Hydrogen power for the Allseas fleet

A methodology to design a hybrid electric propulsion system with fuel cells and batteries

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Thesis report

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by

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Preface

This thesis on developing a design methodology for a hybrid propulsion system with fuel cells and batteries was written as graduation assignment for the master Marine Technology at the Delft University of Technology. The graduation assignment was carried out at Allseas in Delft.

First, I want to thank my Allseas supervisors for all their support, time and help during the process of working on my thesis. Marjolein Ten Hacken thank you for all your time the last year. For giving me feedback over and over on my literature study and helping me with the thinking process of rest of the research.
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Summary

Global warming is a topic of major concern the last decade and for reason the IMO adopted a strategy to reduce the emissions of greenhouse gasses of vessels. In order to meet the IMO requirements ships propulsion systems need to become more sustainable. An option to reduce emission is the implementation of fuel cells running on hydrogen together with batteries. Since hydrogen cannot be stored into conventional fuel tanks different fuel tank options are investigated, which led to the use of cryogenic liquid hydrogen storage tanks.
During the research a case study was preformed for the Pioneering Spirit. The first step in the designing process is investigating the operational profile to get a better understanding of the projects done and the corresponding power demand and to see how the operational profile influences the power demand of the ship.

After investigating the operational profile and its influence on the power demand of the ship a design methodology was written to help the user find an optimal solution for the new hybrid propulsion system. This methodology contains three parts: data importing, solution generation and new system specifications.
In the first part data will be imported and processed to find the power demand during a project. Subsequently, a range of fuel cell capacities will be determine over which solutions will be generated in part two.
The second part of the methodology contains three steps. During the first step solutions will be generated over the range of fuel cell capacities determined in the first part. This first step will be iterated for different battery capacities. After generating solutions in the first step in the second step suitable solutions will be defined. These solutions will be compared in the last step to find an optimal solution.
For the optimal solution, the third part of the methodology will calculate the new system specifications.

Contents

List of Figures

List of Tables

Abbreviations

AC	Alternating current	LOHCs	Liquid organic hydrogen carriers
AFC	Alkaline fuel cell	MARPOL	The international convention for the prevention of pollution from ships
CBF	Carbon-based fuels	MCFC	Molten carbon fuel cell
CFRP	Carbon fiber reinforced plastic	MDO	Marine diesel oil
CH4	Methane	N2	Nitrogen
CHP	Combined heat and power	N2O	Nitrous oxide
CO	Carbon monoxide	NASA	National Aeronautics and Space Administration
CO2	Carbon dioxide	Ni-MH	Nickel metal hydride
DC	Direct current	NOx	Nitrogen oxides
DMFC	Direct methonal fuel cell	O2	Oxygen
H0-LOHC	Hydrogen lean molecule	PAFC	Phosphoric acid fuel cell
H2	Hydrogen	PEMFC	Proton exchange membrane fuel cell
H2O	Water	rpm	Ratios per minute
H3PO4	Phosphoric acid	SOC	State of charge
HFO	Heavy fuel oil	SOFC	Solid oxide fuel cell
Hn-LOHC	Hydrogen-rich molecule	SOLAS	Saftey of life at sea
IMO	International Maritime Organization	SOx	Sulphur oxide
KOH	Potassium hydroxide	TLS	Topside lift system
LCO	Lithium cobalt oxide	VRLA	Valve-regulated lead-acid
LH2	Liquid hydrogen	W.O.W	Waiting on weather
Li-ion	Lithium ion	YSZ	Yittria stabilized zirconia
LNG	Liquid natural gas		

1

Introduction

1.1. Motivation

Global warming is a topic of major concern the last decade. Global warming is an effect of greenhouse gasses, with as major components carbon dioxide (CO_2), methane (CH_4) and nitrogen oxides (NO_x). Most greenhouse gasses are released during the combustion of fossil fuels which are used in transportation, the industry and to generate electricity. In order to reduce global warming, the Paris Agreement entered into force in 2016. In the agreement is stated that the goal is to limit global warming to below 2 degrees Celsius, preferably 1.5 degrees Celsius, compared to pre-industrial levels. The Paris Agreement covers most greenhouse gas emissions, however, it does not apply to the shipping industry.

In 2018 the IMO (International Maritime Organization) adopted a strategy to reduce the emissions of greenhouse gasses of vessels. In this strategy is stated that at ship level a reduction of CO_2 by 2030 is at least 40% compared to 2008 and by 2050 it even should be 70%. It also states that the total annual greenhouse gas emissions from international shipping should be reduced by at least 50% compared to 2008. Besides the CO_2 reduction requirements of the IMO, they also adopted in 2020 new requirements for sulphur. The rule limits the sulphur in the fuel oil used on board ships operating outside designated emission control areas to 0.5%, which is a significant reduction compared to the previous limit of 3.5%. An alternative to reducing sulphur in the fuel oil is using a scrubber. Scrubbers remove sulphur oxides from the ship's engine and boiler exhaust gases [10]. The resulting reduction in sulphur oxide (SO_x) emissions from ships is having major health and environmental benefits for the world, particularly for populations living close to ports and coasts. Sulphur oxides are harmful to human health, causing respiratory, cardiovascular and lung disease. Once released into the atmosphere, SO_x can lead to acid rain, which impacts crops, forests and aquatic species and contributes to the acidification of the oceans [14]. Beside the two requirements motioned above there are a lot of other regulations involving emission control.

In order to meet these emission requirements, it is important to look into alternative fuels as well as the systems that these fuels require. Fuel cells are one of the alternative options to reduce emissions and can run on different kinds of fuels. In this research, fuel cells running on hydrogen are investigated.

1.2. Problem Definition

At the moment IMO has no clear regulations for construction vessels since the IMO is mainly based on SOLAS (safety of life at sea) and MARPOL (the international convention for the prevention of pollution from ships) and so focused on passenger ships and cargo ships. However, in 2023 the greenhouse gas strategy of the IMO will be revised and plans are made to include construction vessels in this strategy. Even though at the moment construction vessels are not part of the strategy, Allseas is seriously looking to not only adhere the vision of the IMO but exceed it by reducing the emissions of its vessels to zero. In some cases, it can even be beneficial if the project can be performed emission-free.

To meet the requirements of the IMO alternative fuels and the corresponding systems are required. One of the options is a fuel cell system running on hydrogen with batteries, which only emits water. No extensive research was found on implementing fuel cells on board of offshore construction vessels. To get a better understanding of the implementation of the fuel cells on board of an offshore construction vessel a case study will be performed. The choice is made to use the Pioneering Spirit as the case vessel and since she is a unique ship in her class, even less is known about the implementation. The Pioneering Spirit is such a unique ship because of her dimensions and the different types of projects she can perform. The fact that she is the largest offshore construction vessel in the world raises the expectation that it is not possible to sail only on the fuel cells. Therefore, the choice is made to look into a hybrid propulsion system with existing diesel generators, hydrogen fuel cells and batteries.
During the design process, the new hybrid power generating system will be optimised to meet the IMO requirements concerning the reduction of CO_2 and greenhouse gasses, while considering different design criteria.

1.2.1. Criteria

The following criteria need to be taken into account during the design of the new hybrid system:

1. The new system needs to meet the IMO requirements for the reduction of CO_2 and greenhouse gasses. This means that by 2050 the emission of CO_2 needs to be reduced with 70%.
2. The batteries will be implemented for peak shaving as well as a spinning reserve in case of an emergency.
3. The fuel cells and the batteries together need to deliver enough power to meet the power demand of the ship during projects.
4. The fuel cells need to be able to charge the batteries between peaks.
5. The hydrogen storage tanks size are depending on the available space on board as well as how often there is a possibility to bunker.
6. The cost of the overall system need to be taken into account.

1.3. Research questions

1.3.1. Main research question

How can a design methodology be developed to design a hybrid propulsion system with hydrogen fuel cells, diesel generators and batteries that will meet the IMO requirements to reduce the CO_2, sulphur and greenhouse gas emission while considering different design criteria?

1.3.2. Sub-questions

How do the different operations of the vessel influence the power demand?

How can the power capacity be determined of the fuel cells, generators and batteries keeping a good ratio between the components?

In which way can the fuel storage for the new system be optimised?

Using the design methodology in a case for the Pioneering Spirit, how can the new hybrid propulsion system be designed?

1.4. Thesis goal

The goal of this thesis is to write a methodology to design a hybrid propulsion system that includes the existing generators, hydrogen fuel cells and batteries applicable to Allseas' construction vessels. During the design process the hybrid propulsion system will be optimised to make sure the IMO requirements for CO_2 reducing will be meet, while looking for as less hydrogen consumption as possible considering the available space on board for hydrogen storage and taking into account that how larger the system become the more it will cost to implement it. The operational profile and completed projects will be used to get more information on the power demand of the vessel during the different operations. A design methodology will be written, which will give the user advice on the capacity of the fuel cells and batteries. The advice is used in making a decision for the capacity of the new components. After making a decision the second part of the design methodology will calculate the size of the total system including the hydrogen storage, air flow rate and coolant flow rate of the system. To validate the use of the design methodology a case study will be performed for the Pioneering Spirit.

1.5. Report outline

After this first chapter, giving an introduction into the research, chapter 2 will give a short background of Allseas and the case vessel used during this research. To get a better understanding of the topic in chapter 3 a study of relevant literature is provided. In addition, this chapter provides the system components chosen for the new power generation system. Since the system configuration is depending on the operational profile and the use of the vessel in chapter 4 the operational profile of the Pioneering Spirit is investigated, which resulted in a typical year for the Pioneering Spirit. In chapter 5 a design methodology was created to help the user design a hybrid electric propulsion system with diesel generators, hydrogen fuel cells and batteries. Subsequently, the design methodology is used in chapter 6 for a case study to design a new power generation system for the Pioneering Spirit. Lastly, chapter 7 gives the final conclusion on the work as well as a recommendation on future work.

2 Background

2.1. Allseas

The Swiss-based Allseas Group, founded in 1985 and headed by Edward Heerema, is a global leader in offshore pipeline installation and subsea construction. Allseas Engineering, located in Delft, provides project management and engineering services to other subsidiaries of the Allseas Group. The versatile fleet of specialesed vessels are designed and optimised in-house and operate worldwide. Allseas is specialised in four core activites: offshore pipeline installation, heavy lift, deep-ocean polymetallic nodule collection and river waste collection [2].

2.2. Case vessel

During this research a case study will be done with the Pioneering Spirit. The pioneering Spirit is the largest construction vessel in the world and designed for single-lift installations and removals of large oil and gas platforms and the installation of record-weight pipelines. The ship is capable of lifting an entire platform topside of up to 48,000 t and jackets up to 20,000 t in a single piece [29]. This capabilities gives the ship an unique operational profile, which makes it interesting case. Table 2.1 shows all the main dimensions of the Pioneering Spirit.

Table 2.1: Dimensions Pioneering Spirit [29]

Length overall (incl. stinger and lifting beams)	477.00 m
Length	382.00 m
Breadth	123.75 m
Slot length	122.00 m
Slot width	59.00 m
Transit draught	11.50 m
Operating draught	10.00 - 27.00 m
Maximum speed	14 knots
Total installed power	95000 kW
Topsides lift capacity	48000 t
Jacket lift capacity	20000 t

The Pioneering Spirit is a twin-hulled vessel, 382 m long and 124 m wide. The ship is able to move around a platform because of the slot in its bow. It can lift and transport entire topsides by using eight sets of horizontal lifting beams. At the stern of the vessel two 170 m long lifting beams are located for the removal and installation of jackets. Besides these two lifting systems the Pioneering Spirit has also a 5000 t special purpose crane which can be used for lighter topsides, jackets, modules and bridges

[29].
Besides heavy lift projects, the Pioneering Spirit can also install record-weight pipelines in all water depths. The ship has an S-lay tension capacity of 2000 t [29].

2.2.1. The propulsion system

The Pioneering Spirit has in total ten diesel generators which provide a total power of 95 MW. Eighth main engines (11200 kW), one harbour generator (5040 kW) and one emergency generator (1626 kW). This power drives 12 azimuth thrusters for dynamic positioning and propulsion. A high transit speed can be achieved, which makes the vessel suitable for worldwide operations. Since the ship is operated fully on dynamic positioning she can work in any water depth [29].
The generators can be start in about 2 minutes, which means in case of an emergency they can be started in maximal 20 minutes from the first detection until fully up and running. This also means that there need to be a spinning reserve for these 20 minutes so at least the ship can be in a safe situation in case of emergency.
Depending on the size of the new hybrid system the choice can be made do remove one or more generators to make space. Table 2.2 provides the properties of one single generator.

Table 2.2: Generator properties [23]

Power production (@100%)		[kW]	11200
Length		[m]	9.86
Width		[m]	3.1
Height		[m]	4.26
Surface		[m^2]	30.57
Volume		[m^3]	130.27
Fuel consumption	@85% @100%	[kg/hour]	1713.6 2032.8
Air flow rate		[m^3/hour]	68030
CO_2 production		[g/kWh]	620

3

Literature review

To get a good insight on the already existing technology and research a literature study was preformed on alternative fuels and their corresponding propulsion systems. Since this thesis report is focused on a hybrid system with fuel cells running on hydrogen and batteries only the parts of the literature review [26] that are relevant on this topic are included in this chapter. In this chapter first the different methods of producing hydrogen, the different fuel cell types and hydrogen storage are discussed. After that different types of batteries and hybrid systems are mentioned.

3.1. Hydrogen production

Hydrogen can be produced in various ways. Figure 3.1 gives an overview of the different processes of making hydrogen. In this section not all the different processes will be mentioned. Only steam reforming, gasification, electrolysis, pyrolysis and thermolysis will be investigated into more detail.

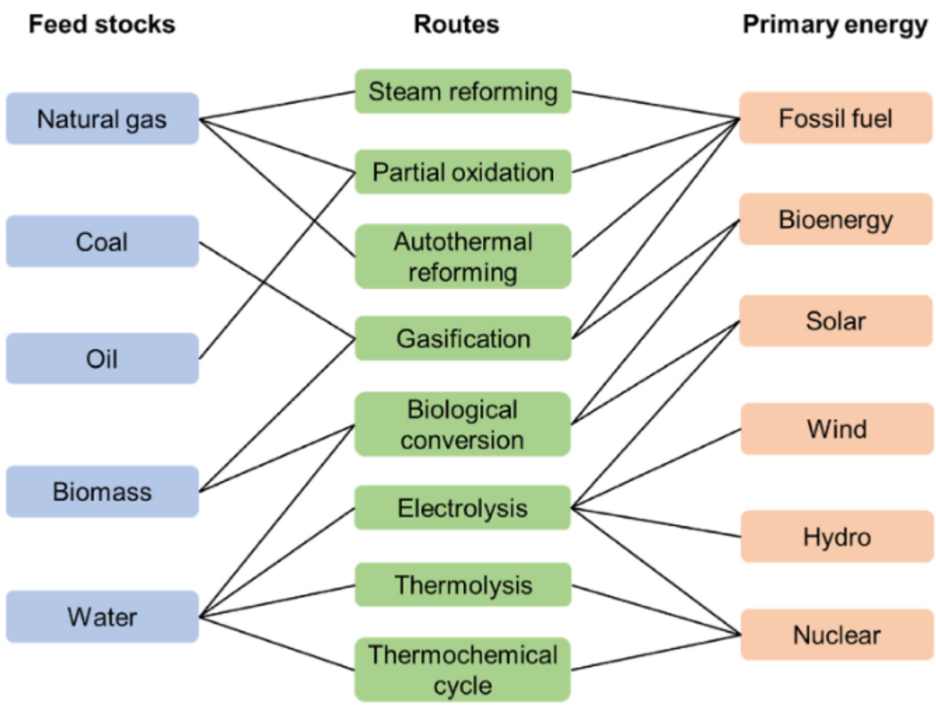


Figure 3.1: Hydrogen production methods overview [15]

In table 3.1 the related costs for the different processes to make hydrogen are shown [20].

Table 3.1: Costs for the different types of hydrogen making [20]

Process	Energy source	feedstock	capital cost (M$)	Hydrogen cost ($/kg)
Methane pyrolysis	Internally generated steam	Natural gas	-	1.59-1.70
Biomass pyrolysis	Internally generated steam	Woody biomass	53.4-3.1	1.25-2.20
Biomass gasification	Internally generated steam	Woody biomass	149.3-6.4	1.77-2.05
Solar PV electrolysis	Solar	Water	12-54.5	5.78-23.27
Solar thermal electrolysis	Solar	Water	421-22.1	5.10-10.49
Wind electrolysis	Wind	Water	504.8-499.6	5.89-6.03
Nuclear electrolysis	Nuclear	Water	-	4.15-7.00
Nuclear thermolysis	Nuclear	Water	39.6-2107.6	2.17-2.63
Solar thermolysis	Solar	Water	5.7-16	7.98-8.40

3.1.1. Electrolysis of water

An electrochemical reaction occurs during the electrolysis process. During this process water is split into hydrogen and oxygen with electricity input. During the electrolysis process water will be exposed to direct current which will start the decomposition reaction of the water. This process produces hydrogen and oxygen at the cathode and anode and so easily separable to obtain pure hydrogen and pure oxygen. Electrolysis is the most developed and commercially used technology to produce hydrogen. Using conventional electricity, grid electrolysis, is a fast and cheap way to produce hydrogen. The electrolyser is connected to the electrical grid. To overcome greenhouse gas emissions by electrolysis the electricity used for the process need to be produced green as well. This can be done for example by wind electrolysis in which the electrolyser is connected to wind turbines to get electricity. Due to this greener method of H_2 production, the greenhouse gas emission was reduced by sharing the clean energy to the electricity grid [18].

3.1.2. Thermochemical conversion

Thermochemical conversion of carbon-based fuels (CBF) is considered as the most potential method for the production of H_2 due to its energy density and huge availability. Thermochemical conversion includes pyrolysis, gasification and steam reforming of natural gas [18].

Thermolysis of water

Water thermolysis is a one-step thermolysis reaction following a very simple chemical principle. However, to decompose of water a large amount of energy is required, which is provided by heat, resulting in a very high operating temperature in the reaction system. Water can be decomposed at a temperature of >1700 °C, and to achieve complete decomposition it even requires a temperature over 4000 °C. Biomass and geothermal heat can provide the needed thermal energy. However, under such extreme conditions, the thermal energy sources may not support the system to operate continuously. Another problem to take into account is the difficulty to find suitable high-temperature resistant materials to build this installation while keeping in mind the costs. The hydrogen and oxygen cannot be produced on two different plates, as in electrolysis, this can also can cause problems. The product obtained by water thermolysis is a mixture of two gases, which are easily recombined into water, not easily separated in the process and is also explosive. Quenching can prevent the recombination of hydrogen and oxygen, but only at low temperatures, where the temperature must drop sharply by 1500-2000 K in a few milliseconds [15].

Pyrolysis

H_2 rich gas, solid char, liquid bio-oil and gaseous hydrocarbon are produced from liquid CBF or a renewable biomass during the pyrolysis process under strict anaerobic conditions. Depending on the temperature, heating rate, working pressure, reactor design, decomposition time and CBF or biomass biochemical composition the quality and quantity of product yield from pyrolysis is different. For a successful process and product yield the temperature and decomposition time are the two major notable factors. The hydrodynamic characteristics and the working conditions of the pyrolysis process influence the rate of conversion and the composition of substrate. Pyrolysis is classified into four types: slow or traditional, vacuum, fast and flash. Slow and fast pyrolysis are the most used types for H_2 production based on heating rate and the speed of the substrate decomposition. During the slow pyrolysis, biochar is produced as a result of higher decomposition time and a heating rate of 5-30 °C/min. In the fast pyrolysis, the heating rate is between (10-200 °C/sec) and with a shorter decomposition time 60% of bio-oil, 15-20% of biochar and 10-20% syngas is produced. Between fast and slow pyrolysis, fast pyrolysis with high temperature is the most preferable method for H_2 production [18].

Gasification

A more traditional method of producing H_2 is gasification, which is done via thermal decomposition of coal (and biomass). At high temperature and under a reactive oxygen environment this process is taken place. This results in partial oxidation of the feedstock. Depending on the feedstock used during the H_2 production process gasification is classified into two types, biomass gasification and coal gasification. Among the two, biomass gasification is the most potential and popular method. During biomass gasification (equation 3.1), the feedstock is partial oxidized into mixture of flammable gases at higher temperature ranges (800 to 900 °C). The biomass gasification leads to generation of tar, which is a black sticky substance used for making roads. Gasification is more energy efficient than the combustion process to produce energy [18].

$$Biomass + H_2O + O_2 \rightarrow H_2 + CH_4 + CO + CO_2 + Tar + Char \tag{3.1}$$

Gasification with as feedstock biomass is considered to have less adverse impact on the environment than hydrogen production based on fossil fuels. This is because of the CO_2 released is first absorbed by the organisms which are still alive and no excess carbon is entered into the atmosphere [15].

Steam reforming of natural gas and methane

Steam reforming is a mature technology for H_2 production using nonrenewable feedstocks such as methanol, liquefied petroleum gas, naphtha, jet fuel and diesel. based on the price of the feedstock, global energy demand and the H_2 economy a selection of feedstock is made for steam reforming. Since steam reforming is an endothermic process a high temperature (700-1200 °C) is required for the operation, which makes it also a more complicated process. In steam reforming with natural gas as feedstock, which consist of 95% of CH_4, 1% of Nitrogen (N_2), 0.5% of CO_2 and small fraction of sulfur compounds, the natural gas reacts with pressurized steam (3 to 25 bar) to produce H_2 and small fraction of CO. During the steam reforming process, inadequate feedstock characteristics (H:C ratio) cause negative impact on H_2 production by emitting excess amount of CO_2. Feedstock with a higher H:C ratio emit less CO_2, which improves the end product's quality [18]. During steam methane reforming, syngas is obtained by a reforming reaction with methane and water vapor. The syngas has as main components H_2 and CO, this CO is converted through a water gas shift reaction (equation 3.2). After this the CO_2 is removed from the gas mixture by using a CO_2 adsorption device to improve the purity of the hydrogen gas [15].

$$\begin{aligned} CH_4 + H_2O &\rightarrow CO + 3H_2 \\ CO + H_2O &\rightarrow CO_2 + H_2 \end{aligned} \tag{3.2}$$

3.2. Fuel cells

There are five different types of fuel cells, which will be discussed in the section below. The main reason for the maritime sector to use fuel cells is that fuel cells emit zero greenhouse emissions. Fuel cell types that work on hydrogen only emit water [12]. A fuel cell is basically an open thermodynamic system. It has four main parts, the anode, cathode, electrolyte and the external circuit. At the anode, hydrogen is oxidized into protons and electrons, while at the cathode oxygen is reduced to oxide species and react to form water. Depending on the electrolyte, either protons or oxide ions are transported through an ion-conductor electron-insulating electrolyte while electrons travel through an external circuit to deliver electric power. The external circuit deliver an electric load, which is needed for the reaction [25].

Alkaline fuel cell (AFC)

This type of fuel cell is the first fuel cell developed in 1939 by Bacon [12]. An AFC generates electric power by utilizing alkaline electrolyte potassium hydroxide (KOH) in water based solution.

$$Oxidation : 2H_2 + 4OH \rightarrow 4H_2O + 4e^- \tag{3.3}$$

$$Reduction : O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \tag{3.4}$$

The fuel cell performs in temperatures between 60 and 90 °C and can generate up to 20 kW. The electrical efficiency is about 60% and CHP (combined heat and power) efficiency is more than 80%. This type of fuel cell is considered as the most cost efficient type, since the electrolyte used is a standard chemical potassium hydroxide. This fuel cell has as advantage that the by-product produced is drinking water. A disadvantage is that they easily are poisoned with carbon dioxide due to the reaction with the electrolyte, which is the reason why AFCs need pure oxygen [12, 25]. This type of fuel cell is mostly used in NASA space shuttles. The investment for this fuel cell type is relatively low [12].

Phosphoric acid fuel cell (PAFC)

PAFCs use carbon paper electrodes and liquid phosphoric acid (H_3PO_4) electrolyte. They can operate at the range of 150 to 220 °C.

$$Oxidation : 2H_2 \rightarrow 4H^+ + 4e^- \tag{3.5}$$

$$Reduction : O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \tag{3.6}$$

The heat is usually exploited for water heating or steam generation at atmospheric pressure. However, steam reforming reactions produce some carbon monoxide (CO) around the electrodes which might poison the fuel cell and affect the PAFC performance. The solution is to increase the anode temperature to improve the CO tolerance of the PAFC. It does not require pure oxygen for its operation since CO_2 does not affect the electrolyte or cell performance. Other fuels such as LNG and diesel fuel can also be used. The initial cost is high since PAFC uses air with 21% oxygen instead of pure oxygen resulting in 3 times reduction in the current density. The electric efficiency is between 40 and 50% and CHP about 85%. The PAFC is typically used for on-site stationary application [12, 25].

Solid oxide fuel cell (SOFC)

SOFC's are high temperature fuel cells with metallic oxide solid ceramic electrolyte.Yittria stabilized zirconia (YSZ) is the most commonly used electrolyte because of its high chemical and thermal stability and pure ionic conductivity. Oxygen is reduced in reduction reaction at the cathode at 1000 °C. The cathode is often made of lanthanum strontium manganite, which is a ceramic material.

$$Oxidation : \frac{1}{2}O_2(g) + 2e^- \rightarrow O_2^-(s) \tag{3.7}$$

$$Reduction : O_2^-(s) + H_2(g) \rightarrow H_2O(g) + 2e^- \tag{3.8}$$

The by-product heat can be used to generate more electricity by turning gas turbines and hence increasing the efficiency between 70 and 80%. Long start-up and cooling-down times as well as various mechanical and chemical compatibility difficulties limit the use of SOCFs [25]. The SOFC has two possible geometries; planar and tubular. The planar SOFC looks the same as the other fuel cell types, it has an electrolyte between two electrodes. The tubular SOFC have inner and outer tubes which are the electrodes and between them there is an electrolyte. The airflow is in the inside of the cell and the fuel is fed from the outer side of the cell. The most important advantage of the SOFC is the highly efficient electric generation and during this operation, it produces waste heat at high quality. Another advantage is that the SOFC has multiple fuel options such as LNG, methanol, hydrogen, and hydrocarbons such as diesel [12].

Molten carbon fuel cell (MCFC)
The MCFC is a high-temperature fuel cell, which operates approximately between 600 and 700 °C. This high temperature provides an effective ion conductivity, furthermore minimizes the needs for high cost catalyst such as platinum. It uses molten carbonate salt mixture as electrolyte suspended in a porous, chemically inert ceramic matrix of beta-alumina solid electrolyte.

$$\begin{aligned} Reform1 &: CH_4 + H_2O \rightarrow CO + 3H_2 \\ Reform2 &: CO + H_2O \rightarrow CO_2 + H_2 \end{aligned} \tag{3.9}$$

$$\begin{aligned} Oxidation1 &: H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^- \\ Oxidation2 &: CO + CO_3^{2-} \rightarrow 2CO_2 + 2e^- \end{aligned} \tag{3.10}$$

$$Reduction : \frac{1}{2}O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-} \tag{3.11}$$

The electrical efficiency is around 50-60%. However with a cogeneration system the total efficiency can reach to 85%. MCFCs are currently employed for natural gas and coal-based power plants in electrical utility, industrial and military applications [12, 25].

Proton exchange membrane fuel cell (PEMFC)
In the proton exchange membrane fuel cell the hydrogen is activated by the catalyst to form a proton ion and eject an electron at the anode. The produced proton ion passes through the membrane while the electron is forced to flow to the external circuit and generates electricity. After generating electricity the electron flows back to the cathode and interacts with oxygen and in combination with a proton ion water is produced.

$$\begin{aligned} Anode &: H_2(g) \rightarrow 2H^+ + 2e^- \\ Cathode &: \frac{1}{2}O_2(g) + 2H^+ + 2e^- \rightarrow H_2O(l) \end{aligned} \tag{3.12}$$

PEMFCs are low temperature fuel cells with an operating temperature between 60 and 100 °C. The higher the working temperature, the higher efficiency can be gained. Mekhilef et al. [25] mentioned an electrical efficiency between 40 and 50% and in the later published paper of Inal and Deniz [12] there is mentioned an efficiency between 50 and 60%. The platinum catalyst can be poisoned by carbon monoxide and so pure hydrogen is a requirement for the PEMFC. The output power can be as high as 250 kW [25]. The disadvantages of PEM fuel cells are the need for platinum as a catalyst, difficulty of water management in cell and use of pure hydrogen as fuel. An important development for PEMFC is the high operating temperature version which less mature than low temperature option. This type can operate up to 200 °C and less sensitive to carbon included fuels in comparison with conventional PEM types [12].

Direct methanol fuel cell (DMFC)
Low temperature operation, long lifetime and rapid refuelling system characteristics are advantages of the DMFC.

$$\begin{aligned} Anode &: CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^- \\ Cathode &: \frac{3}{2}O_2 + 6e^- + 6H^+ \rightarrow 3H_2O \end{aligned} \tag{3.13}$$

DMFCs are classified into active and passive. Actives are high efficient and reliable systems consisting of methanol feed pump, CO_2 separator, fuel cell stack, methanol sensor, circulation pump, pump drives and controllers. These fuel cells are usually used in control applications for quantities such as flow rate, concentration and temperature. By passives the methanol pumping devices and external process for blowing air into the cell are eliminated. They are cheap, simple and capable of substantial reduction in parasitic power loss and system volume. For the active as well as the passive DMFCs vapour feed is preferable to liquid feed in term of cell voltage and power density.

Safety
In the paper of Inal and Deniz [12] a good overview of safety issues is given. The major fuel cell safety issue is related to high-temperature exhaust gases and electricity production. Especially for SOFC and MCFC, the exhaust gas temperature is relatively higher than the other types. During the discharge of exhaust from the fuel cell, pipes must have a double layer and effectively insulated to prevent any leakage. Additionally, internal equipment like membrane, electrolyte, and electrodes must be maintained in good condition to reach the maximum efficiency and safer operation. In any case of leakage of electrolyte from the cell unit, it will be hazardous to human life. Secondly, as an additional precaution for the pure hydrogen using fuel cell units, the storage tank and delivering pipes have to be insulated. Due to the physical properties of hydrogen, volatile and highly explosive, transfer between the storage tank and anode side of the fuel cell must comply with the two barrier principle and it is either achieved by ventilation and gas-tight enclosure. Related to the safety aspect, low-temperature fuel cells have an advantage due to their safe operability, but the need for hydrogen or hydrogen production units causes to need more regulations and standards [12].

3.2.1. Comparison between the fuel cell options

In the paper of Abdelkareem et al. [1] a good overview of the different fuel cell types was already made, summarized in table 3.2. The table is supplemented with information from the paper of B. Yang et al. [38]. Both papers give a different value for the cost of the PEMFC, in the paper of Abdelkareem et al. [1] is stated that the PEMFC cost $50 - 100\$/W$ while in the paper of B. Yang et al. [38] $100\$/kW$ is mentioned. The last cost is however based on fuel cells for the automotive industry so this could be the reason for this large difference.

Table 3.2: Fuel cells comparison [1, 38]

	PEMFC	AFC	PAFC	DMFC	MCFC	SOFC
Optimum operating temperature	~80 °C	23-70 °C	180 °C	>60 °C	550-700 °C	700-1000 °C
Typical fuel	Hydrogen	Hydrogen	Hydrogen	Methanol	Natural gas or methane	Hydrogen, natural gas, ammonia, methanol or diesel
Advantages	Vast power range Easy scale-up short start-up time High power density	possibility of replacing Pt Cheaper High activity Short start-up time Simple heat management Can tolerate a very small amount of CO Fast kinetics	Can tolerate 1-2% CO Cheaper due to lower of Pt usage Ability to be used in CHP systems High stability Low vapor pressure Higher tolerance to CO_2	No CO_2 emissions Low start-up time High energy density Methanol is easy to obtain and store Resistant to CO poisoning Methanol is cheap	High efficiency Variety of fuel Usable with gas turbines Cheap High activity Supports internal reforming	High current and power densities Non-noble metal catalysts High fuel flexibility
Disadvantage	Slow oxygen kinetics Heat and water management CO poisoning Requires high purity H_2	Intolerance to CO_2 Requires pure O_2	Long start-up time Limitation in material selection Low membrane ionic conductivity Low power density Intolerant to CO	Fuel crossover Expensive Methanol is highly flammable Methanol is toxic	Hardware corrosion Low power density Cathode dissolution Long start-up time Limitation in material selection hard to handle liquid electrolyte	Long start-up time High manufacturing costs
Electrical Cell Efficiency System	50-70% 30-50%	60-70% 62%	55% 40% co-gen: 90%	20-30% 10-25%	55% 45-55%	60-65% 55-60%
Power Range	1 W - 500 kW	10 W - 200 kW	50 kW - 1 MW (250 kW module typical)	110 mW - kW	<1 kW - 1 MW	5 kW - 3 MW
Applications	Backup power Portable power Small distributed generation Transportation	Submarines Military Spacecraft Backup power	Distributed generation	Electronic devices (laptops and phones)	Auxiliary power Electric utility Large distributed generation	Stationary power Combined heat and power (CHP) system
Capital cost ($/kW)	100	50-100	-	-	1000	1000

The DMFC runs on methanol and since methanol is a fuel which is only CO_2 neutral if made right, this type of fuel cell will not be considered during the rest of the research.
MCFCs still produces CO_2 since it runs on natural gas or methane, so the Molten carbon fuel cell is also not considered as an option for the new propulsion system.
The best options for fuel cell in the shipping industry are the proton exchange membrane fuel cell, solid oxide fuel cell and the Alkaline fuel cell. All fuel cells can operate on hydrogen. The PEMFC requires a very high purity of hydrogen. The AFC tolerates a very small amount of CO, but requires pure oxygen which is a reason to eliminate this type of fuel cell for new system. The SOFC has a much higher cost per delivered kW which results in the choice to work with the PEMFC for the rest of this research.

After searching for different fuel cell manufactures, the choice is made to work with information for PowerCellution as well as Nedstack for the fuel cell calculations. Figure 3.2 gives an overview of all

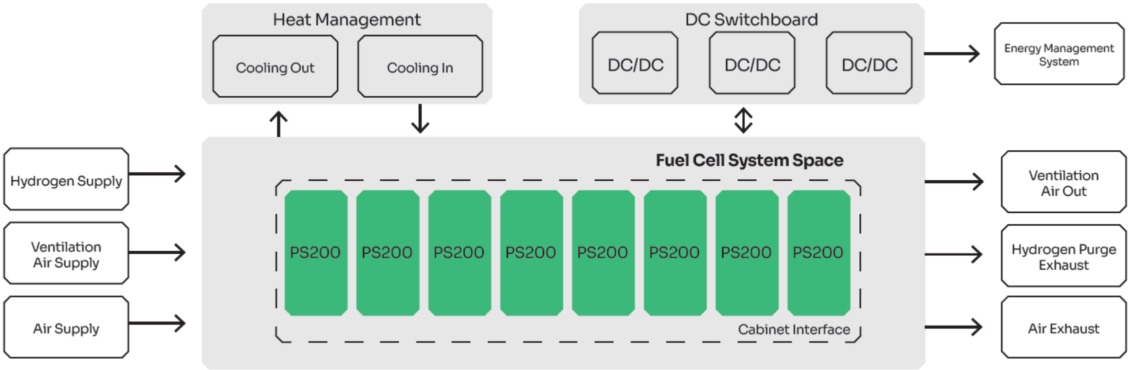


Figure 3.2: PowerCellution fuel cell system layout [24]

components to take into account for the fuel cell system. In addition to the fuel cell stacks also three main parts of the fuel cell system are the hydrogen supply, the air supply and the heat management system. The properties used during the fuel cell calculations are shown in table 3.3.

Table 3.3: Properties fuel cell stack [6, 24]

Power production (maximum)		[kW]	200
Length		[m]	0.73
Width		[m]	0.9
Height		[m]	2.2
Surface		[m^2]	0.657
Volume		[m^3]	1.445
Hydrogen consumption	@100% @50%	[kg/hour]	13 6
Water production	@100% @50%	[L/hour]	125 57.5
Air flow rate		[$m^3/hour$]	690
Coolant flow rate		[L/min]	340

3.3. Hydrogen Storage

As mentioned in the previous section, the fuel cell which will be part of the new propulsion system will run on hydrogen, but this new fuel cannot be stored as easily as the currently used fuel. Hydrogen has a good energy density by weight, but a low energy density by volume. In order to use hydrogen as fuel, its physical state has to be altered to improve its density by volume so more fuel can be stored on board. For that reason different ways of hydrogen fuel storage are investigated and discussed.

