Enhancing Greenhouse Gas Emission Performance of Offshore Installation Vessels through Swappable Energy Containers

Marine Technology MSc Thesis

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JUMBO

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by

Marc Dekker

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Preface

Writing this preface, I realize that it symbolizes the closure of my academic career, marking the end of my time as a marine technology student. During my time at the Technische Universiteit Delft, I pursued my enthusiasm for technical installations on board seagoing vessels. This thesis allowed me to delve deeper into this subject, expanding my knowledge while pushing the boundaries of my intellectual horizon.

I wish to express my gratitude to my supervisor, Mr. L. van Biert, for his guidance and support throughout the MSC graduation process. The meetings every other week served as a significant source of motivation.

I am grateful to the marine engineers working at Jumbo Maritime, for their guidance and valuable insights throughout this graduation project, sharing their experience and pointing out the potential pitfalls. Among this select few, I owe a special debt of gratitude to my company supervisor Mr. M. Teunis for introducing me into the Jumbo community, granting me full autonomy to explore my most preferred topic, and equipping me with all the tools required for my research. The atmosphere in the Schiedam office resulted in a truly enjoyable and enriching experience throughout.

It goes without saying that this thesis would not have been possible without the full support of my family and friends. The process underscored the importance of a secure and supportive environment, allowing me to wholeheartedly dedicate myself to this graduation project.

With respect to the huge challenge that we face as humans to mitigate the effects of the climate crisis, I hope that this work serves as a source of inspiration for future researchers in the maritime sector, emphasizing the need to evaluate all possible means to reduce human dependency on fossil energy.

Marc Dekker
Enkhuizen, November 2023

Abstract

This master's thesis explores an alternative approach to enhance the emission performance and energy efficiency of offshore installation vessels without expensive retrofits. The concept involves employing swappable energy containers, currently used for inland cargo and tug vessels, for offshore installation vessels. These containers are filled with sustainable alternative energy sources and operate alongside conventional internal combustion engines. The study considers various technical architectures to achieve this objective. Regarding this case, the following question could be formulated.

How can swappable energy containers be effectively integrated into offshore installation vessels to reduce greenhouse gas emissions and enhance the energy efficiency, considering real load profiles?

The need for a global energy transition to mitigate the climate crisis has led to international initiatives, such as the International Maritime Organization's (IMO) target to reduce carbon dioxide emissions from shipping by 40% by 2030, 70% by 2040, and near-zero by 2050. The greenhouse gas emission share of the shipping industry is currently marginal in the context of global greenhouse pollution. However, this should not serve as an excuse to burn fossil fuels, as the share would inevitably increase if business as usual continues. Nonetheless, the quantity of emissions remains substantial, and significant gains can be realized by enhancing the efficiency of individual sectors. Undoubtedly, every effort should be made to replace fossil fuels with renewable and sustainable alternative energy sources in the long run, meeting IMO's 2050 goals. Until that time, enhancing the overall efficiency and emission performance of the current vessels seems like the way forward to meet intermediate targets.

This research represents a collaborative effort between the author and Jumbo Maritime, a global heavy-lift shipping and offshore transportation & installation company. The primary objective is to evaluate the most significant relative reduction in emissions per energy container by employing various energy control strategies within different technical architectures.

This thesis assessed whether energy containers can significantly improve the total emission performance for offshore installation vessels, if not, make such a vessel comply with the IMO's climate targets for 2030. However, the required number of batteries has a significant impact on the levelized fuel cost, therefore the most effective solution can be found with the largest relative emission reductions. Nevertheless, the complete elimination of greenhouse gas emissions can only be achieved by transitioning from fossil fuels to renewable and sustainable alternative energy sources. Enhancement of the fuel efficiency through a marginal number of battery containers with strategies such as enhanced dynamic behaviour, boost capacity or spinning reserve, could then contribute to the cost-effectiveness of these renewable fuels.

While this research offers the initial insights, further studies are required to address limitations, such as integrating multiple hybrid control strategies and conducting cost-benefit analyses. Additionally, future research could explore the use of means like machine learning or artificial intelligence, selecting the most appropriate hybrid control strategy at any moment in time to optimise the overall efficiency of offshore vessels.

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1 Introduction

In the middle 18th century, the growing population required more efficient production methods of essentials, which initiated the human dependency on fossil energy. Since then, increased living standard resulted in large quantities of greenhouse gases. Subsequently, the global average surface temperature has increased by about 1 °C in reference to 1900 [United States Environmental Protection Agency, 2020]. Continuing these human activities will further increase the earths surface temperature, a threshold with irreversible consequences for local ecosystems [National Research Council., 2020]. A global energy transition is the key to reduce the climate crisis effects. These effects can be measured by an increase in the annual temperature, which can be linked to an increase of the so-called greenhouse gases in the atmosphere. Carbon dioxide is currently the most dominant greenhouse gas in the maritime sector. Recent estimates by the International Maritime Organization (IMO) show that greenhouse gas emissions of shipping have increased by 9.6% between 2012 and 2018, while the IMO strives to reduce CO_2 emissions by at least 40% by 2030, and 70% by 2040 and close to zero in 2050, in reference to 2008 [IMO and UNFCCC,]. Polluting industries have to cope with new regulations on carbon emissions and subsequently enforced to take action. Accordingly, maritime industry have to participate and is therefore facing a huge transition from fossil fuels to renewable energy sources.

Consuming renewable energy is only partially contributing towards clean operations at sea. The generation of alternative energy carriers is mostly done by the chemical industry, which still predominately uses electricity and feedstock that originates from fossil sources, such as coal or gas. All the losses in the well to wake chain increase the environmental impact, therefore, adding insult to injury. Public opinion in all levels of society is increasingly more in favour of an energy transition, despite economic uncertainties [Thomas et al., 2022]. Ideally, governmental policymakers should influence the energy market with subsidies on renewable energy generation and speed-up legal procedures. Companies can participate in the energy transition by investing in sustainable projects and creating demand for clean energy. However, many climate-neutral shipping practices are currently commercial infeasible and consequently do not compete with conventional ways of shipping at this time [Stolper et al., 2022]. Nevertheless, the urgency of the matter requires action that justify the route to zero goals of the International Maritime Organization. Undoubtedly, every effort should be made to replace fossil fuels with renewable and sustainable alternative energy sources in the long run. Although there is already a significant amount of literature addressing this topic across various maritime sectors, it remains a fact that the majority of the globally operating fleet continues to rely on conventional propulsion systems. Given the extended life expectancy of most seagoing vessels for which, it is often economically impossible to retrofit the technical layout to sustainable alternative energy sources, it becomes necessary to explore alternative resources and solutions that can enhance the emission performance as such that these vessels can at least meet with the IMO's interim goal of 2030.

Improving the fuel efficiency and emission performance of existing vessels through the collaborative efforts of a smart system alongside conventional methods appears to be a promising approach to achieve interim goals. The first part of this thesis explores the most modern solutions that could possibly be used for this approach to extend the operational life of current vessels. Employing such solutions, while avoiding a complete retrofit, offers the advantages of flexibility for different contracts, the ease of upgrading, especially given the rapid pace of technological advancements, and addressing the limited lifespan of state-of-the-art battery and fuel cell systems in comparison to the vessels' extended life expectancy. These arguments indicate that a swappable modern solution could meet these desires. Such concepts already exist and are currently only used for vessels with straight forward operational profiles on limited scale. Organisations that commercially supply swappable energy containers currently focus only on hydrogen and batteries storage. This is mainly due to the bunker complications of both these storage techniques. This research explored the opportunity to use these described energy container infrastructures, that were originally intended for inland cargo and tug vessels, on offshore installation vessels owned by Jumbo Offshore as a means to mitigate greenhouse gas emissions. The containers are filled with sustainable alternative energy forms that will operate alongside the conventional internal combustion engines and in addition, multiple technical architectures are considered. To reach valid results, a research question is formulated that represents the problem. This will define the purpose, scope, and the direction of the thesis. Regarding the case and problem discussed, the following question could be formulated.

How can swappable energy containers be effectively integrated into offshore installation vessels to reduce greenhouse gas emissions and enhance the energy efficiency, considering real load profiles?

1.1. Thesis Structure and Objective

The main objective of this thesis is to assess the most significant relative reduction in emissions per energy container by employing various energy control strategies, within three different technical architectures. To find a satisfactory answer to this objective, the research question is subdivided into several sub-questions, each of which will be addressed in the different chapters.

The initial phase of the thesis research will identify the reference ship and installed power configuration. Furthermore, this chapter identifies the greenhouse gas emission categories and regulatory frameworks, which will also be used later in the thesis to evaluate different hybrid control strategies.

The literature review attempts to develop a valid framework for the main thesis. Therefore, the literature review will focus on technologies that could be implemented on board to achieve this emission objective. This chapter discusses the recent developments in renewable and sustainable alternatives through which potential emission reduction and efficiency enhancement could be achieved. Subsequently, the first sub-question where current low emission technologies and hybrid strategies are introduced, is defined as:

What are the relevant technologies that could reduce greenhouse gas emissions resulting from current diesel generators?

Through real electrical performance data collected from the dynamic positioning computer, a transitional load curve will be defined. The reason for this is to establish a benchmark that acts as a reference to evaluate any emission performance improvements. Therefore, the second sub-question is formulated as follows.

What is the load profile of Jumbo's Heavy Lift Construction vessel during an offshore installation operation, using real performance parameters?

The main part of this thesis is to develop a simulation method in python. Through load profiles, a simulation should determine the impact of different hybrid control strategies and the required amount of energy containers. Subsequently, the potential CO_2 and NO_x reductions are quantified, using the calculations in the methodology 4. The different cases evaluate the defined energy control strategies which are considered applicable in regard to technical architecture and load profile. Therefore, obtaining which technical configuration has the highest emission reducing potential.

Which hybrid control strategy has the highest relative emission reduction potential while enhancing the energy efficiency of the electrical grid?

