. ISSN 03787753. doi: 10.1016/j.jpowsour.2010.11.099.

[61] R. J. Kee, H. Zhu, and D. G. Goodwin. Solid-oxide fuel cells with hydrocarbon fuels. *Proceedings of the Combustion Institute*, 30 II:2379–2404, 2005. ISSN 15407489. doi: 10.1016/j.proci.2004.08.277.

[62] H. Klein Woud and D. Stapersma. *Design of Propulsion and Electric Power Generation Systems*. Institute of Marine Engineers, 2002. ISBN 9781902536477.

[63] A. Klerke, C. H. Christensen, J. K. Nørskov, and T. Vegge. Ammonia for hydrogen storage: Challenges and opportunities. *Journal of Materials Chemistry*, 18(20):2304–2310, 2008. ISSN 09599428. doi: 10.1039/b720020j.

[64] S. Krummrich, B. Tuinstra, G. Kraaij, J. Roes, and H. Olgun. Diesel fuel processing for fuel cells-DESIRE. *Journal of Power Sources*, 160(1):500–504, sep 2006. ISSN 03787753. doi: 10.1016/j.jpowsour.2005.12.100.

[65] R. Lan and S. Tao. Ammonia as a Suitable Fuel for Fuel Cells. *Frontiers in Energy Research*, 2, aug 2014. ISSN 2296-598X. doi: 10.3389/fenrg.2014.00035. URL http://journal.frontiersin.org/article/10.3389/fenrg.2014.00035/abstract.

[66] J. Larminie and A. Dicks. *Fuel Cell Systems Explained (Second Edition)*. Wiley, 2003. ISBN 047084857X. URL www.wiley.co.uk/fuelcellsystems.

[67] K. Law, J. Rosenfeld, V. Han, M. Chan, H. Chiang, and J. Leonard. U.S. Department of Energy Hydrogen Storage Cost Analysis. *U.S. Department of Energy*, 2013. URL https://www.osti.gov/scitech/servlets/purl/1082754.

[68] Y. D. Lee, K. Y. Ahn, T. Morosuk, and G. Tsatsaronis. Environmental impact assessment of a solid-oxide fuel-cell-based combined-heat-and-power-generation system. *Energy*, 79(C):455–466, jan 2015. ISSN 03605442. doi: 10.1016/j.energy.2014.11.035.

[69] K. Leites, A. Bauschulte, M. Dragon, S. Krummrich, and P. Nehter. Design of different diesel based fuel cell systems for seagoing vessels and their evaluation. In *ECS Transactions*, volume 42, pages 49–58, 2012. ISBN 9781566779807. doi: 10.1149/1.4705479.

[70] K. Levander. *System based ship design*. 2007.

[71] Y. Ligen, H. Vrubel, and H. Girault. Mobility from Renewable Electricity: Infrastructure Comparison for Battery and Hydrogen Fuel Cell Vehicles. *World Electric Vehicle Journal*, 9(1):3, may 2018. ISSN 2032-6653. doi: 10.3390/wevj9010003. URL http://www.mdpi.com/2032-6653/9/1/3.

[72] Lloyd's Register. Fuel production cost estimates and assumptions. Technical report, 2019. URL https://www.lr.org/en-gb/insights/global-marine-trends-2030/zero-emission-vessels-transition-pathways/.

[73] B. N. Lukyanov, D. V. Andreev, and V. N. Parmon. Catalytic reactors with hydrogen membrane separation. *Chemical Engineering Journal*, 154(1-3):258–266, nov 2009. ISSN 13858947. doi: 10.1016/j.cej.2009.04.023.

[74] MAN Diesel & Turbo. Basic Principles of Ship Propulsion. Technical report, 2016.

[75] MarineWiki. Ship Design Process, 2020. URL http://www.marinewiki.org/index.php/SHIP{_}DESIGN{_}PROCESS.

[76] J. Markowski and I. Pielecha. The potential of fuel cells as a drive source of maritime transport. In *IOP Conference Series: Earth and Environmental Science*, volume 214, page 12019. Institute of Physics Publishing, jan 2019. doi: 10.1088/1755-1315/214/1/012019. URL https://iopscience.iop.org/article/10.1088/1755-1315/214/1/012019https://iopscience.iop.org/article/10.1088/1755-1315/214/1/012019/meta.

[77] V. Masson-Delmotte, P. Zhai, H. Pörtner, D. Roberts, J. Skea, P. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield. *Global Warming of 1.5°C*. 2019. ISBN 9789291691531. URL www.environmentalgraphiti.org.

[78] A. Mehmeti, S. J. McPhail, D. Pumiglia, and M. Carlini. Life cycle sustainability of solid oxide fuel cells: From methodological aspects to system implications, sep 2016. ISSN 03787753.

[79] H. C. Miller, G. N. Mills, D. G. Bembo, J. A. MacDonald, and C. W. Evans. Induction of cytochrome P4501A (CYP1A) in Trematomus bernacchii as an indicator of environmental pollution in Antarctica: Assessment by quantitative RT-PCR. *Aquatic Toxicology*, 44(3):183–193, jan 1998. ISSN 0166445X. doi: 10.1016/S0166-445X(98)00075-7.

[80] J. J. Minnehan and J. W. Pratt. Practical Application Limits of Fuel Cells and Batteries for Zero Emission Vessels. Technical report, Sandia National Laboratories, Alburquerque, 2017. URL https://classic.ntis.gov/help/order-methods/.

[81] A. Miola, B. Ciuffo, E. Giovine, and M. Marra. Regulating Air Emissions from Ships - The State of the Art on Methodologies, Technologies and Policy Options. Technical report, 2010. URL http://europa.eu/.

[82] C. W. Mohd Noor, M. M. Noor, and R. Mamat. Biodiesel as alternative fuel for marine diesel engine applications: A review, oct 2018. ISSN 18790690.

[83] K. Moirangthem and D. Baxter. Alternative Fuels for Marine and Inland Waterways. Technical report, JRC, 2016. URL https://ec.europa.eu/jrc.

[84] Operations International Association Antarctica Tour. Bylaws - May 2017, 2017. URL https://iaato.org/bylaws.

[85] J. Otomo, J. Oishi, T. Mitsumori, H. Iwasaki, and K. Yamada. Evaluation of cost reduction potential for 1 kW class SOFC stack production: Implications for SOFC technology scenario. *International Journal of Hydrogen Energy*, 38(33), nov 2013. ISSN 03603199. doi: 10.1016/j.ijhydene.2013.08.110.

[86] Ö. Özdemir, B. F. Hobbs, M. Van Hout, and P. Koutstaal. Capacity vs Energy Subsidies for Renewables: Benefits and Costs for the 2030 EU Power Market. 2019. URL www.eprg.group.cam.ac.uk.

[87] C. Pan, R. He, Q. Li, J. O. Jensen, N. J. Bjerrum, H. A. Hjulmand, and A. B. Jensen. Integration of high temperature PEM fuel cells with a methanol reformer. *Journal of Power Sources*, 2005. ISSN 03787753. doi: 10.1016/j.jpowsour.2005.02.056.

[88] H. C. Patel, T. Woudstra, and P. V. Aravind. Thermodynamic analysis of solid oxide fuel cell gas turbine systems operating with various biofuels. *Fuel Cells*, 12(6):1115–1128, dec 2012. ISSN 16156846. doi: 10.1002/fuce.201200062. URL http://doi.wiley.com/10.1002/fuce.201200062.

[89] R. Payne, J. Love, and M. Kah. Generating Electricity at 60% Electrical Efficiency from 1-2 kWe SOFC Products. In *ECS Transactions*, pages 231–239. The Electrochemical Society, 209. doi: 10.1149/1.3205530.