3.3.1. Compressed hydrogen storage

Hydrogen compression is the most widely used method of storage. Hydrogen can be stored in four different types of pressure tanks. Tanks made of metal (type I), made of a thick metallic liner hoop wrapped with a fiber-resin composite (type II), made of a metallic liner fully-wrapped with a fiber-resin composite (type III) and made of polymeric liner fully-wrapped with a fiber-resin composite (type IV). Generally the tanks are cylindrical but composite tanks can also be polymorph or toroid. The choice of the storage is based on the final application which requires a compromise between technical performances and cost-competitiveness. Type I tanks, which are made of metal, are the cheapest and mainly used for stationary applications. The type II tanks are preferred for even higher pressures and mainly stationary applications. Type III and IV are intended for portable applications [4].
In the paper of Hwang and Verma [9] hydrogen storage for fuel cell vehicles are discussed. In this paper is stated that the most important consideration for compressed gas is the material composing the tank. It must be lightweight, inexpensive and sufficiently strong to meet the required stress, strain

Table 3.4: Key characteristics of compressed gas storage pressure vessels [5]

	Technology maturity	Cost performance	Weight performance
Type I	Pressure limited to 50 MPa, ++	++	-
Type II	Pressure not limited, +	+	0
Type III	For P ≤45 MPa	-	+
Type IV	For P ≤100 MPa	-	++

and safety specifications. In addition, thermal conductivity of the material must be high enough to manage exothermic heat during filling the tank. Accounting for these requirements, carbon fiber reinforced plastic (CFRP) is promising as material for the compressed gas tank. The CFRP tanks are lightweight and durable, however, they have relatively low thermal conductivity which requires further improvement [9]. In the automotive industry for cars with a 300 mile driving range, assuming 50% fuel cell efficiency, 5.6 kg of usable H_2 is required. The CFRP tanks are estimated to provide 5.2 and 5.5 wt% H_2 for 700 and 350 bar, respectively. Compressed gas tanks offer a near-term option for initial commercialization and currently focus on reducing the cost of the carbon fiber composite, which dominates the cost of the compressed gas systems. The volumetric capacity and the cost of the tanks, however, are still challenges [9].
Two potential barriers to use compressed H_2 tanks are public acceptance and infrastructure development. In Asia there is significant concern that 70 MPa systems will not gain acceptance as easily as lower pressure systems, energy providers have also endorsed a medium pressure infrastructure [16]. An option is to store the high pressure gas in substructures such as capillaries or microspheres. The advantage is the possibility to use a small number of high pressure filling plants for the storage material, with distribution of the filled spheres or capillary arrays to fuel stations, and presumptively return of the exhausted spheres in the same trucks. The very small dimensions of these structures allow for a thin glass envelope and potentially high specific mass. The wall of the tank can be a low pressure structure that is light, inexpensive and in some cases conformable to the underbody of the vehicle. At present the energy needed to release the hydrogen from microspheres or other glass structures, their lower volumetric efficiency, and the long term durability of the structures have prevented commercial consideration in vehicles [16].
Another alternative compressed H_2 technology is the use of internal skeletons. This concept uses a sophisticated design of struts or web elements in tension to resist the force of compressed gas [16].

3.3.2. Cryogenic liquid hydrogen storage

Cryogenic tanks are used for gases that require low temperature for liquefaction. The tanks are normally vacuum insulated and composed of an inner pressure vessel and an external protective jacket. To reduce the thermal conductivity of the space between the inner vessel and the outer jacket, perlite (powder structure) or super insulation (wrapping with layers of aluminium film separated with glass fiber film) are used [4]. When hydrogen is liquefied the volumetric density increases. Hydrogen does not liquefy until it reaches -253 °C, which makes the process both time consuming and energy intensive demanding. Up to 40% of the energy content can be lost [5]. The advantage of liquid hydrogen is its high energy/mass ratio, three times that of gasoline. However, energy/volume ratio remains low compared to gasoline. Liquid hydrogen is difficult to store over a long period [4]. The theoretical volumetric capacity of hydrogen increases from 24 or 40 g/L (for compressed H_2 at 350 or 700 bar at 27 °C) to 70 g/L (for liquid H_2 at 1 atm and -253 °C) [9].
When hydrogen is stored as liquid at 1 atm, it must be maintained below its boiling point. Therefore, effective thermal insulation is essential to maximize the efficiency of the liquid hydrogen (LH_2) tank. Typical LH_2 tanks consist of metallic double-walled container, where the inner and outer walls are separated by vacuum for thermal insulation purposes [9]. However, boil-off losses are unavoidable due to heat flow from the environment to the liquid hydrogen and thermal conduction through other components. The boil-off rate is not only a function of thermal insulation, but also of the shape of the tank. It can be up to 0.4% per day [21].
During the designing of cryogenic hydrogen tanks a key goal is to achieve a reduced surface area of the liquid, as this would limit the heat flow from the surroundings to the liquid. boil-off losses may

cause safety concerns as well. Especially looking into the automotive industry when parking in a closed garage for several days.
In the paper of Sinigaglia et al. [37] some difficulties are mentioned which need to be surpassed. From 30 to 33% of the total energy of the hydrogen is used for the liquefaction of hydrogen gas, high cost of materials used in storage tanks, problems with security and evaporation losses in storage tanks. This are the main reasons it is unlikely that the storage of liquid hydrogen will be used on large-scale vehicles.

3.3.3. Cryo-compressed storage

Cryo-compressed storage combines properties of both compressed gaseous hydrogen and liquefied hydrogen storage systems. It is developed to minimize the boil-off loss form liquefied hydrogen storage while retaining a higher system energy density. Hydrogen is stored in an insulated tank that can accept cryogenic temperatures and high pressure at ambient temperature [5]. The volumetric density of hydrogen can be increased by pressurizing LH_2 at -253 °C form 70 g/L at 1 bar to 87 g/L at 240 bar, which reduces the requirement for expensive carbon fiber composite. In addition, it can decrease evaporative loss of hydrogen as well as extend the dormancy period in insulated pressure tanks. Cryo-compressed tanks (276 bar, -253 °C) are estimated to provide 5.8 wt% and 43 g H_2/L [9].
In a paper of the research centre Lawrence Livermore National Laboratory [3] a demonstration was done with a prototype car using cryo-compressed H_2. During this demonstration the longest driving distance with a single tank (660 miles) was found. Also no evaporative losses were observed during parking for 8 days.
In a recent computational analysis of cryo-compressed hydrogen storage for FC electric buses, it was found that a cryo-compressed storage system exhibited superior properties to a compressed hydrogen storage system in existing demonstration buses. In 2012, the automotive manufacturer BMW reported a prototype cryo-compressed hydrogen technology. However, the availability and cost of infrastructure are still major hurdles for this storage method, hence limiting its viability [21].

3.3.4. Hydrides storage

A difference can be made by hydrides storage into physical storage in hydrides and chemical storage in hydrides. Storage of hydrogen in solids offers some advantages compared to storage under pressure or in liquid state in terms of volumetric density. Hydrogen can be absorbed reversibly by solid compounds under temperature and pressure conditions. The main advantages of storage in metal hydrides is that it is a safe method, short storage time and it is a reversible process under moderate conditions [37]. The disadvantage with this method is that the by-product needs to be treated with a chemical treatment on a suitable site. The formation of hydrides results of dissociative chemisorption. The hydrogen molecule is first dissociated on the surface of the solid and then its atoms diffuse into the metal host. Depending on the bonding mechanism between the hydrogen and the host material, different families of hydrides exist: ionic hydrides, covalent hydrides and interstitial metal hydrides. Ionic and covalent hydrides are also called complex metal hydrides.

Table 3.5: Hydrogen capacities of selected hydrides [9]

Hydride	Compound	Gravimetric H_2 content (wt%)
Metal hydrides	LiH	12.6
	NaH	4.2
	CaH_2	4.8
	MgH_2	7.6
Complex metal hydrides	$LiAlH_4$	10.6
	$NaAlH_4$	7.4
	$Mg(AlH_2)_2$	9.3
	$LaNi_5H_6$	1.4
Chemical hydrides	$LiBH_4$	18.4
	$NaBH_4$	10.6
	NH_3BH_3	19.8

As compared to conventional metal hydrides, complex metal hydrides offer the potential to improve gravimetric hydrogen capacity. However, complex metal hydrides still provide relatively low hydrogen capacity and slow hydrogen uptake and release kinetics. Many different types of metal hydrides have been studied as means of hydrogen storage. However, superior hydrogen release properties are obtained at temperatures much higher than PEM fuel cell operation conditions. The kinetics can be improved by adding catalyst as well as by introducing ball-milling which improves surface properties. In addition, effective heat management in the system is important to improve the system efficiency [9].
Chemical hydrides are materials that have chemically connected hydrogen. The materials that can store the hydrogen chemically are the metal hydrides, formic acid, carbohydrates, ammonia, synthetic hydrocarbons and liquid organic hydrogen carriers. With the chemical hydrides, it is possible to obtain higher energy densities, in comparison to the metallic hydrides [37].
Sinigaglia et al. [37] refers to a few other research papers where chemical storage is investigated. Lu et al. [22] reviewed the methods of chemical storage with boron-and nitrogen-based materials. The conclusions that can be drawn for the investigation is that by-product regeneration, reaction kinetics control, cost and the catalyst deactivation are limitations which need to be overcome. Moury et al. [27] studied hydrazine and borane derivatives and alkaline derivatives as materials for hydrogen storage. Improving the kinetics of the reaction in necessary, since it is too slow compared to the first reaction was one of the conclusions made. The other conclusion made is that it is necessary to obtain better results with the stability of the catalysts in successive uses. Already for Semelsberger et al. [35] the major shortcomings of hydrogen chemical storage are regeneration efficiency, fuel cost and fuel phase [37].

3.3.5. Liquid organic hydrogen carriers

Hydrogen storage in the form of liquid organic hydrogen carriers (LOHCs) became recently a much more interesting storage option. LOHCs can store organic molecules and release the hydrogen through a reversible catalytic hydrogenation reaction, which is a more convenient way of handing hydrogen than the other storage methods. Figure 3.3 shows the concept of hydrogen storage using liquid organic hydrogen carriers.

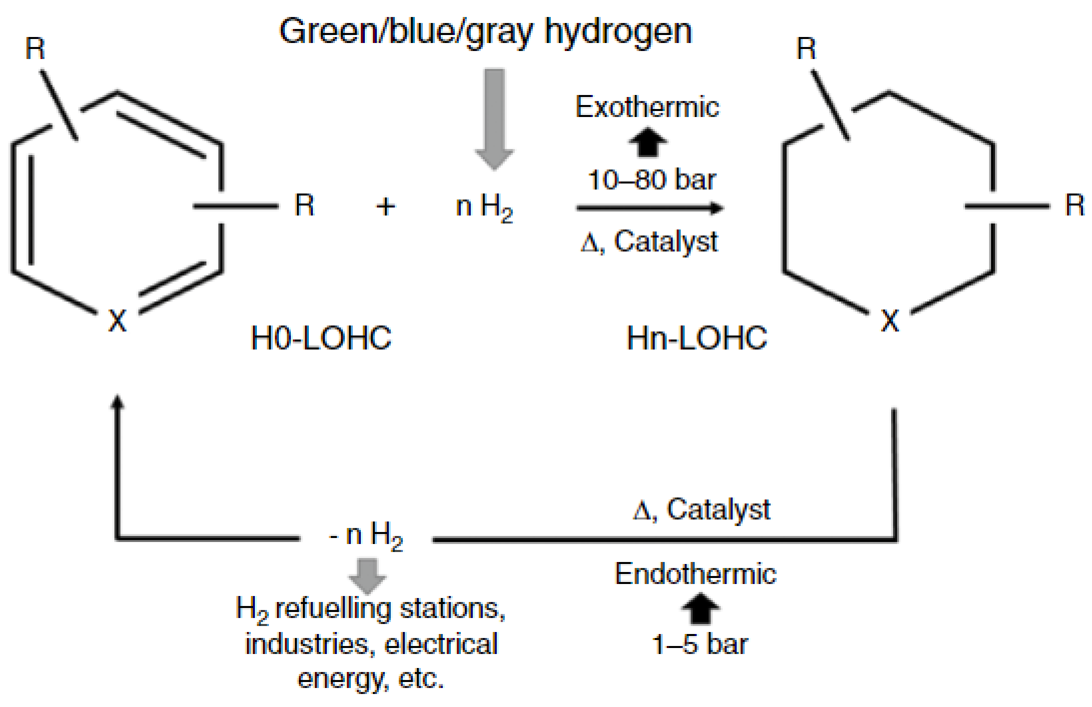


Figure 3.3: Hydrogen storage using LOHCs [21]

In the presence of a catalyst a hydrogen lean molecule (H0-LOHC) is hydrogenated by a certain temperature and pressure. The result is a hydrogen-rich molecule (Hn-LOHC), which then will be dehydrogenated at 1 bar, in the presence of a catalyst, to produce hydrogen gas and a hydrogen lean molecule. The hydrogenated LOHC can be stored under normal conditions (ambient temperature and pressure) for long periods without self-discharge [21].
LOHC molecules must meet the following criteria in order to be considered for hydrogen storage [21]:

- To make sure liquid phase storage and transportation at room temperature is possible the reactants and products should have a low melting point.
- A high boiling point (>300°C) for the molecules of the LOHC molecules is recommended, since highly volatile LOHCs may introduce impurities into the hydrogen gas stream.
- To allow a low dehydrogenating temperature the enthalpy of the reaction should be low.
- The LOHc must be copatible with current infrastructures for fuels and cannot be classified as dangerous goods.
- Readily available and low-cost LOHCs are recommended.

3.3.6. Comparison

In table 3.6 some properties and the cost of different storage systems for hydrogen are shown. For this table there can be concluded that cryo-compressed has the best properties to store hydrogen. Also is the cost of this system lower than compressed hydrogen storage. The chemical hydrides including the liquid organic carriers, have also promising gravimetric and volumetric capacities. The last years this is becoming a more and more promising option but for the near future this is not yet a feasible option.

Table 3.6: Estimated performance and cost for different hydrogen storage approaches [9, 33]

H_2 storage system	Gravimentric, wt% (kWh/kg sys)	Volumetric, g/L (kWh/L)	Costs, $/kWh
700 bar compressed (Type IV)	5.2 (1.7)	27.7 (0.9)	19
350 bar compressed (Type IV)	5.5 (1.8)	18.5 (0.6)	16
Cryogenic liquid	7.5	70	
Cryo-compressed (276 bar)	5.8 (1.9)	43.1 (1.4)	12
Metal hydride ($NaAlH_4$)	1.2 (0.4)	12.3 (0.4)	TBD
Sorbent (AX-21 carbon, 200 bar)	4.0 (1.3)	24.6 (0.8)	TBD
Chemical hydride ($NH_3BH_3 - liquid$)	4.0 (1.3)	33.8 (1.1)	TBD

In table 3.7 the main advantages and disadvantages are mentioned. Compressed and liquid hydrogen have as main advantage that this storage options are commercially available, which is an important parameter. Form table 3.6 the cryo-compressed storage option was the best option looking at gravimetric capacity, volumetric capacity and cost. The main disadvantage of this storage method is the high compression and liquefaction energy, which is higher than for the compressed hydrogen storage. Compressed hydrogen storage is also a much more mature storage option since it is the most used option at the moment.

Table 3.7: Advantages and disadvantages of different hydrogen storage approaches [9]

H_2 storage system	Advantages	Disadvantages	Ongoing efforts
Compressed H_2	Commercially available	Low volumetric capacity High compression energy Heat management during charging required	Develop and design cost-effective vessel/container
Liquid H_2	Commercially available	H_2 loss Safety issue High liquefaction energy Heat management to reduce boil-off	
Cryo-compressed	High volumetric capacity	High compression/liquefaction energy	
Metal hydride	Reversible on-board	Low gravimetric/volumetric capacity Heat management during charging required High operating temperature for H_2 release	Improve kinetics of hydrogen adsoprtion/desorption along with heat management
Sorbent and carbon-based materials	Reversible on-board	Low volumetric density Loss of useable H_2 Low operating temperature for H_2 uptake	Increase dihydrogen binding energies Optimize material's properties
Chemical hydride	Good volumetric capacity Proper operating temperatures	Thermal management required Off-board regeneration	Develop cost effective and energy effective regeneration methods for the spent material

Since large amount of hydrogen need to be stored and from table 3.6 it becomes clear that cryogenic liquid storage will store the most amount of hydrogen per liter, the choice is made to implement cryogenic liquid storage tanks on board instead of compressed storage tanks or cryo-compressed. The storage tanks are based on Van Linde tanks which has a storage density for hydrogen of 64.333 kg/m^3. With liquid hydrogen storage it needs to be taken into account that for every m^3 liquid hydrogen storage an additional 1.8 m^3 space needed is for the system. To compare marine diesel oil (MDO) has an density of 900 kg/m^3, which means that not only much more space is needed to store the same amount of hydrogen also the fuel tanks self take much more space as the MDO tanks.

3.4. Batteries

3.4.1. Basic operation of rechargeable battery

Electric batteries are devices that store electric energy in electrochemical form and deliver direct electricity [17]. A battery has a positive electrode and a negative electrode with an ion-conductive but electrically insulating electrolyte in between. During charging, the positive electrode is the anode with the reduction reaction, and the reaction is reversed, and so, the positive and negative electrodes become cathode and anode electrodes, respectively. In a sealed cell, the liquid electrolyte is held in a separator to prevent the direct short between the two electrodes. The separator also serves as a reservoir for extra electrolyte, a space saver allowing for an electrode expansion, an ammonia trap (in Ni-MH battery), and a safety device for preventing shortage due to Li-dendrite formation (in Li-ion battery) [28].

3.4.2. Battery charging methods

The safety, durability, and performance of batteries are highly dependent on how they are charged or discharged. Abuse of a battery can significantly reduce its life and can be dangerous. A current battery management system includes both charging and discharging control on-board. For electric vehicle batteries there are the following common charging methods [28]:

1. Constant voltage. Constant voltage method charges battery at a constant voltage. This method is suitable for all kinds of batteries and probably the simplest charging scheme. The battery charging current varies along the charging process. The charging current can be large at the initial stage and gradually decreases to zero when the battery is fully charged. The drawback in this method is the requirement of very high power in the early stage of charging, which is not available at all places [28].

2. Constant current. In this charging scheme, the charging voltage applied to the battery is controlled to maintain a constant current to the battery. The SOC will increase linearly versus time for a constant-current method. The challenge of this method is how to determine the completeness of a charge with SOC=100%. The cut-off can bet determined by the combination of temperature rise, temperature gradient rise, voltage increase, minus voltage change, and charging time [28].

3. The combination of constant-voltage and constant-current methods. During the charging process of a battery, normally both the methods will be used [28].

3.4.3. Battery charging options

The batteries within the hybrid system can be charged in a lot of different ways. In this section a few of them will be discussed, these options are charging with shore power, generators, the fuel cells and solar panels.

Shore power

Recharging can be done from the grid alongside, this can reduce fuel consumption and local emissions. However, there need to be taken into account that the generation of the shore power is not always without emissions [7]. Charging in port can be done by different technologies, which are categorized into conductive or wired charging, wireless charging, and battery-swapping [19].

Wired charging

Wired charging system can be categorized into two types: alternating current (ac) charging systems and direct current (dc) charging systems. In general, the main battery charger can be installed on board or in a dedicated charging station located offboard. Because of limitations for size, weight and cost onboard, the charging power is constraint. While using a offboard charging station can provide high power, which will reduce the charging time [19].

Wireless charging

Capacitive and inductive are the two different types of wireless charging. It is based on the energy transfer with an electric field or a magnetic field between two plates or coils. Wireless charging is a promising technology for the marine industry. Cables and plugs are exposed to a harsh environment with salt, which can leads to mechanical wear and tears as well as corrosion. This will lead to additional maintenance requirements and safety issues. By avoiding this problem with wireless charging it gives it a big advantages relative to wired charging. Since the charging process can start as soon as the receiver side on the ship is close enough to the sender side on shore, the time in port can be utilised as best as possible [19]. At the moment there are not much ports with a wireless charging system.

Battery-swapping methods
Replacing batteries has also been considered as charging option. During this method the discharged onboard batteries will be exchanged with fully charged batteries. Advantages of this methods are that the ship does not have to stay in port during the charging period and can sail more often, as well that the battery packs can be charged during off-peak hours when the electricity can be cheaper. Although exchanging the batteries has some benefits it has also drawbacks, an extra battery pack and the mechanical infrastructures that are needed for the changing process bring excessive extra costs with it. Besides the extra costs the batteries also need to be able to be replaced, which means that they need to be placed in a way that they can be easily removed from the ship [19]. This method is for smaller systems an option, but for the larger systems it is not an realistic option.

Generators
A generator converts mechanical energy to electric energy working on the principle of electromagnetic induction. Between the poles of a magnet a conductor coil is rapidly rotated. The conductor coil is connected to the shaft of an engine operating on different forms of fuel [31]. The batteries can be charged by the generator during the operation of the propulsion system, but also when the ship is not sailing and is in port. However, it can be possible that ports have regulations for the use of generators to generate electricity on board. For example in the port of Rotterdam inland ships are not allowed to use generators for generating electricity on board at berths in the port [34].

Fuel cells
Charging the batteries with the hydrogen fuel cells in the hybrid system is a green option and allows the fuel cells to run more constant. By using the fuel cells to charge the batteries it can be ensured that the fuel cells does not need to shut down for a short time which is not in favour of the lifetime of the fuel cells. However if the batteries will be charged with energy provided from the fuel cells it means that extra hydrogen needs to be stored or the sailing range will be reduced.

Solar panels
Another green option for battery charging is the use of solar panels, which is the main advantages of this option. It has also as benefit that it is a way of charging which does not need stored fuel, so it does not take up space in the fuel tanks on board. However, the solar panels need to be placed on board at a safe place where they will collect as much solar radiation as possible and are sensitive for the marine environment. Another drawback of this option is that only during the daytime the batteries can be charged, while if needed it is preferred to charge the batteries when needed so also during night.

3.4.4. Different types of batteries

Nowadays different battery types are available. In this section the most common used and commercial available battery types are discussed.

Lead acid battery
The lead-acid battery was the first known type of rechargeable battery. The lead-acid battery is a combination of a lead electrode, a lead dioxide electrode, and an electrolyte composed of sulfuric acid and water. Two different types of lead-acid batteries are available:

- The flooded type which is the cheapest and tends to be used in automotive and industrial applications. Some of the limitations of this type of battery is the required frequent maintenance to replace water lost in operation and that they are heavy because of the lead.

- The sealed type, also called valve-regulated lead-acid (VRLA), that has been rapidly used in a wide range of applications including power supplies and stand-alone power supplies for remote areas.

Both the power and energy capacities of lead-acid batteries depend on the size and geometry of the electrodes. The power capacity can be improved by increasing the surface area of each electrode, which means greater quantities of thinner electrode plates in the battery. Low cost, high power, a mature system, and easy recyclability are advantages of the lead-acid batteries. The main drawbacks of lead-acid batteries is usable capacity decreases when high power is discharged and the battery has a high self-discharge. Lead-acid batteries also require frequent maintenance to replace water lost in operation and are also because of their use of heavy lead. Because of the use of lead this battery type is also likely to cause environmental pollution. Expected is that lead-acid batteries gradually will be displaced by Li-ion and Ni-MH batteries, due to environmental impact concerns. The Li-ion batteries have also four time more specific energy than lead-acid can offer [17, 28, 39].

Lithium ion battery
Different types of lithium ion batteries are available depending on the cathode material used. Cathode materials which can be used for lithium ion batteries are cobalt, manganese, nickel manganese cobalt, iron phosphate, nickel cobalt aluminum, and titanate. Depending on the cathode material the battery has different properties. By using lithium cobalt oxide (LCO) as the cathode of a Li-ion rechargeable battery, it would be possible to achieve a high density of stored energy with an anode other than metallic lithium. This led to the development of carbon-rich materials that allow for the use of stable and manageable negative electrodes in Li-ion batteries. Lithium-graphite is the most commonly used anode in commercial Li-ion batteries. Because of the LCO cathode and the carbon anode the battery is safer and has a higher practical energy output than metallic lithium batteries. The battery operates through the movement of the lithium ions between the positive and negative electrodes. The Li-ion battery has as advantages that it has a low self-discharge, rapid charging and high-load capabilities. The drawbacks of this battery is the high initial capital cost and the insufficient cycle life of the battery [28, 39].

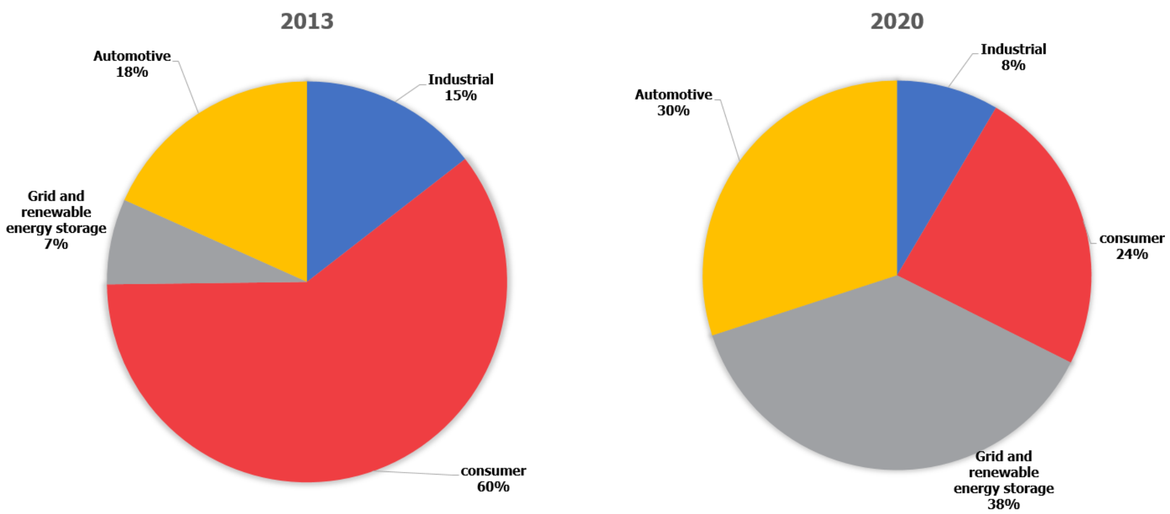


Figure 3.4: Market segment of Li-ion batteries. [28]

Nickel metal hydride battery

The Nickel metal hydride (Ni-MH) battery consists of a positive nickel hydroxide, negative metal hydride, and nylon separator sheets. The electrodes that accommodate active materials required in the battery chemistry and the separator sheets have porous structures, and their pores are filled with a concentrated potassium hydroxide (KOH) solution as the electrolyte. Ni-MH batteries are environmental friendly, relatively low in price, and have a good thermal stability. The drawbacks of this type of battery is that it has half the specific energy compared with Li-ion batteries that limits their application in electric power trains. Also Ni-MH has high self-discharge and loses about 20% of its capacity within the first 24 h and 10% per moth thereafter. Modifying the hydride materials lowers the self-discharge and reduces corrosion of the alloy, but this decreases the specific energy. Moreover, Ni-MH batteries generate heat during fast charge and high-load discharge that can play a crucial role in their safety, performance, and longevity [28].

Other types

Besides the batteries mentioned above there are other types of batteries. Vanadium-based flow batteries, sodium-sulfur batteries, solid state batteries, metal air batteries, and aluminium-ion batteries are some of the types which where also found. Some of these battery types are still very experimental or not commercial available and for that reason not further investigated.

3.4.5. Comparison

In table 3.8 the properties of the in section 3.4.4 mentioned battery types are shown.

Table 3.8: Battery type properties comparison [36]

Energy storage method	Gravimetric energy density (Wh/kg)	Volumetric energy density (Wh/L)	Power density (W/kg)	Capital cost ($/kWh)
Lead-acid battery	20-50	50-100	150-300	70
Nickel-metal hydride battery	60-100	100-250	200-300	300-500
Lithium-ion battery	100-160	200-300	200-400	200-700

Some of the advantages and disadvantages of batteries are mentioned in table 3.9. The lead-acid battery is a mature system with low cost, which makes it a good option, but it has some major disadvantages. The system has a large self-discharge which results in more frequently charging. Also lead is an environmental pollutant so this makes the battery type also a less interesting system and especially with the idea to become more sustainable this is something to keep in mind. The most promising battery type is the Lithium-ion battery, it has the highest energy and power density. Compared to the lead-acid batteries, the lithium-ion batteries have a high cost, which is also a point to take into consideration.

Table 3.9: Battery comparison [39]

Battery type	Advantages	Disadvantages	Energy storage applications
Lead-acid	Low capital cost	Limited life cycle, long charging time and high self-discharge rate Environmental pollution	Hot spare, frequency control and load adjustment
Lithium-ion	High energy densities, high efficiency, and long life cycle	High production cost, requires special charging circuit	Frequency control, load shifting and power quality
Nickel metal hydride	Environmental friendly Relatively low in price	Low specific energy High self-discharge	

For the new hybrid propulsion system, the choice is made to work with lithium-ion batteries from Corvus Energy, partly because Allseas has already looked into this option and of their high energy density. The battery pack has a capacity of 249 kWh which means that the battery can discharge 249 kW during one hour. This battery pack has a c-rate of three which means that in 1/3 of a hour it can discharge 3 times 249 kW. So this battery pack can deliver peaks of 747 kW during 20 minutes. The dimensions of one battery pack are presented in table 3.10.

Table 3.10: Dimensions of one Corvus Orca Energy battery pack

Length	[m]	0.738
Width	[m]	1.345
Height	[m]	3.000
Surface	[m^2]	0.993
Volume	[m^3]	2.978

3.5. Hybrid system

Since the expectation is that a propulsion system only working on fuel cells and hydrogen as fuel is not feasible, the target is to work during certain projects on the fuel cells and batteries if necessary, but for example during transit the diesel generators can be used. So the new propulsion system will be a hybrid system. In figure 3.5 the existing propulsion system configuration is shown, this system is fully electric and can operate the four engine rooms separate from each other.

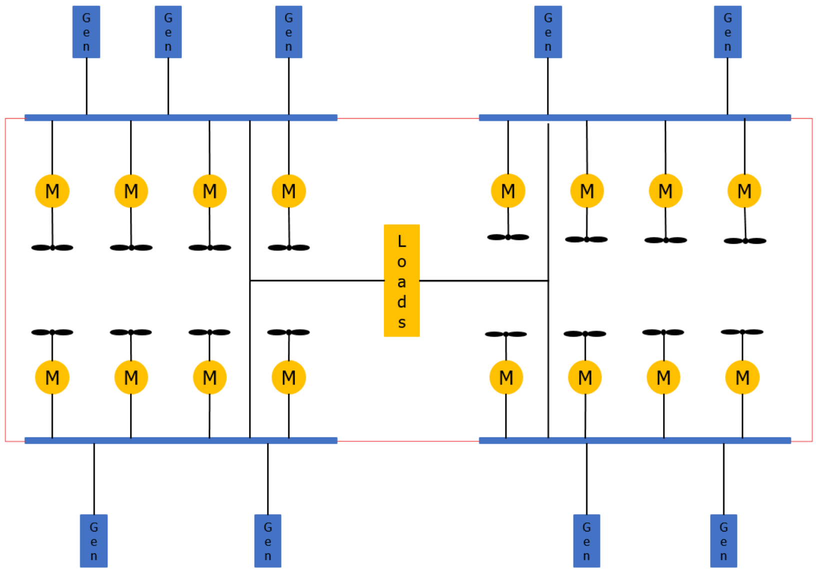


Figure 3.5: Existing propulsion system configuration of the Pioneering Spirit

There are different definitions for a hybrid system, R.D. Geertsma et al. [7] gives as definition a system with a mechanical direct drive and an electric motor with a gearbox connected at the same shaft. During the research of the new propulsion system the definition of hybrid that is used is different energy sources for the electric propulsion system since the system on board is fully electric.

3.5.1. Different hybrid system architectures

The different hybrid system setups can be classified under three different configurations depending on the energy distribution from the energy sources to the propeller: serial, parallel, and combined serial-parallel. A common hybrid power system generally consist of a combination of several power sources and energy storage systems [11]. The main difference between the three configurations is the direct mechanical connection to the propeller, since the Pioneering Spirit has a fully electric propulsion system and so not a direct mechanical connection to the propeller the choice is made to only discuss the serial configuration, for the other configurations see the full literature review [26].

Serial hybrid system
For ships the serial hybrid system configuration (figure 3.6) is relatively mature compared to the other configurations. In this system configuration all the power sources are connected to a main electrical grid. Many combinations of power sources and energy storage systems can be used with this hybrid system configuration. This is depending on the specifications of the ship.

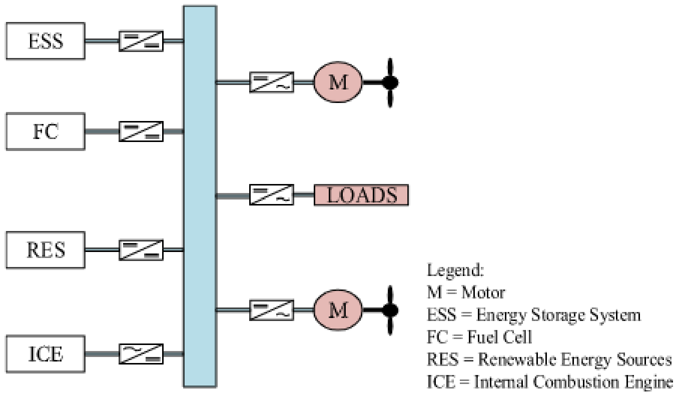


Figure 3.6: Example of a serial hybrid system configuration [11]

The main advantage of this system configuration is that it has various operation modes. Since the total electrical energy of the system is collected and distributed through one common bus bar, multiple working modes can be used especially by using just one or a combination of power supply. This type of system has also the benefit that the batteries can enable load levelling. Batteries can handle the power fluctuation, which results in constant loading of the engines, maintaining a more efficient operating point. The batteries can also enable peak shaving, the batteries deliver than power during periods where high power is required. During the periods less power is required the batteries can recharge, which makes it possible to run the engines more efficiently and reduce installed power. The batteries can also provide back-up power in case of a failure of combustion power. The disadvantage of this system is the low steady-state efficiency and high installation cost [7, 8, 11].

As stated before the system configuration of the existing propulsion system is an fully electric serial configuration and for that reason the new system will also be an electric serial configuration. Depending on the capacity of the fuel cells and batteries some of the generators in figure 3.5 will be removed. Since at this stage of the research it is not clear how many will be remove a more general configuration is shown in figure 3.7.

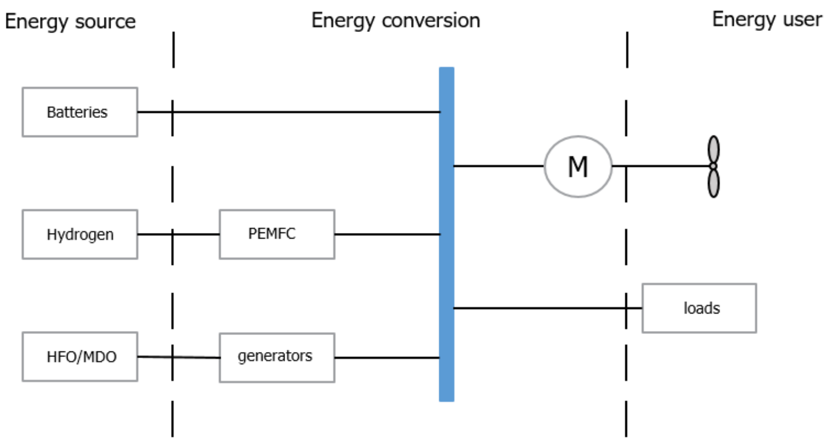


Figure 3.7: Energy flow diagram of the new hybrid system configuration

4 Operational profile

In this chapter the operational profile with corresponding power profile are discussed and analysed. During this part of the research vessel data is used of the last six years (2016-2021) as well as the project planning of the Pioneering Spirit.