After finding the technical configuration that has the highest emission reducing potential, it is possible to assess the final objective of this thesis. This is to evaluate if a swappable power extension is a technically feasible solution. Construction of previous heavy lift vessels resulted in limited space for accommodating the machinery spaces. Installing energy storage that is more spacious than diesel oil seems problematic. Moreover, when faced with the current energy density trends of, for example batteries, it is plausible that the state-of-the-art systems age quickly over the 25-year lifetime of a vessel. Consequently, this makes the application of energy containers appealing.

To what extent can the electricity demand of a heavy-lift construction vessel be made with interchangeable power containers without compromising the offshore operations?

The focus will be on offshore vessels because they have a complex electric energy demand compared to ocean-going shipping vessels. The operational profile of offshore vessels is dominated by heavy lift operations on dynamic positioning (DP), which causes a fluctuating electrical power demand. The input of large consumers such as thrusters, cranes, ROV's, Reel drive and track tensioners, will have the largest impact on the load variations. The electrical consumption data and operational profile of a vessel in current offshore operation will be used as a reference.

1.2. Involved Company, Jumbo Maritime

This master's thesis represents a collaborative effort between the author and Jumbo Maritime, a global heavy-lift shipping and offshore transportation & installation company, aimed to enhance the overall vessel efficiency and reduce emissions. The Schiedam based company operates eighth in-house designed heavy lift vessels with a lifting capacity from 800t up to 3,000t. These ships are equipped to efficiently load and unload a wide range of complex cargo at berths around the world. Jumbo's philosophy is that engineering, safety awareness and environmental care stand at the forefront of a reliable operation. The thesis is therefore a consequence of Jumbo's drive to invest in projects that enhance these objectives.

2
Background

2.1. Greenhouse Gas Emissions

Vessels in the maritime industry effect their surroundings not only by means of exhaust to air emissions. It must be mentioned that the disposal of garbage, ballast water, and in the end the vessel itself have their effect on the overall environmental impact. Also, underwater radiated noise, caused by a vessel's propeller and offshore installation, has an impact on marine life. Among these, exhaust gas to air emissions is still considered the largest contributor to global warming [Anders, 2019]. Reducing these emissions thus has the greatest impact on meeting with IMO's climate targets.

The fourth International Maritime Organisation greenhouse gas study classified the exhaust to air emissions in two groups. The emissions for each system (i.e. main engines, auxiliary engines) have been divided based on how the emissions are commonly calculated. Accordingly, the emissions are defined as Energy-based and Fuel-based [International Maritime Organisation, 2020]. According to this study, energy-based pollutants are calculated depending on the engine's/boiler's rated power output (kW) and an energy-based emission factor in g pollutant/kWh. For this thesis, this energy-based emission factor is load depended. The following emissions enter into the energy-based group: nitrogen oxides (NO_X), methane (CH4), carbon monoxide (CO), nitrous oxide (N2O), particular matter (PM2.5 and PM10) and non-methane volatile organic compounds (NMVOC). Fuel-based pollutants depend on the amount of pollutant found in the fuel. Therefore, the consumed amount of fuel (ton)is multiplied with a specific polluter index (SPI). In this category the emissions are CO_2, sulphur oxides (SO_x). To demonstrate the potential impact of energy containers on both these categories, this thesis will evaluate one type of green house gasses of each category, namely nitrogen oxides (NO_X) and carbon dioxide (CO_2).

2.2. Regulations

The regulatory framework is evident for this thesis as for some of the battery control strategies regulation play a dominant factor in sizing the appropriate amount of batteries.

2.2.1. International regulatory framework regarding emissions

The international maritime community has agreed that greenhouse gas emissions originating from the sector must be diminished. Regulations are a vital tool to guide all maritime sectors towards a green strategy and establish sustainable standards. As of 2023, multiple governmental agencies work on new conventions that enforce these goals. The best-known agency with the highest level of jurisdiction is the International Maritime Organisation (IMO) [Kim et al., 2020]. Rules on the emissions of ships are contained in the 'International Convention on the Prevention of Pollution of Ships', better known as MARPOL 73/78. Air pollution is described in Annex VI. Tier 1 to 3 regarding sulphur oxides, nitrogen oxides, and ozone depleting substances. The Latest Amendments added a new Tier 4 to Annex VI on "Regulations on energy efficiency for ships". This strategy aims to reduce carbon dioxide emissions to 70% in reference to 2008 by 2050. This transition is divided into stages, and Phase II has already been established since 1 January 2020. The next phase is due in 2025 when carbon emissions must be reduced to 30%, 40% by 2030 when the fourth stage begins, and by 50% to 70% by 2040 when the fifth stage begins [IMO and UNFCCC,].

In MARPOL Annex VI, Chapter 4, three mechanisms are presented. These are the Energy Efficiency Design Index (EEDI), for new building vessels, the Ship Energy Efficiency Management Plan (SEEMP) for all ships and Energy Efficiency Operational Indicator (EEOI) which is voluntary. Respectively, EEDI is a mechanism that requires a certain level of efficiency from a new ship. It is not restricted to what technologies must be applied to satisfy these requirements. SEEMP offers a mechanism to optimise the energy efficiency of ships [Dieselnet, 2023]. It is good to note that EEDI requirements do not apply to all ship types. For example, cargo ships with ice-breaking capability or ships which have nonconventional propulsion, such as a diesel-electric or hybrid propulsion system, do not account for these mechanisms.

On the domestic level, many countries impose their own additional regulations. Authorities of, the US, Europe, China, Norway or South Korea, each have their additional requirements, however these surpass the scope of this master's thesis. To illustrate the complexity of these frameworks, [Kim et al., 2020] and [Ni et al., 2020] offer a good overview of domestic and international regulations.

Regarding the regulations for NO_X emissions, the IMO emission standards are commonly referred to as Tier I to IV standards. When the J-1 and J-2 vessels were built Tier I was into force, therefore engines with a classification "tier I" complied with the legislation. Despite the fact that tier II is into force globally, for vessels with keels laid on or after 1 January 2021, operating in the Baltic Sea or North Sea NECA, must be equipped with Tier III engines. Moreover, newly installed engines onboard of excising vessels need to comply with this new regulation as-well [Dieselnet, 2023]. The consequence of this is that the replacement generators need to be at least "tier II" certified.

2.2.2. IMO guidelines regarding Dynamic Positioning

For vessel with DP capabilities constructed before the 16 June 2017, IMO MSC/Circ. 645 Guidelines for Vessels with Dynamic Positioning Systems of 6^{th} June 1994 apply. For the use of alternative means of energy as a redundant source of power, these guidelines provide the following requirement [Stetow, 2019]:

> **3.1.4:** *Redundant components and systems should be immediately available and with such capacity that the DP-operation can be continued for such a period that the work in progress can be terminated safely. The transfer to a redundant component or system should be automatic as far as possible, and operator intervention should be kept to a minimum. The transfer should be smooth and within acceptable limitations of the operation*

With the battery characteristics described in subsection 3.2.3, swappable batteries qualify for application in modern DP systems.

2.2.3. DNV: Battery class rules for redundancy

For a battery to be used as a redundancy source in the DP system, the configuration needs to be approved by a classification bureau. Classification societies are organizations that enhance maritime safety by establishing and enforce technical standards and regulations on the design, construction, and operations of ships. Among others, DNV-GL is a well known classification society that has defined such a regulatory framework. Class notations regarding the use of battery hybrid technologies are located in Part 6 Chapter 2 and Part 6 Chapter 3 under DNV-GL rules for classification of ships (RU-SHIP). Within these guidelines, there are two levels of class notations when a large battery system is installed on board:

- **Battery safety notation;** General requirement mandatory where battery is used for power source when battery capacity exceeds 50kWh. The application is an additional source of power or for improved dynamic performance of power.
- **Battery power notation;** Additional notation for vessels when battery is used as propulsion power during normal operations, or when battery is used as redundant source of power for main or/and additional source.

As batteries will replace one or more running generators with instant available power, the battery power notations will be used. This notation is more challenging than the safety notation in terms of safety, energy management and testing. One crucial rule in this notation when a battery is used as redundant power source is chapter 3, section 1.

4.3: Redundancy
For DYNPOS(AUTR), DYNPOS(AUTRO) and DPS(3): The DP system shall be designed with redundancy. A position keeping ability shall be maintained without disruption upon any single failure.

4.3.1: ***Guidance note:*** *Component and system redundancy, in technical design and physical arrangement, should in principle be immediately available with the capacity required for the DP system to safely terminate the work in progress. The consequence analysis required in [6.13] will give an indication whether the position and heading can be maintained after a single failure.*
—e-n-d—o-f—g-u-i-d-a-n-c-e—n-o-t-e—

4.3.2: *For DPS(2): The requirement in [4.3.1] also applies to this notation, however it can be accepted that the system is dependent on change-over of a single stern thruster in order to maintain position keeping ability after loss of one redundancy group. The change over may be based on full stop and restart.*

Guidance note: *A typical thruster configuration with two bow tunnel thrusters, one single stern tunnel thrusters and two pitch propellers with high- lift rudders, distributed between two redundancy groups will be accepted for DPS(2) notation as long as the single stern tunnel thruster is arranged for being changed over between the two redundancy groups. When such design is chosen as basis for the redundancy the possibility for hidden failures causing loss of the change-over function and the possibility for single failures affecting more than one redundancy groups should be carefully considered in order to minimize the possibility of such failures. Adequate evaluations should be included in the FMEA required in [1.6]*
—e-n-d—o-f—g-u-i-d-a-n-c-e—n-o-t-e—

The battery system must have enough capacity for the ship to halt its operation and move away from danger if needed. For instance, in case of the Viking Energy, the utmost duration permissible for operation termination is 7 minutes [Langåker-Westcon, 2017]. The classification society requires the ship designers to obtain all the operations of the vessel to determine the duration of escaping. And then, the maximum abortion time defines the time requirement for the battery. Regarding the enhanced dynamic performance, batteries are sized according to the following citations from DNV RU-SHIP Part 6 Chapter 3, Section 2, 8 Power systems:

8.3: Batteries supplying power to DP thrusters.
These requirements are applicable to DP systems where batteries are used as source of power to thrust producing units, hereafter named thrusters.