[90] J. S. Perry Hobson. Analysis of the US cruise line industry. *Tourism Management*, 14(6):453–462, 1993. ISSN 02615177. doi: 10.1016/0261-5177(93)90098-6.

[91] R. Peters, R. Deja, M. Engelbracht, M. Frank, V. N. Nguyen, L. Blum, and D. Stolten. Efficiency analysis of a hydrogen-fueled solid oxide fuel cell system with anode off-gas recirculation. *Journal of Power Sources*, 328:105–113, 2016. ISSN 03787753. doi: 10.1016/j.jpowsour.2016.08.002. URL `http://dx.doi.org/10.1016/j.jpowsour.2016.08.002`.

[92] Politecnico di Milano. DEMCOPEM-2MW. URL `https://demcopem-2mw.eu/`.

[93] J. W. Pratt and L. E. Klebanoff. Feasibility of the SF-BREEZE: a Zero-Emission, Hydrogen Fuel Cell, High-Speed Passenger Ferry. Technical report, Sandia National Laboratories, Albuquerque, 2016. URL `http://www.ntis.gov/search`.

[94] Precision Combustion Inc. WGS/PROX Reactors, 2019. URL `https://www.precision-combustion.com/products/fuel-processors/wgs-prox-reactors`.

[95] R. V. Ramasesh and T. R. Browning. A conceptual framework for tackling knowable unknown unknowns in project management. *Journal of Operations Management*, 32(4):190–204, may 2014. ISSN 02726963. doi: 10.1016/j.jom.2014.03.003.

[96] I. Ridjan. *Integrated electrofuels and renewable energy systems.* PhD thesis, Aalborg University, 2015. URL `https://www.researchgate.net/publication/292708910_Integrated_electrofuels_and_renewable_energy_systems`.

[97] A. C. Riekstin, S. James, A. Kansal, J. Liu, and E. Peterson. No More Electrical Infrastructure: Towards Fuel Cell Powered Data Centers. 2013.

[98] RVO. INTERREG 2014-2020, 2020. URL `https://www.rvo.nl/subsidie-en-financieringswijzer/interreg-2014-2020`.

[99] R. G. Sargent. Verification and validation of simulation models. In *Proceedings - Winter Simulation Conference*, pages 166–183, 2010. ISBN 9781424498666. doi: 10.1109/WSC.2010.5679166.

[100] J. Schneider and S. Dirk. ZEMShip. In *18th World Hydrogen Energy Conference*, volume 78. Zentralbibliothek, Verlag, 2010. ISBN 978-3-89336-656-9.

[101] SDR. Start of initiative for construction of 1 GW electrolysis plant for green hydrogen in Zeeland, 2019. URL `https://www.smartdeltaresources.com/en/news/start-of-initiative-for-construction-of-1-gw-electrolysis-plant-for-green-hydrogen-in-zeeland`.

[102] T. A. Semelsberger, R. L. Borup, and H. L. Greene. Dimethyl ether (DME) as an alternative fuel. *Journal of Power Sources*, 156(2):497–511, jun 2006. ISSN 03787753. doi: 10.1016/j.jpowsour.2005.05.082.

[103] EG&G Technical Services. *Fuel Cell Handbook (Seventh Edition).* 2004.

[104] M. W. Shin, D. Shin, S. H. Choi, and E. S. Yoon. Optimal operation of the boil-off gas compression process using a boil-off rate model for LNG storage tanks. *Korean J. Chem. Eng*, 25(1):7–12, 2008.

[105] Shippax. Shippax Database, 2020. URL `https://www.shippax.com/en/shippax-database.aspx`.

[106] SIEMENS. SINAVY PEM Fuel Cell. Technical report, 2013. URL `https://www.industry.siemens.com/verticals/global/de/marine/marineschiffe/energieverteilung/Documents/sinavy-pem-fuel-cell-en.pdf`.

[107] R. Soltani, M. A. Rosen, and I. Dincer. Assessment of CO2 capture options from various points in steam methane reforming for hydrogen production. *International Journal of Hydrogen Energy*, 39(35):20266–20275, dec 2014. ISSN 03603199. doi: 10.1016/j.ijhydene.2014.09.161.

[108] T. Søndergaard, J. O. Jensen, D. Aili, Y. Hu, L. N. Cleemann, and Q. Li. *High-Temperature Polymer Electrolyte Membrane Fuel Cells*. PhD thesis, Technical University of Denmark, 2017.

[109] C. Strazza, A. Del Borghi, P. Costamagna, A. Traverso, and M. Santin. Comparative LCA of methanol-fuelled SOFCs as auxiliary power systems on-board ships. *Applied Energy*, 87(5):1670–1678, may 2010. ISSN 03062619. doi: 10.1016/j.apenergy.2009.10.012.

[110] X. Sun, Y. Jiao, and P. Tian. Marketing research and revenue optimization for the cruise industry: A concise review, sep 2011. ISSN 02784319.

[111] P. Thounthong, S. Raël, and B. Davat. Energy management of fuel cell/battery/supercapacitor hybrid power source for vehicle applications. *Journal of Power Sources*, 193(1):376–385, aug 2009. ISSN 03787753. doi: 10.1016/j.jpowsour.2008.12.120.

[112] Engineering Toolbox. Air - Composition and Molecular Weight. URL `https://www.engineeringtoolbox.com/air-composition-d{_}212.html`.

[113] R. L. Townsin. Block coefficient and service speed. *Naval architect*, 1979.

[114] T. Tronstad and L. Langfeldt. Study on the use of fuel cells in shipping. Technical report, EMSA European Maritime Safety, 2017.

[115] UNFCCC. Paris Agreement. Technical report, 2015.

[116] L. van Biert. *Solid Oxide Fuel Cells for Ships*. PhD thesis, Delft University of Technology, 2020.

[117] M. van de Kerkhof. Clean Shipping - Vision 2030 and Action Plan until 2021. Technical report, Port of Rotterdam, 2019.

[118] S. van den Berg. Low Carbon Shipping. Technical report, Delft University of Technology, 2018.

[119] C. van Dijk. Budgetary quotation LNG Fuel Gas System (FGS). Technical report, Cryonorm, 2017.

[120] F. Vogler and G. Würsig. Fuel Cells in Maritime Applications challenges, chances and experiences. In *4th International Conference on Hydrogen Safety*, pages 1–13, 2011.

[121] C. Volger. Alternative fuels on board of carbon-neutral cruise vessels. Technical report, Delft University of Technology, 2019.

[122] Wärtsilä. Exhaust Treatment solutions. URL `https://www.wartsila.com/marine/build/exhaust-treatment{#}NOxReduction`.

[123] Y. M.A. Welaya, M. M. El Gohary, and N. R. Ammar. A comparison between fuel cells and other alternatives for marine electric power generation. *International Journal of Naval Architecture and Ocean Engineering*, 3(2):141–149, jun 2011. ISSN 20926782. doi: 10.2478/ijnaoe-2013-0057.

[124] World Heritage Centre UNESCO. Norwegian parliament adopts zero-emission regulations in World Heritage fjords, 2018. URL `https://whc.unesco.org/en/news/1824`.

[125] C. Zamfirescu and I. Dincer. Using ammonia as a sustainable fuel. *Journal of Power Sources*, 185(1):459–465, oct 2008. ISSN 03787753. doi: 10.1016/j.jpowsour.2008.02.097.

A

Fuel cell system data

A.1. Fuels

Table A.1: Safety characteristics of selected fuels.