4.1. Different operation types

The Pioneering Spirit can perform two different project types, Pipelay and heavy lift. In addition to the projects, the ship will the rest of the year be in port or is sailing between different ports. All projects have five main phases: mobilise, sail to location, work, sail to port and demobilise.

4.1.1. Pipelay

During a pipelay project single length pipes are welded, inspected and coated in a horizontal working plane (the firing line). The vessel moves forward, while at the same time the pipe gradually exits the firing line, curving downward through the water until it reaches the seabed. The S-lay technology is used, which is a fast installation technology and applicable in all water depths. The name S-lay refers to the shape of the pipe between the ship and the seabed. A stinger controls the upper curvature of the pipeline, it is a steel structure with rollers at the end of the firing line to prevent buckling of the pipe. The curvature in the lower section of the pipeline is controlled by pipe tensioners, which are caterpillar tracks that grip the pipe. The amount of tension during the process is one of the most important factors in the capabilities of an S-lay vessel [30].
The projects are as mentioned above divided into 5 phase, the work phase of a pipelay project is then further subdivided into recover pipe, lay pipe and laydown pipe.

4.1.2. Heavy lift

Heavy lift projects can be categorised into two types: removal and installation. As well as by a pipelay project heavy lift projects have 5 phase. During the work phase of a heavy lift project the distinction is made between lift, installation and removal.

Installation

Prior to sailing to the location of installation the topside and/or jacket are transferred to the vessel in sheltered water. With the topside and/or topside on board the vessel sails to the location and stays in position using the dynamic positioning system. All motions of the topside relative to the base of the structure are eliminated by the active motion compensation system. After this the topside can be lowered onto the base structure without impact.
The Pioneering Spirit can use its topsides lift system (TLS) for the installation of entire topsides, up to a weight of 48000 t, in a single lift. As a result the entire platform topside can be installed in one piece and pre-fabricated onshore, which can lead to significant field development cost savings [13].

Removal
Similarly to the installation, the Pioneering Spirit is able to remove an entire topside in a single lift. Removing a topside in a single lift reduces the man-hours spent on offshore cleaning, partitioning, installing lifting points and rigging the platform modules significantly, which also reduces the health and safety risks during the project.
Prior to the arrival of the Pioneering Spirit the topsides legs are cut from the base structure. The topside is lifted by ”yokes” or ”horseshoes” mounted on the TLS beams. These yokes or horseshoes are previously adjusted to the exact dimensions of the platform legs or the underside of the topside [32].
Using the dynamic positioning system the vessel positions herself around the platform base structure. All motions of the yokes or horseshoes relative to the platform are eliminated by engaging the active motion compensation system. At the underside of the topside the yokes are positioned at the pre-determined strong points, or the horseshoes are placed around the pre-installed lift points on the topsides legs. After the connection, pre-tension is gradually increased in the lift system in order to transfer the weight of the topside from the jacket to the vessel. In the final stage a rapid lift is performed, using hydraulic lift cylinders [32].

In addition to topsides the Pioneering Spirit is also able to remove jackets weighting up to 20000 t in a single lift, which limits subsea work and the risks associated with it. Prior to lifting cuts have been made in the foundation piles of the jacket at seabed level, or above the pile clusters. The main hoist blocks from the jacket lift system beams raise the jacket at the main legs. Subsequently, the jacket will be aligned with the beams, reclined, and brought further inboard before transit. It is not required to first offload the topside before the vessel performs a jacket removal [32].

4.2. Year overview

In order to determine the optimal power contribution of the fuel cells and batteries, the operational profile of the vessel is investigated. By determining average power demand during the different operations, a choice can be made on the size of the fuel cells.
First the year schedule of the Pioneering Spirit is investigated. The vessels year schedule provided the information on how often the vessel is in operation and which operations the vessel is doing. This information is used in combination with the vessels schedule for upcoming projects to generate a typical year for the Pioneering Spirit, provided in figure 4.1. In this figure a distinction is made in four different categories: pipelay and heavy lift projects, time in port (not on a project) and transits between different ports (not on a project).

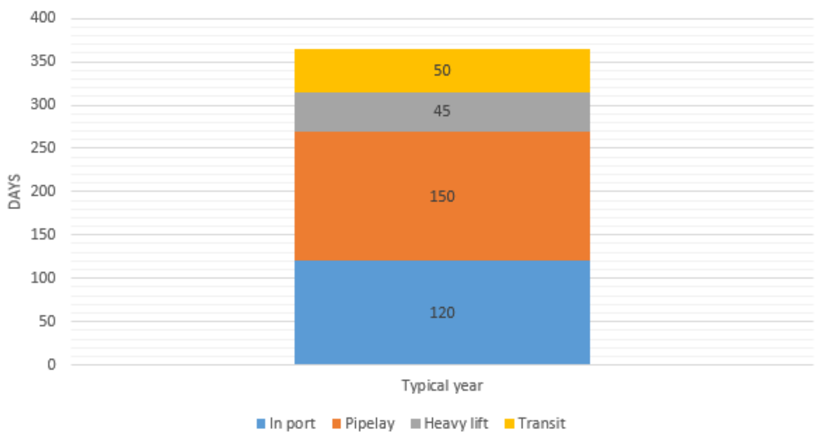


Figure 4.1: Typical operational year for the Pioneering Spirit

Figure 4.2 reveals the percentage of the year spent on the different project phases over the last six years. Note that in the phase work also the time in port is included and in the sail to location phase also the transit time between ports is included.

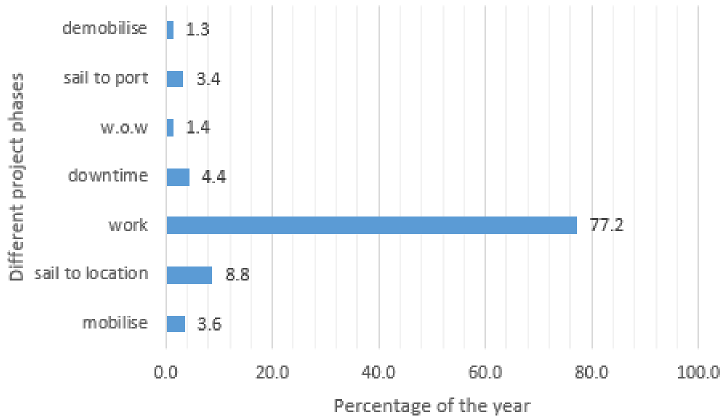


Figure 4.2: Percentage of the year spent on the different project phases

The average amount of days spent on a heavy lift and pipelay projects are shown in figure 4.3. Similar to figure 4.2 the two projects are divided into the different project phases. It reveals that a pipelay project on average cost much more time than a heavy lift project, which can be done on average within two weeks.

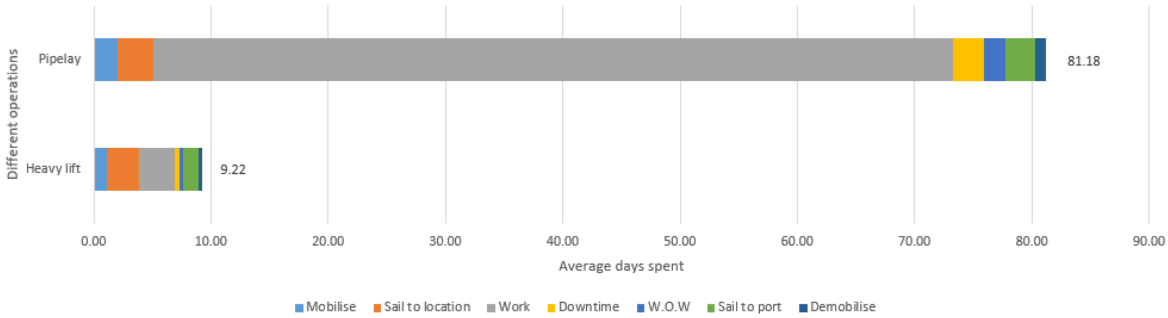


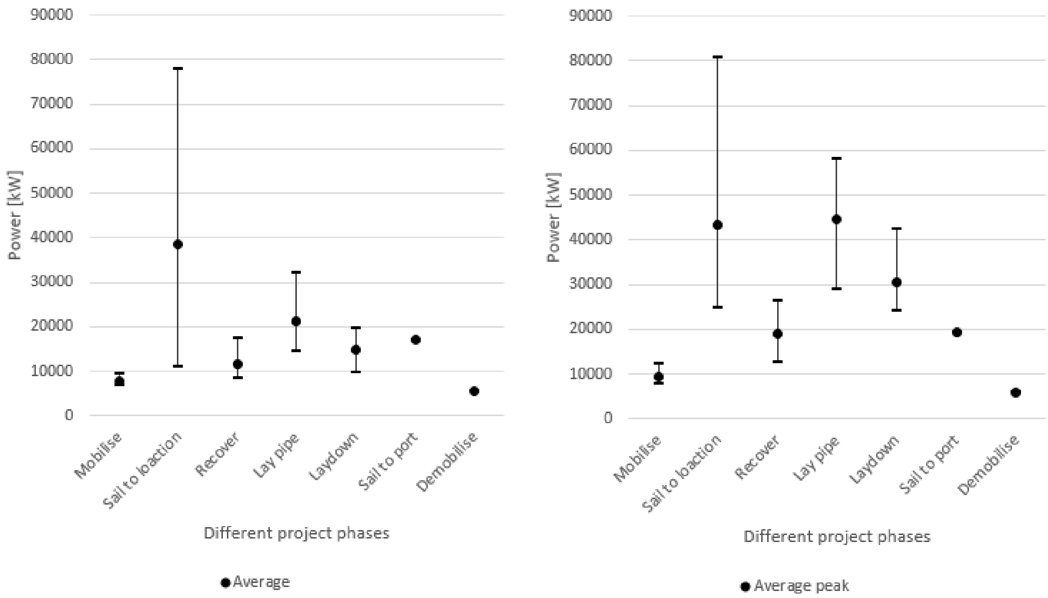
Figure 4.3: Average amount of days spent on different disciplines within the operations

4.3. Average power and peak power demand

To get a first insight in the power demand of the vessel data moments with a length of maximum three hours are randomly collected for the different operations and phases. For all these data moments the average power and the peak power are gathered and used to calculated an overall average of the average power and the peak power. In figure 4.4, 4.5, 4.6 and 4.7 reveal the results, including the range of the data.

4.3.1. Pipelay

For figure 4.4 three different pipelay projects are investigated and in total 23 data moments are used. This figure reveals that during a pipelay project the sail to location and lay pipe phases are the most power demanding phases as well as that during the lay pipe phase difference between the average power and the peak power is the largest.



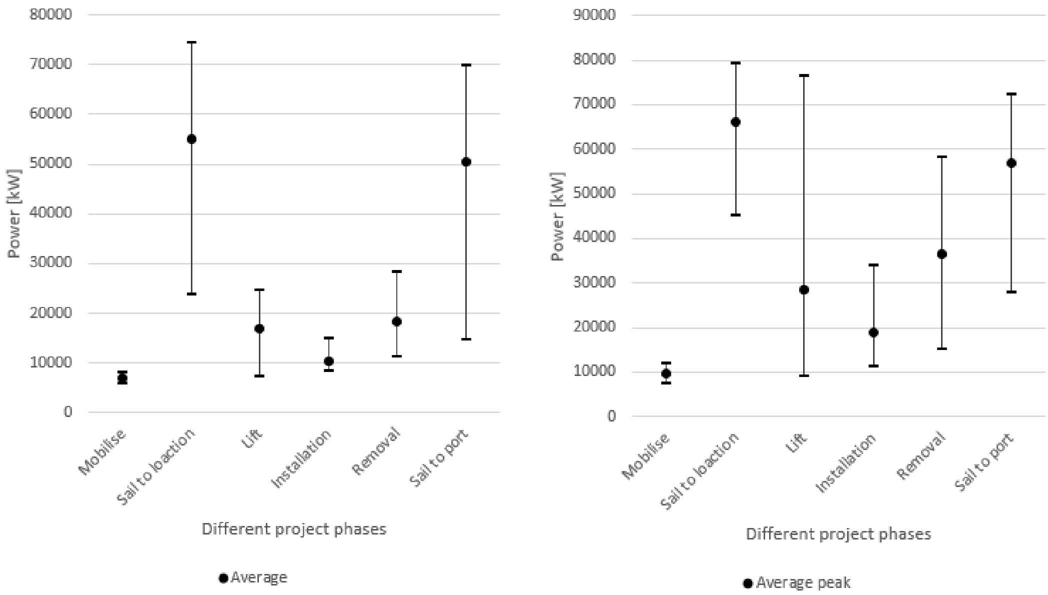
(a) Average power demand per project phase

(b) Peak power demand per project phase

Figure 4.4: Pipelay projects - Average of the average power and peak power per project phase relative to the range of the used data points [kW]

4.3.2. Heavy lift

In addition to the pipelay projects also four heavy lift projects are investigated and shown in figure 4.5a. In total 36 data moment are used to generate this figure. This figure reveals that during a heavy lift project the high power demanding periods are the sail to location and to port phases. The largest peaks range is occurring during the lift phase.



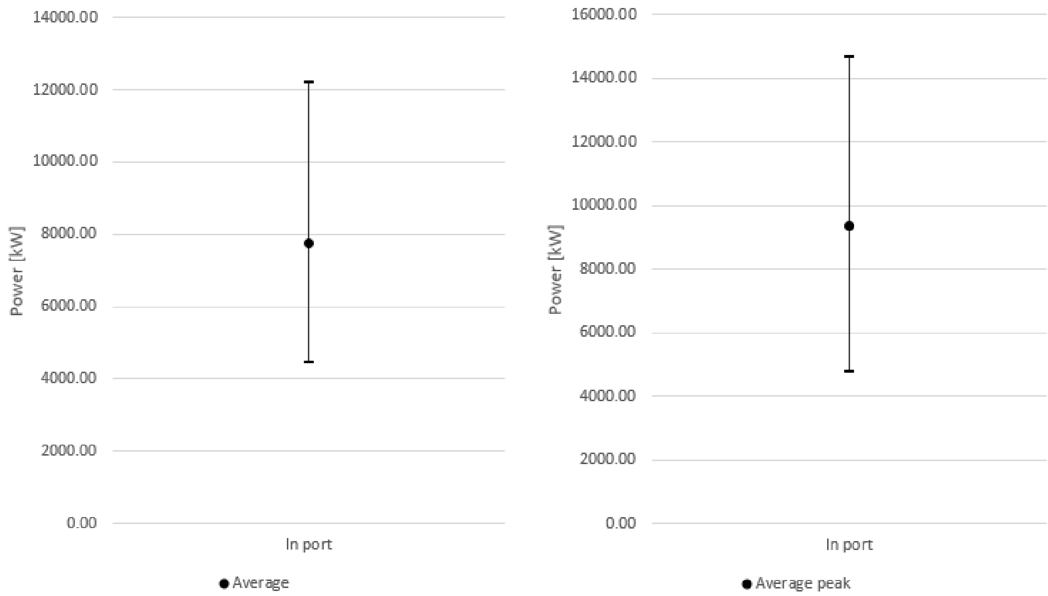
(a) Average power demand per project phase

(b) Peak power demand per project phase

Figure 4.5: Heavy lift projects - Average of the average power and peak power per project phase relative to the range of the used data points [kW]

4.3.3. In port

In order to get a complete overview also periods of time in port are investigated. In total 17 data moments are investigated and used for figure 4.6. Figure 4.6a reveals that on average the average power used in port is slightly less than 8 MW with peaks up to almost 10 MW.



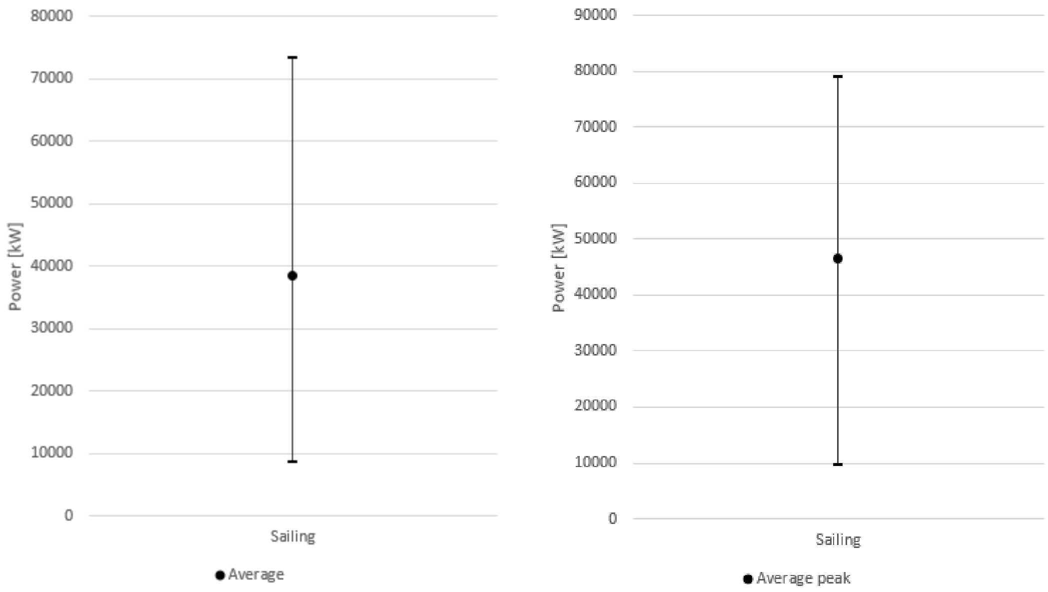
(a) Average power demand

(b) Peak power demand

Figure 4.6: In port - Average of the average power and peak power per project phase relative to the range of the used data points [kW]

4.3.4. Sailing

Lastly also 18 data moments of sailing between ports are investigated. This are transits where the ship was not on a project. Figure 4.7 reveals that the range of average power demand is large, with a minimum of less than 10 MW and a maximum around 75 MW. This difference is mainly depending on the sailing speed and weather conditions.



(a) Average power demand

(b) Peak power demand

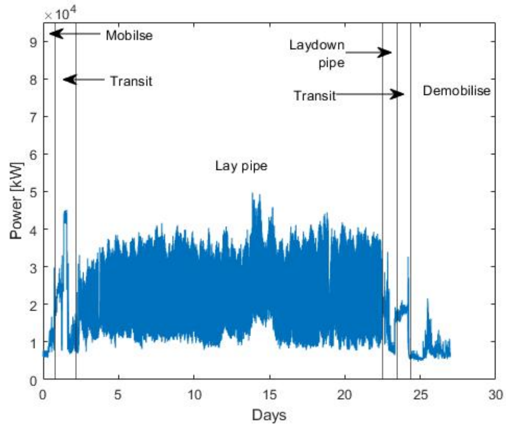
Figure 4.7: In port - Average of the average power and peak power per project phase relative to the range of the used data points [kW]

4.4. Full projects

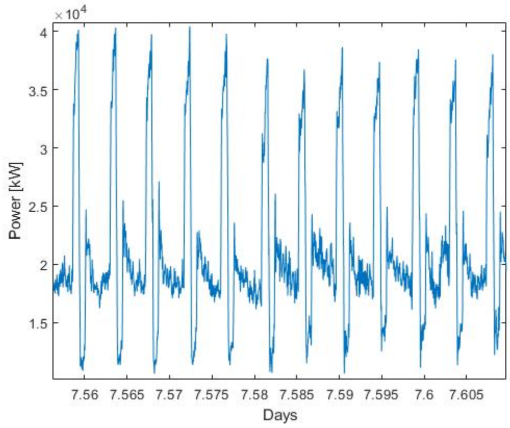
In section 4.3 the values are based on snapshots of the full projects. To make sure no peaks or other high power demanding periods are missing the choice is made to look also into full projects.

4.4.1. Pipelay

In figure 4.8a a full pipelay project is shown. On average a pipelay project takes over 80 days, which makes this with less than 30 days quite a short project. This figure reveals many short term variation in the power profile, which is shown in a detailed excerpt in figure 4.8b.



(a) Total power demand



(b) Total power detailed excerpt

Figure 4.8: Pipelay Project

Additionally to the variation in the power profile, figure 4.8a shows a transit period at the beginning of the project which has for a longer time a higher power demand. During the design phase of the new power generating system, this period can have an influence on the capacity of the system.

4.4.2. Heavy lift

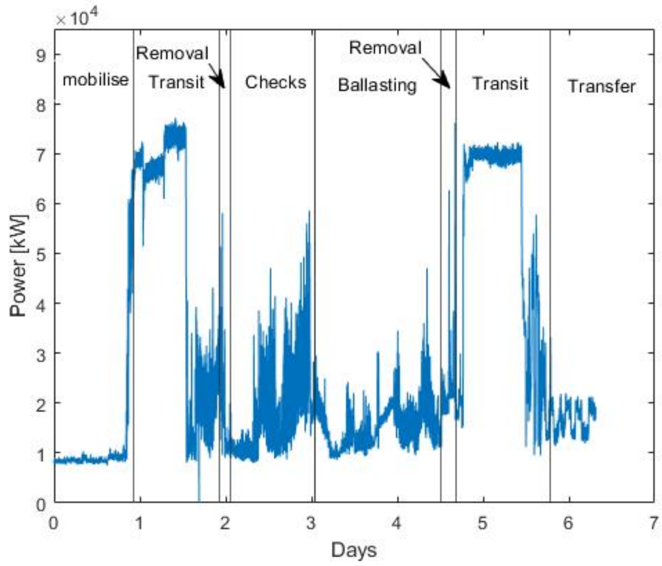


Figure 4.9: Heavy lift project - Total power

Figure 4.9 reveals that during the transits the power demand is high for long periods of time. As well as the peak during the second removal. The average power demand of the full project lays much lower

as the periods mentioned.
During the design phase of the new power generating system, especially the transit periods have a big influence on the size of the system.

4.4.3. In port

Figure 4.10 shows the power demand of the ship during a period of time in port. The maximum power demand during this time in port was round 30 MW, which is more than the harbour generator can deliver.

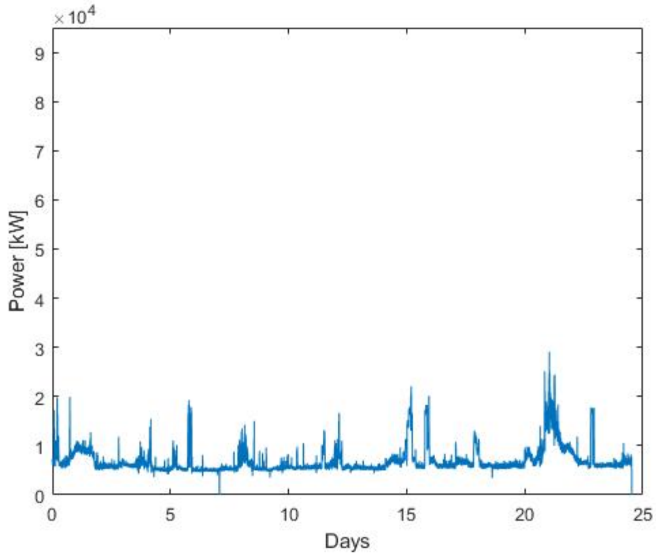
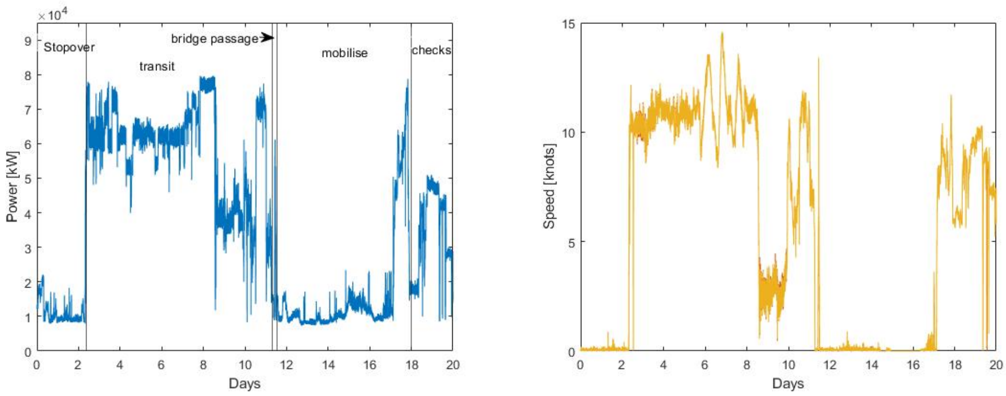


Figure 4.10: In port - Total power

4.4.4. Sailing

The power demand during a transit between ports is shown in figure 4.11a. The power demand is high for some long periods of time. The power demand during a transit is depending on the transit speed as well as the weather conditions.



(a) Sailing - Total power
(b) Vessel speed

Figure 4.11: Sailing - Total power with corresponding vessel speed

The power demand during the transit periods differs depending on the vessel speed. Figure 4.11 reveals the vessel speed corresponding with the transit period in figure 4.11a. For the average transit, the power consumption corresponding to a transit speed of approximately ten knots is assumed.

4.5. Yearly CO_2 production

Figure 4.1 revealed already a typical year for the Pioneering Spirit. Based on this typical year and the average power demand found in figure 4.4, 4.5, 4.6 and 4.7, the amount of CO_2 produced during the year is calculated. Note that the amount of days days in table 4.1 do not match with the typical year in figure 4.1, this is because the projects have also transit time and time in port which is in this table included in transit and in port.

Table 4.1: CO_2 production for the typical year

		Time [Days]	Average power [MW]	CO_2 production [kg/sec.]	Total CO_2 production [Tonnes]	CO_2 percentage of the year [%]
Transit		68	69	12	69858	55
Pipelay	Peak	23	31	5	37187	29
	Average	111	16	3		
Heavy lift		19	15	3	4191	3
In port		145	8	1	16684	13
Total		365			127920	100

Figure 4.12 is used to determine the average time of the peak of a pipe pull. In table 4.1 difference is made between the peaks and the average power demand for the calculations of the CO_2 production during a typical year. On average the peaks have a duration of 1.32 minutes and between two peaks there are 5.16 minutes of average power. In total during a pipelay project 20% of the project is spent on peak power and 80% on average power. Since the average power demand is much lower than the peak power demand it has an influence on the CO_2 production during a pipelay project, which is the reason why the pipelay part is split up into peak and average.

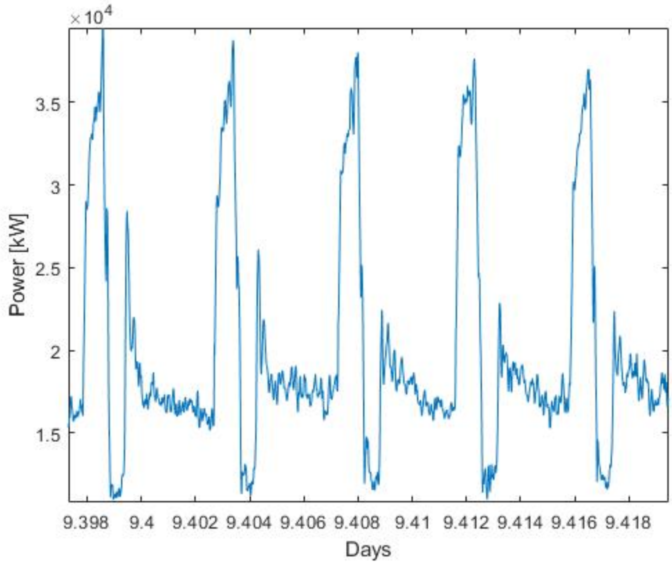


Figure 4.12: Pipelay project - pipe pull peaks

Table 4.1 reveals in addition to the amount of CO_2 produced during the typical year also how much each operation contributes to the total CO_2 production. The transit periods contributes over 50% to the total production of CO_2, because of the higher power demand during this periods.

4.6. Conclusion

The two operations on which most time is spend in the typical year are pipelay and in port. A pipelay project takes on average over 80 days, which is the main reason why it takes a large part of the year. Since a heavy lift project takes around nine days, the total time spent is much lower compared to a pipelay project. The time of 45 days spend on heavy lift projects in the typical year, therefore corresponds to approximately five heavy lift projects in this year.

From the average of the average power and the average peak power demand (figure 4.4, 4.5, 4.6 and 4.7) it becomes clear that during the different operations the power demand is fluctuating. During a pipelay project the sail to location phase is a high power demanding phase, but the difference between the average power and the peak power is not large. On the other hand, during the pipelay phase, there is a significant difference between the average power and the peak power demand. This can be clearly seen in figure A.10b.

For a heavy lift project the transit periods are the high power demanding periods. During a lift the difference between the average power demand and the peak power demand is the largest. Inspecting the full project power demand figure, the transit periods are distinguishable from the rest of the phases.

The periods of time the ship is in port it have a significant lower power demand as during the other operations. The main reason for this is that the ship does not need propulsion power so the power demand is for hotel load and the use of equipment on board for example the crane or lift systems.

From figure 4.6 it becomes clear that the average power demand is around 8 MW with peaks over 9 MW and a maximum peak of 15 MW, while in the full project plot of figure 4.10 these peaks are around 30 MW. A reason for the difference between these peaks can be that during the data collection of figure 4.6 snap shots of three hours are used and this peak is not including in one of these snap shots.

Lastly, sailing is investigated. During this operation the ship sails from one port to another not during a project. Figure 4.11a reveals that during this operation the power demand can fluctuate a lot within this period, since there is also mobilise time included in this period.

To meet the IMO requirements for the reduction of CO_2, a reduction of 70%, the periods in port, the heavy lift projects and the pipelay projects need to be done fully on the fuel cells. Since this will reduce the CO_2 emissions with less than 50% also a part of the transit periods need to be done on the fuel cells.

5 Design methodology

To make sure the calculations for the hybrid fuel cell system can be used for the entire Allseas, fleet a design methodology is written. The methodology caontains three parts and will help the user in making a choice concerning the capacity of the fuel cell and battery system. Figure 5.1 gives a global overview of the design methodology. In the first part data from past projects will be used to determine a total power demand, which will be used to calculate the total CO_2 production. In the next part power generating system solutions will be generated with varying fuel cell and battery capacities that are capable of supplying the energy needed for the subject operational mode. This will lead to different solutions and a comparison need to be made between the different solutions. After the comparison a optimal fuel cell size and battery capacity will be found. This optimum is the solution with the highest CO_2 reduction while the fuel cells are as small as possible but are able to charge the batteries during the project if needed. All calculations will be done with the use of Matlab.

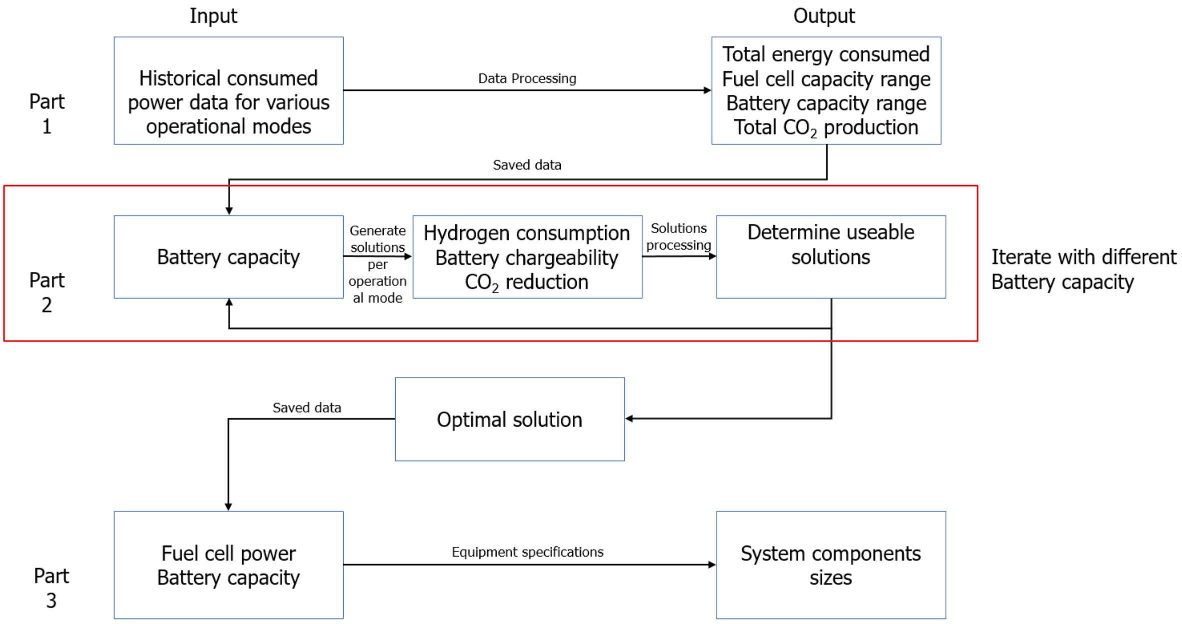


Figure 5.1: Global overview of the design methodology

5.1. Part 1: Data importing

In the first part of the design methodology the data will be imported and processed. First a few input parameters need to be filled in, subsequently the data will be generated, processed and used to calculate the power demand during the period of time, total CO_2 production as well as a range for the fuel cell size and battery capacity which will be used for further calculations.

5.1.1. Data input

The input parameters for first part of the design methodology are:

- Vessel abbreviation
- Parameter id's generators
- Start date and time
- End date and time
- Total installed power [kW]
- CO_2 production per generator [g/kWh]
- Installed power one generator [kW]

5.1.2. Data processing

After changing the input parameters, the data on the power generation of each generator will be imported to the Matlab model. The first step in processing the data is interpolating the data, which will be done with the Matlab function interp1. The data sets will be interpolated because the sets do not have all the same length and in order process them further it is necessary that all data sets have the same length. After interpolating the data sets there is a data point for every second over the period of time chosen as input parameter. The interpolated generator data sets will be summed up to determine the total power demand during the period of time (figure 5.2). The total power demand is used to calculate the CO_2 production during the time period by multiplying it with the input parameter CO_2 production per generator.

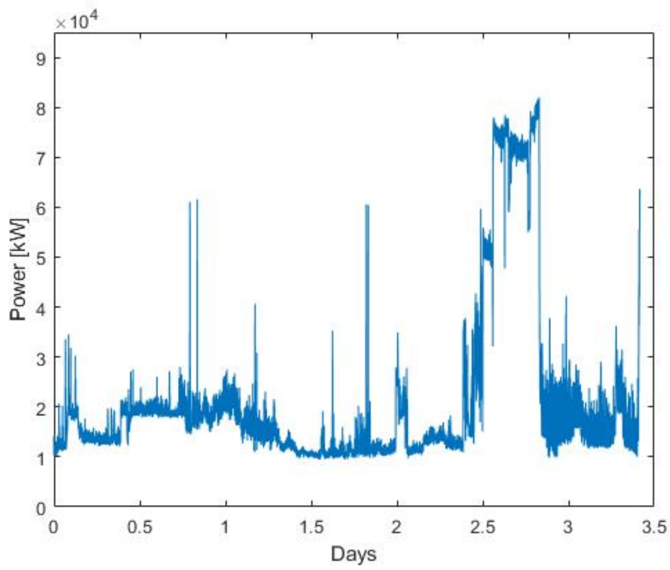


Figure 5.2: Total power demand

To get a insight in the usage of the installed power, a histogram is generated. The histogram, figure 5.3a, reveals the percentage of data points and thus the percentage of time spent on each MW power demand. In addition a figure is generated which shows the percentage of data point which can be covered per MW power (figure 5.3b).