8.3.1: ***Guidance note:*** *Battery installations not used as a redundant source of power, but only used e.g. for peak shaving, handling of dynamic responses in the power system, etc., may not have to comply with these requirements.*
—e-n-d—o-f—g-u-i-d-a-n-c-e—n-o-t-e—

8.3.2: *Batteries can be accepted as source(s) of power for DP thrusters, but the DP system shall be designed such that the vessel also can fulfil the relevant dynamic positioning class notation(s) requirements without the batteries. Guidance note:*

Guidance note: *The vessels DP position keeping capacity (both before and after failure, i.e. the redundancy design intention) may vary when batteries are connected or disconnected.*
—e-n-d—o-f—g-u-i-d-a-n-c-e—n-o-t-e—

8.3.6: *When batteries are used in combination with standby-start of generator sets, the battery power and energy shall generally be such that the DP system in all intended technical system configurations, immediately after failure of any combination of generators/batteries subject to a relevant single failure (i.e. before any standby-start), can produce minimum 1/3 of the power available before failure. The system shall, without considering contribution from standby start, be able to deliver this power level in a time period equal to the specified minimum time requirement.*

> ***Guidance note:*** *The 1/3 requirement is based on a standard system with 2 equally sized generator sets in each redundancy group, where a 2+1 mode will result in 1/3 available power in case of failure of the two generator sets belonging to the same group. Based on a case by case evaluation other system arrangements and battery sizes (power and/or energy) may be accepted.*
> *—e-n-d—o-f—g-u-i-d-a-n-c-e—n-o-t-e—*

2.2.4. Hydrogen as a fuel, regulatory framework

Starting from top to bottom, firstly IMO regulations are explored. IMO's operations are organized into multiple subcommittees, one of which is the Marine Safety Committee (MSC). This committee has a subcommittee on carriage of cargo and containers (CCC) that is responsible for work on the IGF code. This code, serves as the regulatory framework for the safe utilization of low-flashpoint marine fuels, thus hydrogen. Currently, any specific regulations are not yet in place for the use of hydrogen as marine fuel. However, through this IGF code, it is possible to verify safety compliance for ships using gas fuels other than LNG such as, hydrogen. If the design process is based on risk assessment, any unconventional ship types and power systems can be accepted. According to [Alvestad and Berge, 2021], it is expected that any gaps for ships using fuel cell technology will be included as well in the IGF code in the next revision. As of today, ships with fuel cell technology regardless of their fuel type are still required to follow SOLAS regulation II-1/55. In this document it is also suggested that standards and codes for industrial use of hydrogen are in already enforced among all industrial sectors, and that some of these codes such as the transport of hydrogen on board of container vessels (International Maritime Dangerous Goods IMDG code) could form a framework for the use of hydrogen as fuel on board ships.

Regional regulations regarding on board storage of hydrogen are quite complex. To indicate how complex worldwide regional regulations are, the European legislation relevant to hydrogen storage in 20ft to 40ft containers are [Alvestad and Berge, 2021]:

- SEVESO Directive (Directive 2012/18/EU): above 5 tons,
- ATEX Directive 2014/34/EU: Equipment and protective systems to be used in potentially explosive atmospheres,
- SEA (Directive 2001/42/EC) and EIA (Directive 2011/92/EU): Environmental impact assessment procedure,
- Pressure equipment directive: Applies to the design, manufacture and conformity assessment of pressure equipment.
- Directive 2010/35/EU: Applied to the design, manufacture and conformity assessment of cylinders,
- EU no 453/2010: Requirements for safety data sheets, etc.

In general, classification societies are more detailed and specific when assessing the safety level of international regulations and their application on board. For ship that have fuel cell technology on board DNV Ru-Ship, Pt.6 Ch.2 Sec.3 FC rules apply. While existing class rules can facilitate the alternative design process, it's important to note that if hydrogen containers in combination with fuel cell technology are being considered as a potential emission-reducing alternative, these DNV rules are not applicable [San Marchi et al., 2017]. According to [Alvestad and Berge, 2021] the current rules for gas-fuelled ship installations 'Section 5 – Gas fuelled ship installations – Gas Fuelled' are not applicable for hydrogen used as fuel. In addition, part A-1 of IMO's IGF Code provides specific requirements for ships using natural gas as fuel, and Chapter 6 covers the fuel storage systems. While these are not applicable for hydrogen powered vessel, some of these natural gas rules have also been used in some cases to provide guidance for classifying ships that are powered by hydrogen.

Regarding the hydrogen containers which use cylinders internally, ISO 17519 is a standard that can be used to design gas cylinders. ISO 11623:2002 for transportable gas cylinders, describes periodic inspection and testing of composite gas cylinders, and ISO technical committee 197 are relevant sources for hydrogen tank requirements and bunkering [Abma et al., 2019]. Currently, most certified systems use compressed hydrogen techniques. The result is that the application of hydrogen has matured and undergone relevant risk studies, yet the relatively low volumetric energy density compared to liquid storage is increasing the required amount of containers.

2.3. Vessel: Jumbo Fairplayer

The reference vessel from which the electrical grid will be evaluated is Jumbo's Fairplayer, internally referred to as jumbo's J-class design. The vessel was constructed and launched in 2008 as a heavy lift vessel and was used intended for long haul transportation of heavy lifts. However, due to a change in jumbo's business perspective, she was built as a DP2 vessel to be operated in the Offshore industry as an Offshore Construction Vessel. Despite Jumbo having four vessels of the J-class design in service, the technical layouts deviate from each other, implying that the results of this thesis may have another outcome if another vessel was considered

2.4. Power- and Energy systems

This section provides an overview of the technical layout of the Jumbo Fairplayer, stating the properties of the installed equipment used for the benchmark calculations. Table 2.1 gives an overview of the energy converters that are currently installed on board.

Table 2.1: Energy converters currently on board the Fairplayer

No.	Emission source	Technical description	Potential Fuel types
1	Main engine PS: Make: Caterpillar Type: 9M32C	Rated Power: 4500 kW@600 rpm SFOC: 187 g/kWh	Heavy Fuel Oil (HFO) VLSFO Marine Diesel/Gas Oil Bio-Fuel
2	Main engine SB: Make: Caterpillar Type: 9M32C	Rated Power: 4500 kW@600rpm SFOC: 187 g/kWh	Heavy Fuel Oil (HFO) VLSFO Marine Diesel/Gas Oil Bio-Fuel
3	Auxiliary engine FWD: Make: Caterpillar Type: 3516B	Rated Power: 1901 kW@1800rpm SFOC: 215 g/kWh	Marine Diesel/Gas Oil
4	Auxiliary engine AFT: Make: Caterpillar Type: 3516B	Rated Power: 1901 kW@1800rpm SFOC: 215 g/kWh	Marine Diesel/Gas Oil
5	Emergency generator: Make: Caterpillar Type: C18	LSA 49.1 S4 AREP Rated Power: 465 kW SFOC: 214 g/kWh	Marine Diesel/Gas Oil

2.4.1. Internal Combustion Engines

There are 3 types of engines on board, firstly the emergency or harbour generator, which is not evaluated in this research. The vessel's main propulsion configuration consists of two turbo-charged, 9-cilinder, four stroke, in line MAK 9M 32C, 600 rpm diesel engines rated at 4500kW output power. Both main engines drive a CPP directly through a gearbox and both main engines each drive a shaft generator of the make AEM, type SE 630 M4. Despite the main engines are capable of delivering 4500 kW, a maximum of 3750 kW can be used for the generation of electric power. Both auxiliary diesel generator sets are powered by turbo-charged, 16-cilinder, four stroke Caterpillar engines, type 3516B. The fuel is delivered to the auxiliary generator engines by means of gravity from a daytank design through pre-fuel duplex filters and a fuel cooler.

2.4.2. Electric generators

The electric generators are machines coupled to the diesel engines and converts the mechanical shaft power into electric power. Electric alternators are categorised by half a dozen different types, yet the generators in table 2.2 are all synchronous machines.

Table 2.2: Electric generators

Generator	Manufacturer	n	Tag plate Output
Shaft	AEM SE 630 M4	2	3$\sim$690VAC/60Hz/1800rpm/3750kVA
Auxiliary	AEM generator SE 500M4	2	3$\sim$690VAC/60Hz/1800rpm/2280kVA
Emergency	Leroy Somer LSA 49.1 S4 AREP	1	3$\sim$440VAC/60Hz/1800rpm/550kVA

For this thesis a power factor of 0.8 was assumed which matches the real electric power output of the generators. The electric outputs of the 3750 kVa and 2280 kVa generators are then 3000 kWe and 1825 kWe respectively.

2.4.3. Electrical distribution system

The main switchboard illustrated in figure 2.1 is the electrical scope of this thesis that will be evaluated for the modular power extension. This switchboard distributes 690V AC to large consumers such as, Bow thrusters, Azimuth thruster, Cranes, and also they supply the ASB 440 VAC transformers. Despite, the scope is limited to the main switchboard, a 440 VAC auxiliary switchboard and 230 VAC distribution panel further distribute electrical power to smaller consumers. All these switchboards are divided in two busbars that are separated by a bus-tie breaker. Each switchboard is operated with an open bus-tie breaker during DP2 operations, to mitigate the risk of an electrical problem migrating from one side to the other side. Therefore, the risk of a total black out is minimized. The Portside 690V, 440V and 230V switchboards and Starboard 690V, 440V and 230V switchboards of the bus tie breakers are interconnected by transformers.