Fuel		**LH2**	**LNG**	**MeOH**	**NH3**
State		liquid	gas	liquid	gas
Storage temperature	K	20	100	293	293
Density at T	ton/m^3	0.07	0.44	0.79	0.72
Boil temperature	K	20	111	338	240
Flash point	K	-	358	282	405
Auto-ignition	K	833	811	713	903
Lower explosive limit (LEL)	%	4	4	6	15
Upper explosive limit (UEL)	%	77	17	50	28
Safety	GHS01 Explosive				✓
	GHS02 Flammable	✓	✓	✓	
	GHS04 Gas	✓	✓	✓	
	GHS05 Corrosive				✓
	GHS06 Toxic			✓	✓
	GHS07 Harmful				
	GHS08 Health			✓	
	GHS09 Environment				✓

A.2. Fuel cell systems

Table A.2: Data of fuel cell systems of fuel cell suppliers. All data is of fuel cell power packs, meaning it includes thermal management, water management systems but exludes fuel processing equipment.

Brand	Type	Efficiency	Volumetric power density	Gravimetric power density
		%	kW/m^3	kW/ton
Ballard	LT-PEMFC		129.0	256.4
Swiss hydrogen	LT-PEMFC	58%	138.0	625.0
Nedstack	LT-PEMFC	50%	414.1	350.0
Hydrogenics	LT-PEMFC		204.1	218.2
Power Cell	LT-PEMFC	50%	362.3	588.2
Serenergy	HT-PEMFC		60.2	76.9
MTU	MCFC	47%	2.2	
fuelcellenergy	MCFC	47%		14.1
Bloom energy	SOFC	53%	10.6	19.0
Mitsubishi	SOFC	55%	2.0	
Hexis	SOFC	90%	17.0	4.8
Solid power	SOFC	85%	2.5	5.1

Table A.3: Characteristics of fuel processing equipment.

Equipment	Volumetric power density	Gravimetric power density	LHV efficiency	Source
	kW/m^3	kW/ton	%	
LNG steam reformer	45-90	50-250		[11]
Methanol steam reformer	22-45	25-120	70-90	[11]
Ammonia cracker	50-115	50-250	80-90	[11]
Preferential oxidation unit	30000	28000		[94]
Membrane seperation/ Pressure swing adsorbtion	1000	840		[73]

Table A.4: Percentage margins to take into account capital cost of fuel processing and electrical balance of plant components.

Fuel type	Fuel cell type	$a_{\text{fuel processing}}$	a_{BOP}
LH2	LT-PEMFC	0%	0%
LH2	HT-PEMFC	0%	1%
LH2	MCFC	0%	3%
LH2	SOFC	0%	5%
LNG	LT-PEMFC	25%	3%
LNG	HT-PEMFC	20%	4%
LNG	MCFC	10%	6%
LNG	SOFC	10%	8%
MeOH	LT-PEMFC	15%	2%
MeOH	HT-PEMFC	10%	3%
MeOH	MCFC	10%	5%
MeOH	SOFC	10%	7%
NH3	LT-PEMFC	5%	1%
NH3	HT-PEMFC	5%	2%
NH3	MCFC	5%	4%
NH3	SOFC	0%	6%

A.3. Emissions

Table A.5: Global Warming Potential (GWP) of common green house gasses [35].

	$\mathbf{CO_2}$	$\mathbf{CH_4}$	$\mathbf{N_2O}$
factor	1	30	265

B

Cruise ship parent set

B.1. Luxury classes

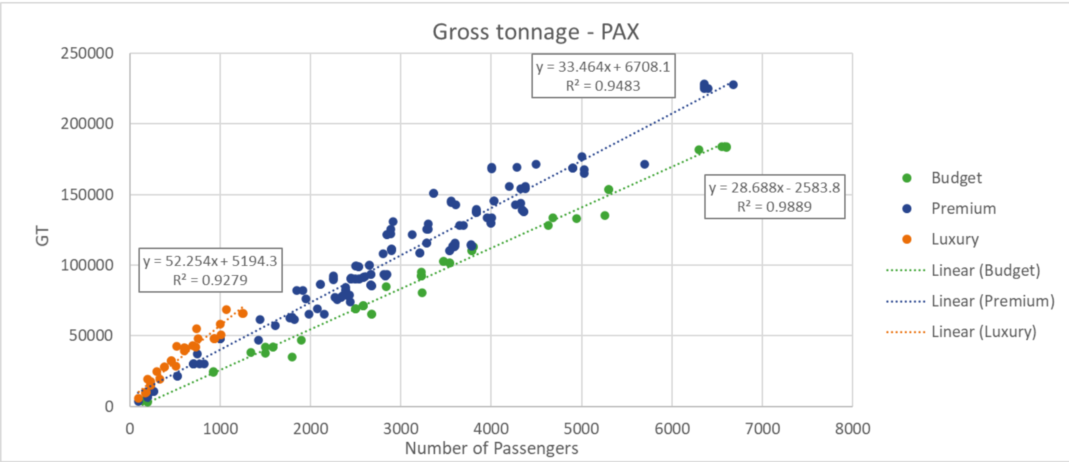


Figure B.1: Luxury classes of cruise ships, based on differences in GT/PAX

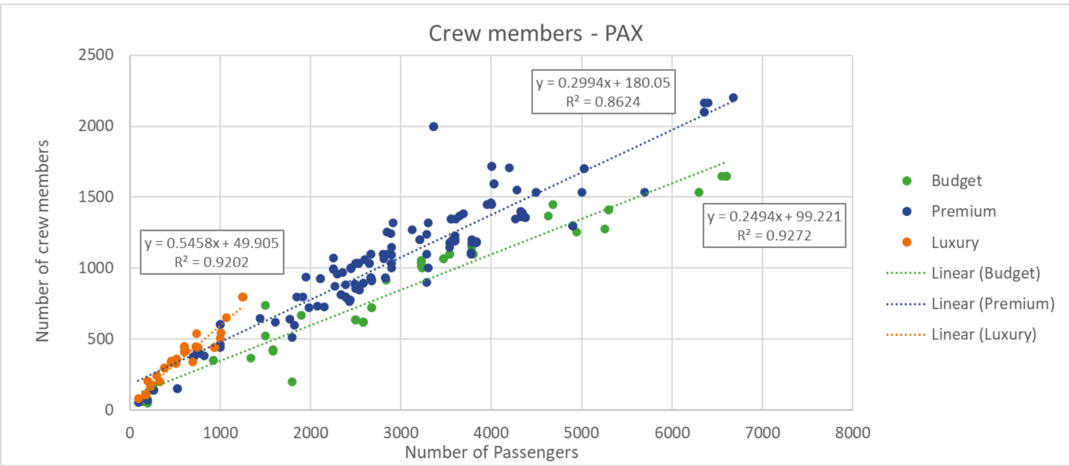


Figure B.2: The number of crew members plotted as function of the number of passengers for the parent set, divided in three classes based on GT/PAX

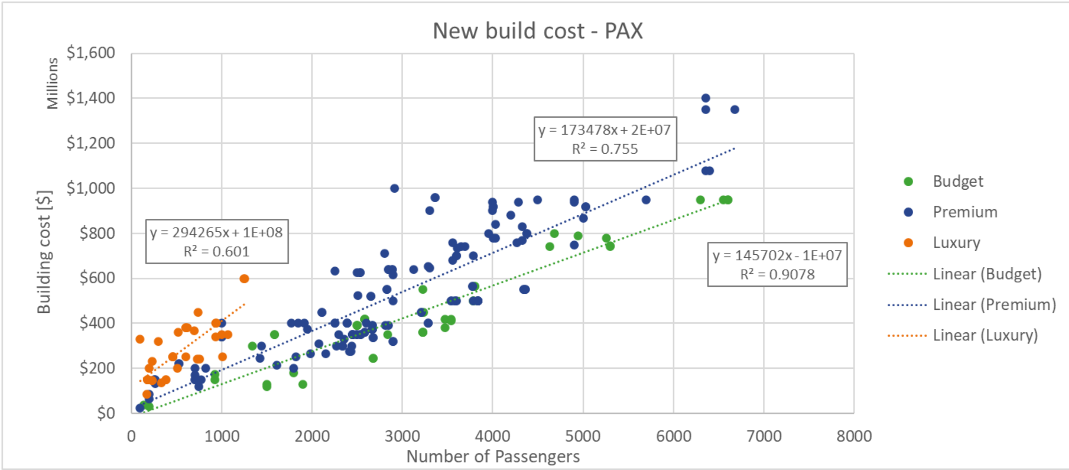


Figure B.3: The new build cost plotted as function of the number of passengers for the parent set, divided in three classes based on GT/PAX