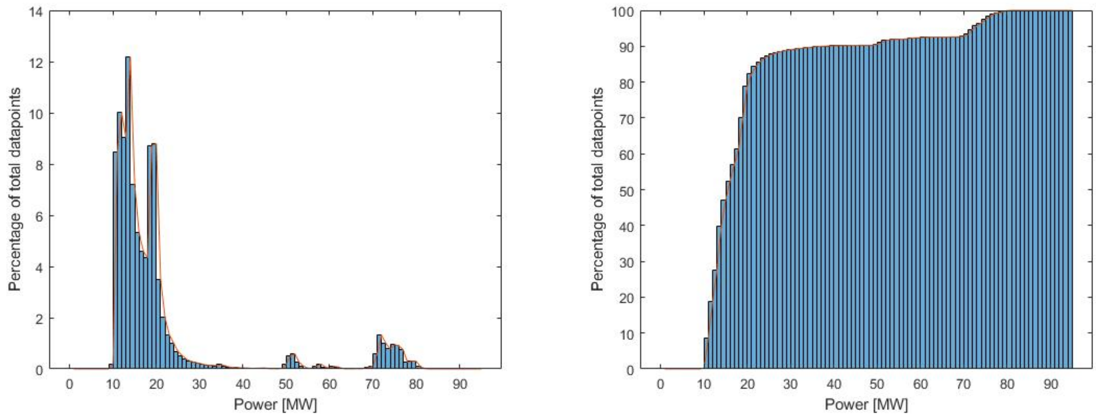


Figure 5.3: Data processing

5.1.3. Fuel cell and battery range

The second part of the design methodology will calculate the hydrogen consumption, CO_2 reduction and the chargeability of the batteries over a range of fuel cell capacities. To determine the start value of this range of fuel cell capacities the mean of the total power demand is used. The choice is made to not start at zero, because no usable solutions will be generated keeping in mind the target of 70% CO_2 reduction. The reason for this is that during the project all power need to be generated by the fuel cells. The only energy not provided by the fuel cells is the energy stored in the batteries at the beginning of the project, since the assumption is made that the batteries are fully charged at the beginning of the project. Thus to shorten the calculation time solutions will be generated for a range of fuel cell capacities beginning at the mean power demand during the project.

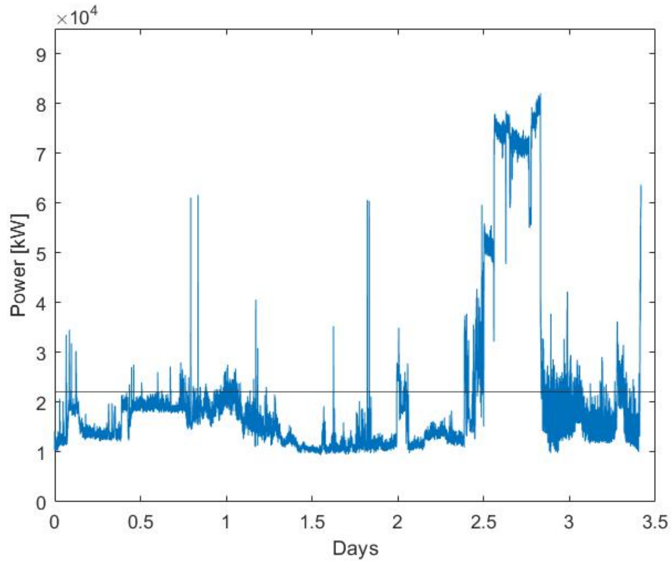


Figure 5.4: Mean power demand - Minimum fuel cell size

In chapter 3 the choice was already made to work with batteries which have a 3C-rate. The batteries will not only be used for peak shaving, but also as a spinning reserve in case of an emergency. For that reason, the batteries must be able to deliver the same amount of power as one of the generators. Therefor, the minimum battery capacity will be 1/3 of the power which one generator can deliver. To be on the safe side the capacity is round up to whole MWh.

$$Minimum\ battery\ capacity = one\ generated\ (round\ up) \cdot \frac{1}{3} \tag{5.1}$$

The maximum fuel cell size in the range is the maximum power demand after subtracting three times the minimum battery capacity.

$$Maximum\ fuel\ cell\ size = maximum\ power\ demand - minimum\ battery\ capacity \cdot 3 \tag{5.2}$$

The maximum power demand is used again to determine the maximum battery capacity in the range. By subtracting the minimum fuel cell range value from the maximum power demand and multiplying it with 1/3.

$$Maximum\ battery\ capacity = (maximum\ power\ demand - minimum\ fuel\ cell\ size) \cdot \frac{1}{3} \tag{5.3}$$

5.1.4. Outcome

The following output values will be generated in part 1 of the design methodology:

- The total power demand [kW]
- Total CO_2 production of the project with current power generating system [kg]
- The fuel cell size range [MW]
- The battery capacity range [MWh]

Part 1 of the design methodology will generate the following plots:

- Total power consumption over time
- Histogram of power demand
- Cumulative histogram of power demand
- Minimum fuel cell size

5.2. Part 2: Solution generation

In this second part different solutions will be generated. During this process iterations will be done with different battery capacities. After generating solutions a comparison will be made to find the optimal solution.

Data input

From the first part the following output will be used in as an input parameter for the second part:

- The total power demand [kW]
- Total CO_2 production of the project with current power generating system [kg]
- The fuel cell size range [MW]

The following new input parameters are needed for the second part of the design methodology:

- Total installed power [kW]
- CO_2 production per generator [g/kWh]
- Battery power [kWh]

5.2.1. Step 1: Generating different solutions

During this first step solutions will be generated for the different operational modes. For some projects it can be beneficial if the project can be performed fully without emissions, which is the reason why solutions will be generated for the different operational modes and not over a whole year.
The solutions for the different operational modes, except for the transit periods, must meet the following requirements:

- The fuel cells need to be able to charge the batteries during the project.
- The fuel cells and batteries must be able to deliver the total power demand during the period.
- The CO_2 reduction during this periods need to be 100%.

For the transit periods the batteries will not be used and so the fuel cells will be supplemented by the generators. The fuel cell need to deliver enough power to make sure the overall CO_2 reduction during the year is 70% CO_2.

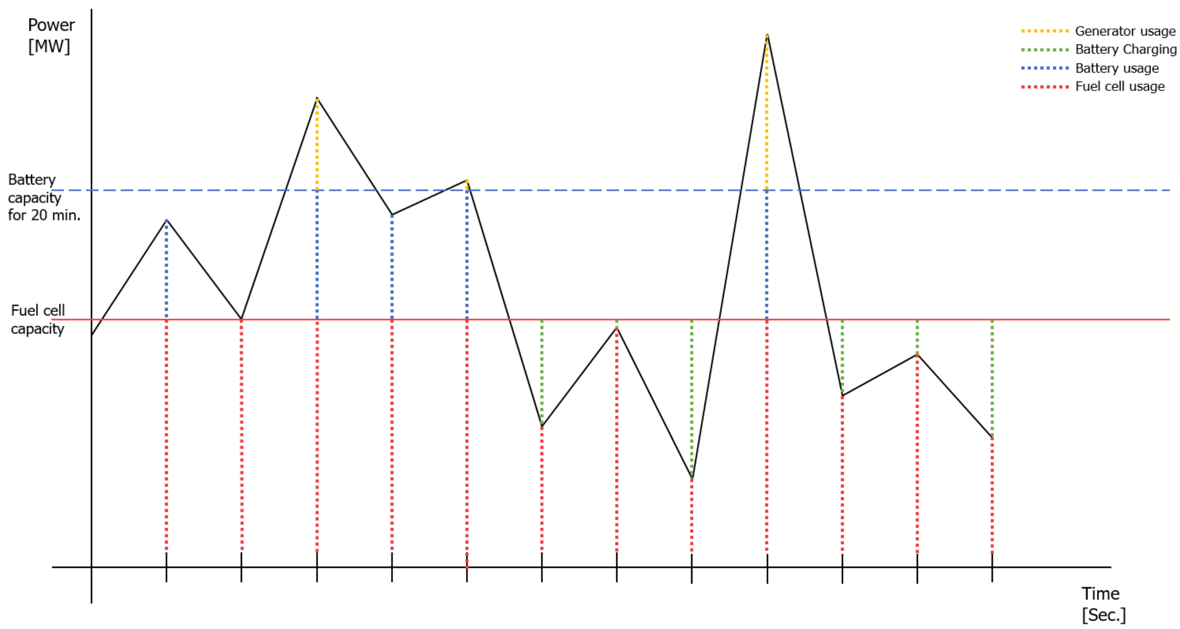


Figure 5.5: Example of how the Matlab code works with minimum fuel cell power

In figure 5.5 an example is giving of how the Matlab model looks at the data. In this example the starting value of the fuel cell range is used. Figure 5.6 shows the steps the Matlab model will follow.
For every data point, so every second, the model will first look what the power demand is. First as much power as possible will be provided by the fuel cell if there is more power demand than the fuel cell can deliver the battery will be used and if that is even not enough the rest of the power demand will be provided by the generator. During this process it will be registered at which percentage of the installed power the fuel cell runs, since this will influence the hydrogen consumption. In addition the battery usage will be registered to control the charging state of the battery. When the power demand is lower as what the fuel cell can deliver the battery will be charged if needed with the fuel cells. When the model will find a battery state of zero it will give the response that the batteries cannot be charged and will go to the next fuel cell size and does the same again with a higher fuel cell power. The battery capacity will stay the same during the run of the model and will later be changed during the iterations.

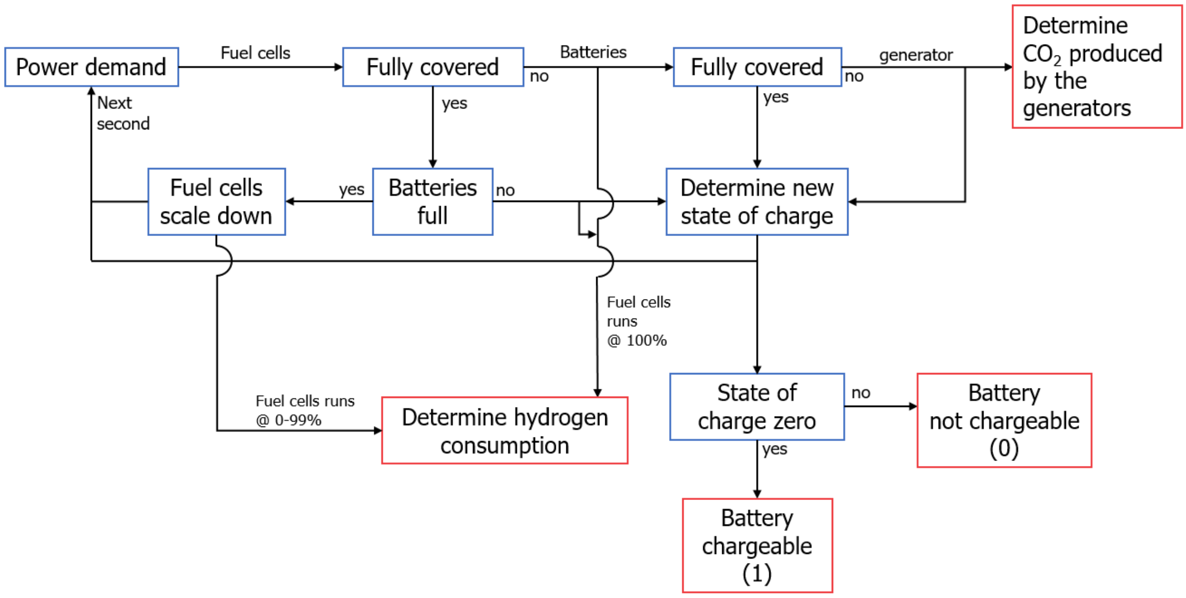


Figure 5.6: Flow chart of the working of the Matlab model

The red boxes in figure 5.6 are the output for every data point and will be combined as an output for every fuel cell capacity. A plot will be made form the output over the range of fuel cell capacities, which will be used in step 2 to determine suitable solutions.

Battery Chargeability

In order to check if the fuel cells are able to charge the batteries, the Matlab model will go over every data point in the total power demand set and first checks if the fuel cells are able to provide all power. When the power demand is higher as the capacity of the fuel cells the batteries will start to discharge. For this process the assumption is made that during the start of the project the batteries are completely charged. At the moment that the fuel cells cannot deliver enough power to meet the power demand the discharge of the batteries begins. After the first discharge the model will check what the charge state of the battery is after every data point. When the charge state becomes zero, it means that the fuel cells are not able to charge the batteries enough during the project and the model will go on to the next part of the calculations for this fuel cell size. This will be done for all the fuel cell sizes in the range and results in a figure as shown in figure 5.7. In this figure zero means that the fuel cells are not able to charge the batteries and one means that it is possible.

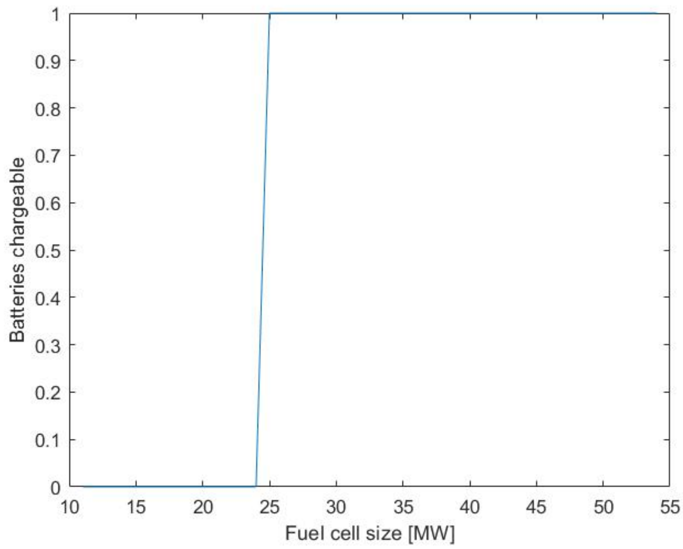


Figure 5.7: Battery chargeability over the fuel cell range

Hydrogen consumption

After checking the battery state of charge, the hydrogen consumption of the fuel cells will be calculated. The Matlab model will use again the total power demand of the project. It will check if the total power demand is higher or lower than the fuel cell capacity. When the power demand is higher it means that the fuel cell needed to provide full power and so is running on 100%. If it is less than the power demand calculations will be done on which percentage the fuel cell is running of it total power. Corresponding to the percentage of the fuel cell power the hydrogen consumption is known. For example when the fuel cell is running on full power is consumes 0.065 kg/kWh, but when it running on 50% of its power it consumes only 0.03 kg/kWh. For every fuel cell size in the range the total hydrogen consumption will be determined by looking at how often the fuel cell runs on which percentage of its total power and multiplying it to the corresponding hydrogen consumption parameter. An example of the results are shown in figure 5.8.

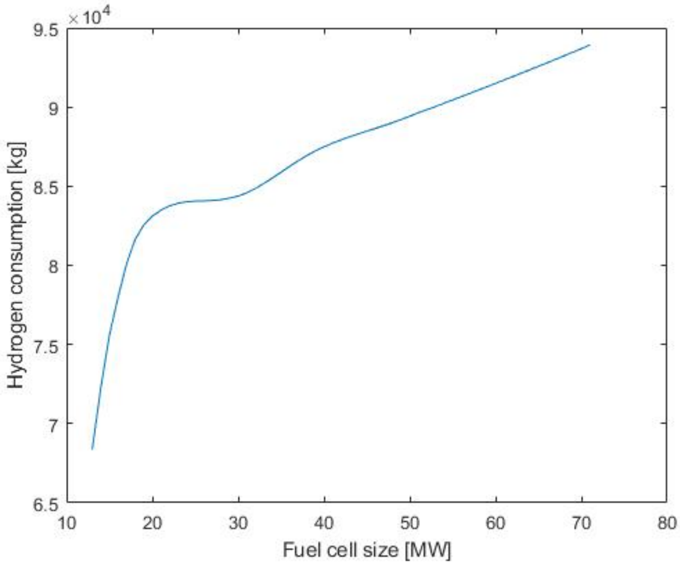


Figure 5.8: Hydrogen consumption

CO_2 reduction

Lastly in this part the CO_2 reduction will be calculated. The total power demand is also used for these calculations. From the total power demand is the power delivered by the fuel cell and the batteries deducted. The power demand that is over and thus need to be delivered by the generators is multiplied by the CO_2 production rate of the generators. This is the produced CO_2 during the project with the fuel cells and batteries implemented. Figure 5.9 reveals an example of the outcome over the fuel cell range.

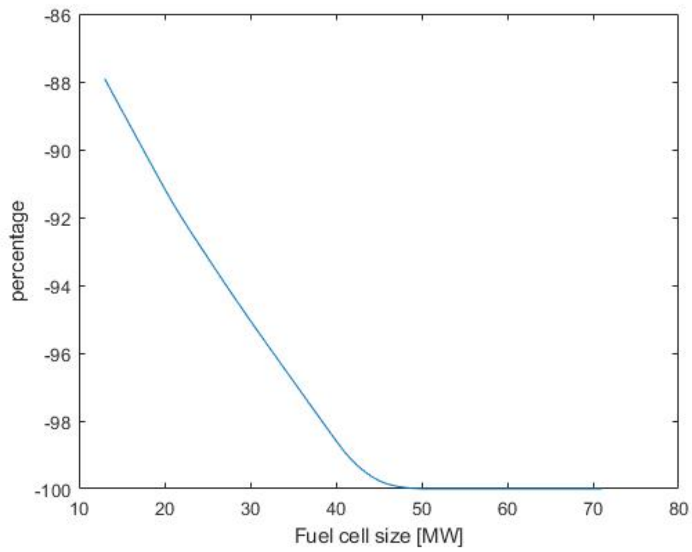


Figure 5.9: CO_2 reduction

Outcome

The first step from part 2 of the design methodology will generate the following plots which will help the user find suitable solutions in the step 2:

- Hydrogen consumption over the fuel cell range
- CO_2 reduction over the fuel cell range
- Battery chargeability over the fuel cell range

Before going to the next step of this second part the first step will be iterated with different battery capacities.

5.2.2. Step 2: Suitable solutions

After generating solutions during step 1 in this second step the suitable solutions will be defined as solutions which meet the following requirements:

- The fuel cells need to be able to charge the batteries during the project.
- During the different operational modes, except for transits, the batteries and fuel cells together deliver enough power to meet the power demand, which results in a 100% CO_2 reduction.

All solutions will be processed as the example in table 5.1. In this table the transits periods are taken into account during the calculation of the hydrogen consumption and the CO_2 production.

Table 5.1: Example of solution processing

	Fuel cell power [MW]	Battery capacity [MWh]	hydrogen consumption [tonnes]	CO_2 production [tonnes]
Solution 1				
Solution 2				
Solution 3				

5.2.3. Step 3: Optimal solution

After processing, the solutions will be compared with each other to find the optimal solution. The optimal solution has to meet the following requirements:

- The overall CO_2 reduction need to be at least 70%.
- Except for the transit periods the operational modes are emissions free.
- The batteries will not be used during transits the fuel cells need to be big enough to reduce the CO_2 emissions with 70%.
- The batteries will be implemented for peak shaving and as a spinning reserve and thus the battery capacity will not be greater as the fuel cell capacity.

Taking into account all these criteria an optimal configuration can be found.

5.3. Part 3: New system specifications

After choosing the capacity of the fuel cells and the batteries, in this last part of the design methodology first a final check will be done to make sure the new power generating system has enough power to meet the power demand. In addition, a check will be done to confirm that the fuel cells are able to charge the batteries during the operation if needed. If the checks are fulfilled, this last part will calculate the size of the new system.

5.3.1. Data input

The input parameters for the third part of the design methodology:

- Total installed power [kW]
- Fuel cell power [kW]
- Battery capacity [kWh]
- Days between bunkering

5.3.2. Checks

First two checks are done before the model calculates the components of the new power generation system. Figure 5.10 gives the results of the first check which is the check if all data points can be covered with the chosen size for the fuel cells and batteries. In this figure, the horizontal line battery capacity is the power the batteries can deliver for a hour. The short term battery capacity is the capacity which the batteries can deliver with its 3C-rate. Therefor, the power batteries can deliver for 20 minutes.

If not all points can be covered by the fuel cells and batteries the model will return an error which says: " Error using battery_charging (line 9) NOT POSSIBLE SYSTEM IS TO SMALL". When this error occurs the capacity of the total system needs to be increased until it stops showing.

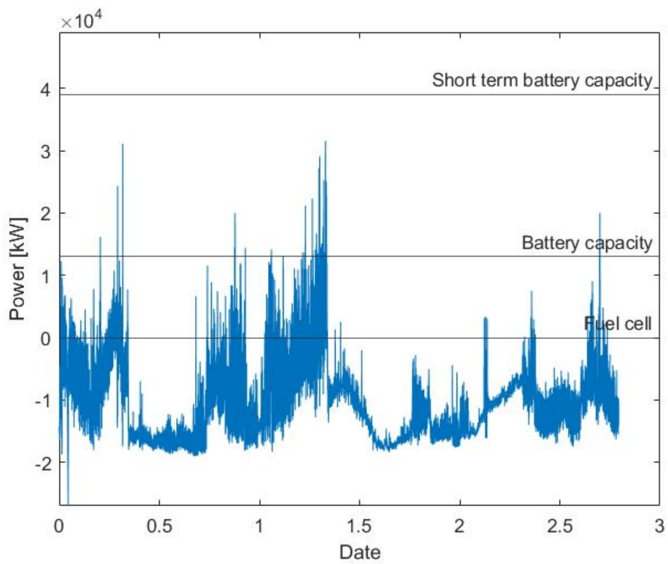


Figure 5.10: Pipelay project - Check if all data points can be covered by the fuel cells and batteries

The second check is if the batteries can be charged enough during the project to makes sure the generators are not needed to charge the batteries during these periods. Figure 5.11 the charging state of the batteries are shown over the time. When the charging stage goes on to zero it means that the batteries are not able to deliver the power needed during that moment in time. If this is the case an error will occur as well which says: "Error using battery_charging (line 63) NOT POSSIBLE BATTERIES CAN NOT BE CHARGED ENOUGH". The solution to this problem is to either increase the fuel cell power or to increase the battery capacity so it discharged slower.

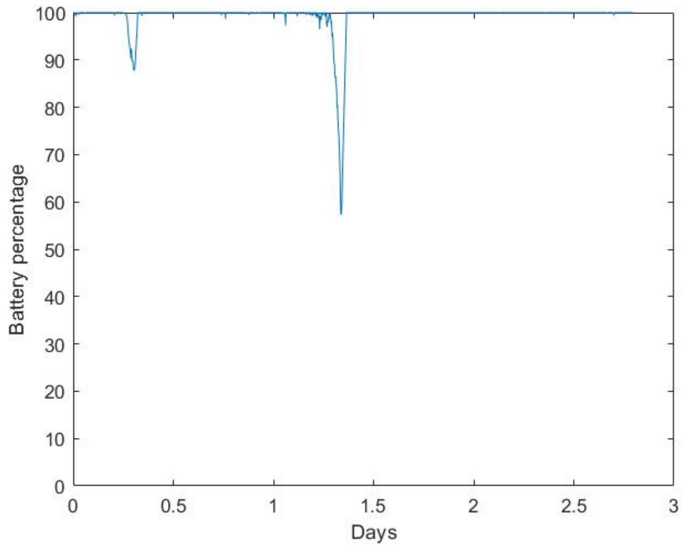


Figure 5.11: Pipelay project - The charging stage of the battery during the project

5.3.3. Outcome

After all the checks are passed the model will use the information given in chapter 3 to calculate the components for the new power generation system. The following list with output is given:

- Number of 200 kW fuel cell stacks needed
- Total surface space needed for the fuel cell stacks [m^2]
- Total volume needed for the fuel cell stacks [m^3]
- Total hydrogen consumption [tonnes]
- Hydrogen consumption between bunkering [tonnes]
- Amount of times bunkering is needed during the project
- Total water generation [tonnes]
- Air flow rate needed [$Nm^3/hour$]
- External coolant flow [NL/min]
- Number of 249 kWh battery packs needed
- Total surface space needed for the battery packs [m^2]
- Total volume needed for the battery packs [m^3]
- Total volume needed for hydrogen storage full project [m^3]
- Volume needed for hydrogen when bunkering is needed during the project [m^3]

6 Pioneering Spirit case

During this chapter, the design methodology from chapter 5 is used to design a new hybrid power generation system for the Pioneering Spirit. The information found in chapter 2 and 4 will be used during the case.

6.1. Part 1: Data importing

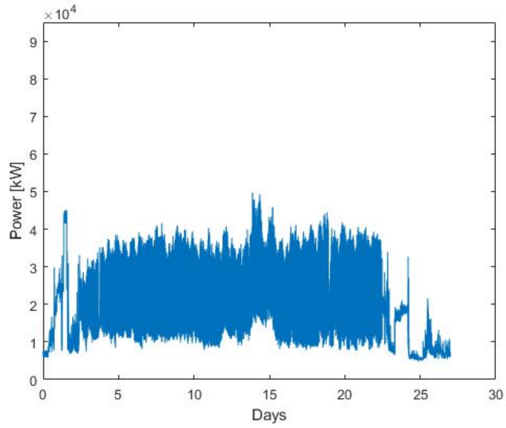
For the first part of the design methodology in total six projects will be investigated, two pipelay projects, two heavy lift projects, a transit period between two different ports not under project and a period of time in the port not under project are imported.

6.1.1. Data input

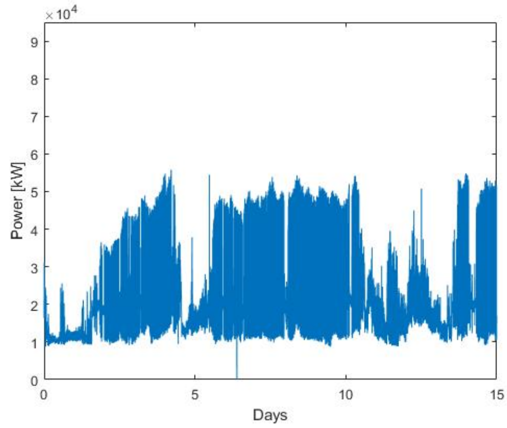
The input parameters total installed power, CO_2 production per generator and installed power one generator can be found in table 2.2.
As mentioned before, in total six projects will be investigated. For five projects the full projects are used and for pipelay project 2 are 15 consecutive days used, since this project took over two months. The choice is made to work with projects instead of a whole year, because during the work time on for example a heavy lift project it can be beneficial if this period can be done without emissions. For this reason first the different projects will be optimised before looking back at the typical year to see if the target of 70% will be met.

6.1.2. Data processing

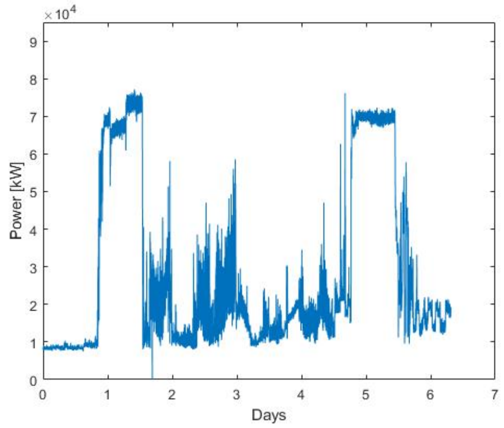
First for all the different projects the total power demand is plotted in figure 6.1. The figure reveals that during the heavy lift projects and the transit between ports the vessel has the highest power demand. During the heavy lift projects are the transit periods the high demanding periods, only during heavy lift project 1 there is a high peak around a lift.



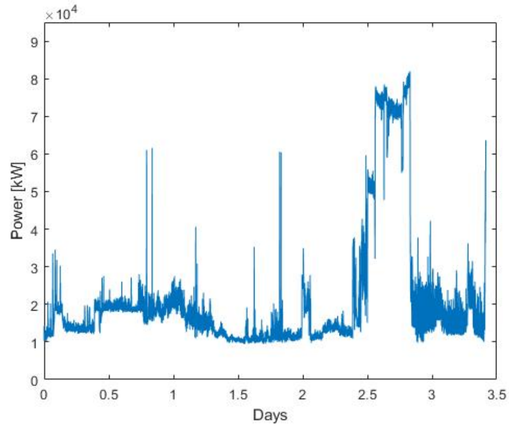
(a) Pipelay project 1



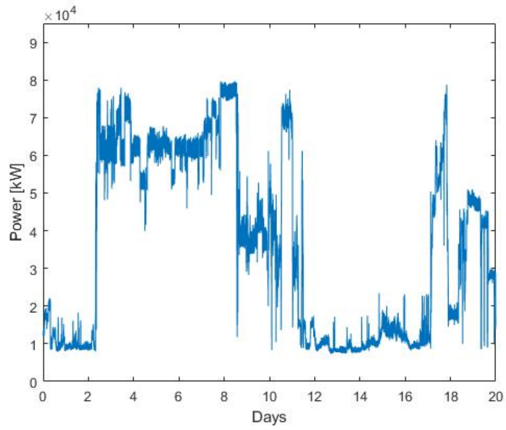
(b) Pipelay project 2



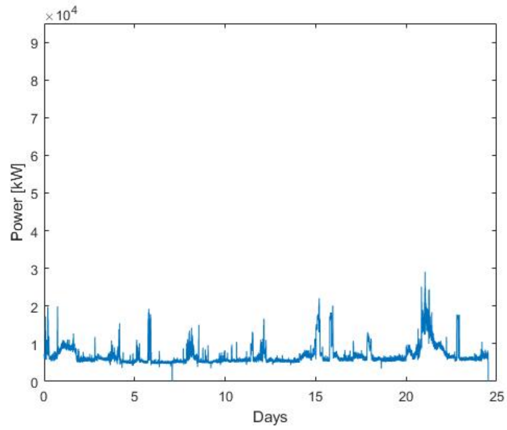
(c) Heavy lift project 1



(d) Heavy lift project 2



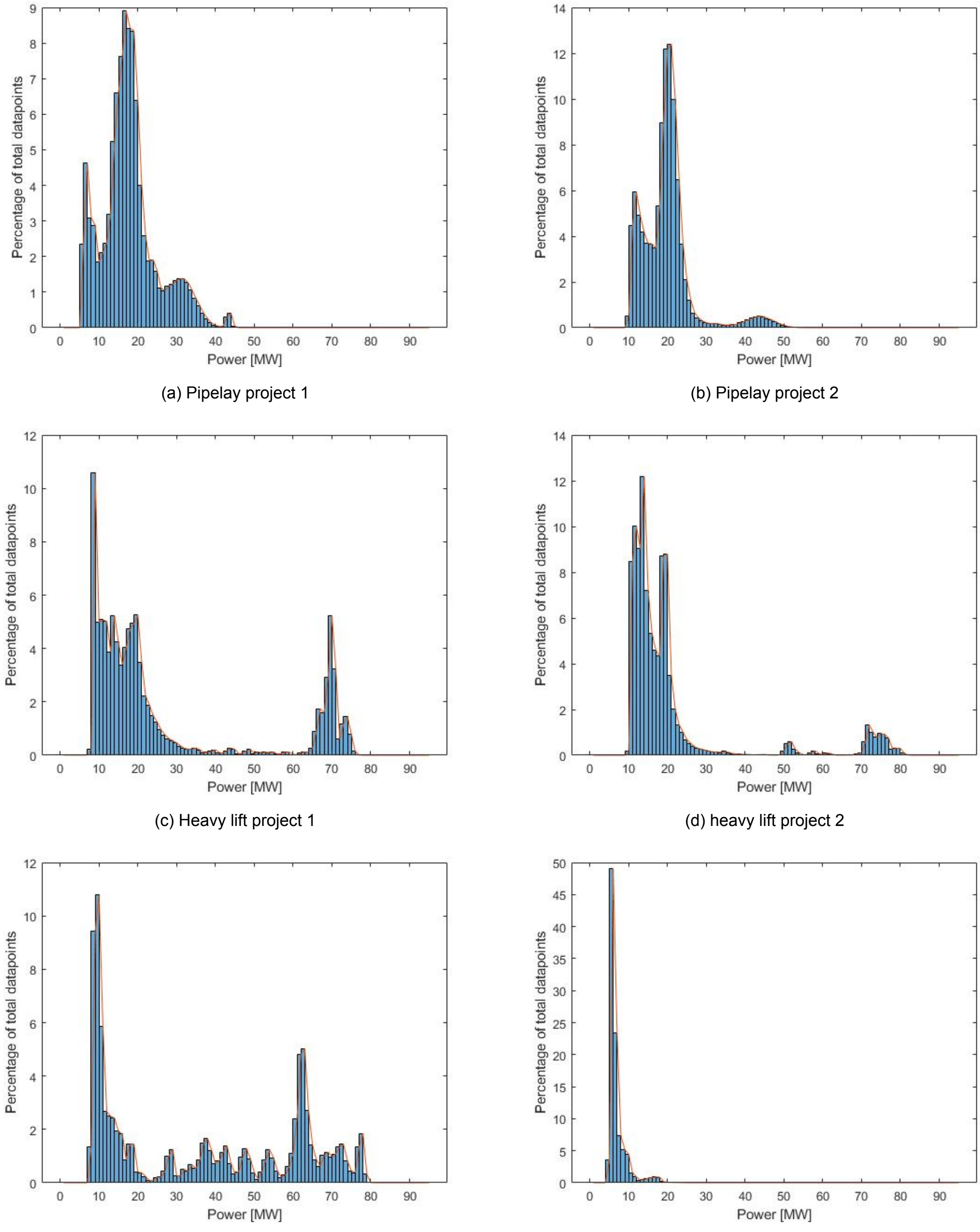
(e) Transit between ports



(f) Period in port

Figure 6.1: Total power demand

After determining the total power demand of the projects, figures 6.2 and 6.3 are generated. Figure 6.2 reveals that the vessel uses only around 1/3 of the installed power on board during the projects.



(a) Pipelay project 1

(b) Pipelay project 2

(c) Heavy lift project 1

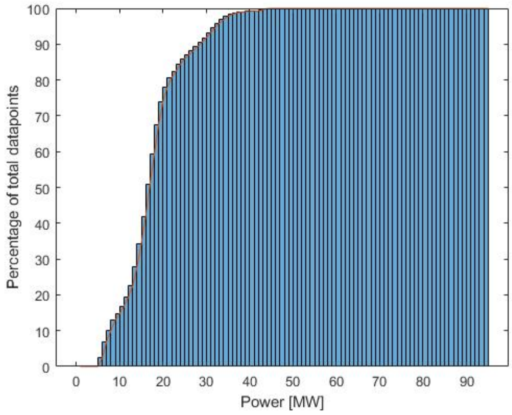
(d) heavy lift project 2

(e) Transit between ports

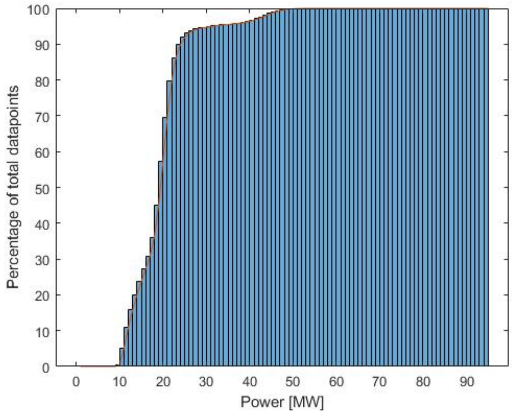
(f) Period in port

Figure 6.2: Histogram - The amount of data points per power [MW]

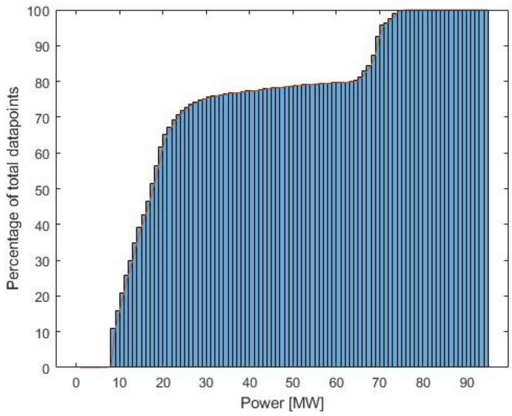
From the figures in figure 6.3 it becomes clear at which fuel cell size the full project can be done on only fuel cell power. Only the period in port can already be fully done with fuel cell smaller than 20 MW. All the other projects much more than 20 MW.