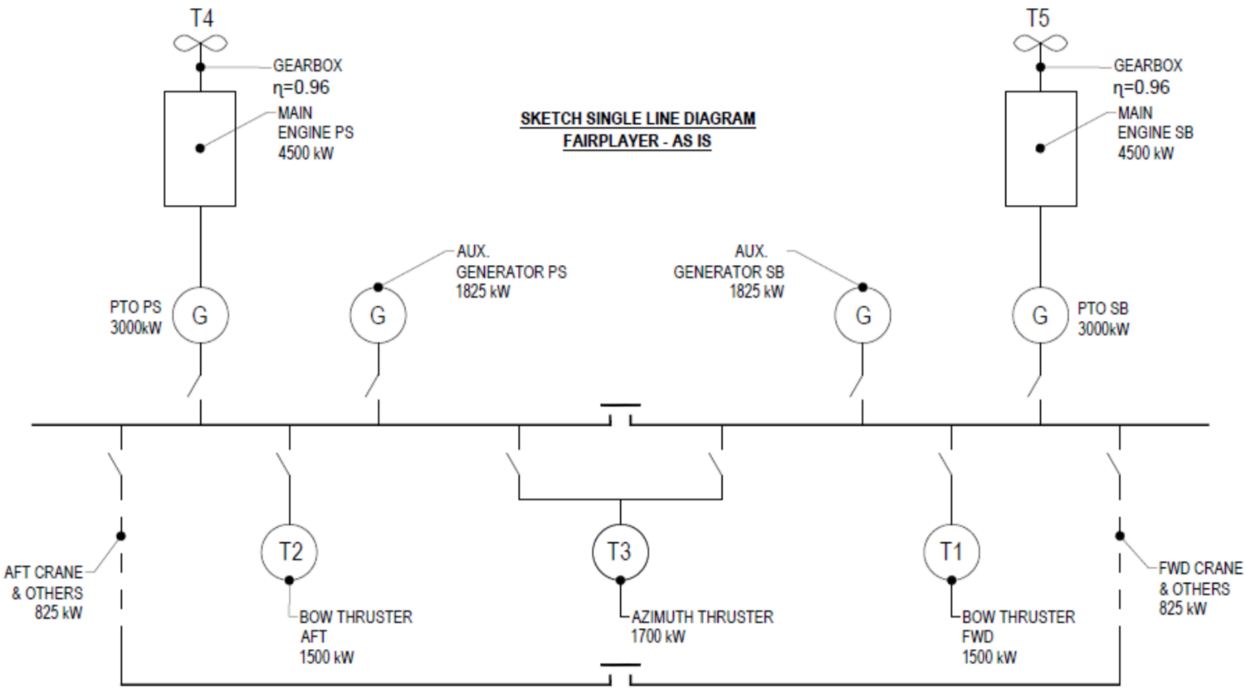


Figure 2.1: Inline diagram of the main switchboard on board the Fairplayer

2.4.4. Dynamic positioning System

The vessel is equipped with a dynamic positioning system, that is indispensable for the offshore installation contracts the ship executes. One of the requirements is that any alternation to the power and energy system should not compromise the dynamic positioning system's capabilities. For this argument, it is significant to gain enhanced understanding of the system's role and requirements.

DP class

There are 3 levels of DP that each class having its own requirements mainly regarding redundancy. IMO defines three primary DP Equipment Classes as follows:

- Equipment Class 1: Loss of position may occur in the event of a single fault.
- Equipment Class 2: Loss of position should not occur in the event of a single fault in any active component or system. Normally, static components will not be considered to fail where protection from damage is demonstrated and reliability meets Administration standards. Single failure criteria include any active component or system and any normally static component that is not properly documented with respect to protection and reliability.

- Equipment Class 3: For this class, a single failure includes items listed above for class 2, and any normally static component is assumed to fail, as well as all components in any one watertight compartment from fire or flooding, and all components in any one fire subdivision from fire or flooding.

Following that, Jumbo's Fairplayer is Equipment Class 2 DNV-GL classified, only the requirements of this class will be considered within the scope of this thesis. This classification also covers the IMO DP class 2 requirements. However, additional requirement to the DP system are demanded by classification bureau's. Since the classification societies deviate in requirements to some extent, this thesis focuses only on class guidelines of DNV-GL. The classification requirements necessitate that any systems that could potentially result in the Fairplayer lack of ability to maintain position, should be configured and installed in such a way that any malfunction in any active component or system will not lead to a loss of position. Any systems represent, technical components such as main engines, auxiliary generators and their excitation equipment, reduction gearing, appendages, electrical components, control gear, and thrusters. Furthermore, systems that are not part of the DP system but could impact its proper operation in the event of a malfunction, such as fire suppression systems, engine ventilation systems, and shutdown systems, are integrated into the Failure Mode and Effects Analysis (FMEA).

Electrical distribution operating philosophy DP2

In operational terms, the dynamic positioning class 2 (DP2) system facilitates accurate and reliable positioning so that the vessel is able to provide a stable platform for offshore construction operations. During offshore installation on DP, all 4 generators are online. Both main engines with shaft generators and both auxiliary engines are then running. For the shaft generators to be synchronised to the grid, the main engines operate on a fixed rotational speed. Propellers are loaded by alternating the pitch angle of the blades. The bus tie circuit breaker of the 690V switch board is open.

The DP2 operation manual of the Fairplayer describes a low power configuration that meets DP2 redundancy requirements. In this configuration, the bus tie circuit breaker of the 690V switch board is open. Both main engines with shaft generators, yet one auxiliary engine is then running. The circuit breaker connecting the azimuth thruster feed is closed at bus-bar side where the auxiliary engine is connected. Weather workability limits and other limiting factors are not mentioned as to when this configuration is technically feasible.

2.4.5. Power management system

Any modular power expansion has to be linked to the main electrical grid. This is done via a power management system (PMS), a crucial item in the electrical grid of marine vessels, and in particular vessels that have dynamic positioning capabilities. There are different methods for combining multiple power sources. Defining the most suitable solution for this thesis is beyond the scope and highly depends on the final configuration. Accordingly, available solutions vary in their load flexibility and installation cost. However, it is beneficial to understand the basics of this system, since this thesis aims to find a technical solution for the current load profile. In general, a power management system ensures safe, reliable and efficient operations via smart distribution of the power electronics to the consumers. According to [Damir, 2008] this is achieved by the following main tasks:

- Generator allocation control (generator auto-start and auto-stop): The PMS decides which power source or combination of generators is required according to the load consumption.
- Propulsion load limiting control: under normal operations the PMS will ensure that the load consumption of the electrical equipment does not exceed the load limits
- Fast load reduction: The power consumption of variable frequency drives (DP thrusters, cranes) is controlled to avoid overloading the generators or batteries.
- The PMS has to ensure that this energy does not reverse power the generators, causing extensive engine damage.
- Blackout restart: The PMS will automatically perform a cold ship startup in the event of a total or partial blackout.
- Performance monitoring: The PMS can assess if the system operates under normal conditions in event of damage or malfunctions, operators are alarmed.

3

Literature Review: Low Emission Technologies

This chapter discusses the recent developments in renewable and sustainable alternatives through which a potential emission reduction and efficiency enhancement could be achieved. Therefore, fossil fuels are not discussed. There is a variety of fuels that each have their specific advantages and disadvantages, and therefore, multiple options could be beneficial. In addition to this, applications that convert these renewable energy carriers into electrical energy for the auxiliary consumers are discussed. The goal of this chapter is to provide insight in the first sub question;

"What are the relevant technologies that could reduce the greenhouse gas emissions resulting from the current diesel generators."

3.1. Alternative energy carriers

Despite nitrogen oxide (NO_X), the most significant greenhouse gas emissions such as CO_2 SO_x PM originate from fossil fuels that are used in conventional power plant configurations. Therefore, alternative energy carriers are the promising solution to reduce greenhouse gas emissions in the maritime sector. This section discusses the most promising fuel technologies to achieve the climate objectives.

3.1.1. Favourable fuel properties

The energy density or specific energy is often considered of great importance when new cleaner sources of energy are reviewed. High energy density (MJ/L) and specific energy (MJ/kg) are preferred to minimise fuel volume and mass, which compromises the amount of cargo ships can transport. Furthermore, high-density fuels allow for long-distance travel and long bunker intervals. Energy densities of different fuels are compared in figure 3.1. The figure illustrates that diesel oil still the most ideal fuel in terms of volumetric and gravimetric energy density. The blue lines in 3.1 indicate the effect that different storage techniques have on the density. Ideally, a sustainable fuel should produce low local emissions to ensure compliance with regulations and minimise the effects of global warming. However, to meet the IMO's goal of reducing emissions from shipping by 50% by 2050, the so-called well to wake emitted life cycle emissions (gCO_2e/MJ) have to be accounted for. Feasibility and competitiveness of sustainable fuels with low quality residual fossil fuels depend on the energy cost ($/MWh) [Gray et al., 2021].

Bunker logistics are important as ships operate worldwide. Therefore, uncertainties with fuel availability slow down the energy transition, as this impacts both fuel infrastructure and manufacturing projects and new building projects. This is often referred to as the chicken-and-egg scenario [Foretich et al., 2021]. The transition to sustainable fuels on a large scale is only possible with a large scale-up. The annual consumption of the maritime sector is more than 330 million tons [Foretich et al., 2021] [IMO and UNFCCC,]. Therefore, the scale up is challenging as production from renewable sources is desired. Accordingly, certain fuel types are better suited for massive scale-up than others.