B.2. Cruise ship regression charts

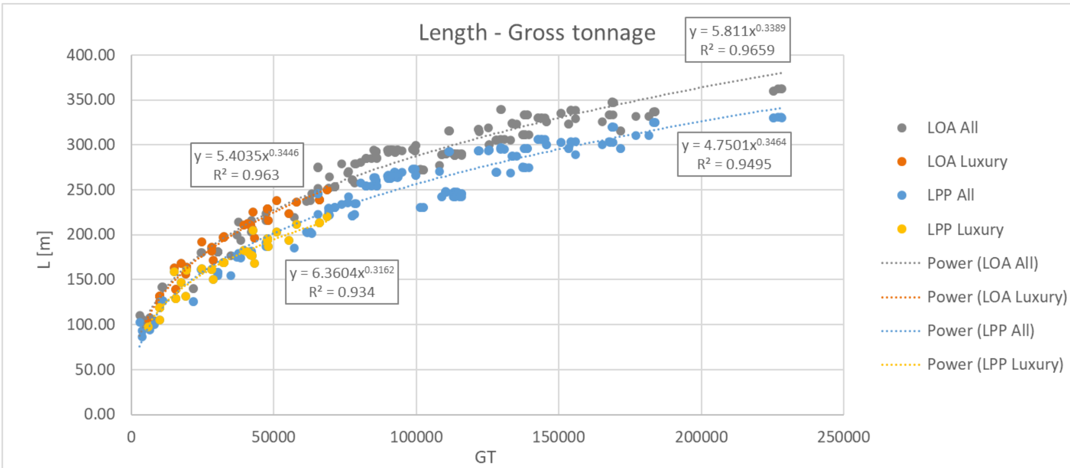


Figure B.4: Length overall and length between perpendiculars as function of gross tonnage for luxury cruise ships and all cruise ships

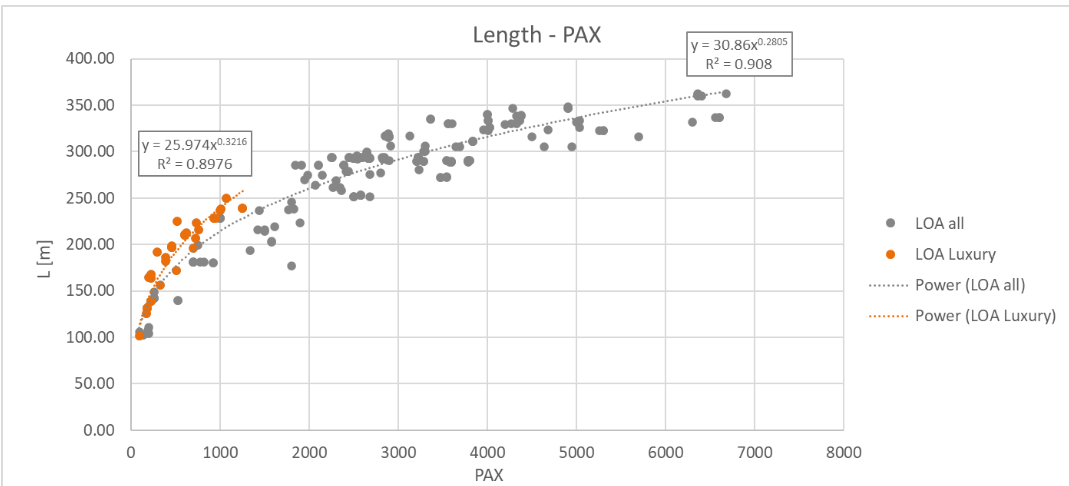


Figure B.5: Length overall as function of number of passengers for luxury cruise ships and all cruise ships

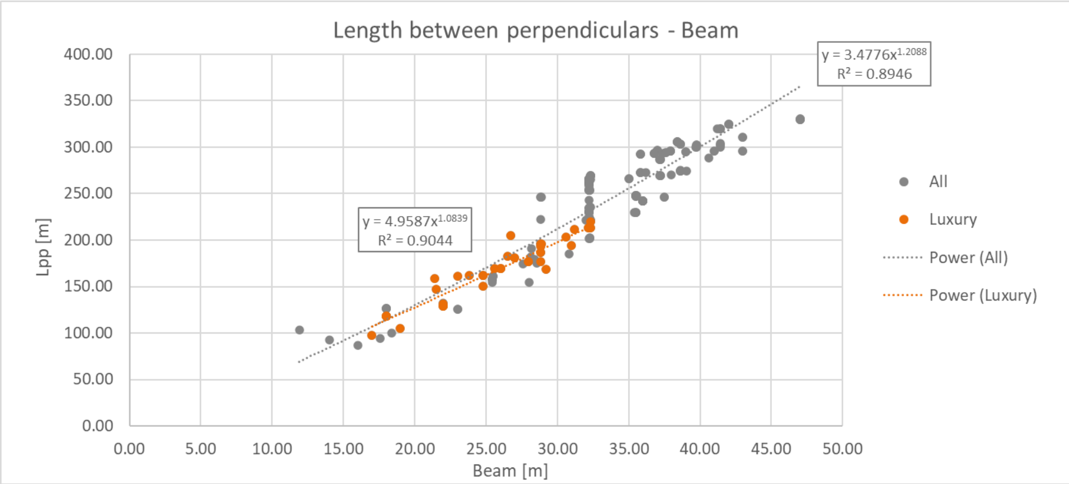


Figure B.6: Length between perpendiculars as function of beam for luxury cruise ships and all cruise ships