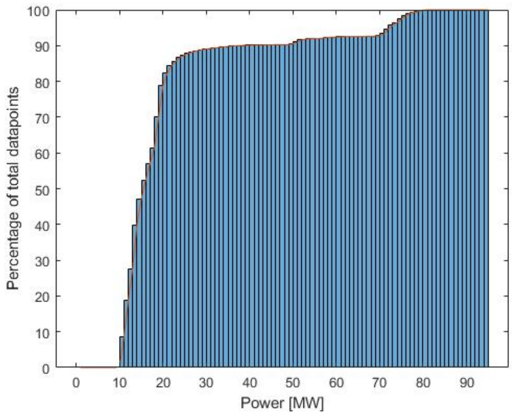
(a) Pipelay project 1



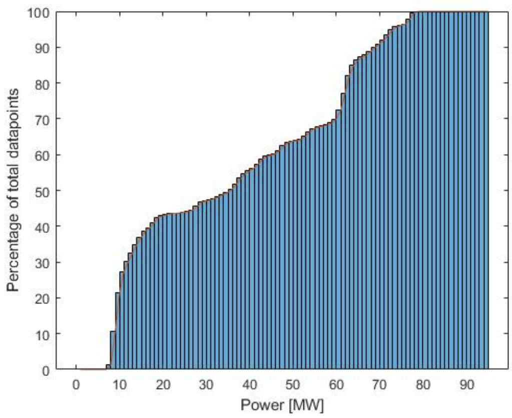
(b) pipelay project 2



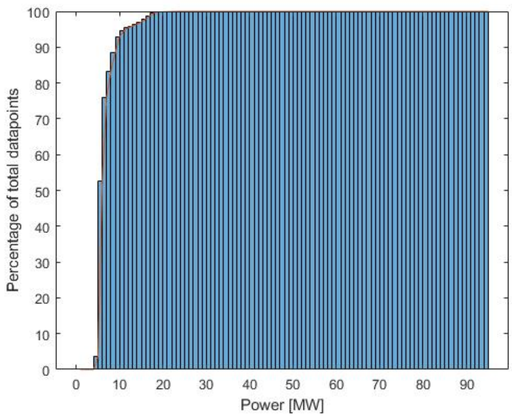
(c) Heavy lift project 1



(d) Heavy lift project 2



(e) Transit between ports

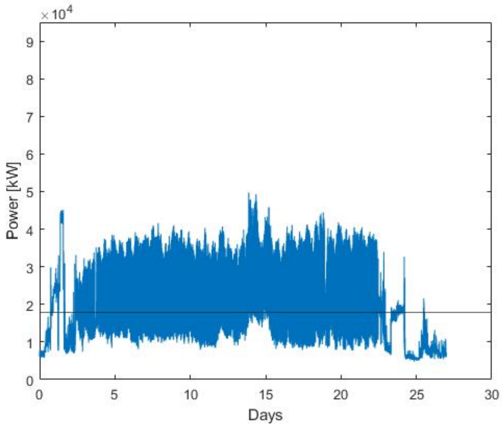


(f) Period in port

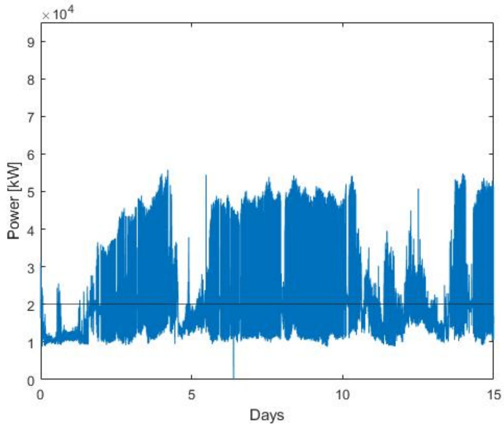
Figure 6.3: Cumulative histogram - Percentage of data points covered

6.1.3. Fuel cell and battery range

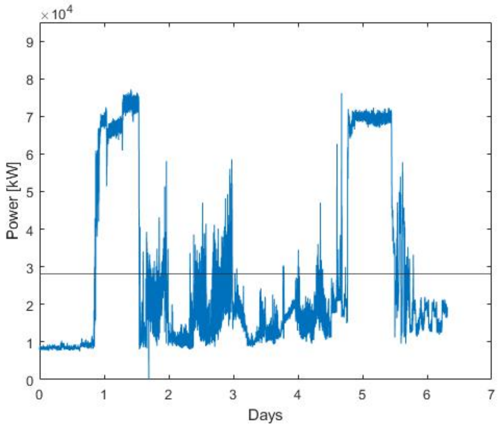
The total power demand plots from figure 6.20 are used to determine the start value of the fuel cell range over which different solutions will be generated. The start value of the range will be the mean power demand during the project.



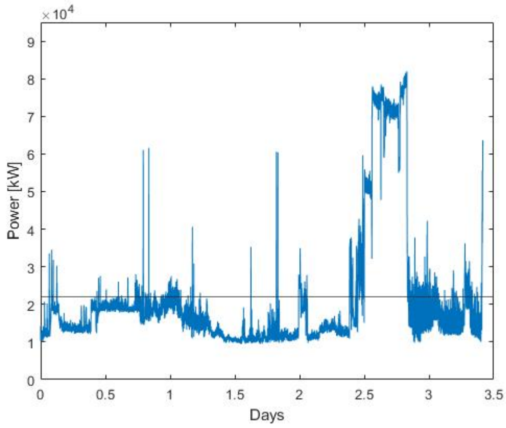
(a) Pipelay project 1



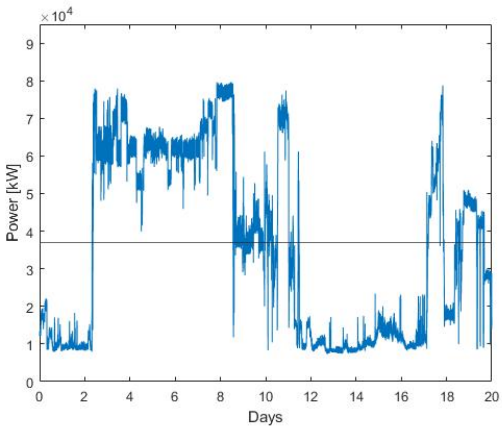
(b) Pipelay project 2



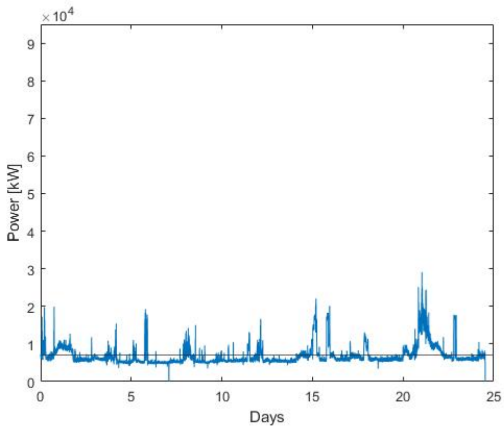
(c) Heavy lift project 1



(d) Heavy lift project 2



(e) Transit between ports



(f) Period in port

Figure 6.4: Determining minimum fuel cell range

As mentioned in chapter 5 the minimum battery capacity depends on the power of one of the installed generators, which is 11,2 MW for the Pioneering Spirit. Combining this information with the battery 3C-rate property, the minimum battery capacity will be 4 MWh.

$$Minimum\ battery\ capacity = 12000 \cdot \frac{1}{3} = 4\ MWh \tag{6.1}$$

The maximum fuel cell size in the range is the maximum power demand of the project after subtracting 3 times the minimum battery power. For the maximum battery capacity of the range the minimum fuel cell power is subtracted from the total power demand and subsequently divided by three.
The result of the range calculations for the different projects are revealed in table 6.1. These ranges will be used as input for the second part of the design methodology.

Table 6.1: Fuel cell and battery range for the different projects

	Range fuel cells [MW]	Range batteries [MWh]
Pipelay project 1	18-38	4-11
Pipelay project 2	20-44	4-12
Heavy lift project 1	28-66	4-23
Heavy lift project 2	22-71	4-24
Transit between ports	37-68	4-24
Period in port	7-18	4-8

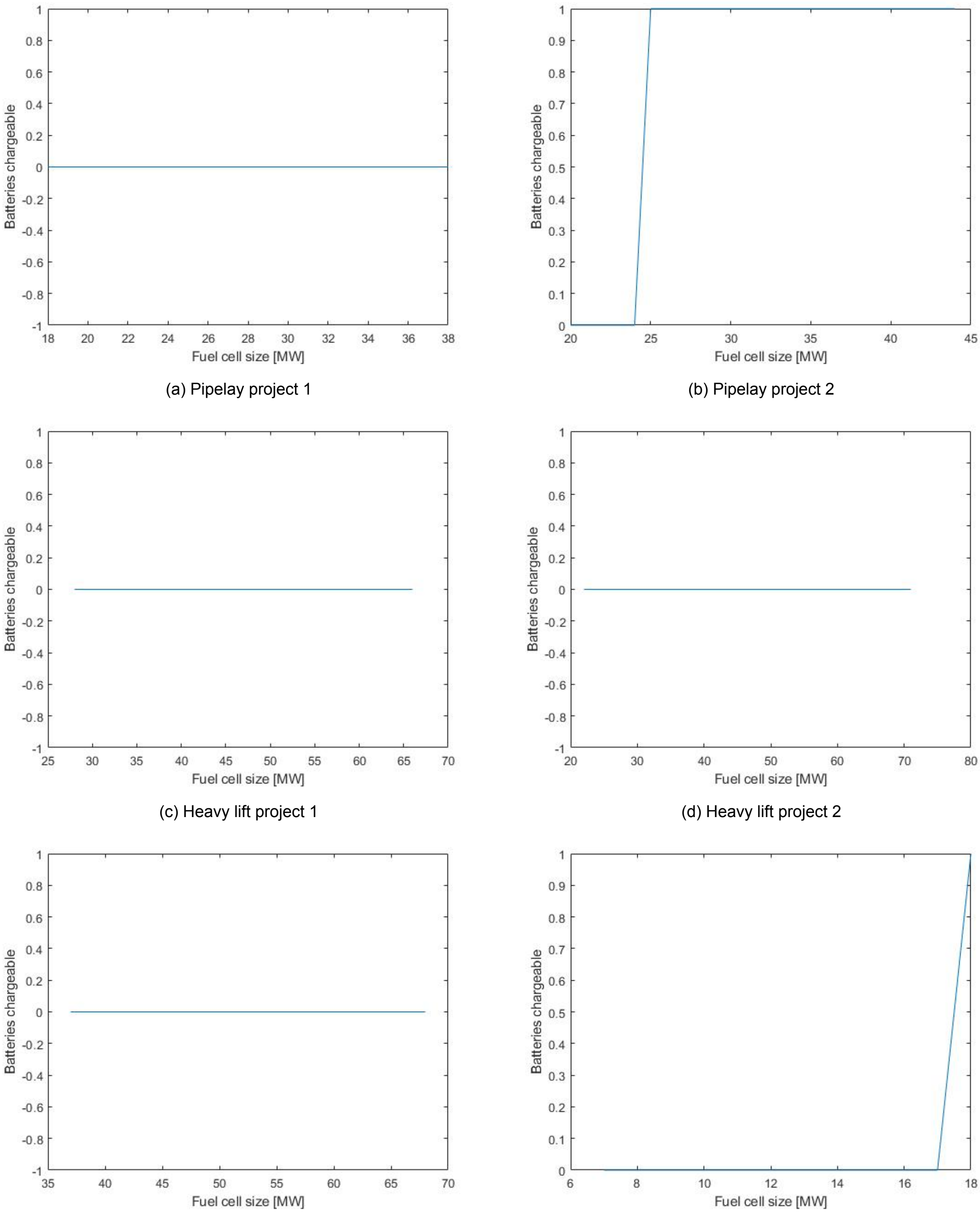
6.2. Part 2: Solution generation

For each iteration in this part of the design methodology the battery chargeability, CO_2 reduction and hydrogen consumption of the projects are plotted. The relevant plots are shown during the iterations, all other plots can be found in Appendix A.

6.2.1. Step 1

First iteration

During the first iteration a battery capacity of 4 MWh is used. Figure 6.5 reveal that even with the smallest battery size and the largest fuel cells size the fuel cells are not able to charge the batteries during the project.



(a) Pipelay project 1

(b) Pipelay project 2

(c) Heavy lift project 1

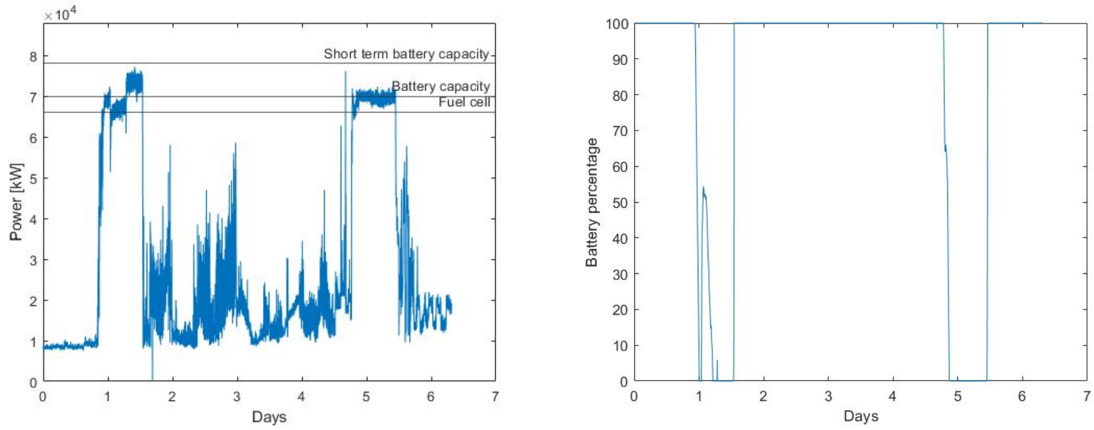
(d) Heavy lift project 2

(e) Transit between ports

(f) Period in port

Figure 6.5: Chargeability of the batteries

To find out why the fuel cells are not sufficient enough to charge the batteries, the total power and the battery stage over the project shown in figure 6.6. From sub-figure 6.6a it becomes clear that the total power generated in this configuration is theoretical enough to meet the power demand. However, sub-figure 6.6b reveals that during the transit periods the batteries will be totally discharged, because during the transit periods the power demand will not drop below the power generated by the fuel cell. Therefor, during these periods the fuel cells can not charge the batteries.



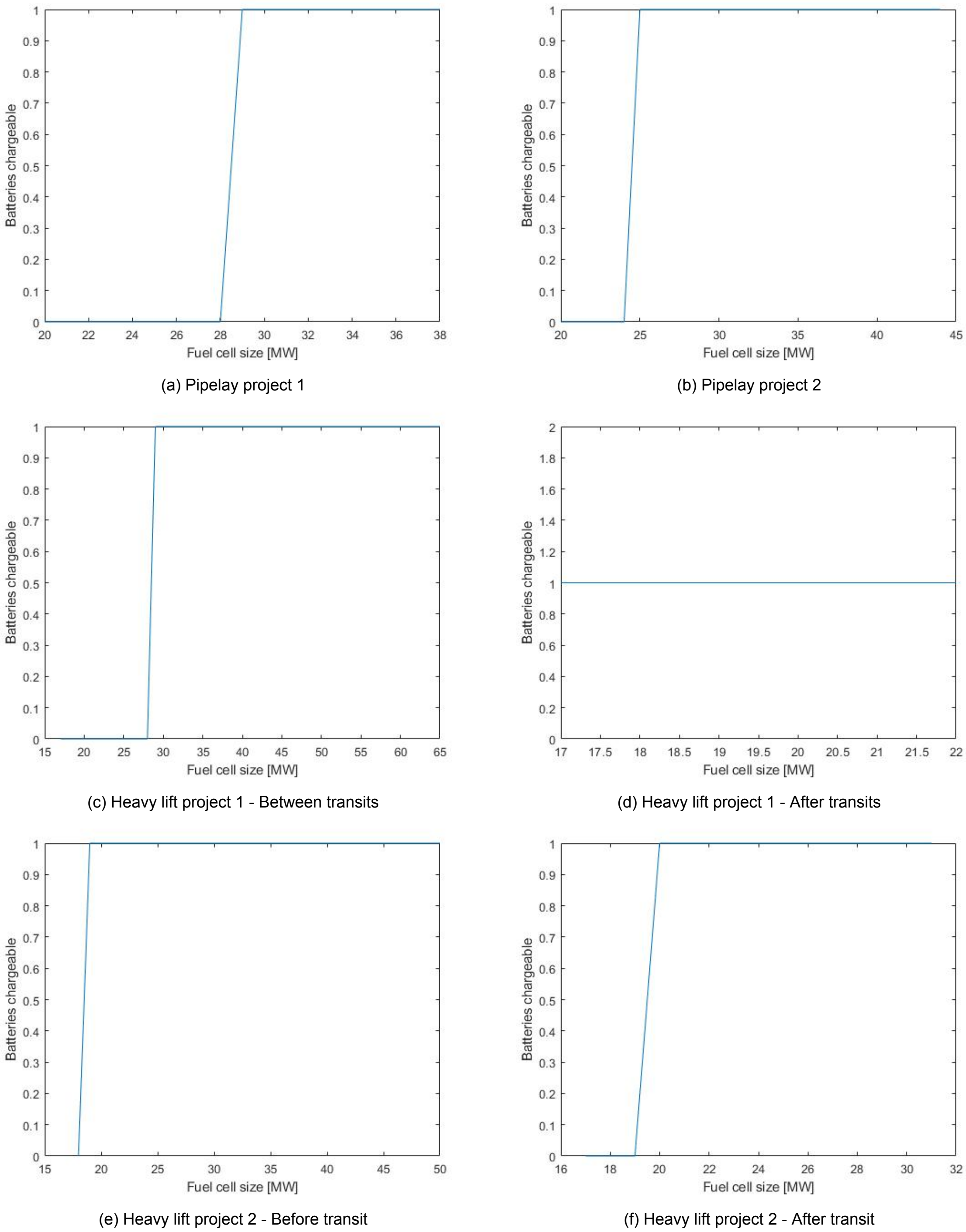
(a) Total power (b) Battery stage

Figure 6.6: Heavy lift project 1 - 66 MW fuel cells and 4 MWh batteries

In chapter 4 it was already determined that during the transit period the batteries will not be used and the fuel cells will be supplemented by the generators. To make sure the projects can be done fully on fuel cells and batteries, in the next iterations the transit periods are taken out of the projects. Also the period of time in port is not included in the upcoming iterations, since the fuel cell range is not greater as 18 MW all other ranges start from 18 MW minimum.

Second iteration

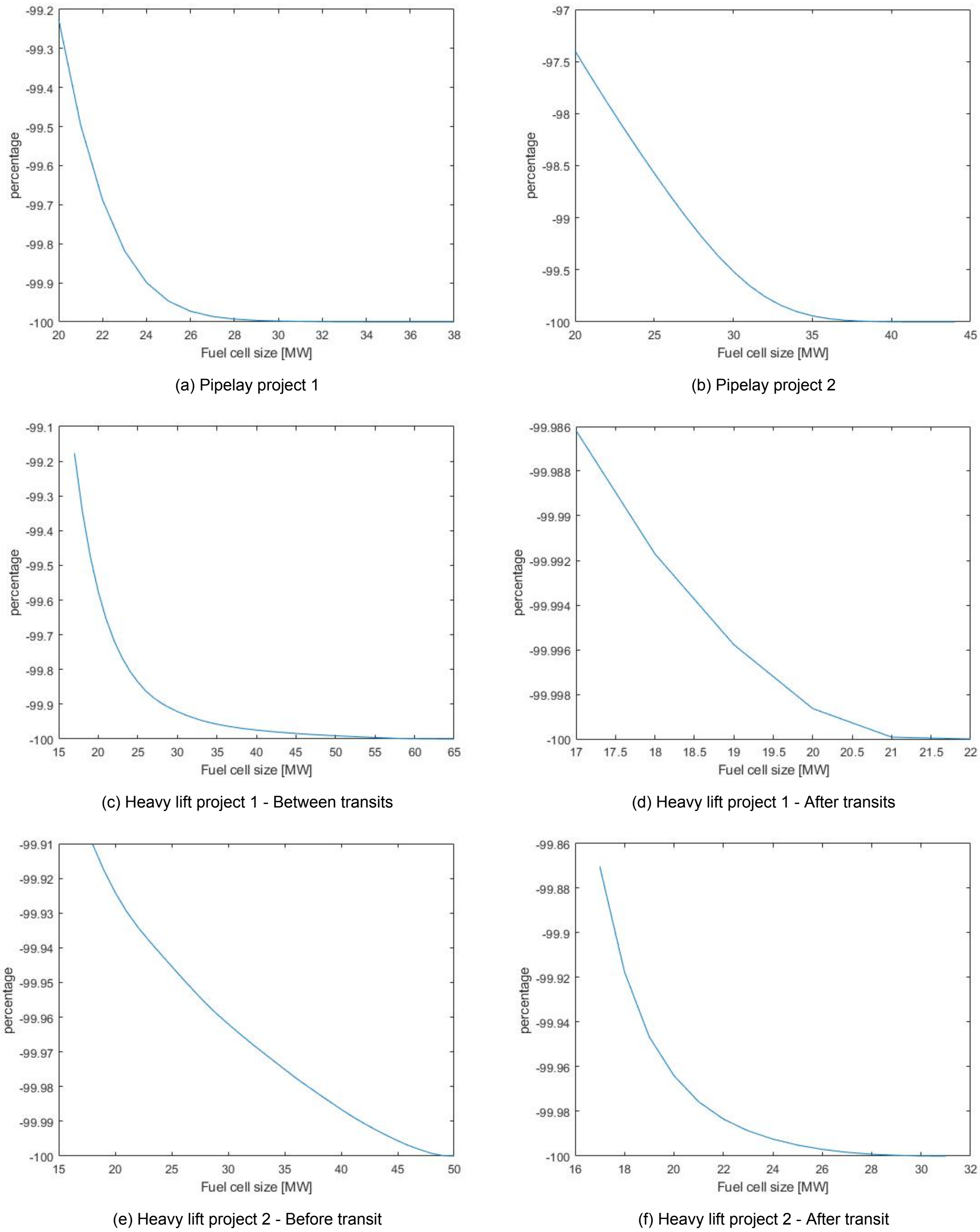
During this second iteration only the pipelay projects and the heavy lift projects are investigated. Since the transit periods are removed from the projects, for this iteration the battery capacity of 4 MWh is used again. Figure 6.15 reveals that with fuel cell of 29 MW the batteries can be charged for all the projects.



(a) Pipelay project 1
(b) Pipelay project 2
(c) Heavy lift project 1 - Between transits
(d) Heavy lift project 1 - After transits
(e) Heavy lift project 2 - Before transit
(f) Heavy lift project 2 - After transit

Figure 6.7: Chargeability of the batteries - Minimum battery capacity of 4 MWh

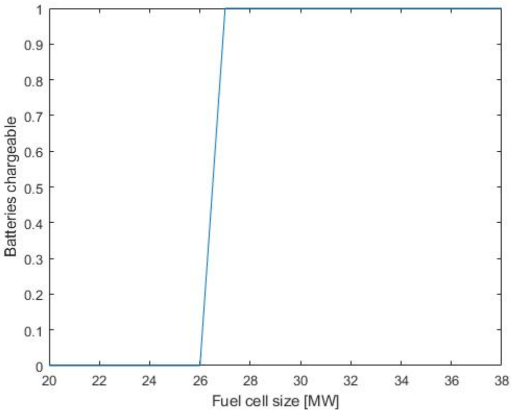
Looking at the CO_2 reduction in figure A.2, it becomes clear that with a battery capacity of 4 MWh the fuel cell need to be over 45 MW in order to become completely emission-free.



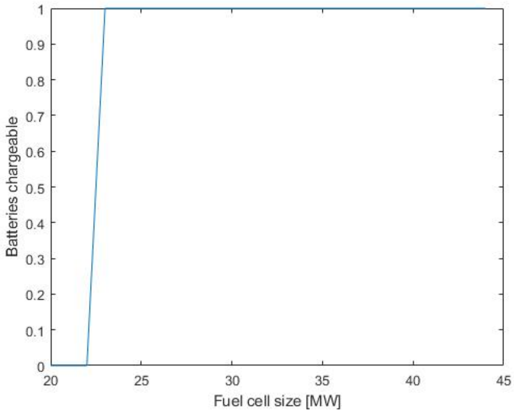
(a) Pipelay project 1
(b) Pipelay project 2
(c) Heavy lift project 1 - Between transits
(d) Heavy lift project 1 - After transits
(e) Heavy lift project 2 - Before transit
(f) Heavy lift project 2 - After transit

Figure 6.8: CO_2 reduction - Minimum battery capacity of 4 MWh

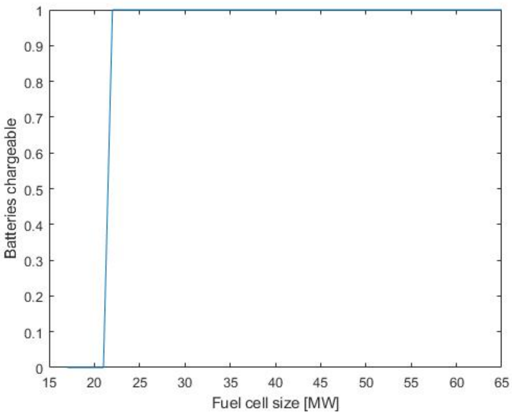
Third iteration
For the third iteration the maximum battery capacity is used. To make sure the battery capacity is applicable for all projects the choice is made to take the maximum battery capacity of all range, which is 24 MWh.



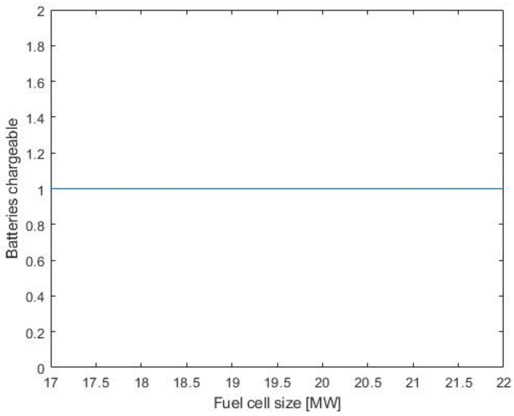
(a) Pipelay project 1



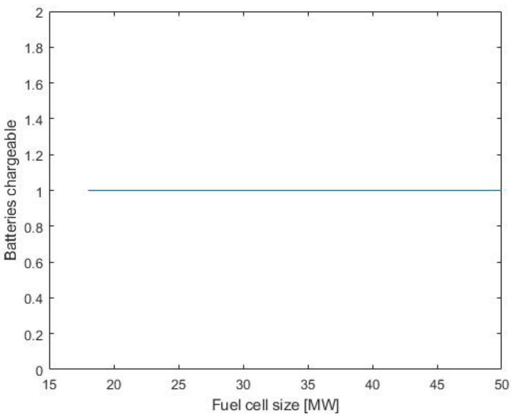
(b) Pipelay project 2



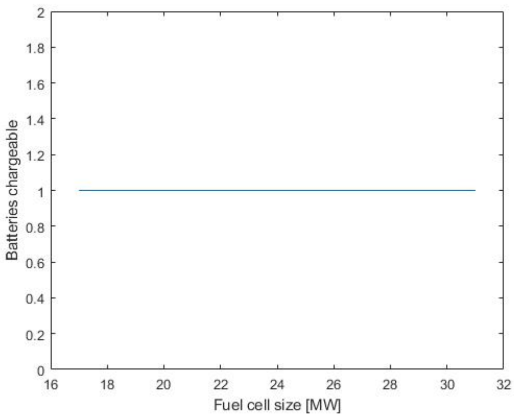
(c) Heavy lift project 1 - Between transits



(d) Heavy lift project 1 - After transits



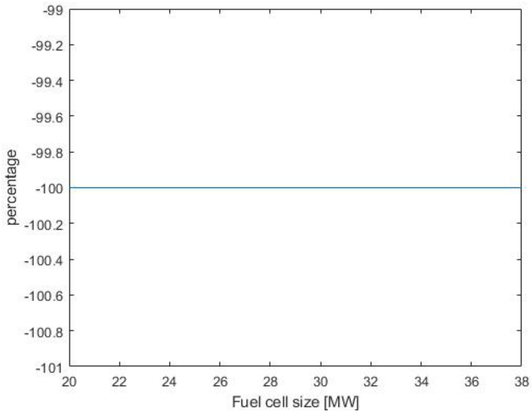
(e) Heavy lift project 2 - Before transit



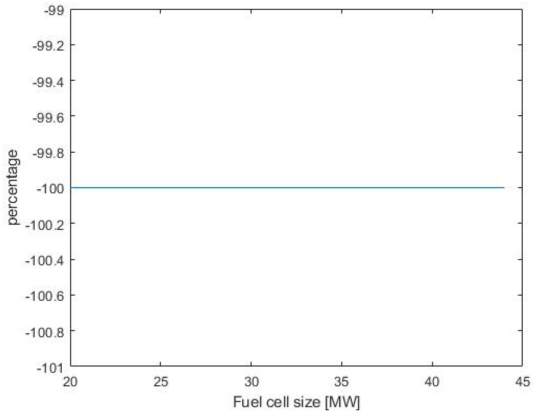
(f) Heavy lift project 2 - After transit

Figure 6.9: Chargeability of the batteries - Maximum battery capacity of 24 MWh

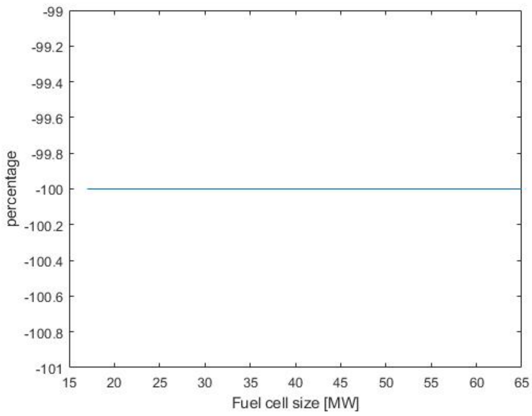
The CO_2 reduction is for all projects 100% regardless of the size of the fuel cells.



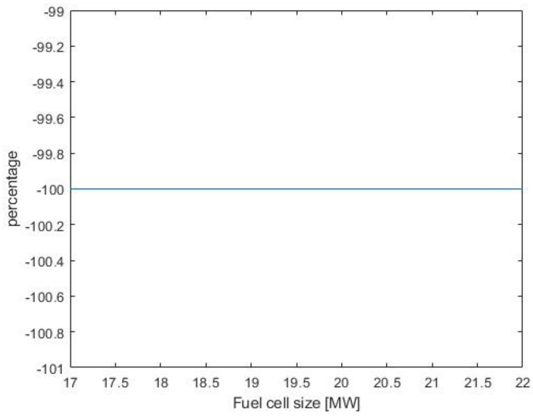
(a) Pipelay project 1



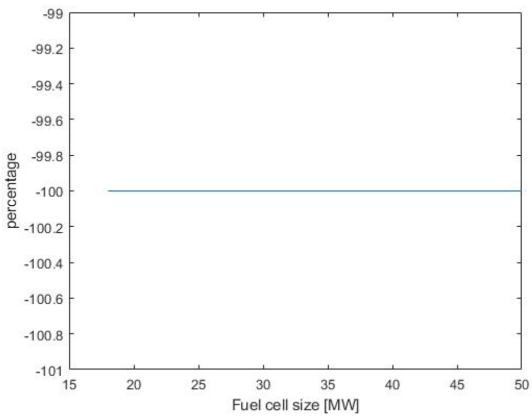
(b) Pipelay project 2



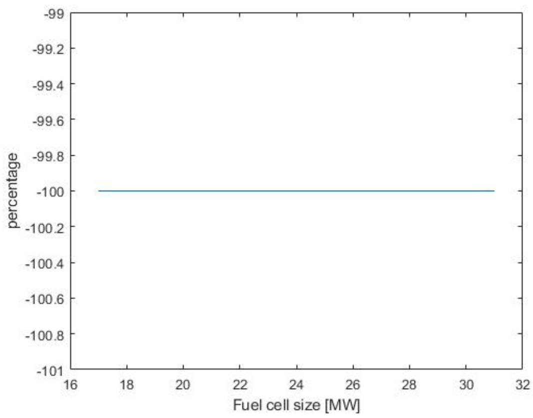
(c) Heavy lift project 1 - Between transits



(d) Heavy lift project 1 - After transits



(e) Heavy lift project 2 - Before transit

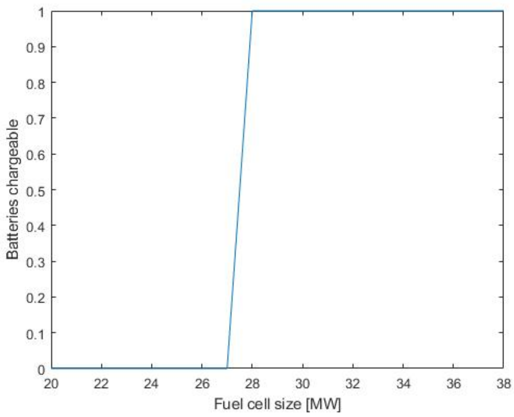


(f) Heavy lift project 2 - After transit

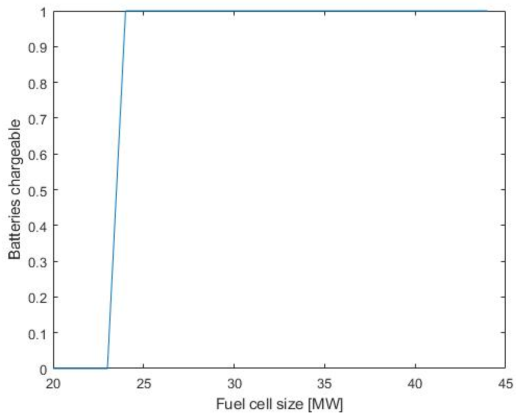
Figure 6.10: CO_2 reduction - Maximum battery capacity of 24 MWh

Fourth iteration

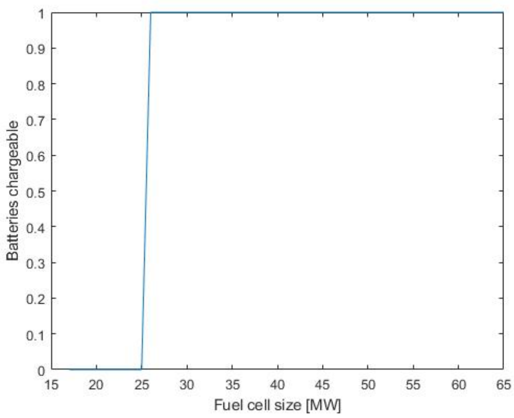
Since the batteries will not be used during transit periods and to make sure enough power can be provided during the transit periods a different ratio between the fuel cells and batteries is needed. For that reason and because the choice is made that the batteries are not bigger as the fuel cells the choice is made do another iteration which is halfway the range of the batteries, 10 MWh.