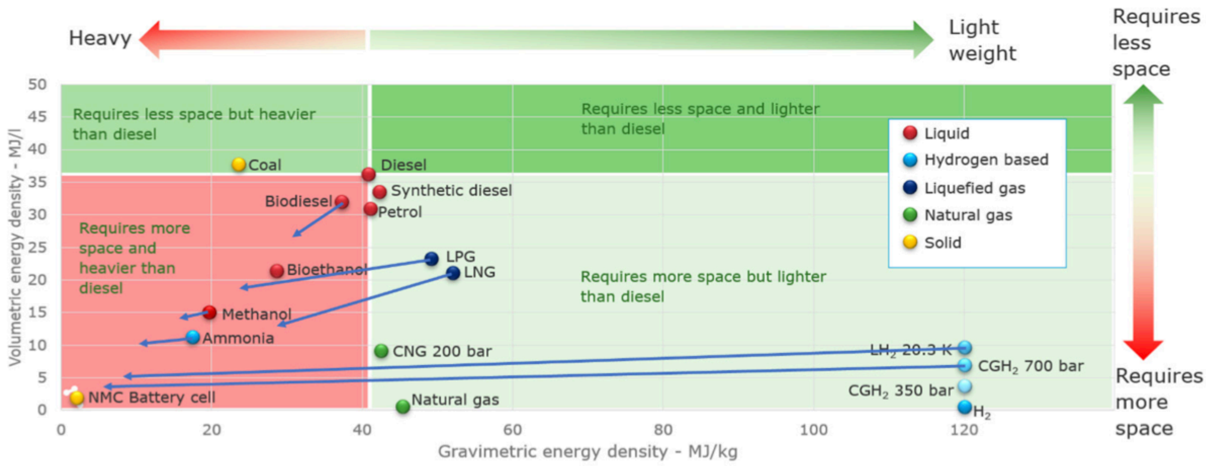


Figure 3.1: Comparison of different energy carriers [Anders, 2019]

3.1.2. Well-to-wake emissions

The maritime energy transition includes more than only reconsidering established shipboard power configurations. The production of alternative fuels must be sustainable to reduce the total emissions. Well-to-wake is the term that is often used for this. Life-cycle emissions, are the sum of upstream (well-to-tank) and downstream (tank-to-wake) emissions [Bond et al., 2013]. The life cycle of a particular energy carrier is illustrated in figure 3.2. In 3.2 energy carriers are classified as green, blue, or grey. These colours indicate whether energy carriers are produced with renewable energy or not. Carbon neutral fuels do not produce net CO_2 emissions during their life cycle, which means that they offset equal carbon particles during the production processes as they are released after combustion.

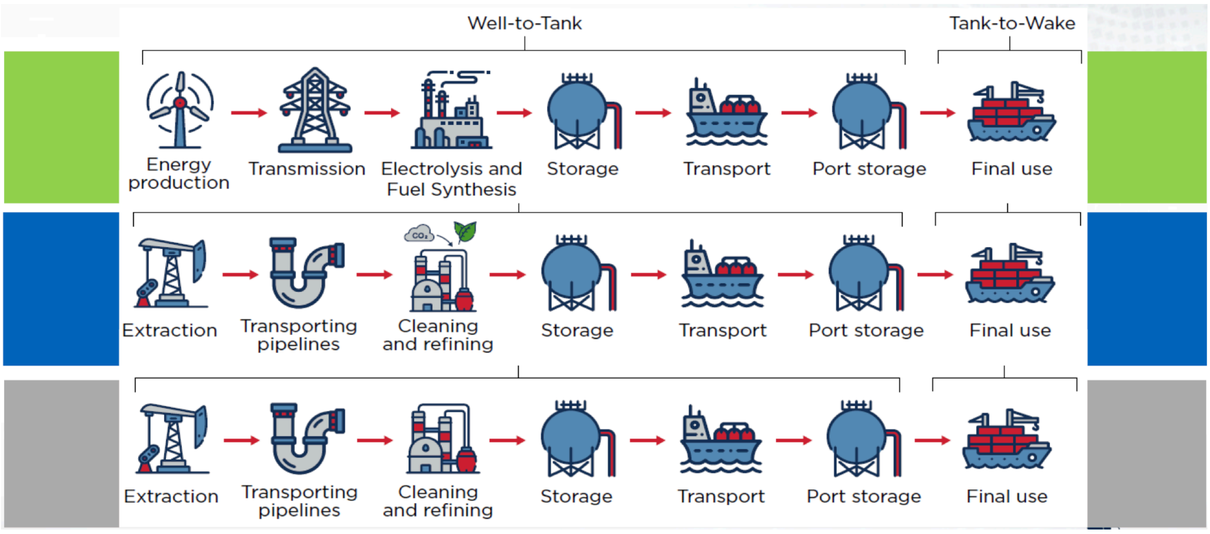


Figure 3.2: Well to Wake life cycle of a marine energy carrier, sorted by environmental impact[Laursen, 2022]

The goal of reaching net zero carbon emissions via alternative energy carriers can only be successful if the sum of the well-to-tank and tank-to-wake emissions is zero. As will be discussed later in this section, large-scale production of green alternative energy carriers is not yet available. However, demand from the maritime industry could accelerate the construction of these green production chains.

3.1.3. Biofuels

Biodiesel fuels were chosen as one of the environmentally friendly alternative energy solutions. Diesel alternatives or drop-in fuels have the potential to reduce emissions while conventional tank-to-wake configurations of excising ships are maintained. The carbon neutrality of the currently available biofuels is controversial because of the energy that is required to plant, maintain and process the feedstock [Calvin et al., 2021]. However, it has the potential to become carbon-neutral in the future. Potential diesel alternatives often originate from vegetable oils, bio-alcohols or lignocellulosic biomass which is agricultural or forest residues. Examples of such liquid distilled biofuels produced from vegetable oils are straight vegetable oils (SVO) and hydrotreated vegetable oils (HVO). Biofuels originating from lignocellulosic biomass and bioalcohols are hydrotreated pyrolysis oil (HDPO), Fischer-Tropsch diesel (FT-diesel), and alcohol-based diesel (ATD) [Carvalho et al., 2021]. [Gray et al., 2021] predicts that the future challenge with fuels based on biomass is that a large scale up will result in increased food prices and land-use. Therefore, pushing these types of biodiesel to meet global demand seems irrational.

With the Fischer-Tropsch method, diesel is produced from a variety of different feedstock, such as coal, natural gas or biomass. The process starts with the production of a synthesis gas, which consists primarily of carbon moNO_Xide and hydrogen. This mixture is then synthesised to a range of hydrocarbons. These are then upgraded to the final product [Watanabe et al., 2022]. Despite the drop-in advantages, the Fischer-Tropsch process is less efficient and more expensive than its competitors. Moreover, Fischer-Tropsch has the lowest biomass to biofuel conversion among the other drop-in technologies.

Another method of extracting biodiesel involves a chemical reaction called esterification in which a biodiesel feedstock is mixed with either methanol or ethanol, and a catalyst (Potassium Hydroxide). The resulting biodiesel is often referred to as Fatty Acid Methyl Ester (FAME) [Mohd Noor et al., 2018]. The properties of FAME depend on the feedstock. Some of these properties, which are relevant for the engine performance include; viscosity, density, flash point, cetane number, acid value, oxidation stability, cloud and pour points. The viscosity is relatively high because of the chemical structure and large molecular mass. In general, the density of biodiesel ranges from 830 to 960 kg/m^3 The combination between these two can create problems with the injection system [Tesfa et al., 2010]. Another disadvantage of FAME over marine diesel is oxidation stability, therefore compromising the fuel stability during storage. Unsaturated fatty acids chains that react with oxygen may cause the fuel to deteriorate overtime. In addition, this type of biodiesel is sensitive for the growth of bacteria [Mohd Noor et al., 2018].

3.1.4. Methanol

Methyl alcohol or methanol (CH3OH) is a colorless, flammable, and toxic liquid. It is the simplest alcohol form and currently a key product in the chemical industry, producing chemicals such as formaldehyde, acetic acid and plastics. Around 98 million tons (Mt) are produced annually [IRENA, 2021]. Compared to fossil fuels, renewable methanol in combustion engines cuts carbon dioxide emissions by up to 95%, reduces nitrogen oxide emissions by up to 80%, and completely eliminates sulphur oxide and particulate matter emissions [Methanol Institute, 2023]. Despite, methanol having the same carbon to hydrogen ratio as methane (CH4), the specific CO_2 emission for methanol is 70 kg CO_2/GJ, whereas that of methane is 50 kg CO_2/GJ [Seoyeon Tara Hong et al., 2022]. The difference in specific CO_2 emissions can be explained by the difference in energy density.

Despite lower tank-to-wake emissions of natural gas, the overall carbon footprint of methanol is more favourable, as methanol can be produced from renewable sources by extracting carbons from the environment, and natural gas releases fossil carbon dioxide in the atmosphere [McKinlay et al., 2021]. There are several routes to produce methanol from renewable sources, such as biomass gasification to methanol and e-Methanol from green hydrogen and captured carbon dioxide [Mukherjee et al., 2023]. To classify methanol as a sustainable fuel, production sites must convert to renewable resources such as hydro, solar or wind energy. The availability of sustainable methanol is limited, with current production capacity accounting for less than 1% of the total volume of methanol produced annually [IMO and UNFCCC,].

In the maritime sector, methanol has proven to be a reliable energy source. Already since 2015 a ferry from Stena sails with Wartsila engines that run on either diesel or methanol and diesel. While methanol can be used in internal combustion engines, it can also be used to power fuel cells. In that case, methanol is reformed on board a ship into hydrogen. At ambient temperature and with atmospheric pressure, methanol is liquid, which is beneficial for avoiding costly on-board systems that are required to store and transfer hydrogen gas [IRENA, 2021]. In contrast, methanol is toxic and can be extremely dangerous. Exposure could lead to significant morbidity and mortality if left untreated. Sailing with methanol requires extra safety measures to ensure that contamination is impossible. An alternative to improve safety is dimethyl ether (DME). This is a methanol derivative that has some advantages, such as being less toxic and having a higher cetane number [Mukherjee et al., 2023]. Increasing the cetane number of methanol shortens the injection delay, resulting in better engine performance. However, renewable DME is as of 2023 still not widely available and expensive. In addition, DME has several challenges with stability and storage [IRENA, 2021].

3.1.5. Ammonia

Ammonia (NH3) is considered a promising hydrogen carrier for maritime application as it offers a way to achieve carbon-neutral electricity storage and generation, without being constrained by material scarcity or storage limitations [ISPT, 2017]. Ammonia is a colorless substance which is in gas form at ambient temperature and atmospheric pressure. Similar to methanol, ammonia can be produced from green hydrogen. Due to the chemical structure of ammonia (NH3), the energy converter emits no carbon emissions that originate from ammonia. There is already an infrastructure for ammonia production, storage, and distribution. Annual global production is 150 million tons, which is predominantly used for fertilisers [Al-Aboosi et al., 2021]. Ammonia is only considered renewable when it is produced using renewable electricity for hydrogen production and nitrogen purification from air. Renewable ammonia has been produced on a commercial scale since 1921. However, this accounts for only 0.01% of the total global ammonia production [Blanco et al., 2022]. Most of the Ammonia is still being produced via the Haber-Bosch process using natural gas-. [Biyani and Jagdale, 2016] identifies ammonia as a maritime hydrogen carrier, as it has the potential to solve the storage problem on board. Liquefied ammonia can be stored at 10.3 bar or at atmospheric pressure if cooled down to -33.4 °C. It therefore has an advantage in storage conditions when compared to liquid hydrogen [Brinks H and Hektor E, 2020].