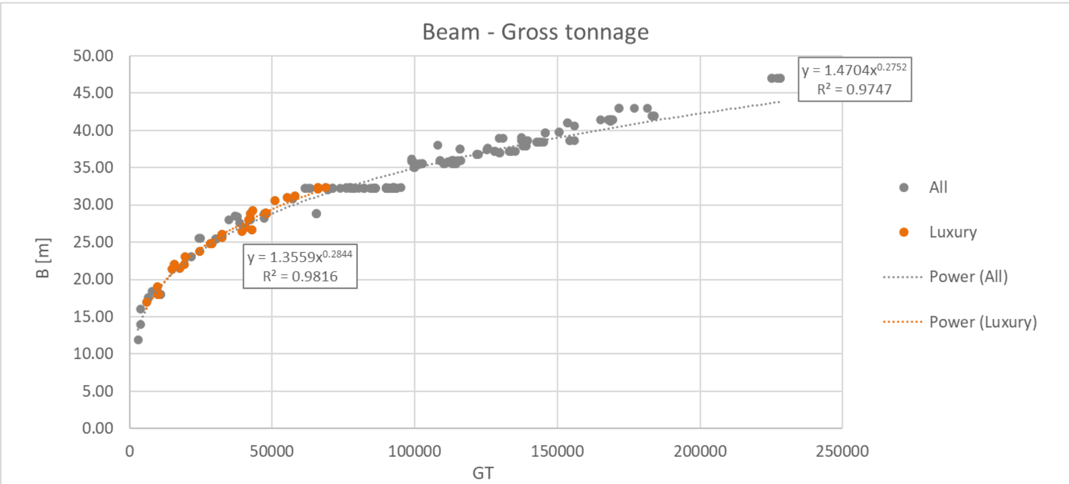


Figure B.7: Beam as function of GT for luxury cruise ships and all cruise ships

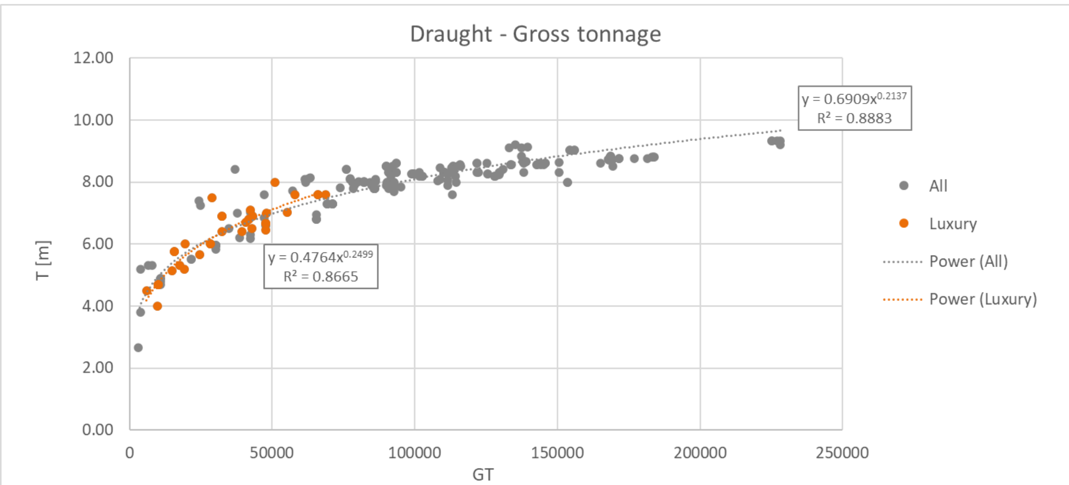


Figure B.8: Draught as function of GT for luxury cruise ships and all cruise ships

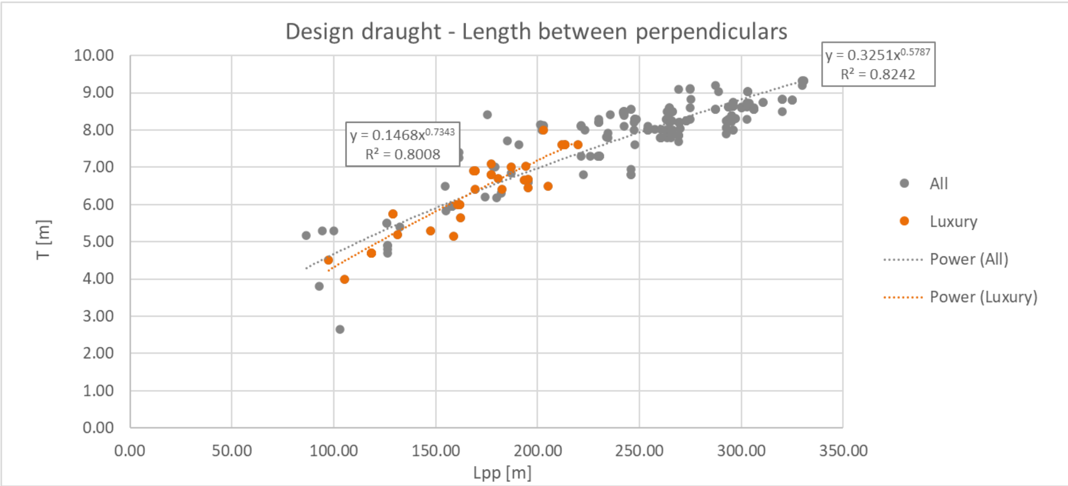


Figure B.9: Draught as function of length between perpendiculars for luxury cruise ships and all cruise ships

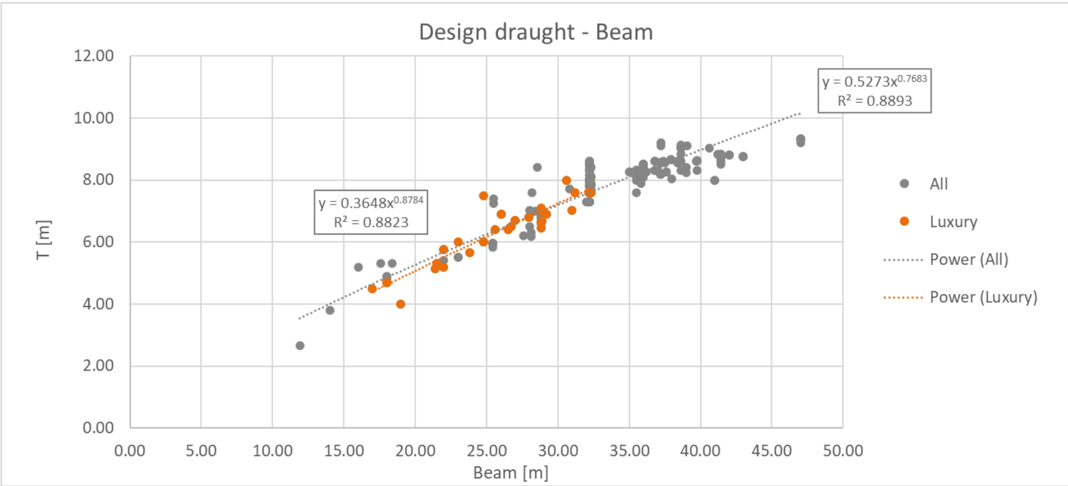


Figure B.10: Draught as function of beam for luxury cruise ships and all cruise ships

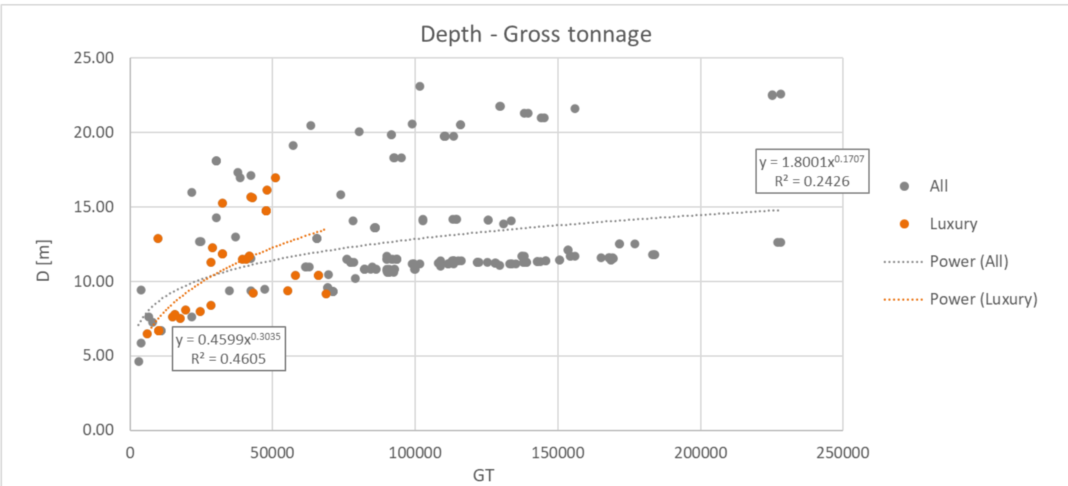


Figure B.11: Depth as function of GT for luxury cruise ships and all cruise ships