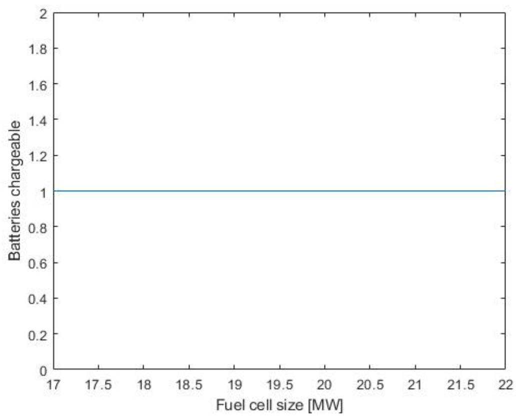
(a) Pipelay project 1



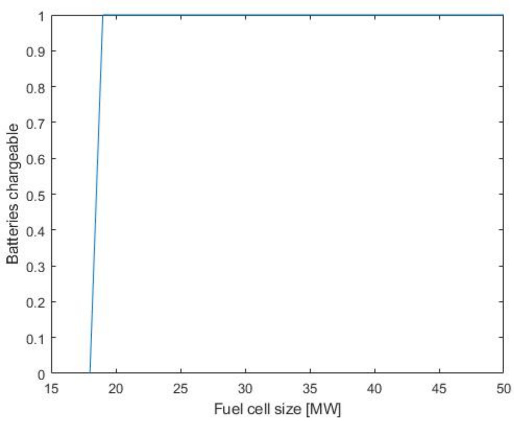
(b) Pipelay project 2



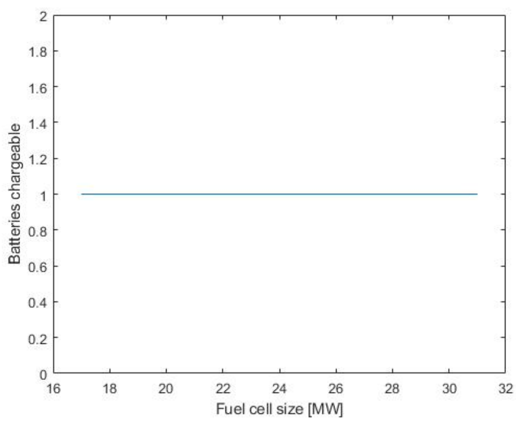
(c) Heavy lift project 1 - Between transits



(d) Heavy lift project 1 - After transits



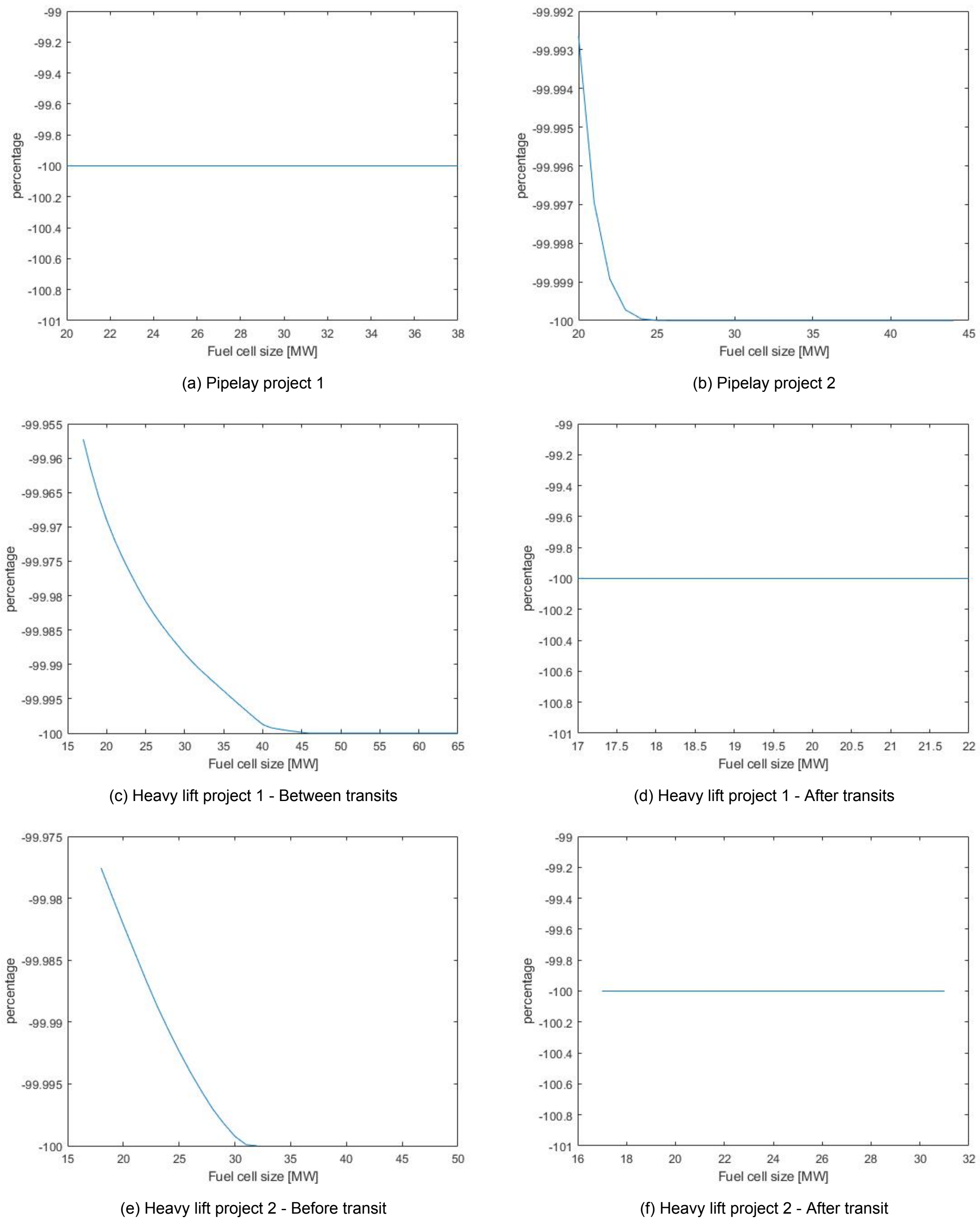
(e) Heavy lift project 2 - Before transit



(f) Heavy lift project 2 - After transit

Figure 6.11: Chargeability of the batteries - Battery capacity of 10 MWh

For all projects the fuel cells are able to charge the batteries if the fuel cell are 29 MWh, however figure 6.12 reveals that by a battery capacity of 10 MWh the fuel cells need to be over 40 MW in order to have a 100% reduction of CO_2 during heavy lift project 1 - Between transits.



(a) Pipelay project 1

(b) Pipelay project 2

(c) Heavy lift project 1 - Between transits

(d) Heavy lift project 1 - After transits

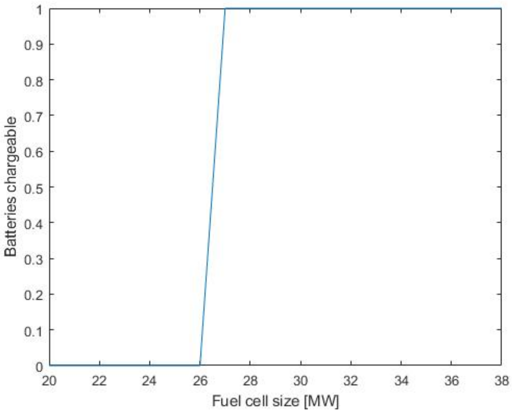
(e) Heavy lift project 2 - Before transit

(f) Heavy lift project 2 - After transit

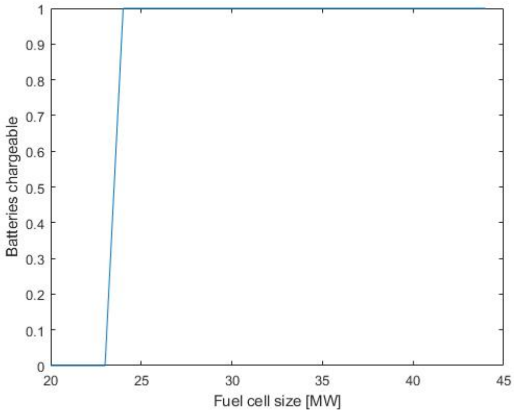
Figure 6.12: CO_2 reduction - Battery capacity of 10 MWh

Fifth iteration

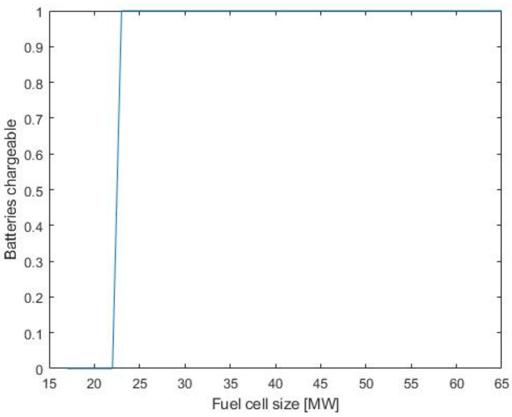
Since the optimal battery capacity lays somewhere between the 10 and 24 MWh during this fifth iteration the choice is made to use 19 MWh.



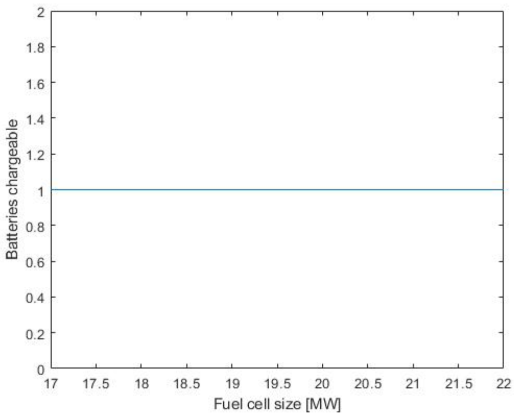
(a) Pipelay project 1



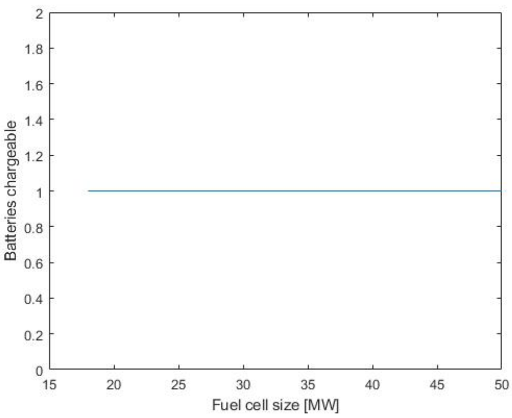
(b) Pipelay project 2



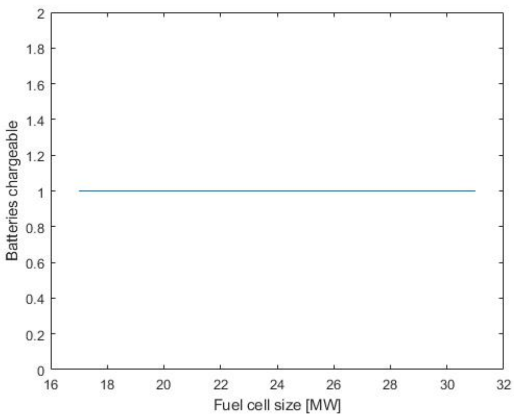
(c) Heavy lift project 1 - Between transits



(d) Heavy lift project 1 - After transits



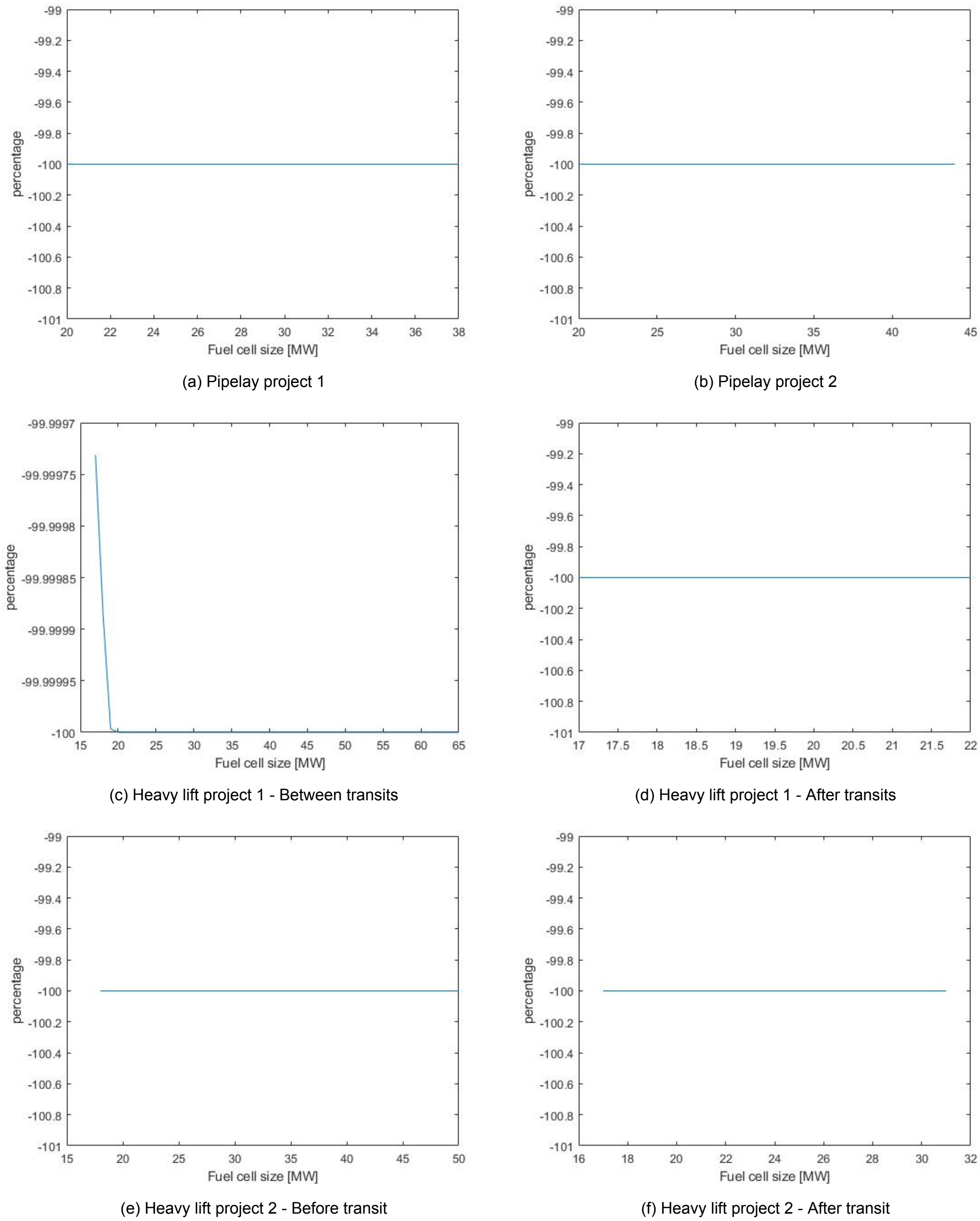
(e) Heavy lift project 2 - Before transit



(f) Heavy lift project 2 - After transit

Figure 6.13: Chargeability of the batteries - Battery capacity of 19 MWh

The wanted 100% CO_2 reduction is already found with this battery capacity with less than 20 MW fuel cells, which is lower than the fuel cell size needed to charge the batteries during the project.



(a) Pipelay project 1

(b) Pipelay project 2

(c) Heavy lift project 1 - Between transits

(d) Heavy lift project 1 - After transits

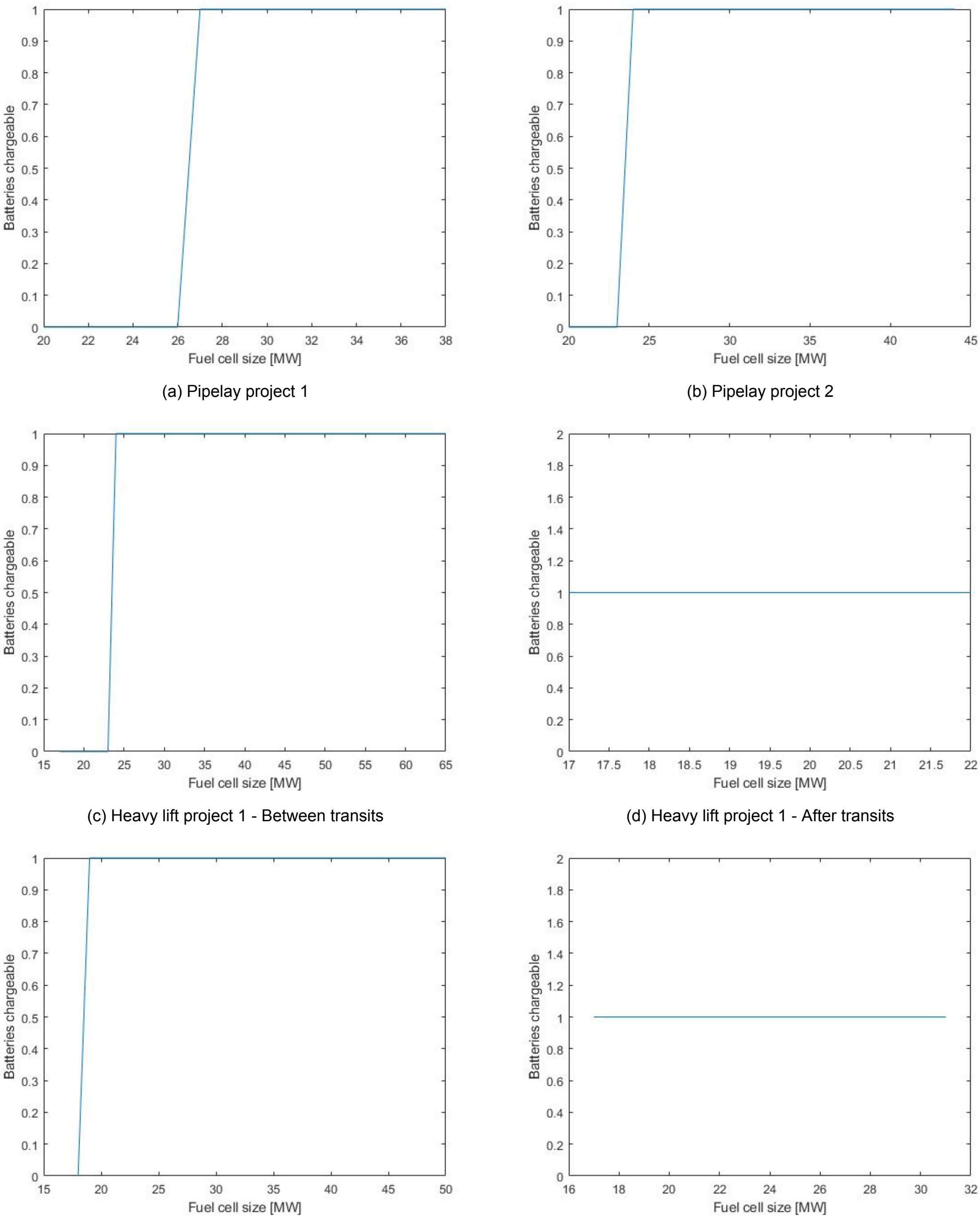
(e) Heavy lift project 2 - Before transit

(f) Heavy lift project 2 - After transit

Figure 6.14: CO_2 reduction - Battery capacity of 19 MWh

Sixth iteration

From the last two iterations it became clear that the optimal battery capacity is somewhere located between the 10 and 19 MWh and thus during this next iteration a battery capacity of 14.5 MWh is used.



(a) Pipelay project 1

(b) Pipelay project 2

(c) Heavy lift project 1 - Between transits

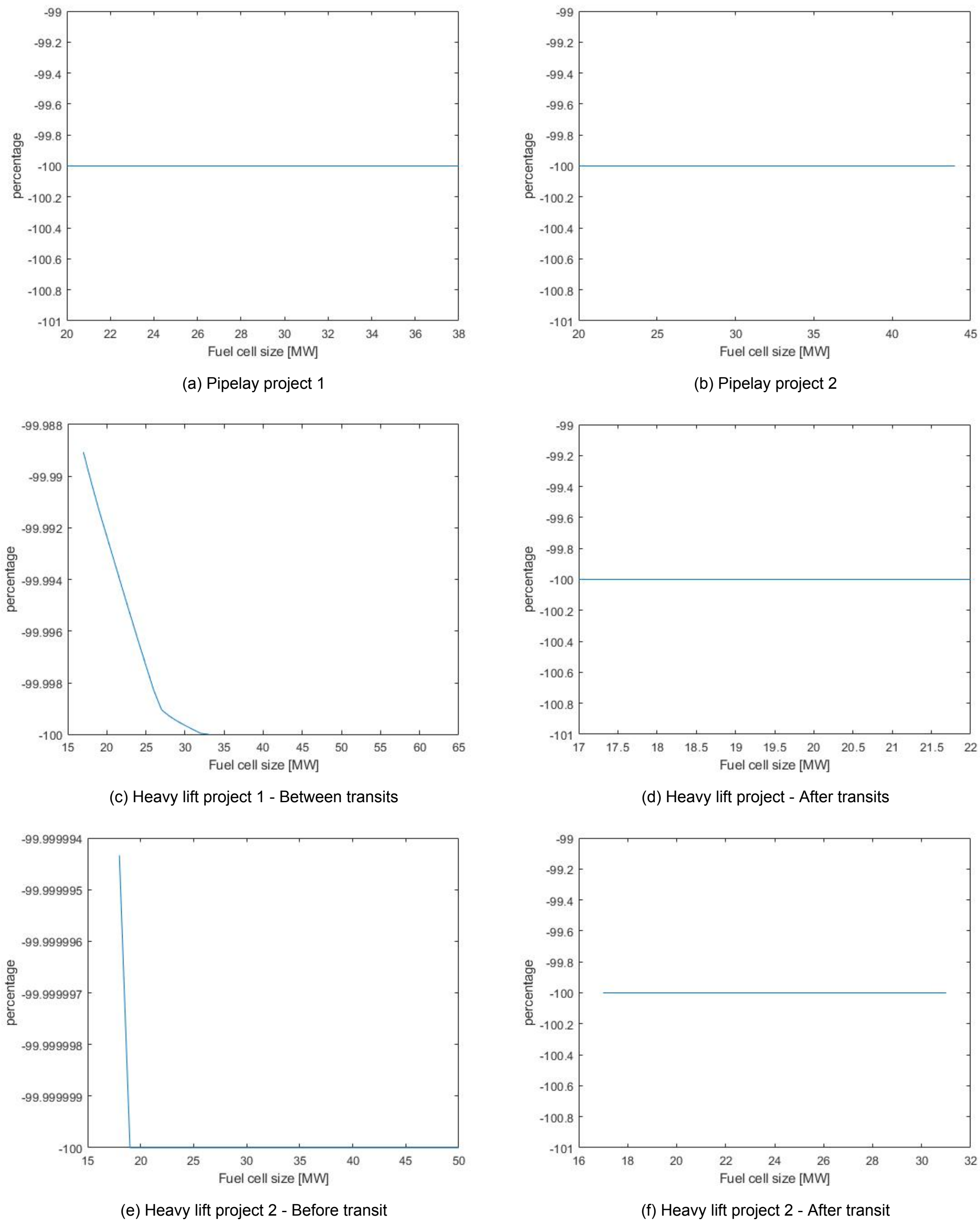
(d) Heavy lift project 1 - After transits

(e) Heavy lift project 2 - Before transit

(f) Heavy lift project 2 - After transit

Figure 6.15: Chargeability of the batteries - Battery capacity of 14.5 MWh

Figure A.9 reveals that in order to get a CO_2 reduction of 100% the fuel cell size need to be 33 MW.



(a) Pipelay project 1

(b) Pipelay project 2

(c) Heavy lift project 1 - Between transits

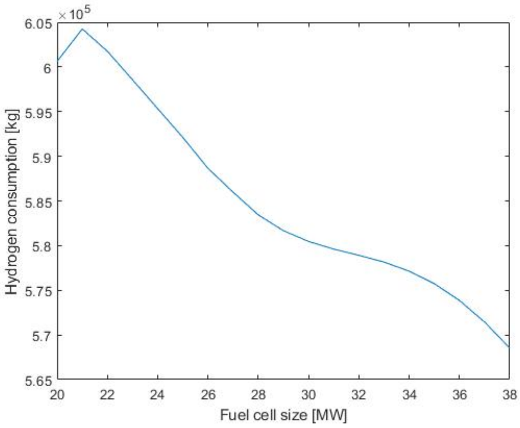
(d) Heavy lift project - After transits

(e) Heavy lift project 2 - Before transit

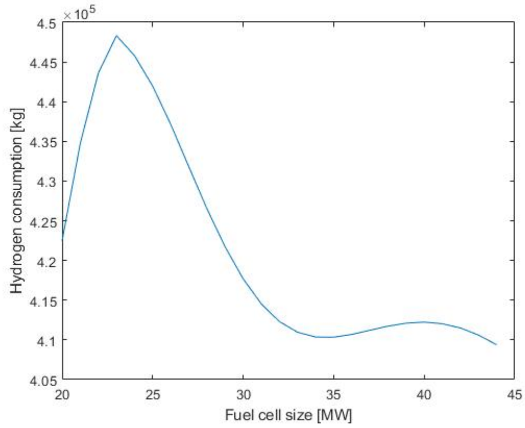
(f) Heavy lift project 2 - After transit

Figure 6.16: CO_2 reduction - Battery capacity of 14.5 MWh

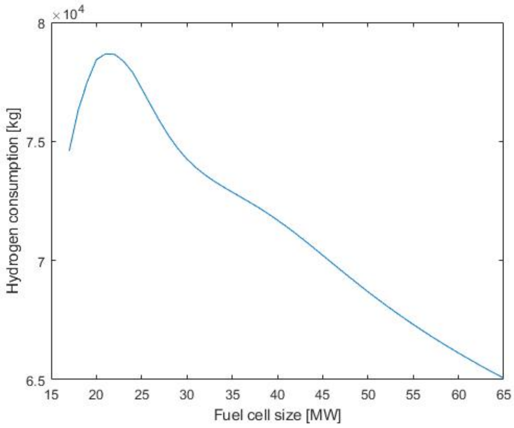
Figure 6.17 reveals that for a battery capacity of 14.5 MWh and a fuel cell size of 33 MW the hydrogen consumption around the lowest for these projects.



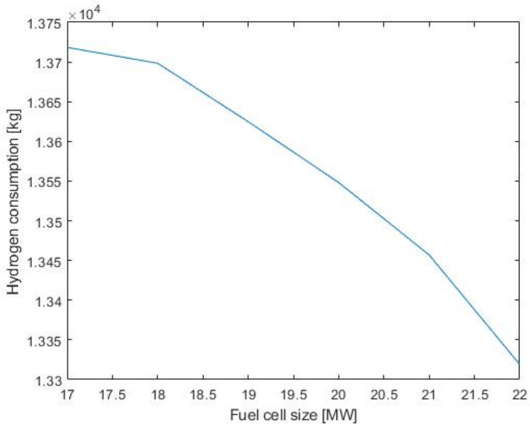
(a) Pipelay project 1



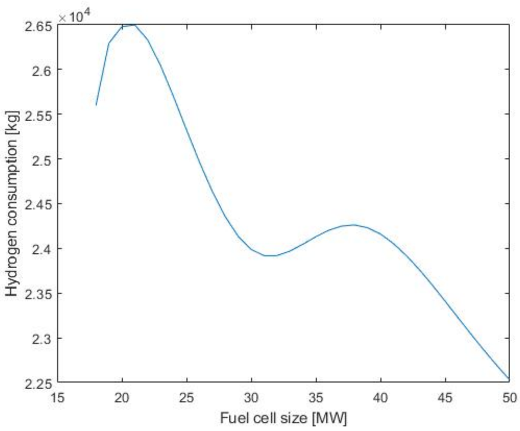
(b) Pipelay project 2



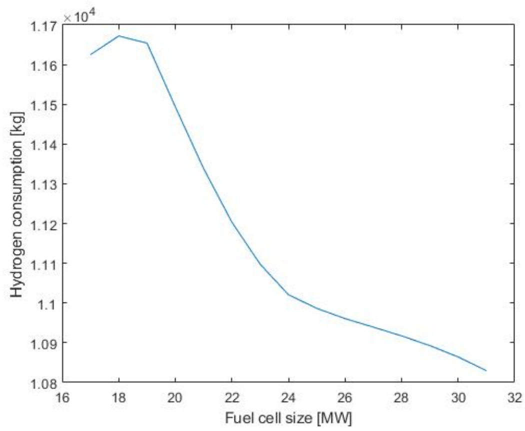
(c) Heavy lift project 1 - Between transits



(d) Heavy lift project 1 - After transits



(e) Heavy lift project 2 - Before transit

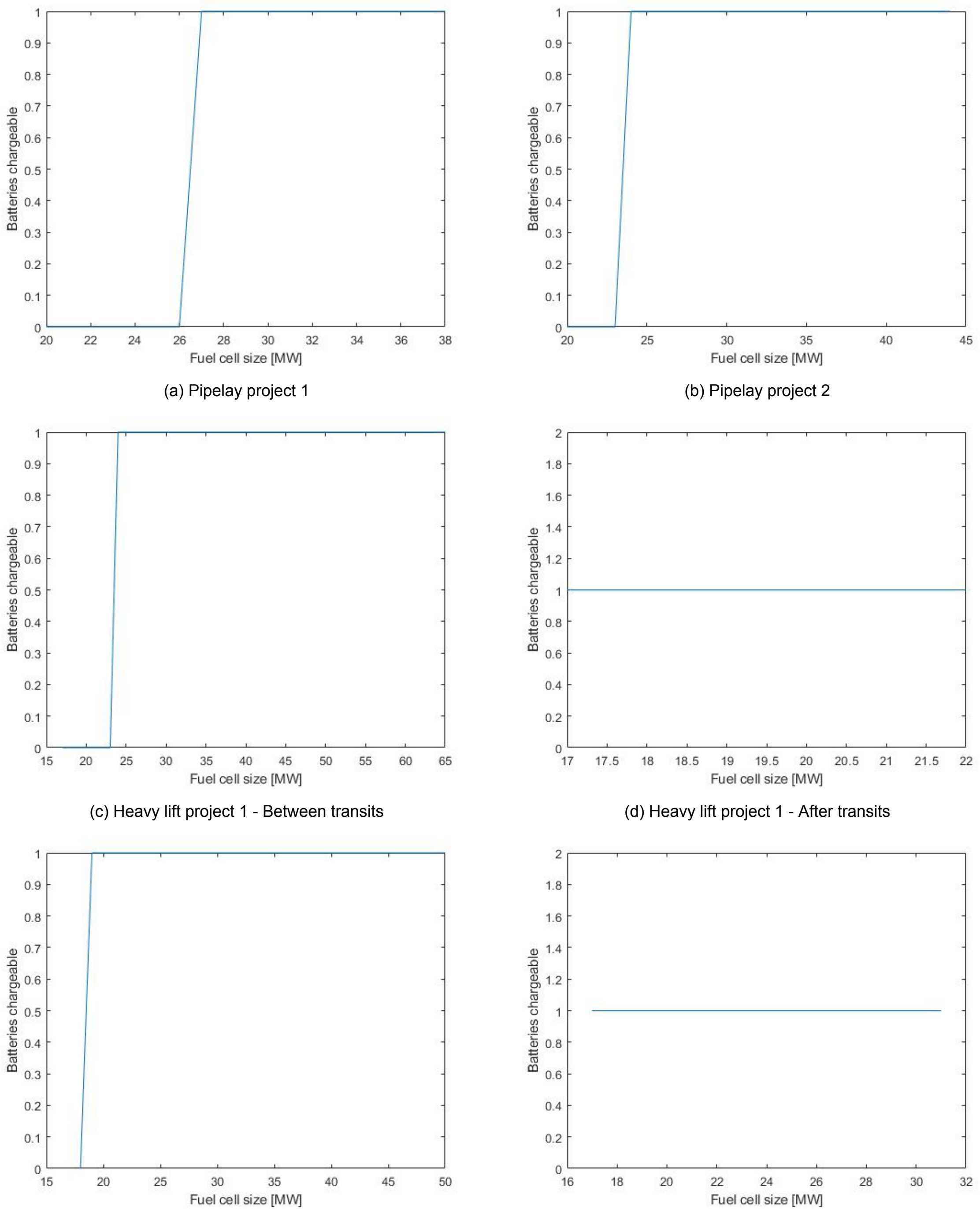


(f) Heavy lift project 2 - After transit

Figure 6.17: Hydrogen consumption - Battery capacity of 14.5 MWh

Iteration 7 & 8

Since the batteries come in packs of 249 kW, two extra iterations are done to round off at whole battery packs. During iteration 7 a battery capacity of 14.442 MWh was used.



(a) Pipelay project 1

(b) Pipelay project 2

(c) Heavy lift project 1 - Between transits

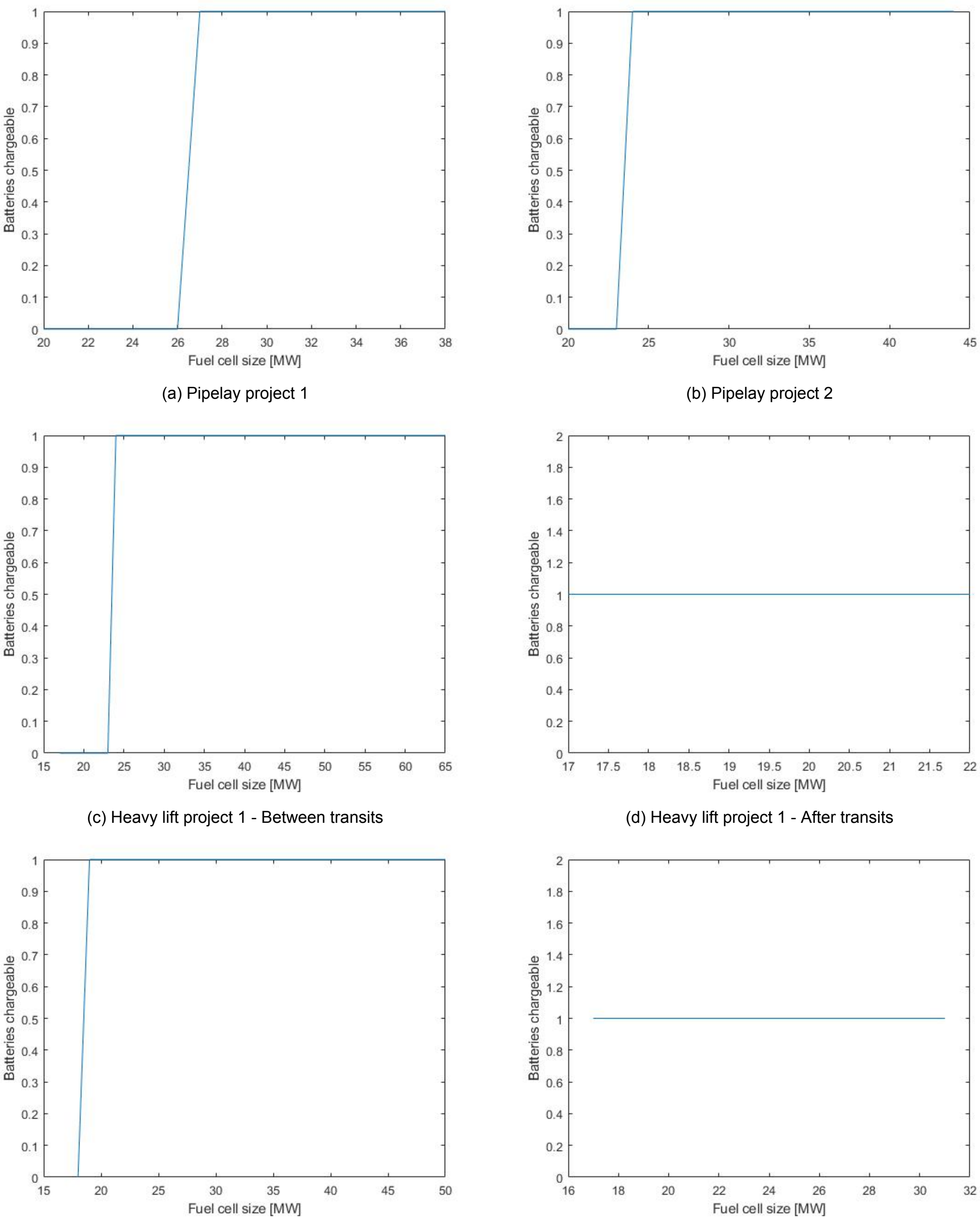
(d) Heavy lift project 1 - After transits

(e) Heavy lift project 2 - Before transit

(f) Heavy lift project 2 - After transit

Figure 6.18: Chargeability of the batteries - Battery capacity of 14.442 MWh

For iteration eight a battery capacity of 14.94 MWh was used.



(a) Pipelay project 1

(b) Pipelay project 2

(c) Heavy lift project 1 - Between transits

(d) Heavy lift project 1 - After transits

(e) Heavy lift project 2 - Before transit

(f) Heavy lift project 2 - After transit

Figure 6.19: Chargeability of the batteries - Battery capacity of 14.94 MWh

6.2.2. Step 2

After generating different solutions during the first step in table 6.2 the solutions which are usable are displayed. The hydrogen consumption and the CO_2 production are for all projects together including the transit periods. All these solutions are chosen because the fuel cells are able to charge the batteries during the project as well as that the work part of the project can be done fully without emissions. In step 3 from the solutions in table 6.2 the optimal solution will be determined.

Table 6.2: Solutions for the fuel cell battery combination

	Fuel cell power [MW]	Battery capacity [MWh]	Hydrogen consumption [tonnes]	CO_2 production [tonnes]
Solution 1	58	4	2401	1065
Solution 2	27	24	2119	5875
Solution 3	26	10	2110	6073
Solution 4	27	19	2119	5875
Solution 5	33	14.5	2191	4740
Solution 6	33	14.442	2191	4740
Solution 7	32	14.94	2176	4925

6.2.3. Step 3

In order to find the optimal solution table 6.2 and 6.3 are used together. Since the target is 70% CO_2 reduction solution 2, 3 and 4 are not sufficient and are no longer considered a solution. Solution 1 has the highest fuel cell power of all the solutions and for that reason also a higher hydrogen consumption and since the CO_2 reduction of this solution is far above the 70% target the choice is made to eleminated this solation as well.