For humans, pure ammonia is toxic because it has a strong affinity for water. NH3 is lethal at 5000 ppm, yet it can already be smelled at 5 ppm. Therefore, a leak can be detected before serious danger emerges. As a result of ammonia's violent reaction to water, a non-water-based fire extinguishing medium for burning liquid ammonia should be used. For storage, it should be noted that ammonia can cause corrosion stress cracking in carbon steel [ISPT, 2017].

3.1.6. Hydrogen

Hydrogen is one of the energy carriers that is considered in the maritime energy transition. Hydrogen, when combusted, only emits water vapour since hydrogen is carbon free. Pure Hydrogen can be utilised in fuel cell technologies directly, boosting the efficiency of converting hydrogen into eclectic energy. Hydrogen is predominantly obtained by steam reforming of fossil sources such as natural gas and coal. To reduce hydrogen's well to wake emissions, it is necessary to obtain its production from methods that use renewable power. Such methods are for instance electrolysis of water or photo-electrochemical water splitting [San Marchi et al., 2017].

Hydrogen is not directly toxic to humans, still it requires appropriate precautions due to its high flammability and low ignition energy. In addition, hydrogen is lighter than air and can therefore displace the air in a poor ventilated closed room, which increases the danger of asphyxiation. However, this risks is higher with substances that are heavier than air, as ventilation is commonly from above. Limitations of hydrogen are predominately due to unfavourable storage characteristics. To store hydrogen in liquid form, it needs to be cooled down to -253 °C and compressed to somewhere between 1 and 10 bar. Gaseous hydrogen is stored in high pressure tanks that have pressures ranging from 350 to 700 bar(a) [IRENA, 2021]. Moreover, the risk of leaks is higher due to hydrogen's low density. This makes hydrogen storage complex dangerous and expensive. Pressurised hydrogen tanks require that a certain over pressure in the tanks remains. Therefore, not the full tank capacity can be used. There are alternative storage solutions being developed, such as storing hydrogen chemically in sodium borohydride. Despite the limitations, hydrogen has already been successfully implemented in ships. Its availability and suitability for fuel cells technology make hydrogen technical and economically interesting for the maritime industry.

3.1.7. Nuclear

Nuclear energy has often been considered a viable power source for maritime operations. There is a wide variety of concepts and different methods. According to the research of [Houtkoop, 2022] in which the generation IV reactors are compared, the Molten Salt reactor and the Very High Temperature Gas-cooled reactor seem most promising for maritime applications. The concept of molten salt reactors has already been known since the 1950s. However, the technical readiness level of these systems is somewhere between 4 and 6, which corresponds with the validation to testing phase. Current test outputs vary from 50 MWth up to 100's of MWth [IAEA, 2020]. The main advantage of a molten salt reactor is that the load is variable. Loads cause the temperature to drop, which results in more reactivity, thus more power.

In contrast to Molten Salt reactors, the Very High Temperature Gas-cooled reactor concept has already been in service for 50 years. Therefore, the technical readiness level of these systems is higher than that of other reactor types. The systems currently under development range in power from 10 MWth to 625 MWth. The main advantages of this reactor are relative safe operation, high achievable burnup and temperatures [IAEA, 2020]. These technologies seem promising for maritime application, mainly due to their high energy density. According to the research of [Houtkoop, 2022], the molten salt reactor seems the most favourable solution in the future, as this type offers good burnup and more possibilities for the fuel cycle. Currently, these systems are not available for commercial application due to their low technical readiness level.

3.1.8. Conclusion

In the previous sections, renewable fuels introduced. These hydrogen carriers each have their pros and cons. Biodiesel is a convenient concept in terms of safety and drop-in potential. Accordingly, existing tank to wake infrastructure can be maintained. The carbon neutrality of the currently available biofuels is controversial, and many studies indicate that a biodiesel scale-up could complicate the global food market. Nuclear energy for maritime utilisation is still underdevelopment and not likely to be implemented in the very near future. Methanol, hydrogen, and ammonia have the potential to reduce emissions in the maritime sector as they can be produced from renewable energy sources. The storage complications of hydrogen and ammonia, make methanol a favourable solution in terms of storage. Moreover, methanol has good energy density and specific energy with respect to hydrogen and ammonia.

In conclusion, the choice of fuel in the maritime industry involves considering energy density, emissions, scalability, and safety. While diesel oil currently offers the highest energy density, sustainable fuels like biofuels, methanol, ammonia, hydrogen, and even nuclear energy hold promise for reducing emissions and transitioning to cleaner energy sources.

3.2. Energy Converters and Storage Technologies

In recent years, more and more technologies have become available for marine application. There is a wide variety of low carbon emission dual fuel systems [Wang et al., 2022]. In this section different energy converters are discussed. Energy converters is the definition used for technical installations that reform energy from one state to another.

3.2.1. Fuel cells

When renewable hydrogen carriers are applied in maritime operations, fuel cells could be an interesting alternative for the internal combustion engine. Fuel cells are an exciting technology in maritime applications and operate at significantly high energy conversion efficiencies. These high efficiencies are possible because chemical energy in the fuel is directly converted to electrical energy. Furthermore, this technology could reduce the nitrogen oxide emissions which are formed at high temperatures during combustion. Electricity is generated through electrochemical reactions. The process is often compared to that of batteries, with electrochemical reactions occurring at the interface between the anode or cathode and the electrolyte membrane.

Many types of fuel cell technology are currently under development or have already been implemented in ships. Some of the most promising technologies according to [EMSA, 2017] are described in table 3.1. According to the study of [Veldhuizen B van et al., 2021] all the hydrogen carriers that are described in chapter 3 can be used to power fuel cells. However, the overall choice of fuel cell depends on the specific requirements of the application, such as power output, operational condition, size, and choice of fuel.

Table 3.1: Overview of different types of fuel cell technologies with corresponding properties [EMSA, 2017]

Technology	Module Power levels (kW)	Lifetime	Fuel	Maturity	Size	Emissions	Efficiency9
Alkaline fuel cell (AFC)	Up to 500 kW	Moderate	Hydrogen	High, experience from several applications including one ship	Small	No	60% (electrical)
Phosphoric acid fuel cell (PAFC)	$100-400$ kW	Excellent	LNG, Methanol, Diesel, Hydrogen	High, extensive experience from several applications	Large	$CO_2$and low levels ofNO_x if carbon fuel is used.	40%(electrical) 80%(with heat recovery)
Molten carbonate fuel cell (MCFC)	Up to 500 kW	Good	LNG, Methanol, Diesel, Hydrogen	High, extensive experience from several applications including ships	Large	$CO_2$and low levels ofNO_x if carbon fuel is used	50%(electrical) 85%(with heat recovery)
Solid oxide fuel cell (SOFC)	$20-60$ kW	Moderate	LNG, Methanol, Diesel, Hydrogen	Moderate, experience from several applications including ships	Medium	$CO_2$and low levels ofNO_x if carbon fuel is used.	60% (electrical) 85% (with heat recovery)
Proton Exchange Membrane fuel cell (PEMFC)	Up to 120 kW	Moderate	Hydrogen	High, extensive experience from several applications including ships	Small	No	60% (electrical
High Temperature PEM fuel cell (HT-PEMFC)	Up to 30 kW	Unknown	LNG, Methanol, Diesel, Hydrogen	Low, experience some applications including ships	Small	CO_2 and low levels ofNO_X if carbon fuel is used.	60% (electrical)
Direct methanol fuel cell (DMFC)	Up to 5 kW	Moderate	Methanol	Under development	Small	CO_2	20% (electrical)

Alkaline Fuel cell

Alkaline fuel cells (AFCs) are one of the most developed fuel cell technologies and have been successfully implemented in numerous projects such as the Hydra passenger vessel and NASA's Apollo and space shuttle programmes [Kalogirou, 2014]. The fuel cells on board these spacecraft provide electrical power for onboard systems, as well as drinking water, which is possible as the only residual is water. This can be seen in the following chemical reaction:

$$Anode\ \ 2H_2 + 4OH^- \rightarrow 4H_2O + 4e^- \tag{3.1}$$

$$Cathode\ \ O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \tag{3.2}$$

$$Total\ \ H_2 + O_2 \rightarrow 2H_2O \tag{3.3}$$

Alkaline fuel cells require very high fuel and air purity to achieve this reaction. If the fuel contains carbon-dioxide, it will react with the alkaline electrolyte, reducing the efficiency and eventually resulting in precipitation and blocking of the cell [EMSA, 2017]. The manufacturing costs are relatively low, and the system size is small.

Phosphoric acid fuel cell

Phosphoric acid fuel cells have been around since the mid-1960s, and were the first to operate with temperatures up to 200 °C [Kalogirou, 2014]. These temperatures mean that energy can be recovered from heat, significantly improving the overall efficiency. The simple construction, low electrolyte volatility, and long-term stability are additional advantages. Higher temperatures make that other fuel sources than pure hydrogen can be utilised, such as LNG and methanol. The hydrogen carriers need to be reformed in a separate stage before the Phosphoric acid fuel cells. Higher operating temperatures reduce the platinum loading and increase CO tolerance [van Biert et al., 2016]. Although these are favourable aspects, the system has a low power density and will thus be large and heavy, making maritime application difficult.