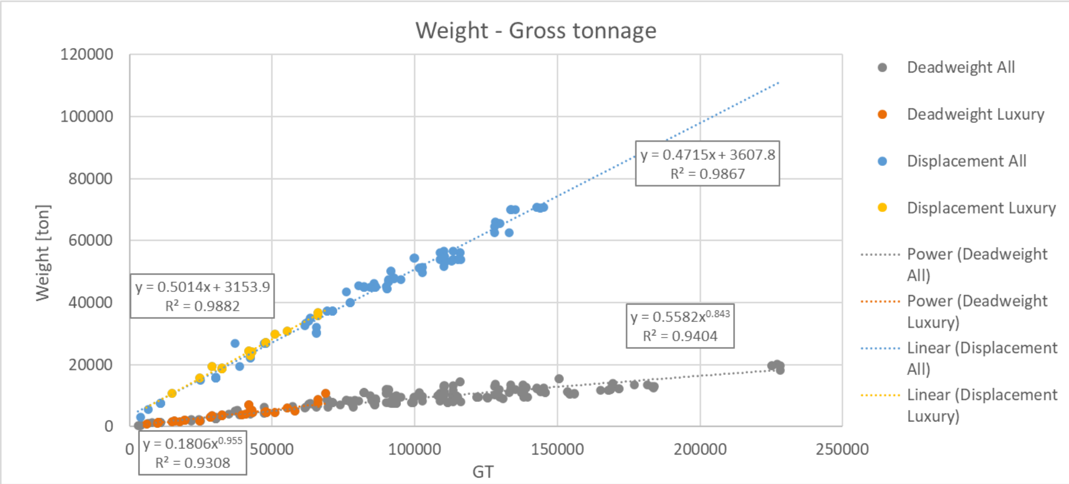


Figure B.12: Weight and displacement as function of GT for luxury cruise ships and all cruise ships

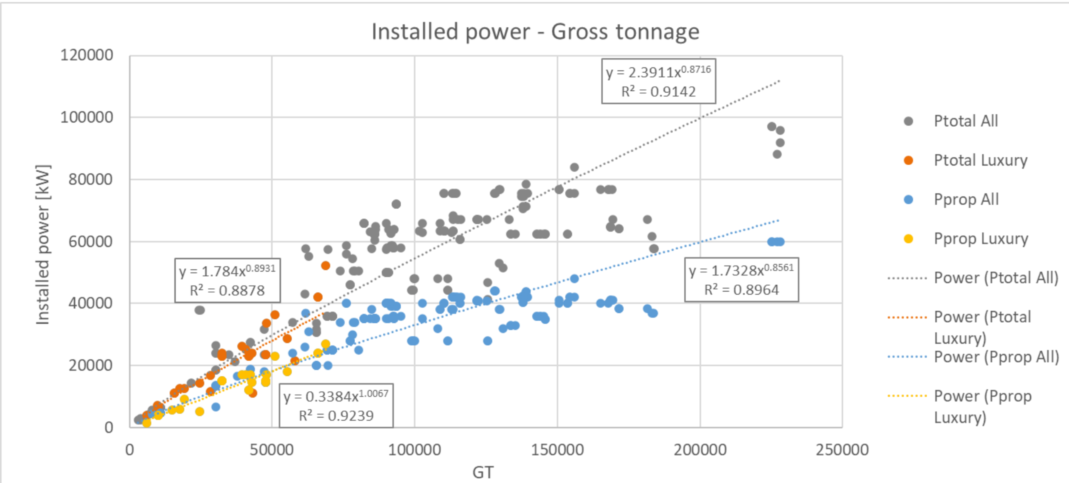


Figure B.13: Installed total power and installed propulsion power as function of GT for luxury cruise ships and all cruise ships

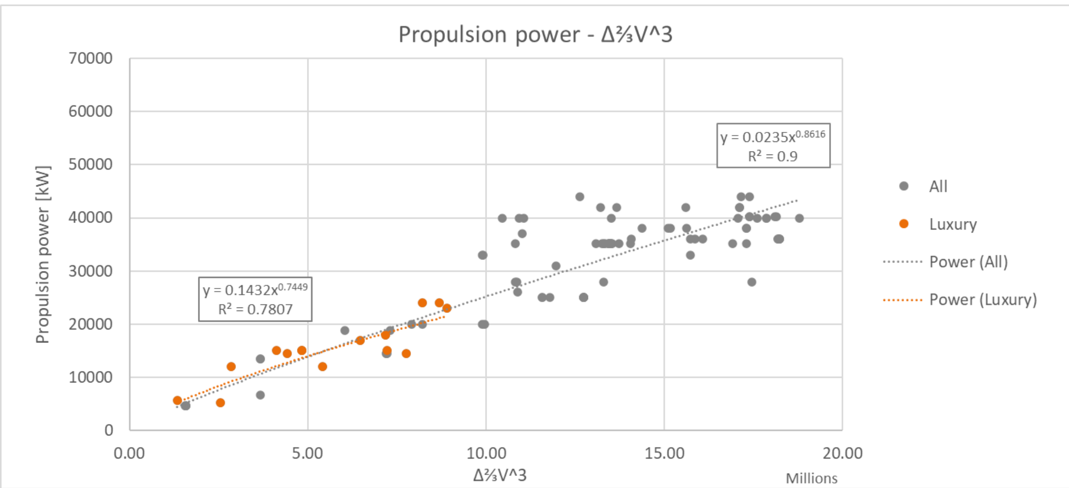


Figure B.14: Propulsion power as function of $\Delta^{\frac{2}{3}} V^3$ for luxury cruise ships and all cruise ships

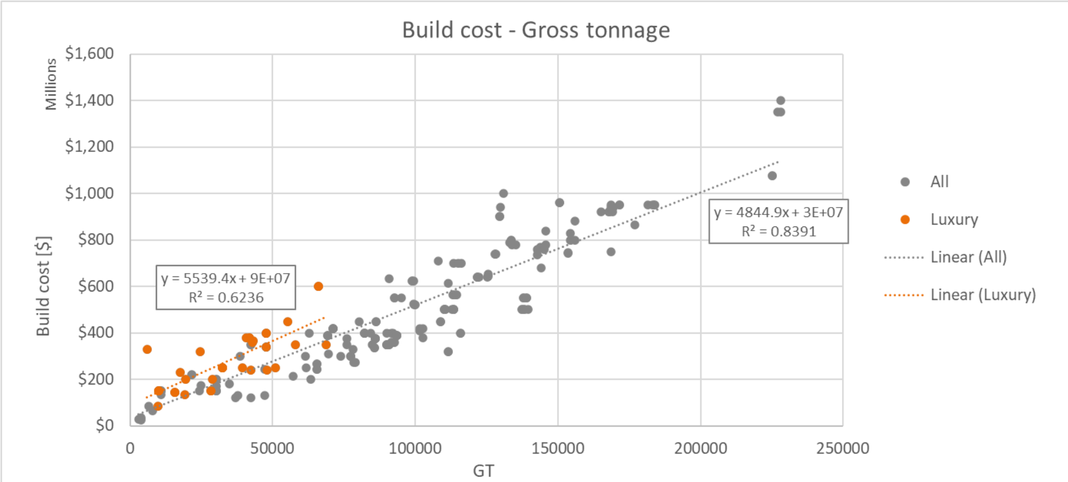


Figure B.15: New build cost as function of GT for luxury cruise ships and all cruise ships