Table 6.3: CO_2 reduction for the different solutions

	Fuel cell power [MW]	Battery capacity [MWh]	CO_2 reduction [%]
Solution 1	58	4	91
Solution 2	27	24	67
Solution 3	26	10	67
Solution 4	27	19	67
Solution 5	33	14.5	72
Solution 6	33	14.442	72
Solution 7	32	14.94	71

The difference between solution 5 and 6 is that the batteries in solution 6 are a bit smaller which is looking only at those two solutions preferable since the cost will go down. This is the reason to eliminate solution 5 from the options. The only two solutions left are solution 6 and solution 7. By increasing the batteries with two extra packs of 249 kWh the fuel cells can be decreased with 1 MW, which are in total 5 200 kW stacks. Increasing the battery capacity will lead to an significantly more decrease of the fuel cells power which will lead to a decrease in cost and as can seen in table 6.3 the CO_2 reduction still will meet the target of 70%. For these reasons the choice is made to work with solutions 7 for the next part of the design methodology.

6.3. Part 3: New system specifications

6.3.1. Data input

From the iterations in part 2 of the design methodology the choice is made to work with a fuel cell size of 32 MW and a battery capacity of 14.94 MWh, which will be the input for the third part of the design methodology. In addition to the fuel cell power and the battery capacity, the time between bunkering will be set for 10 days, which is enough to perform a full heavy lift project, which takes on average 9.22 days.

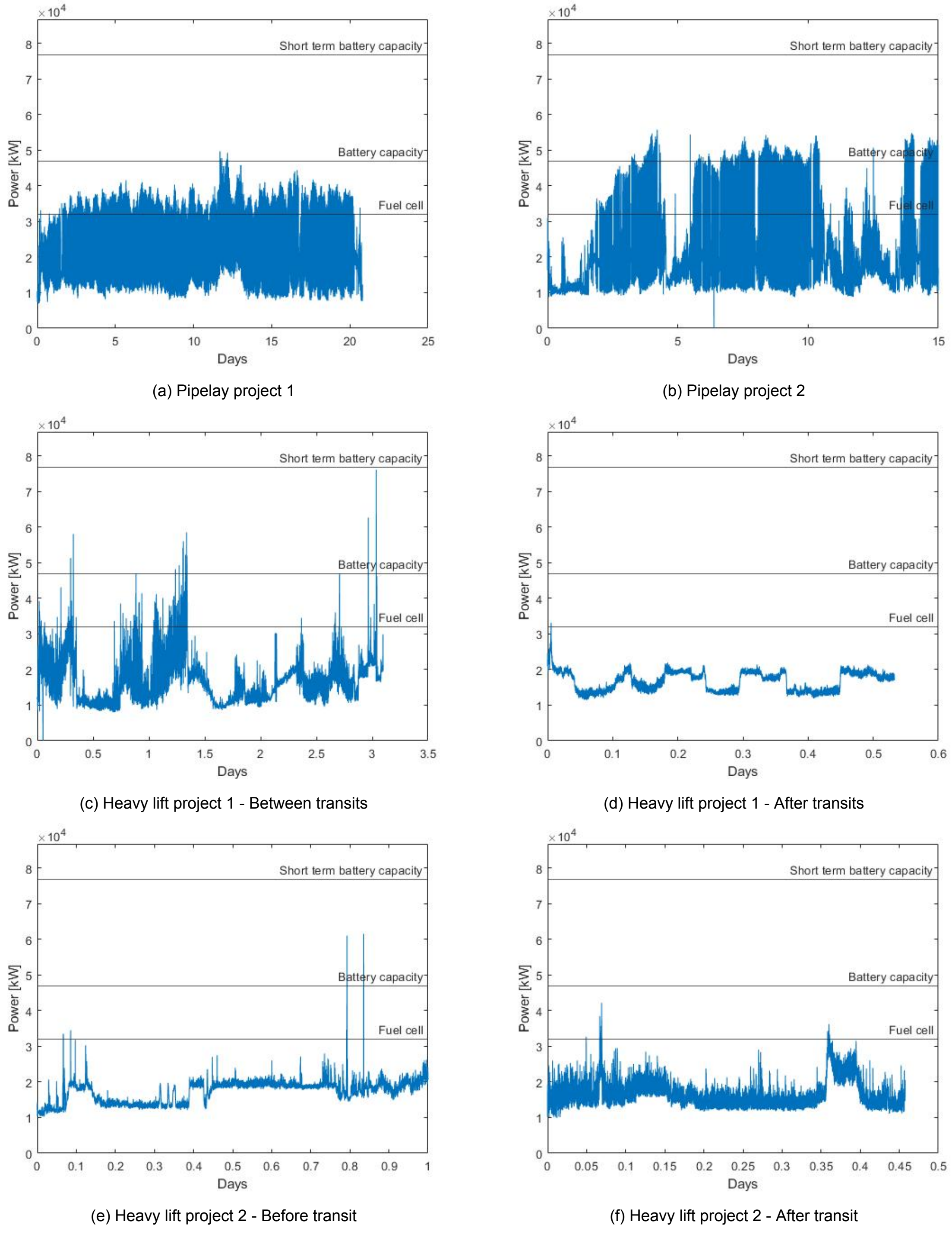
6.3.2. Checks

All projects were put into the second part of the methodology so the checks could be done before the rest of the system is calculated. The result of these checks are shown in table 6.4. From this table it becomes clear that the total capacity of the new system is sufficient enough to meet the power demand and has the capacity to charge the batteries during the projects.

Table 6.4: The checks done for the system with Pfc = 32 MW and Pbat = 14.94 MWh

		Capacity system	Battery charging
Pipelay project 1	without transit	x	x
Pipelay project 2		x	x
Heavy lift project 1	Between transits	x	x
	After transits	x	x
Heavy lift project 2	Before transit	x	x
	Between transits	x	x
Period in port		x	x

In figure 6.20 and 6.21 the results of the checks are shown again. From these figures it becomes clear that the new system mainly is sized for heavy lift project 1 - between transits. For all other project the new power generating system can be sized much smaller, but since a 70% CO_2 reduction only can be achieved when the projects without transits are fully on the fuel cells and batteries the total power can not be decreased.



(a) Pipelay project 1

(b) Pipelay project 2

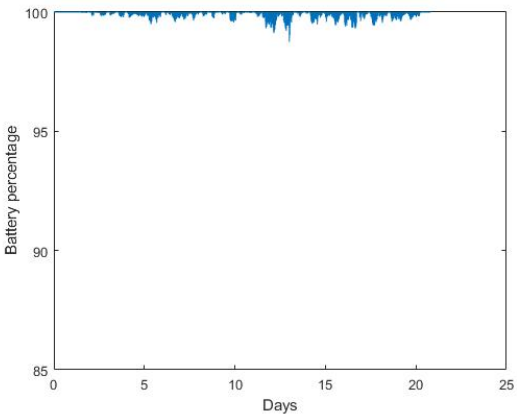
(c) Heavy lift project 1 - Between transits

(d) Heavy lift project 1 - After transits

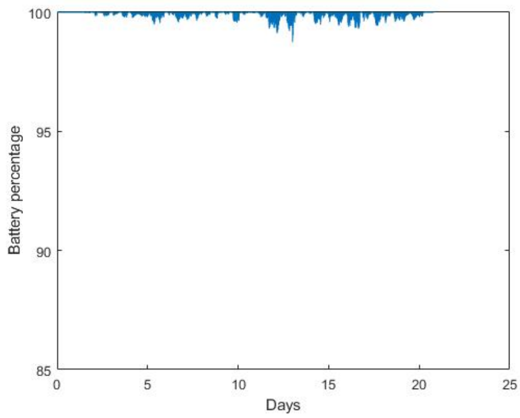
(e) Heavy lift project 2 - Before transit

(f) Heavy lift project 2 - After transit

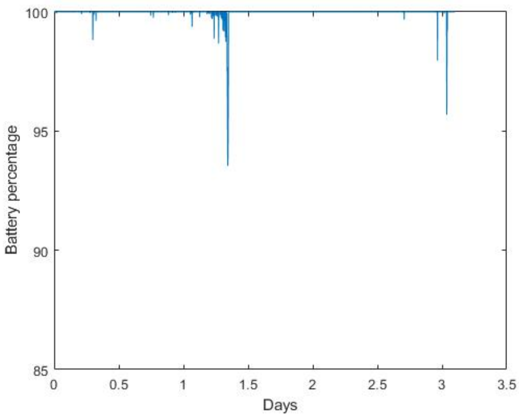
Figure 6.20: Distribution of power delivery by the fuel cells and batteries



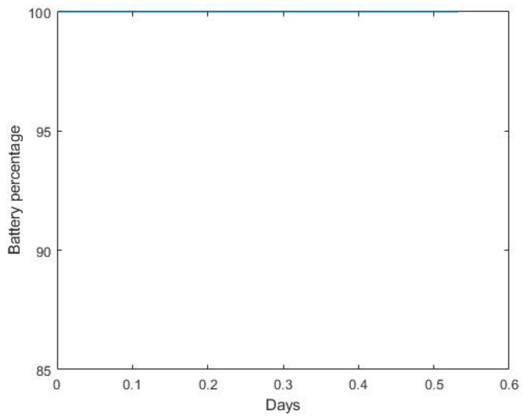
(a) Pipelay project 1



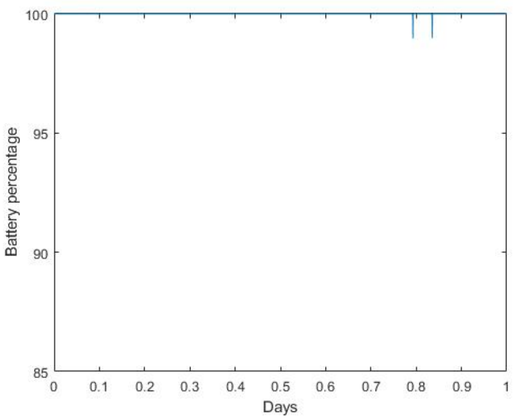
(b) Pipelay project 2



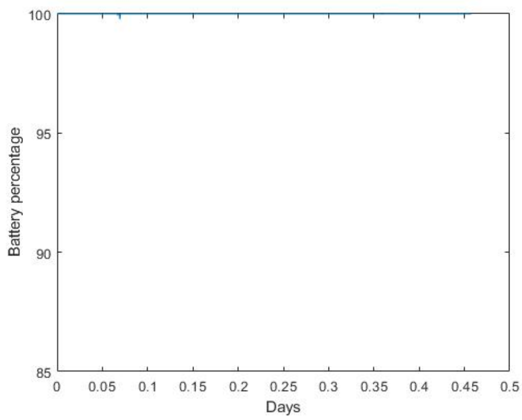
(c) Heavy lift project 1 - Between transits



(d) Heavy lift project 1 - After transits



(e) Heavy lift project 2 - Before transit



(f) Heavy lift project 2 - After transit

Figure 6.21: Battery stage during the project

6.3.3. CO_2 reduction

Looking back at the typical year for the Pioneering Spirit and especially at table 4.1 the CO_2 reduction of the vessel can be determined. The new power generating system can deliver enough power to meet the power demand during the pipelay projects, heavy lift projects and the time in port. Only during the transit periods the diesel generators need to be switched on and by using the fuel cell on full power the diesel generators only have to deliver around 37 MW. This results in a reduction of 71% for the typical year.

Table 6.5: CO_2 reduction

	Time [Days]	Total CO_2 production current system [Tonnes]	Total CO_2 production new system [Tonnes]	CO_2 reduction [%]
Transit	68	69858	37646	46
Pipelay	134	37187	0	100
Heavy lift	19	4191	0	100
In port	145	16684	0	100
Total	365	127920	37646	71

6.3.4. System capacity

The outcome from the third part of the methodology is summarised in table 6.6. This new power generation system will contain 33 MW fuel cells and 14.5 MWh batteries. The choice is made to remove only two generators, since for the transit periods in some cases around 85 MW is needed. Safety is another reason for not removing an extra generator, since it is not possible to place the fuel cells or batteries direct next to a generator.

The new system will contain 165 fuel cell stacks and 59 battery packs. The fuel cells need an air flow of 113850 $m^3/hour$, which is less as the air flow needed for the two removed generators together (table 2.2), so by placing the fuel cells in the engine room this will not give problems with the existing ventilation of the engine room. The fuel cells will take more surface space as the generators, but since the engine room has 5 different decks the fuel cells will be placed on two different decks. The fuel cells will be in two parts connected to the grid, so in case one part will loses its power the other half will still be able to give power.

Table 6.6: Outcome system capacity

		Total hydrogen consumption [tonnes]	Times bunkering [-]	Total tank capacity [tonnes]	Number of fuel cell stacks [-]	Number of battery packs [-]	Size air flow system [Nm^3/hour]	Size coolant system [NL/min]	Total water generation [tonnes]
Pipelay project 1	without transit	579	2	304	160	60	110400	56100	5617
Pipelay project 2		412	1	276	160	60	110400	54400	4127
Heavy lift project 1	Between transits	74	0	74	160	60	110400	54400	721
	After transits	12	0	12	160	60	110400	54400	123
Heavy lift project 2	Before transit	24	0	24	160	60	110400	54400	240
	After transit	11	0	11	160	60	110400	54400	104

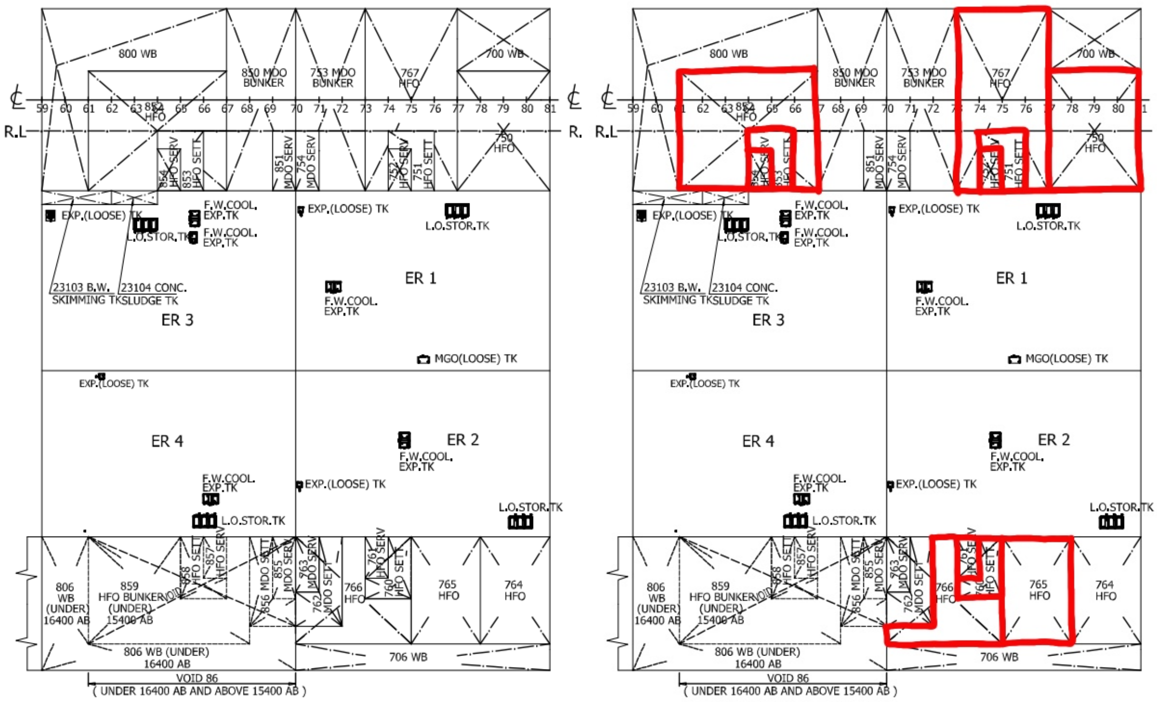
In the engine room there is not sufficient enough space to place the batteries as well so for that reason they will get another place in the ship. After discussing this with the crew on board it was found out the under the winch rooms there is space to place them, and since these are on both sides of the ship half of them are placed on starboard and half on backboard. This will give the new system also some of its redundancy.

During the same discussion on board it was found out that at the moment the HFO tanks are not used. Two of them are cleaned and now used for MDO storage but the others are empty and for that reason the choice is made to look if all hydrogen can be stored in tanks which will fit into the HFO tanks. Figure 6.22a shows the fuel tanks around the engine rooms. The choice was already made to use engine room 2 for the new system and for that reason the HFO service and settling tank can be sacrificed for hydrogen storage as well as two of the HFO storage tanks on that side of the ship. The other one is used for MDO storage at the moment. Sacrificing those tanks frees up 4828.8 m^3, which is just enough

Table 6.7: Space needed for the new power generation system and the hydrogen storage

		Volume needed [m^3]	surface needed [m^2]
Fuel cells		232	105
batteries		179	60
hydrogen storage	only hydrogen	4725	Depending on the diameter of the tanks
	full system	17945	Depending on the diameter of the tanks

space for only the hydrogen,but not for the whole storage system. Since MDO is a cleaner fuel as HFO the choice is made to sail only on MDO, so that all HFO tanks can be used for the storage of hydrogen. In figure 6.22b the tanks which will be used for the hydrogen storage tanks are lined red. Using all these tanks gives a lot more space to work with, but still not enough since there is now 12101.3 m^3 space available and the system needs 13207 m^3 as can be seen in table 6.7. This means that in other places on board available need to be found or the choice need to be made to not be able to sail full heavy lift projects on hydrogen without bunkering in between. An option is to look into the water ballast tanks and if some of them are always filled. If this is the case, the weight of the water can be compensated with the storage tanks for hydrogen, but this is something which is not looked into at the moment.



(a) Engine room tank plan

(b) Tanks used for hydrogen storage

Figure 6.22: Tank plan

7 Evaluation

7.1. Conclusions

In this section of the evaluation first the sub-questions of the research will be answered before the main research question will be answered as well.

7.1.1. Sub-questions

How do the different operations of the vessel influence the power demand?

In order to see what the influence of the different operations is on the power demand of the vessel a typical year is investigated. It gives insight on the time distribution between the different operations. From the average power demand and the peak power demand it becomes clear that during the different operations the power demand fluctuates. The transit periods are the most power demanding periods of time, however the periods in port have in relation to the other operational modes a low power demand. The power demand during the transits is depending on the vessel speed but also on the weather conditions. During the pipelay projects the difference between the average power and the peak power is the largest. Pipelay projects have a distinguish power demand pattern, where during the pipe pulls a peak occurs for around 2 minutes and after that the power demand drops. During heavy lift work some high peaks can occur as well. After investigating how much CO_2 the typical year will produce with the current power generating system, it became clear that in order to meet the target of 70% CO_2 reduction all projects and the time in port need to be done fully without emissions and during the transits also a part of the emissions needs to be reduced. This will influence the design of the new power generating system.

How can the power capacity be determined of the fuel cells, generators and batteries keeping a good ratio between the components?

During the design process a design methodology will be used which contains three different parts. In the second part different solutions will be generated with different ratios between the fuel cell power and the battery capacity. The batteries will be used for peak shaving as well as a spinning reserve, which means that the minimum capacity will be 4 MWh since this corresponds with 1/3 of a generator. The battery can deliver for 20 minutes 3 times this 4 MW, which should be enough time to start up a generator in case of an emergency. Since the batteries are mainly for peak shaving during the projects the choice is made that the batteries are not bigger as the fuel cells. The fuel cells need to be able to charge the batteries during the projects, which influences the size of the fuel cells. During the transit periods the fuel cells will deliver their full power capacity in order to reduce emissions. To create space for the new system and since not all generators are needed anymore the choice is made to remove two generators from the same engine room.

In which way can the fuel storage for the new system be optimised?

Hydrogen cannot be stored in the same tanks as conventional fuel, for that reason different storage options are reviewed. Since the available space on board is limited for the storage of hydrogen the choice is made to work with liquefied hydrogen. Liquid hydrogen storage tanks have the best volumetric storage density, so larger amounts of fuel can be stored.

Using the design methodology in a case for the Pioneering Spirit, how can the new hybrid propulsion system be designed?
The Pioneering Spirit has an unique operational profile since she can perform pipelay projects as well as heavy lift projects. These two different operation types result in two different types of power profiles. During the transit periods the ship has the highest power demand and this reason the choice was made to use the diesel generators in addition to the fuel cells. Two heavy lift project and two pipelay projects were used during the case study. After letting the transit periods out of it six periods of time were put into the design methodology. After doing different iterations for the battery capacity and fuel cell size, one was chosen to use for the third part of the methodology. For all six periods of time the checks were done if the system is sufficient, which resulted in a final design of the new power generation system will contain 32 MW fuel cells and 14.94 MWh batteries. This new power generation system will result in an overall CO_2 reduction for the typical year of 71%.
After the checks the third part of the methodology calculates the space needed for the fuel cells and the batteries. For this system engine room 2 will be cleared out and the space will be used for this new system. Since the fuel cells and batteries take much more space than the original generators only the fuel cells will be place in the engine room. After discussing it with the crew on board the choice is made to place the batteries under the winch rooms on both sides of the ship. For the hydrogen storage the choice is made to use the HFO fuel tanks. Unfortunately this will be not enough to provide enough space to store for ten days hydrogen, so the choice need to be made to look into different available space or to decrease the sailing days between bunkering.

7.1.2. Main research question

How can a design methodology be developed to design a hybrid propulsion system with hydrogen fuel cells, diesel generators and batteries that will meet the IMO requirements to reduce the CO_2, sulphur and greenhouse gas emission while considering different design criteria?
In order to meet the IMO requirements to reduce the greenhouse gas emissions ships propulsion systems need to become more sustainable. An option are fuel cells running on hydrogen, and especially proton exchange membrane fuel cells. This option emits only water which is a big advantage.
To make it easier to design a new hybrid power generating system for the Allseas fleet a design methodology is developed. During the development process different criteria are taken into account. The most important criteria is that the new hybrid system need to lead to the reduction of CO_2 emission with 70%. The batteries are not only for peak shaving but also as a spinning reserve. Since during some projects it is beneficial to have zero emissions this is also taken into account during the development of the design methodology. In addition a criteria is set that the fuel cells need to charge the batteries during the project.
After investigating the operational profile of the vessel it became clear that in order to meet the target of 70% reduction the vessel has to be fully emission free during the projects and in port. Only during the transit periods the generators will be used and so produce emissions.
The design methodology will use historical project data during the search for solutions. To reduce calculation time on solutions which are not feasible, first a range of fuel cell power over which the the search will be preformed, will be determined in the first part of the methodology. In the second part a battery capacity will be chosen to work with. For the first step, over the fuel cell range and with the battery capacity solutions will be generated. The second part will be iterated with different battery capacities to generated different solutions. In the second step the different suitable solutions will be determined. In the third and last step of the second part the solutions will be compared and an optimal solution will be chosen. In the last part of the design methodology the specifications of the new power generating system will be calculated, with as a result the number of fuel cell stacks and battery packs needed, the hydrogen consumption during the input period as well as the water production. In addition the air flow rate, external coolant flow and the amount of times bunkering during the project are given.

7.2. Recommendations

7.2.1. Jacket lift system

The project data investigated during this thesis is from 2016 until 2021. In 2022 the Pioneering Spirit has for the first time used her new jacket lift system, which means that the power demand for this system is not included during the research. Since this new system will increase the power demand of the vessel, it is important to run also iterations with project data of projects using the JLS to see what influence the JLS has on the size of the system.

7.2.2. Fire saftey

If the choice will be made to implement the new hybrid propulsion system, it is important to look into fire safety and especially for the lithium-ion batteries, since this type of batteries are not easy to extinguish. It is important to look further into the different ways of extinguishing this kinds of fires and reducing the chances of fires.

7.2.3. Hydrogen storage

At the moment one of the main problems during the design phase of a propulsion system which runs on hydrogen as a fuel is the hydrogen storage on board. Besides the fact that in the same space as where MDO is stored more than 10 times less liquid hydrogen can be stored, the hydrogen storage system for liquid hydrogen needs also an additional 1.8 times extra space for the system it self. For future research it is important to stay up to date with the development of hydrogen storage.

7.2.4. Redundancy

The Pioneering Spirit has at the moment four engine rooms which can all be used independently from each other, but also in pairs. The reason for this is that the ship has a DP-3 classification, which means that in case of a failure of the propulsion system, for example due to a fire or flooding of one of the engine room, the operation still can go on. Looking into how often the DP-3 classification is required, can give a insight in if it is necessary to meet with the new system also a DP-3 classification or that it is possible to reduce to a DP-2 classification which makes it easier to implement the new system.

7.2.5. Battery options

Allseas was already looking into batteries for other vessels in the fleet and for that reason the choice was made to work with the same batteries. These batteries have a 3C-rate which means that in 20 minutes they can deliver 3 times the energy which they can deliver for an hour, before they are completely empty. In chapter 6, figure 6.21, the battery use over the project is shown. These figures reveal that the batteries are barely used. The capacity is now chosen because of a high peak during one of the heavy lift projects. For future research it can be useful to look into batteries with a higher C-rate. A battery with a higher C-rate will be empty earlier but can deliver a more energy in during this period. Since the peaks which need to be covered by the batteries are on average not longer than a couple of minutes it should not be a problem that the batteries will be empty faster. However it should be investigated if the batteries can be charge fast enough between the peaks.

7.2.6. Vessel usage

Investigating the usage of the vessel can give more insight in the power demand of the vessel and if it is possible to for example sail slower and be able to remove more generators, which creates space for the new system. In addition it can give a better idea on why there are some high peaks in the system. Using the ship more efficient can also lead to a smaller power generating system which will cost less and is easier to implement.

7.2.7. Cost

Lastly the cost of the new system need to be investigated in more detail. At the moment the assumption is made that batteries cost less as fuel cells and after implementing the first fuel cell the cost will grow linear, but before making a choice on the system it is important to do a more in depth research about the cost of fuel cells combined with batteries.

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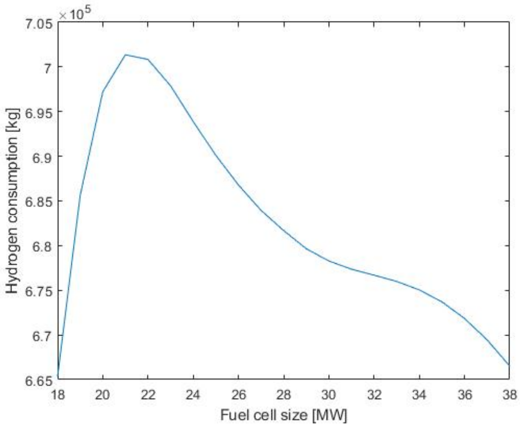
A

Range Calculations

A.1. First iteration



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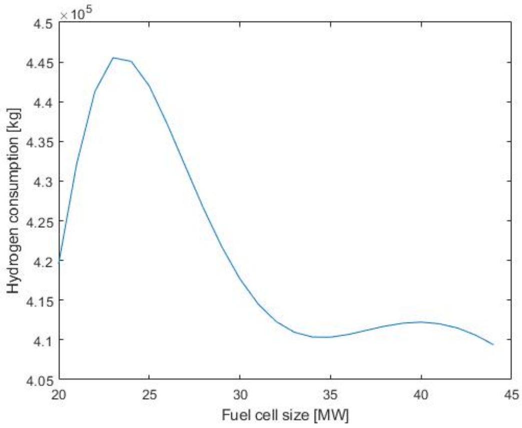

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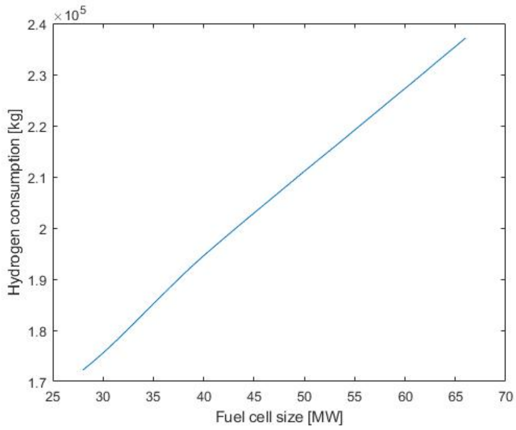

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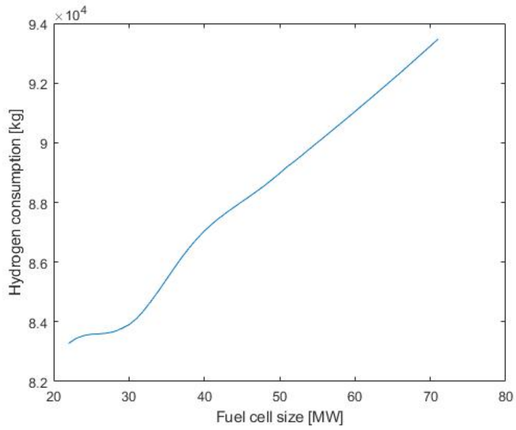

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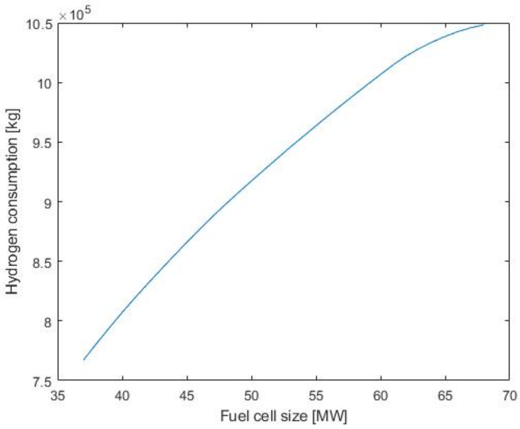
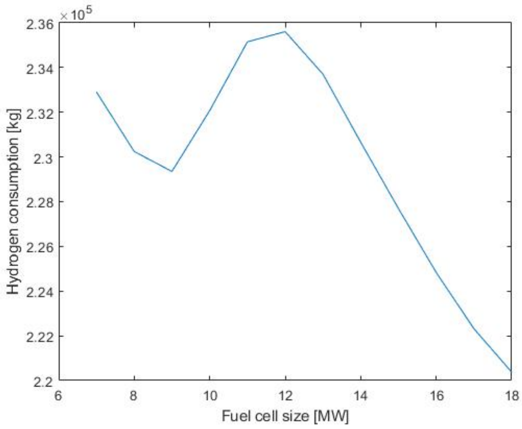
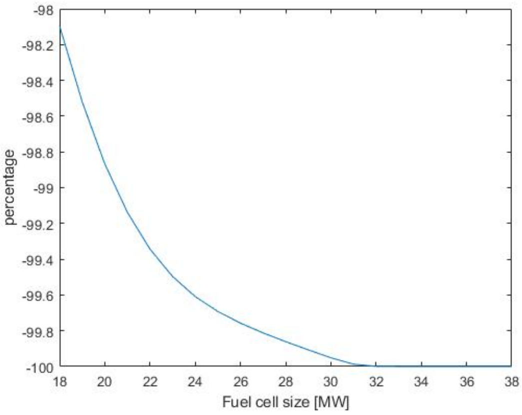


(e) Transit between ports



(f) Period in port

Figure A.1: Hydrogen consumption - Minimum battery size of 4 MWh



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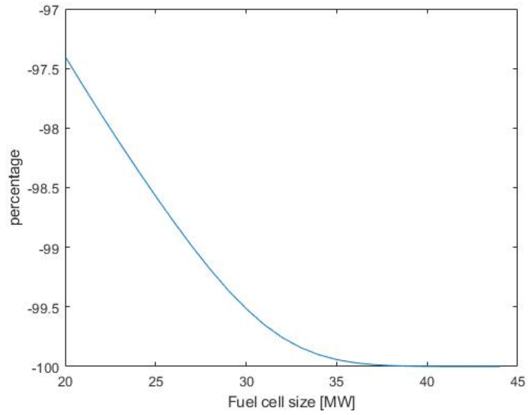

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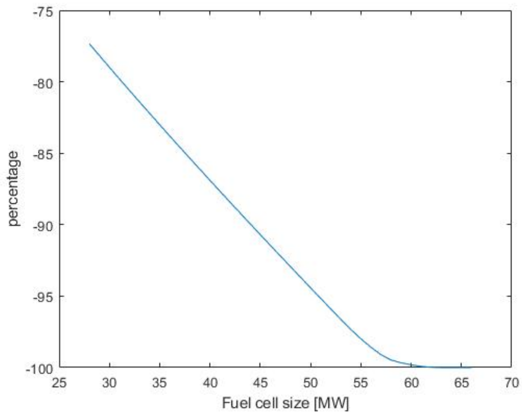

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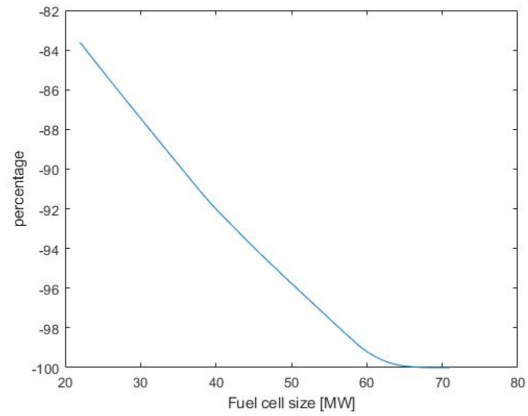

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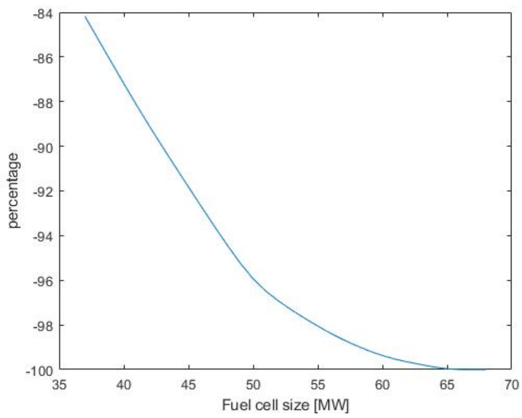

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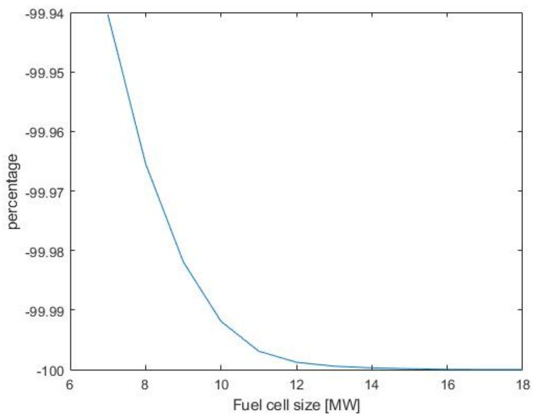
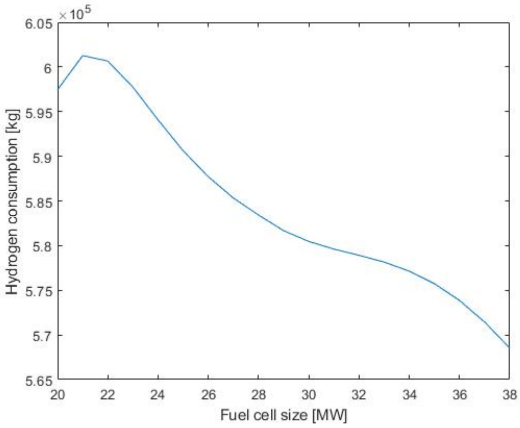


(f) Period in port

Figure A.2: CO_2 reduction - Minimum battery size of 4 MWh

A.2. Second iteration



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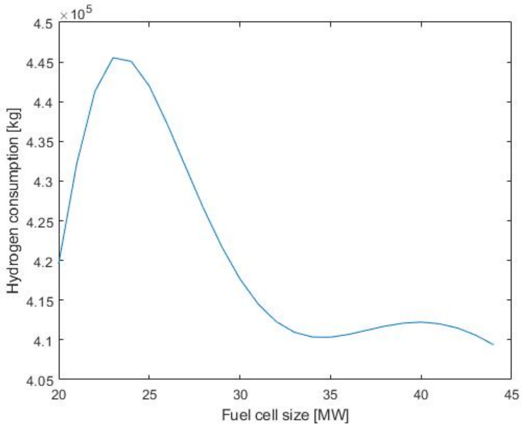