Molten carbonate fuel cell

The molten carbonate fuel cell is considered highly efficient when heat recovery is applied. Efficiency can be as high as 85 %. These high efficiencies can be explained as a result of their high operation temperatures of 600-700 °C. [Verda and Nicolin, 2010] showed that the total energy conversion efficiency increases with the operating temperature of the fuel cell. In contrast, high temperatures increase the chance of corrosion and cracking of components. Furthermore, the molten carbonate fuel cell has a slow start-up time and poor power characteristics with respect to irregular loads. In that case, a molten carbonate fuel cell must be combined with another system, such as batteries. The high temperatures make such system flexible to the choice of fuel. The fuel reformation occurs in the fuel cell itself. The chemical reaction is slightly different, as this system requires carbon dioxide to operate, indicating that these systems are mainly suitable for carbon based fuels.

$$Anode\ \ 2H_2 + 2CO_3^{2-} \rightarrow 2H_2O + 2CO_2 + 4e^- \tag{3.4}$$

$$Cathode\ \ O_2 + 2CO_2 + 4e^- - > 2{CO_3}^{2-} \tag{3.5}$$

$$Total\ \ 2CO_2(\text{ cathode }) + 2H_2 + O_2 \longrightarrow 2H_2O + 2CO_2\ (\text{anode }) \tag{3.6}$$

Solid oxide fuel cell

The solid oxide fuel cell (SOFC) is another high temperature technology that can reach even higher temperatures than the molten carbonate fuel cell. The solid oxide fuel cell operates at temperatures of 500-1000°C, which enables internal fuel reformation. Fuel efficiency and flexibility are also similar to molten carbonate fuel cells. Due to this fuel flexibility, the SOFC is able to use hydrogen, LNG, methanol and hydrocarbons such as diesel. The large difference is that this type does not require carbon dioxide to be added at the cathode. The disadvantage of solid oxide fuel cells is that the high temperatures require more expensive construction materials. According to [Veldhuizen B van et al., 2021], all currently commercially available systems (Solid Power, BlueGen; Mitsubishi, Megamie; Bloom Energy, Energy Server; Hexis, Galileo) are designed for LNG operation. Modifications to some of these systems make the use of renewable ammonia or methanol feasible.

Proton Exchange Membrane fuel cell

Proton Exchange Membrane fuel cells, also known as polymer electrolyte membrane fuel cells, are considered a clean and highly efficient solution for maritime applications. The main advantage of proton Exchange Membrane fuel cells are their high power to weight ratio compared to other technologies (100-1000 W/kg)[EMSA, 2017]. This makes the system compact and lightweight. This type of fuel cell requires pure hydrogen and oxygen. If other hydrogen carriers than pure hydrogen are to be used, it needs to be converted to hydrogen prior to injection to the proton Exchange Membrane fuel cell. Operational temperatures are between 30-100 °C, therefore the startup time is short, and transitional loading is favourable [Kalogirou, 2014]. The use of platinum makes these systems expensive, although developments on new membrane materials could improve this in the future. Water-management is difficult as the membrane is kept wet, while the gas-diffusion pores have to remain dry [Dai et al., 2009].

High temperature PEM fuel cell

In addition to the proton Exchange Membrane fuel cells, there is also a variant with high operating temperature. The so-called high temperature proton exchange membrane fuel cell can reach operating temperatures up to 200 °C, therefore heat recovery could be applied. This is possible as mineral acid electrolyte instead of water is used as a liquid. Accordingly, the fuel cell has no need for a water management system. Compared to the Proton Exchange Membrane fuel cell, this type is less sensitive to poisoning by CO and sulphur. Disadvantages of these systems are the lower power density, and that the system is unable to cold start.

Direct methanol fuel cell

These fuel cells have the advantage that they can use methanol directly instead of first reforming it to hydrogen. Low power output and poor efficiency make maritime applications currently difficult. The chemical reaction of direct methanol fuel cells is:

$$CH_3OH + 3/2O_2 \rightarrow CO_2 + 2H_2O$$

Fuel processing

The basic chemical reaction in fuel cells, except for direct methanol fuel cells, rests on the reaction of hydrogen with oxygen. Therefore, depending on the type of fuel and the fuel cell, reformation has to take place. There is also a difference in fuel purity requirements between low- and high-temperature fuel cells. Low-temperature fuel cells require the hydrogen to be as pure as possible. This is due to the fact that gasses such as CO compete with hydrogen for surface adsorption on the platinum catalyst, significantly reducing the fuel cell's performance [Becker et al., 2020]. In contrast, high-temperature fuel cells manage fuels of much lower purity, and fuel processing can take place internally. The required fuel processing equipment can significantly influence the overall system characteristics, such as efficiency size, weight, cost and transient behaviour [van Biert et al., 2016].

The equipment used for this process is roughly divided into four groups:

- Reforming: On reforming of fuel, carbon hydrates are converted into hydrogen dominant syngas. There are multiple possible methods for this, such as steam reforming. Steam reforming (SR), catalytic partial oxidation, and autothermal reforming (ATR), which are described by [van Biert et al., 2016].
- CO clean-up: Fuel cells with low CO tolerance require CO clean-up for efficient operation.
- Purification: With purification, hydrogen is separated from carbons, most notably CO. The most commonly used methods for this are membrane separation and pressure swing adsorption.
- Other fuel processing equipment includes mainly auxiliary equipment, such as heat exchangers, heat recovery, burners, and filters.

Power output characteristics of fuel cells

Fuel cells deliver power through flux of chemical reagents and electrochemistry of electric current generation. The intensity of the electric current is determined by Faraday's law. Electricity is generated continuously as long as the fuel is supplied [Sieniutycz and Jeżowski, 2018]. Depending on the type of fuel cell and protective systems that prevent overheating and fuel starvation, the response characteristics are challenging. In general, fuel cells are most efficient when the load is kept constant. High temperature fuel cells are attractive due to their high efficiency, still poor load dynamic behaviour makes stand-alone implementation difficult. Low temperature fuel cells on the other hand have low startup time and are therefore more suitable for dynamic loading, nevertheless irregular loading can also affect the system's lifetime due to corrosion. Low temperature proton exchange membrane fuel cells and alkaline fuel cells are therefore most suitable for load steps.

3.2.2. Internal Combustion Engines.

Internal combustion engines running on diesel have been the main energy converter for the last century. These energy converters are highly developed and easy to scale. Therefore, modern engines are reliable and durable. The energy in internal combustion engines generating electricity changes formation three times, which has negative effects to the overall efficiency. Chemical energy is converted into thermal energy at first, then into mechanical, and eventually into electrical energy. Moreover, the emission performance of internal combustion engines is not environmentally friendly in terms of NO_X formation. These NO_X formations are caused by the high combustion temperatures inside the cylinder. If internal combustion engines are optimized for the combustion of renewable hydrogen carriers, this would greatly reduce the emissions of SO_x, PM, and CO_2. The performance of engines running on these fuels are discussed in the next subsections.

ICE on Methanol

Methanol combusting inside marine engines has already proven to be successful and demonstrates satisfactory engine power and fuel consumption. There are several methods to combust methanol in internal combustion engines [Márquez and Andersson Karin, 2015]. Methanol is difficult to self-ignite due to the high autoignition (463.85 °C) temperature and high heat of vaporization [Verhelst et al., 2019]. The first method that can be used is spark ignition, whereby pure methanol can be utilised. In general, this method is applied to Otto cycle engines, whereby methanol is ignited through an electrically generated spark. Secondly, with combustion ignition, pure alcohols have been successfully implemented. However, this requires more significant engine modifications with respect to the compression ratio.

Most implemented methanol systems use pilot fuel to ignite the methanol. This dual fuel solution offers fuel flexibility and makes retrofit of conventional diesel engines possible. Biofuels can be used as drop-in pilot fuel. In figure 3.3 a dual fuel setup is illustrated, here methanol is directly injected in the cylinder, however this is not mandatory hence evaporation before the inlet valve is also possible. This is called port fuel injection. Other examples of combustion methods are the use of special high temperature glow plugs, homogenous charge compression ignition (HCCI), premixed charge compression ignition (PCCI) and reactivity controlled compression Ignition (RCCI).

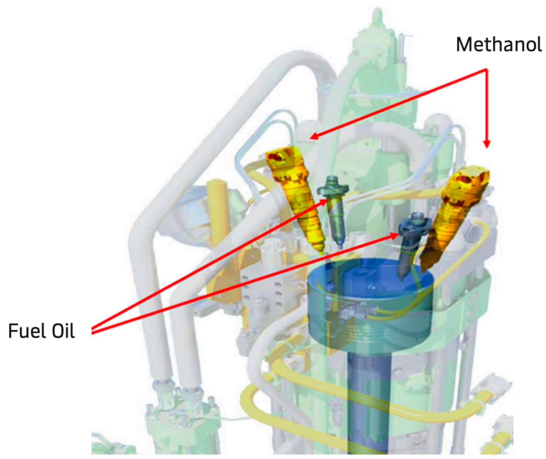


Figure 3.3: Example of a methanol dual fuel injection setup [Stråby and Løth, 2021].

ICE on Ammonia

The performance of pure ammonia in combustion engines has several challenges. Compression ignition of ammonia is possible despite a high autoignition temperature of 924K. However, this requires significant engine modifications to enable regular combustion. The poor combustion characteristics of ammonia are mainly due to the low flame speed. The most important engine modifications are the compression ratio of 35:1 and the preheated inlet air of 405K [Cornelius et al., 1966]. In contrast, high combustion temperatures cause NO_X emissions, so this manner of combustion in not ideal, although two-stage injection could reduce these emissions. A consequence of two-stage injection is incomplete combustion, resulting in ammonia slip [Donggeun Lee, 2018]. Compression ignition of ammonia is technically possible, nevertheless inconvenient.

According to [Van Duijn, 2021] the combustion of pure ammonia in spark ignition engines seems technically possible. However, the technology is still under development. To overcome this autoignition problem for both ignition methods, one could suggest a dual fuel solution. With hydrogen, the autoignition temperature is lowered and the flame speed of the mixture is improved. Tests performed by [Biyani and Jagdale, 2016] look promising, yet they suffered from problems like backfiring due to the very high combustion velocity and wide flammability range. Poor combustion speed and narrow flammability limits between 15 and 28% make engine management difficult [N. De Vries, 2019]. Under circumstances of transitional loading, the combustion of pure ammonia seems technically not realistic for commercial implementation. This in combination with the low cetane number of ammonia, a dual fuel strategy for combustion seems more feasible.