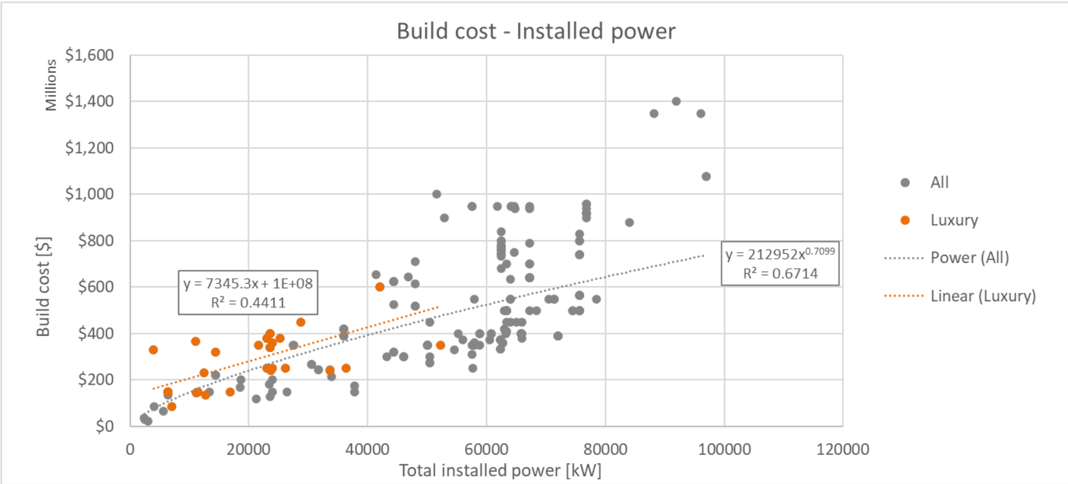
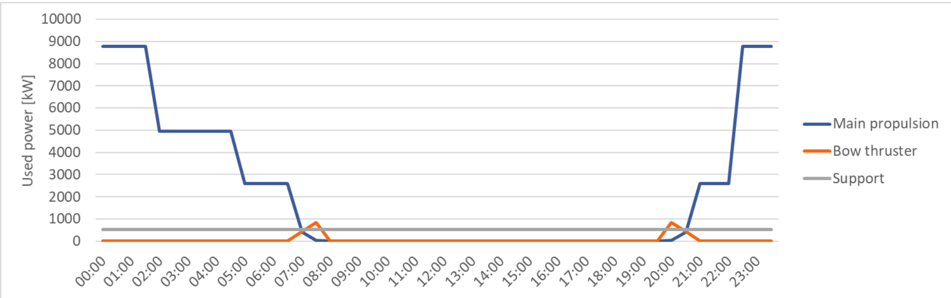


Figure B.16: New build cost as function of total installed power for luxury cruise ships and all cruise ships

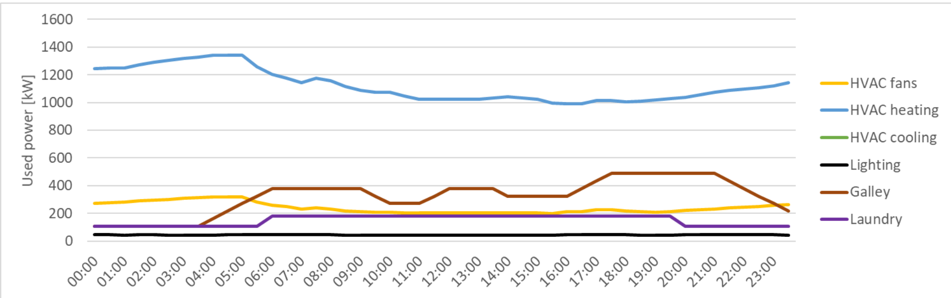
C

Simultaneous research into real time power demand on expedition cruise ships

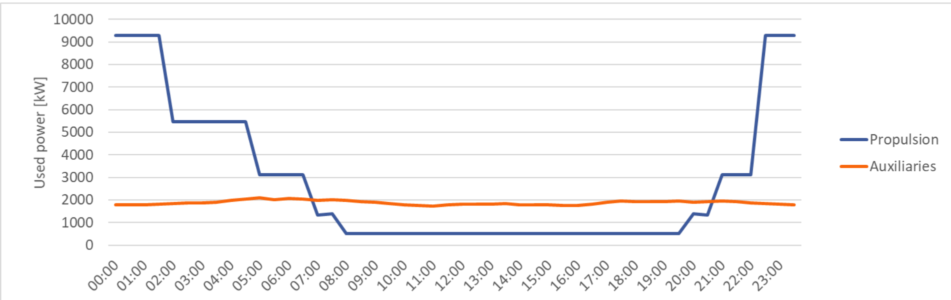
C.1. Winter condition



(a) Propulsion load.



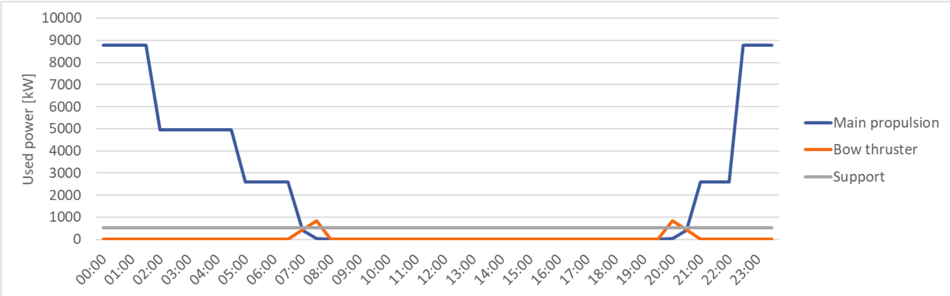
(b) Hotel load.



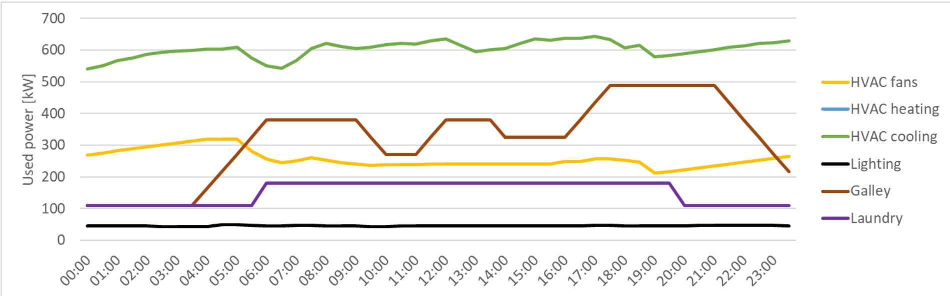
(c) Total load.

Figure C.1: Power demand of different consumers for a typical operational day of a coastal itinerary during winter condition. Retrieved from simultaneous research into power demand on board of expedition cruise ships.

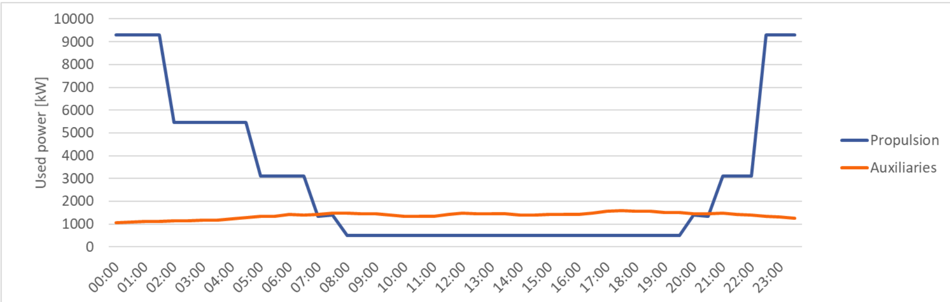
C.2. Summer condition



(a) Propulsion load.



(b) Hotel load.



(c) Total load.

Figure C.2: Power demand of different consumers for a typical operational day of a coastal itinerary during summer condition. Retrieved from simultaneous research into power demand on board of expedition cruise ships.