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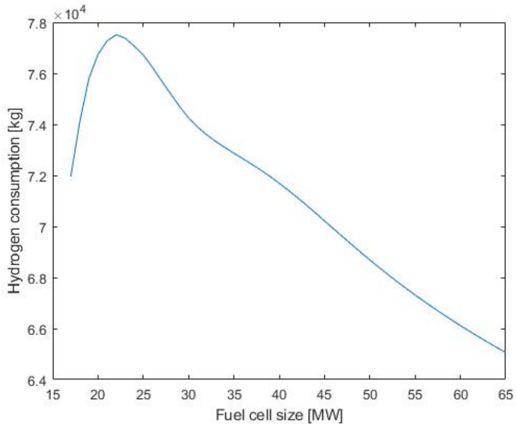
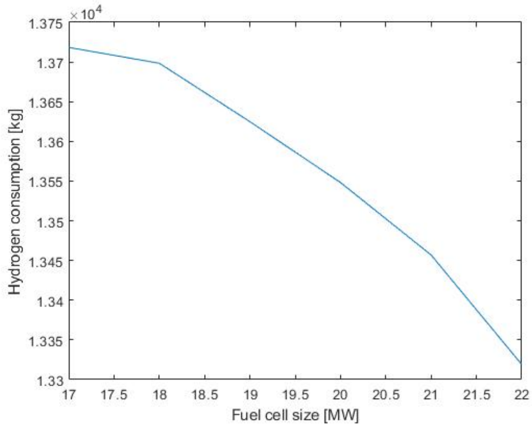


(c) Heavy lift project 1 - Between transits



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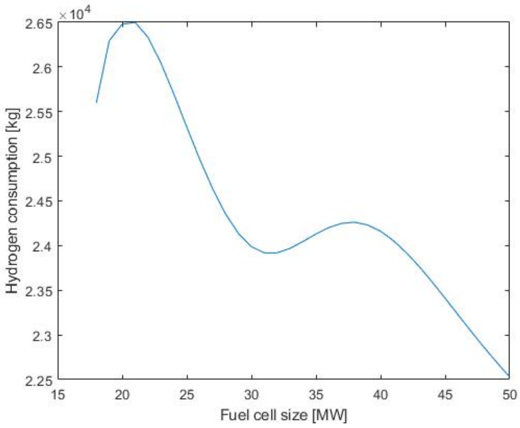
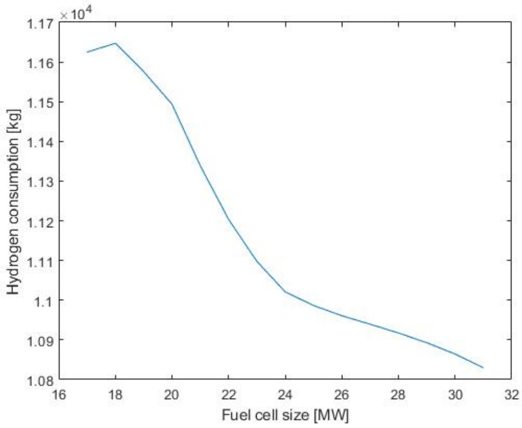


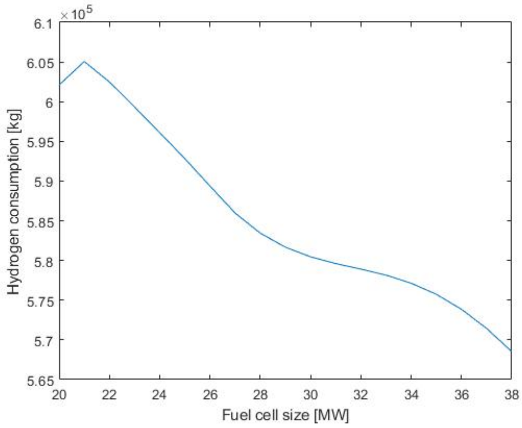
(e) Heavy lift project 2 - before transit



(f) Heavy lift project 2 - After transit

Figure A.3: Hydrogen consumption - Minimum battery size of 4 MWh

A.3. Third iteration



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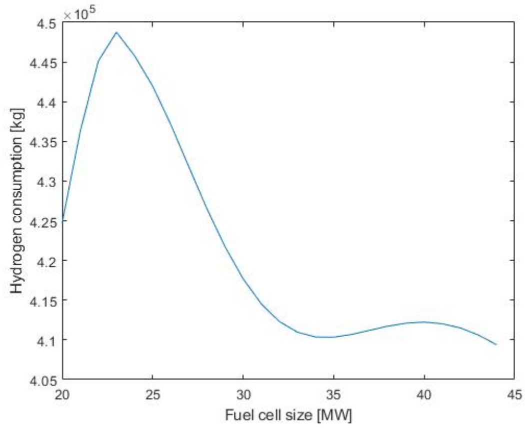

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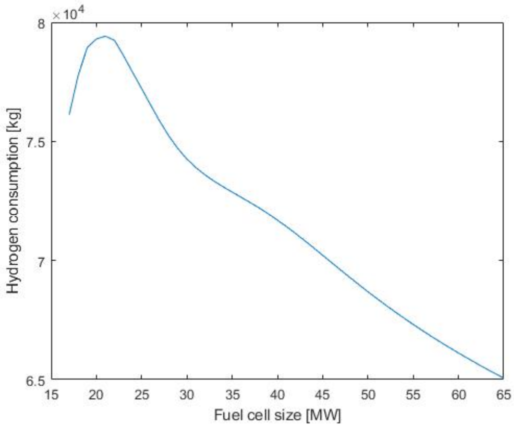
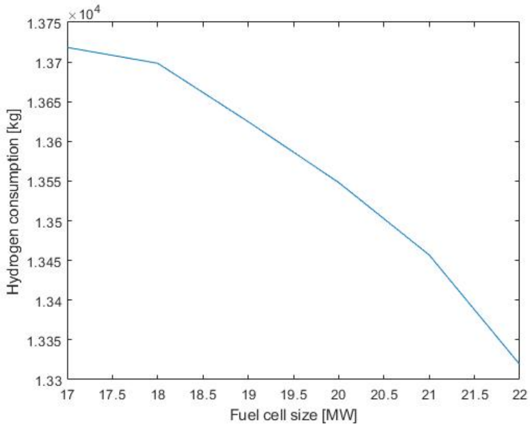
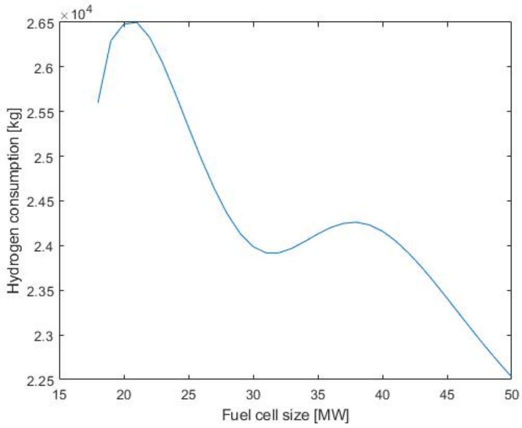


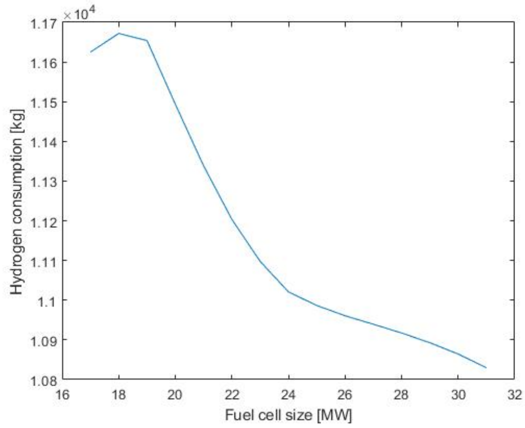
(c) Heavy lift project 1 - Between transits



(d) Heavy lift project 1 - After transits



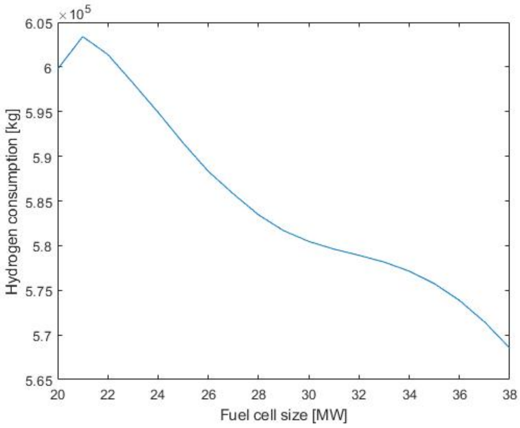
(e) Heavy lift project 2 - Before transit



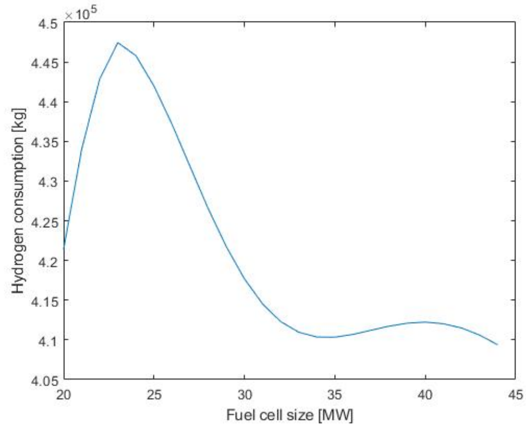
(f) Heavy lift project 2 - After transit

Figure A.4: Hydrogen consumption - Maximum battery capacity of 24 MWh

A.4. Fourth iteration



(a) Pipelay project 1



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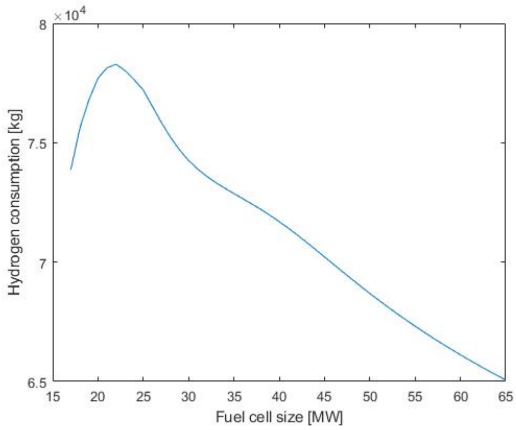
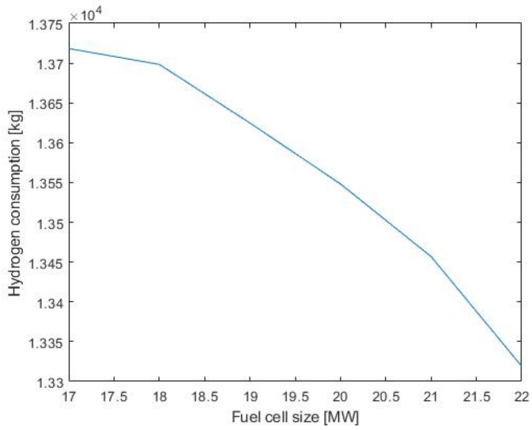
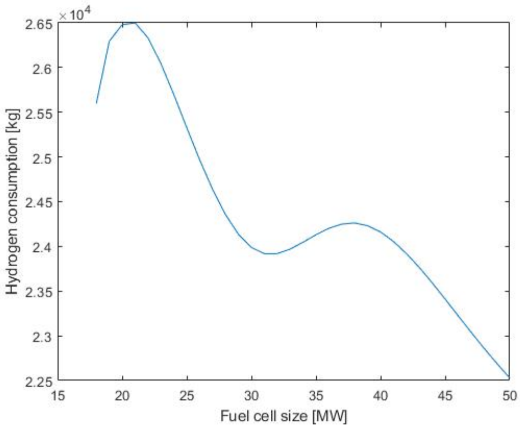


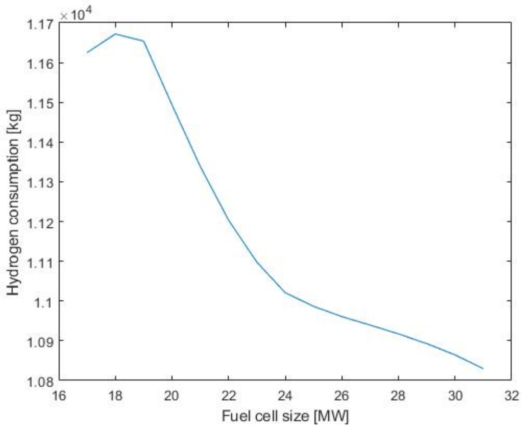
(c) Heavy lift project 1 - Between transits



(d) Heavy lift project 1 - After transits



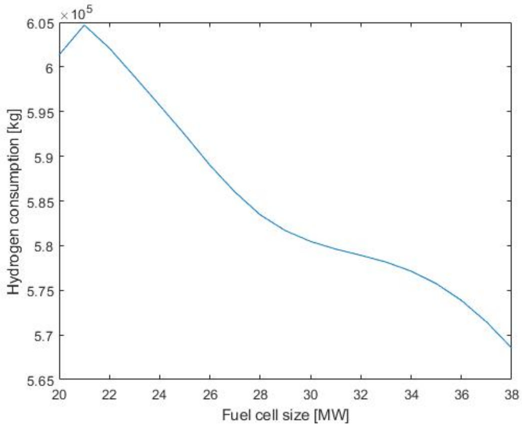
(e) Heavy lift project 2 - Before transit



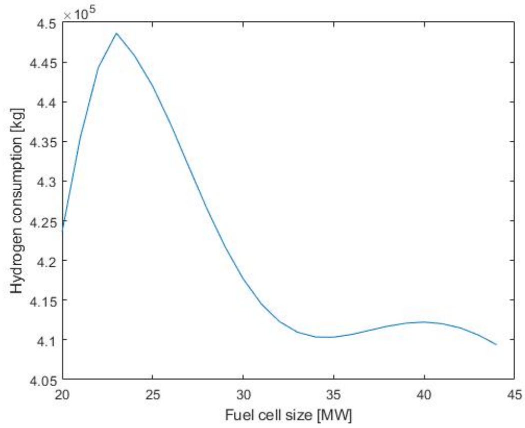
(f) Heavy lift project 2 - After transit

Figure A.5: Hydrogen consumption - Battery capacity of 10 MWh

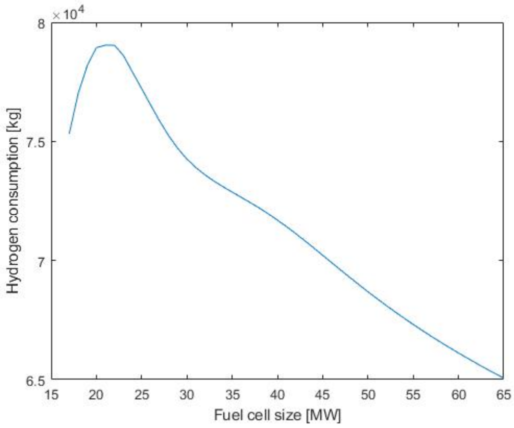
A.5. Fifth iteration



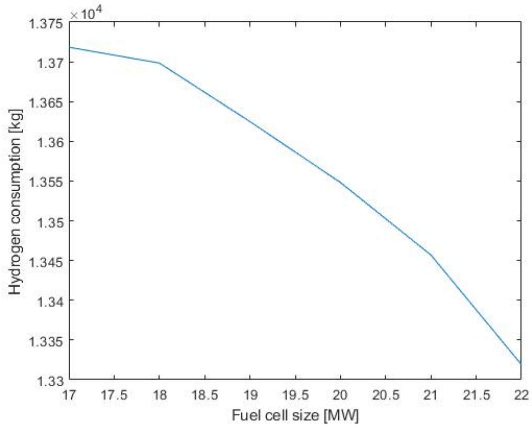
(a) Pipelay project 1



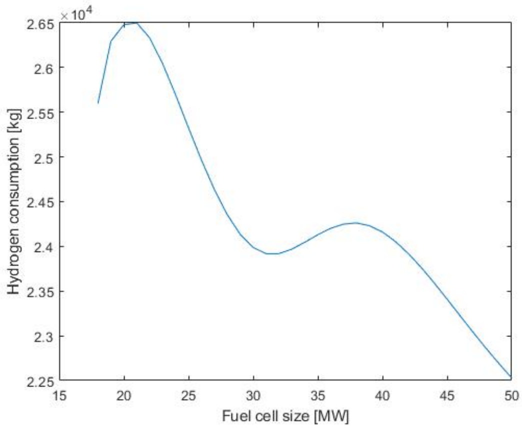
(b) Pipelay project 2



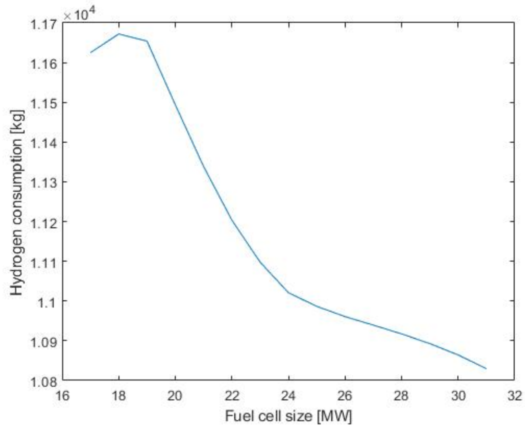
(c) Heavy lift project 1 - between transits



(d) Heavy lift project 1 - After transits



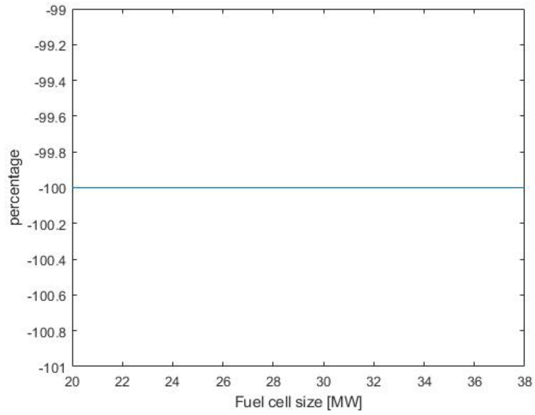
(e) Heavy lift project 2 - Before transit



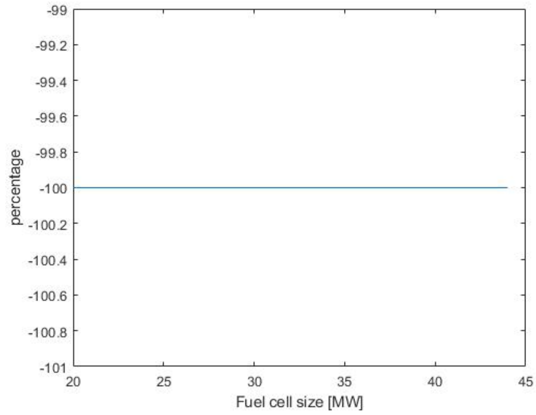
(f) Heavy lift project 2 - After transit

Figure A.6: Hydrogen consumption - Battery capacity 19 MWh

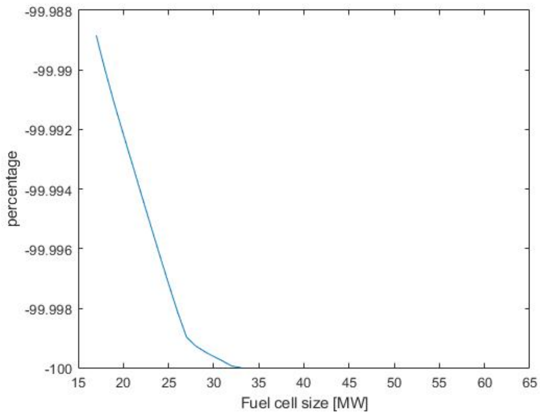
A.6. Seventh iteration



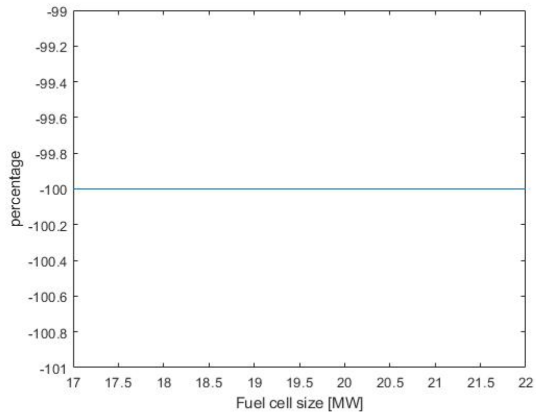
(a) Pipelay project 1



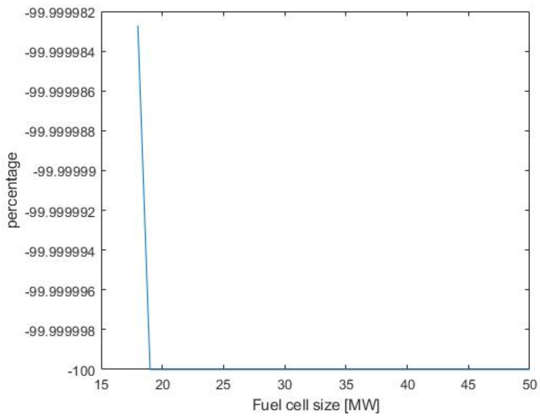
(b) Pipelay project 2



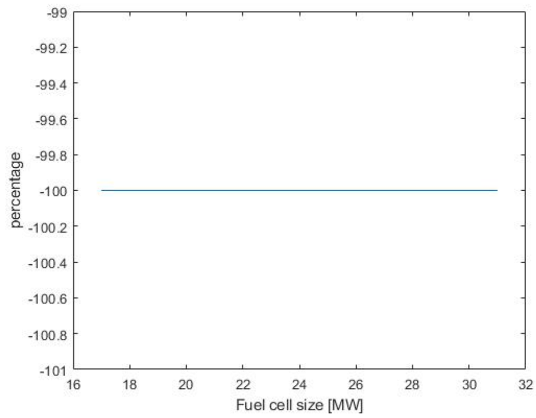
(c) Heavy lift project 1 - Between transits



(d) Heavy lift project - After transits

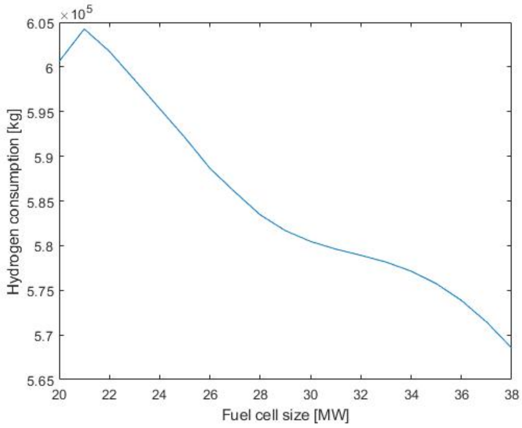


(e) Heavy lift project 2 - Before transit

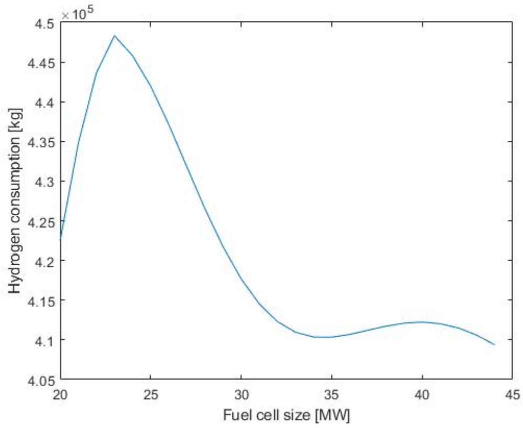


(f) Heavy lift project 2 - After transit

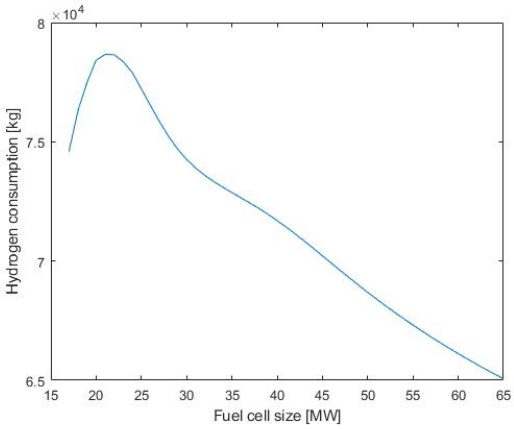
Figure A.7: CO_2 reduction - Battery capacity of 14.442 MWh



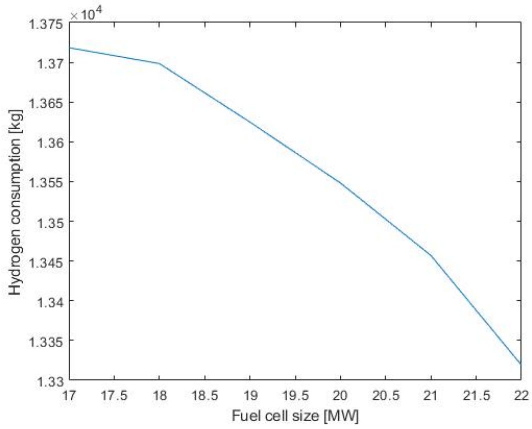
(a) Pipelay project 1



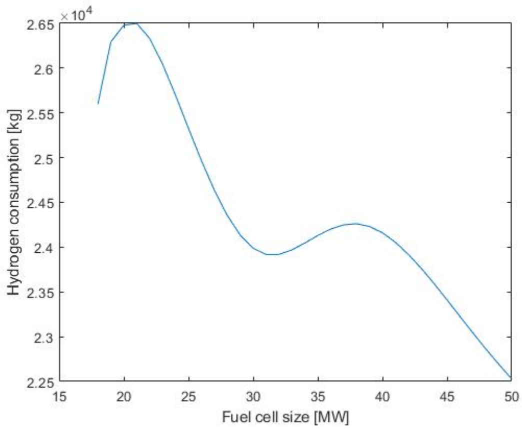
(b) Pipelay project 2



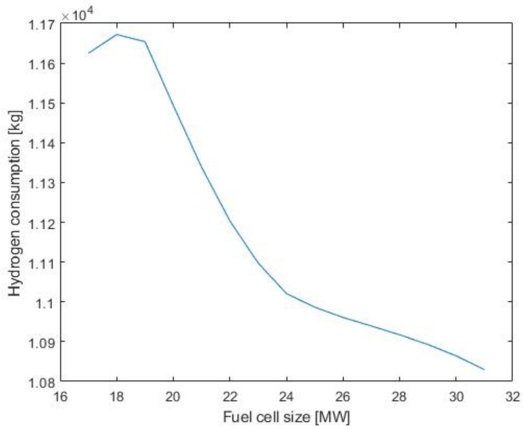
(c) Heavy lift project 1 - Between transits



(d) Heavy lift project 1 - After transits



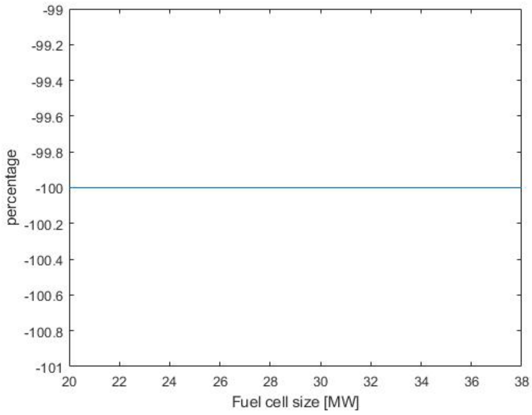
(e) Heavy lift project 2 - before transit



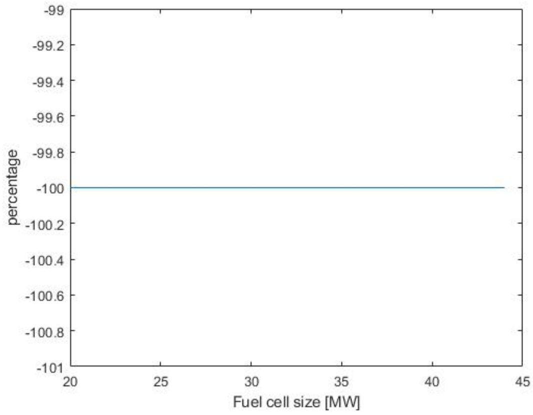
(f) Heavy lift project 2 - After transit

Figure A.8: Hydrogen consumption - Battery size of 14.442 MWh

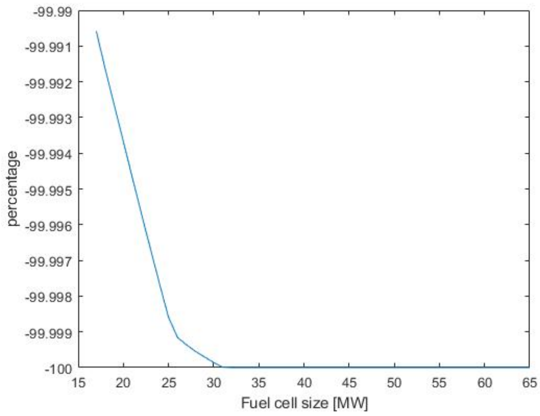
A.7. Seventh iteration



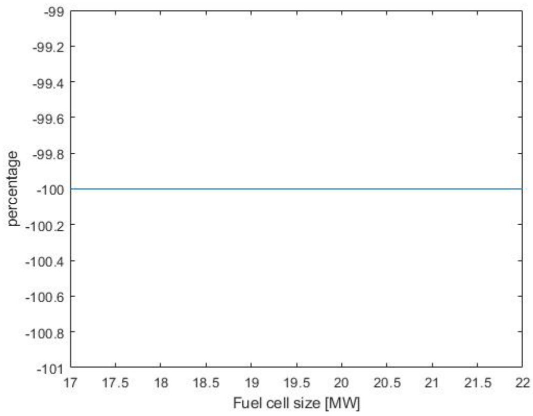
(a) Pipelay project 1



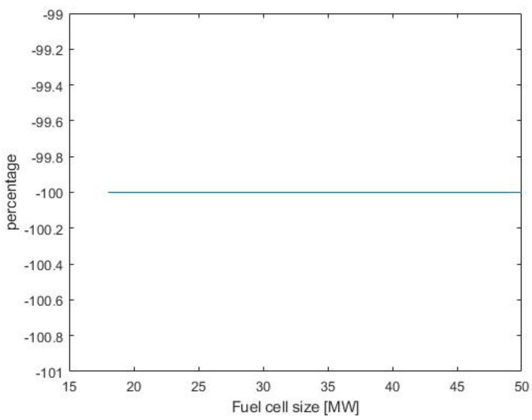
(b) Pipelay project 2



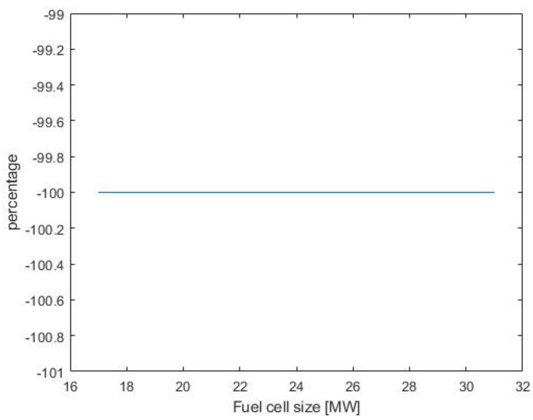
(c) Heavy lift project 1 - Between transits



(d) Heavy lift project - After transits

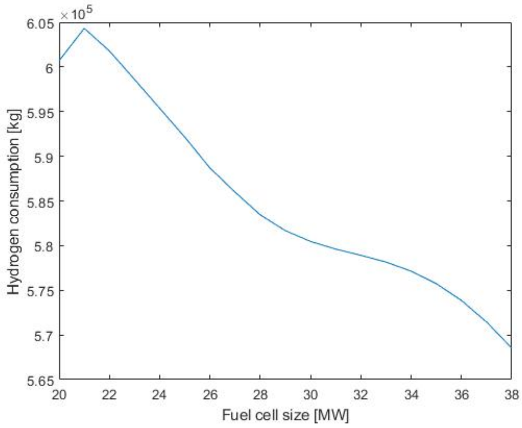


(e) Heavy lift project 2 - Before transit

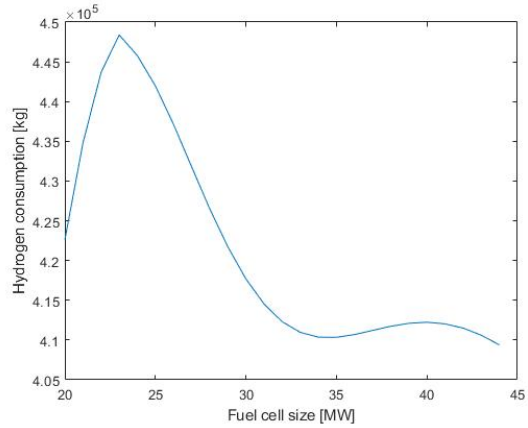


(f) Heavy lift project 2 - After transit

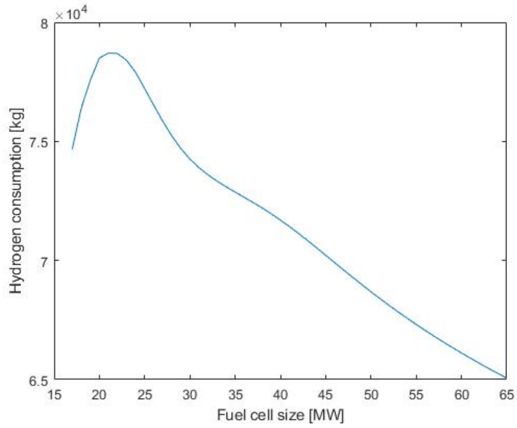
Figure A.9: CO_2 reduction - Battery capacity of 14.94 MWh



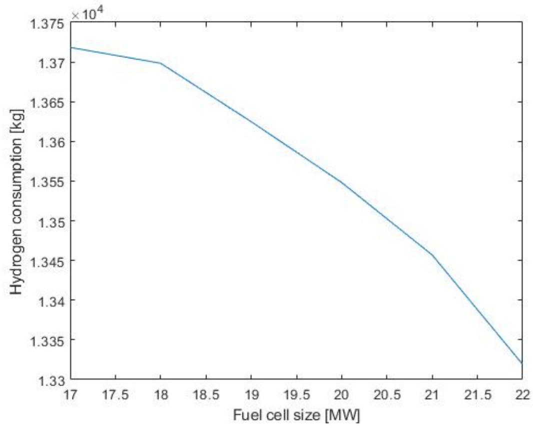
(a) Pipelay project 1



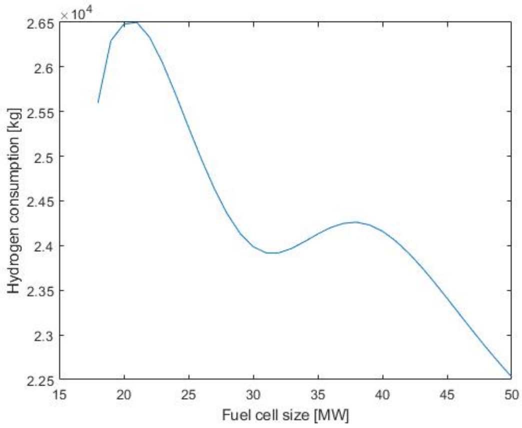
(b) Pipelay project 2



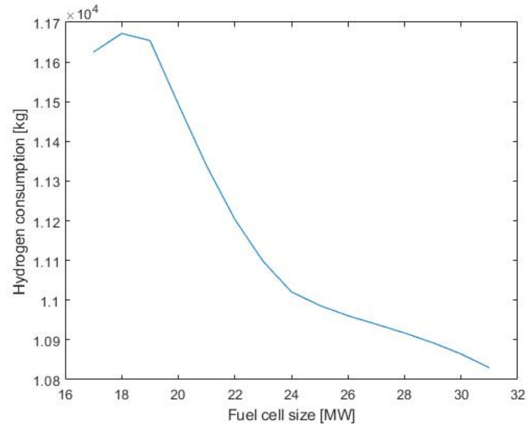
(c) Heavy lift project 1 - Between transits



(d) Heavy lift project 1 - After transits



(e) Heavy lift project 2 - before transit



(f) Heavy lift project 2 - After transit

Figure A.10: Hydrogen consumption - Battery size of 14.94 MWh