D

Damen process

Table D.1: Design activities for different design stages at Damen CRO

	ROM (1-2 weeks)	Budgettary (8-12 weeks)	Fixed & Firm (4-6 months)
General arrangement	List of spaces including area requirements Quick analysis of main logistic and person flows Basic evacuation flows and escape route check Remarks/suggestions on client GA plan	GA plan with validated area quantities Initial evacuation plan (incl LSA positioning) Main vertical zone (MVZ) placement Initial fire integrity check Initial hazardous zone check Visualized flow of passengers, food, garbage Lifeboat placement Set Main Vertical Zones	Contractual GA plan Space type plan Active/Passive fire fighting plan Space categorisation plan Fire integrity plan Hazardous/EX zone plan
Hull design	Principle dimensions Form coefficients	Sectional area and waterline characteristics Linesplan	Hullform hydrodynamic optimization (CFD) Hull appendages
Weight, COG and Construction	Rough weight and COG check (based on factors) Basic Mainframe (reference ship)	Weight and COG calc. incl. breakdown on main weight groups Determine margins Mainframe design including principle detail designs (eg. girders, pillars) Longitunial strength analysis	Initial NAPA construction weight study Weight and COG calc. incl. breakdown on system level High level section plan
Stability	Initial intact stability check (based on client input) Floating position of ship	Intact and Damage stability study Bulkhead positioning / MVZ	Intact and damage stability report
Speed & Power	Quick Power & Speed check based on Client input (PSD diagram)	Power Speed calc. (multiple loadcases, incl SRtP, prop design) Initial sailing profile and propulsion config. Study High level demarcation check with suppliers and yard (engine, pods)	Power speed calculation (multiple loadcases, incl SRtP) Detailed sailing profile and propulsion config. study Detailed demarcation handshake between suppliers and yard (engine, propulsion)
Range, DWT, Tanks	Initial range calc based on client input (tanks, provision)	Global Tank layout DWT distribution Range calculation	Detailed tank arrangement Range calc. update Deadweight composition for specifications
Rules & Regulations	Initial SRtP screening of GA Initial SOLAS 2020 screening of GA Cross check remaining rules & regulations	Initial compliance matrix Rules & Regulations Initial GP-FB-EN-GT-NT calculation Alternative design topics overview SRtP approach	Detailed compliance matrix Rules & Regulations Exemptions list Alternative design discussed and covered Passenger evacuation flow analysis Safe Return to Port failure mode study GP-FB-EN-GT-NT calculation
Electrical, Automation, AV/IT	Preliminary hotel load verification (factors reference ships)	Estimated load balance Initial single line diagrams (propulsion, ship service power, hotel) High level demarcation check with suppliers and yard (electrical, automation, Nav/Naut and AV/IT) Space reservations main E&A equipment	Load balance Single line diagrams main networks Detailed demarcation handshake between suppliers and yard (electrical, automation, Nav/Naut and AV/IT) Space reservations in each MVZ (GA, technical arrangement) Conceptual routing of main cable runs Identify EMC/EMI zones
Mechanical (HVAC), diagr. and tech. arrangements		High level demarcation check with suppliers and yard (HVAC, stabilizers & other significant systems) Initial main system diagrams and incl. component placement (input SRttP) Space reservations HVAC auxiliary systems, piping and equipment Initial space reservation for routing main ducts (GA and mainframe)	Detailed demarcation handshake between supplier and yard (HVAC, stabilizers & other significant systems) System diagrams main systems (fuel and stored energy, LNG-fuel storage, HVAC, Hydraulics Fresh/technical/sewage water) Basic technical arrangements Conceptual routing of main ducts Heat balance
Interior design	Example interior renders Determine level of interior required (reference ships)	High level demarcation check with suppliers and yard Initial interior design studies incl. renders Preliminary weight budgets	Detailed demarcation handshake between supplier and yard Detailed interior design studies incl. 3D renders Agreed weight budgets
Noise and vibrations	Preliminary check of noise & vibration requirements	Asses sound requirements and define sound & vibration risk areas on GA Initial noise isolation space reservation on GA/mainframe in problem areas Vibration natural frequency check	Detailed noise study, floating floor and cavity design Natuaral frequency/plate vibration analysis Frequency response analysis
Seakeeping, manouevring, DP, Bollard Pull		Seakeeping analysis Crabbing analysis	Funnel smoke analysis
Standardization	Select and process re-useable documents/calculation sheets for future use	Select and process re-useable documents/calculation sheets for future use	Select and process re-useable documents/calculation sheets for future use

E

Ship design

E.1. Method of Townsin

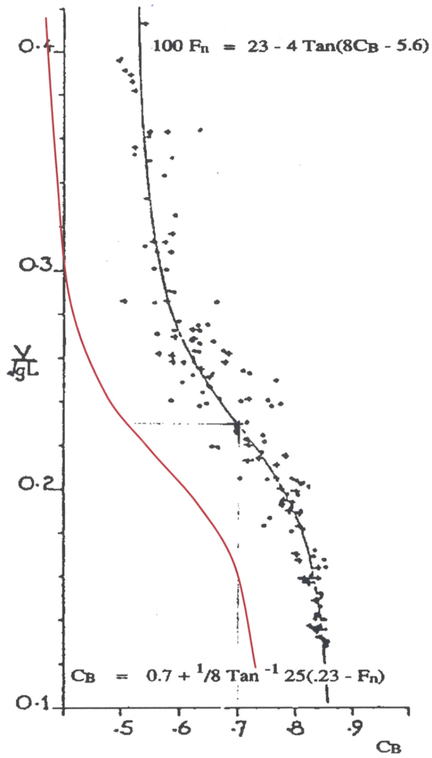


Figure E.1: Correlation between C_B and Fn by Townsin

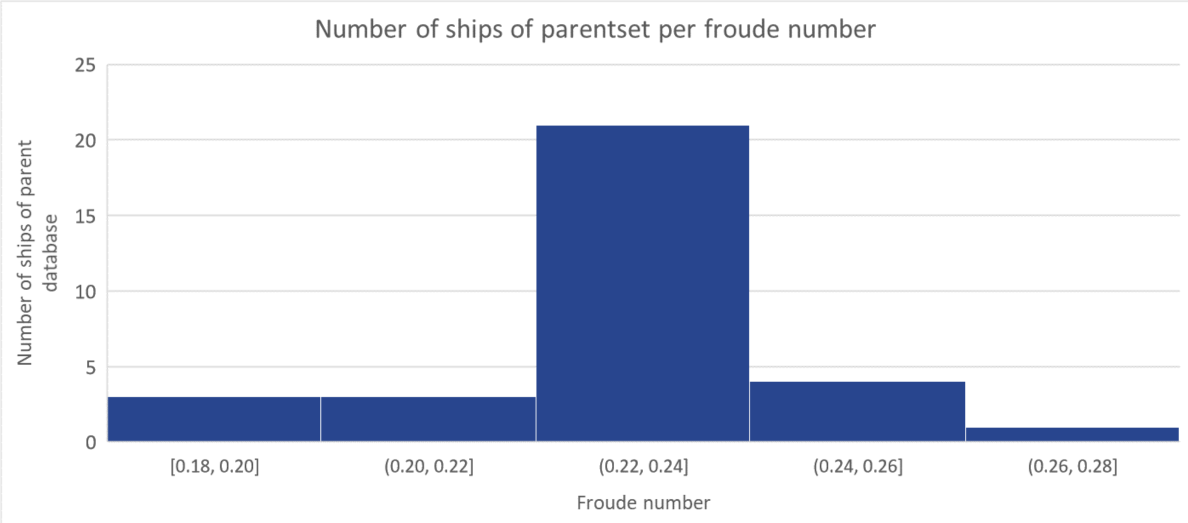


Figure E.2: Number of ships of parent set per Froude number