ICE on Hydrogen

Internal combustion engines are able to run on pure hydrogen. For compression ignition engines, the operation range of the single hydrogen fuel operation is very limited, as self-ignition is difficult to achieve due to the high auto-ignition temperature of 584.85 °C. Engine modifications, such as increasing the compression ratio, are therefore required to enable steady power characteristics. However, according to [Teoh et al., 2023] high compression ratio cause the engine to suffer from knocking. Subsequently, diesel engine that are converted to hydrogen are most likely dual fuel in combination with diesel. Spark ignition engines on pure hydrogen are technically feasible. Hydrogen can be introduced in the charge air, port fuel injected, as well as directly injected. Methods that include injection before the inlet valve are still preferable due to low costs, low pressure injection equipment and simplicity [Teoh et al., 2023]. The Belgium company ABC has developed a pure hydrogen engine for marine application, that is a low-pressure Otto engine with spark ignition [ANGLO Belgian Corporation, 2022].

ICE on Bio-fuels

Bio fuels are considered drop in fuels, this means that the conventional diesel setup on board of ships can be used with minor changes to the injection pressure. On the contrary, several engine issues could be encountered as a result of burning biofuels, such as the accretion of carbon particles on the piston and cylinder head and excessive wear of the cylinder liner and piston rings. [Veldhuizen B van et al., 2021]

3.2.3. Batteries

Batteries are devises that can store energy chemically. There are significant differences in techniques and materials used to construct batteries. This implies that there is a large variety of batteries available, and each have their own specific advantage and this advantage. This study will only consider batteries that store energy chemically. These batteries contain a composition of multiple electrochemical cells. These consists of a positive and a negative electrode, with an electrolyte between them. The electrolyte allows ions to move between the two electrodes. When the circuit is closed, electrons start flowing and this results in current.

Current battery technologies

Lithium-ion (Li-ion) batteries are currently the most dominant battery technology in maritime projects [ABS, 2021]. Lithium based batteries have higher gravimetric energy density compared to conventional lead-based batteries and are, therefore, more suitable for energy storage than conventional lead based batteries. However, it must be noted that not all batteries containing lithium are equal. The compounds used to construct the cathode and anode determine the properties.

Table 3.2: Battery densities of lithium batteries

Battery	Cathode	Anode	Density
Lithium Cobalt Oxide (LCO)	$LiCoO_2$	Graphite	150-200 Wh/kg
Nickel Manganese Cobalt (NMC)	$LiNiMnCoO_2$	Graphite	140-200 Wh/kg.
Lithium Manganese Oxide (LMO)	$LiMnO_2$	Graphite	100-140 Wh/kg
Lithium Iron Phosphate (LFP)	$LiFePO_4$	Graphite	90-140 Wh/kg
Lithium Titanate Oxide (LTO)	$LiFePO_4$	Lithium-titanate nanocrystals	45-100 Wh/kg

LCO batteries are not considered as a result of their short life cycles and limited power rates. NMC batteries have the highest energy density of 140-200 Wh/kg. NMC batteries are often used in electric vehicles or within the maritime sector as their life cycle is long in addition to the satisfying energy density. For LMO batteries, the energy density is 100-140 Wh/kg. LMO batteries offer high C-rate nevertheless, limited life cycle make maritime application difficult. LFP batteries have an energy density of 90-140 Wh/kg. LFP systems are stable for thermal runaway, have good cycle life, and C-rate. Finally, LTO batteries have a relatively low energy density of 45-100 Wh/kg [MAN Energy Solutions, 2019]. The most favourable lithium-ion battery compound will depend on the operational profile of the system. The different types of Li-ion batteries each have their own limitations and advantages. In general, lithium systems require complex monitoring systems in order to keep temperature and voltages within safe limits. Lithium batteries are sensitive to thermal runaway, and lithium cobalt oxide batteries are one of the most unstable systems. According to [Stoiber and Valøen, 2016] lithium-ion-based systems have reached their technical storage limit.

Future types

Alternative batteries technologies are in different stages of development, yet they may show promise in allowing battery systems to become more practical and feasible for marine applications. Safety risks and energy limitations are the driving force behind the development of new energy-storing technologies. Some examples of these technologies are metal-air batteries, ammonia batteries and solid state batteries.

Metal air batteries are promising because their specific energy can be up to 10 times higher than that of lithium-ion batteries [ABS, 2021]. The general structure is similar to lithium-ion batteries. However, they use air as cathode, while the anode is made from a metal such as zinc, aluminium, or lithium. Some issues these batteries have are instability which limit the cycle lifetime, and limited C-rate. These make maritime implementation still very difficult. As of March 2023, tests with titanium air are conducted and seems promising to solve these issues [Forschungszentrum Jülich GmbH, 2023]. This is possible due to the electrochemical behaviour of titanium, which is stable and inactive due to its passivation layer [Durmus et al., 2023].

Redox flow batteries function due to a chemical reduction and oxidation (REDOX) reaction between two liquid electrolytes in the battery cell [ABS, 2021]. This technology is unique because the theoretical capacity depends on the amount of electrolyte stored in the tanks. Therefore, the system can be scaled to meet ship specific power requirements. In addition, multiple cells can run from one set of electrolyte tanks. The system is very stable and flammability is low [Weber et al., 2011]. The biggest challenge for this technology in maritime applications is the low energy density, which currently varies from 15 up to 40 Wh/l [Clemente et al., 2023]. Future developments to improve electrolytes should increase the energy density.

Ammonia batteries use an electrolyte with added ammonia and electrodes in a standard cell configuration. This battery concept uses thermal energy to refresh the ammonia electrolyte and recharge. Waste heat originated from other systems can be used as a source for electricity. Cycle life and chemical efficiency are to poor for use outside of lab settings. However, the potential to utilise waste heat which improves the overall performance and high power density make these systems very promising [ABS, 2021].

Solid state batteries have solid electrolytes, making them more light and compact, opposed to batteries that use liquid electrolytes. Therefore, the energy density is potentially improved and weight is decreased compared to lithium-ion batteries. This is because the electrolyte can be thinner when constructed with solid materials. Further developments on interface coating and separators to stop dendrite formation should improve the poor life cycle of these systems. Solid state batteries are possibly going to outperform lithium-ion batteries in the future because of the combination of safety, high energy density, and fast C-rate. [ABS, 2021] [Bates et al., 2022]

Supercapacitors, also known as ultracapacitors or double-layer capacitors, can store and deliver electrical energy. Instead of an electrochemical reaction, capacitors store energy by means of static charge [Shruti et al., 2023]. Supercapacitors have several advantages over batteries. Because there is no chemical reaction, much less heat is produced during the charge and discharge cycles. Therefore, they can be charged and discharged more quickly and have a longer cycle life than batteries. These abilities make them suitable for buffering the load fluctuations in an electric power system [Zhou et al., 2013]. Due to their limited energy density, batteries still outperform capacitors in terms of energy storage.

3.2.4. Other energy converters

As the study focuses on stationary operations energy converting system that convert wind energy into green energy are reviewed. Wind-assisted ships could also imply ships that use kites. However, these are not able to generate electricity. A concept that has already been successfully implemented in a ship is the flettner rotor. This type of turbine is mostly applied for its propulsion potential. Finally, shipboard wind turbines could be used for the generation of electricity. When on dynamic positioning, the ship has to compensate for the imposed drag, therefore these systems will not be considered. In addition, solar panels are not considered due to their limited energy density. This, in combination with limited available installation surfaces, cause solar energy to be insufficient to support the onboard systems.

3.2.5. Conclusion

This section discussed various energy converters that could contribute to reduce the emissions of offshore installation vessels. Phosphoric acid fuel cells offer the advantage of high operating temperatures, allowing for the recovery of energy from heat and the use of several fuels. However, their low power density and large size make them less suitable for maritime applications. Molten carbonate fuel cells are highly efficient at temperatures of 600-700 °C in combination with heat recovery, yet they require the use of carbon-based fuels. In addition, they have a slow start-up time and poor power characteristics for irregular loads, requiring additional systems such as batteries. Direct methanol fuel cells have the advantage of using methanol directly without reforming, but they currently face challenges of low power output and poor efficiency in maritime applications. Therefore, this type is excluded.

Solid oxide fuel cells (SOFC) can reach even higher temperatures and offer fuel flexibility due to internal fuel conversion, but their high operating temperatures will require the use of expensive materials. Proton Exchange Membrane fuel cells (PEMFC) are considered clean and efficient for maritime applications due to their high power-to-weight ratio. They require pure hydrogen and oxygen, but developments in membrane materials may improve their economical feasibility. High-temperature PEMFCs eliminate the need for water management and are less sensitive to CO and sulfur poisoning, but they have lower power density than PEMFC and cannot cold start. Despite the shortcomings of SOFC systems with respect to size and costs, the fuel flexibility makes this type advantageous over PEMFC systems in the context of global operations and the availability of hydrogen. Subsequently, PEMFC systems are not considered further in this report.

Internal combustion engines (ICE) running on diesel have been the primary energy converters in the maritime industry, but they have negative environmental impacts due to NO_X formations. Methanol can be successfully combusted in ICEs using spark ignition or pilot fuel methods, offering fuel flexibility and the possibility of retrofitting existing diesel engines. Combustion of pure ammonia in internal combustion engines poses some performance challenges, and it therefore requires further development. Internal combustion engines running on hydrogen are feasible but require modifications to ensure steady power characteristics. Biofuels can be used as drop-in fuels with minor modifications to the engine setup.

Batteries offer energy storage solutions with considerations for specific energy, charge/discharge rates, safety, and lifetime. High-energy marine battery systems have a relatively low specific energy compared to fossil fuels. Many of the batteries discussed are still being developed. The currently available systems are mainly based on lithium-ion, so this type is considered in further calculations. Supercapacitors could be considered for high regenerated C-rates from the Huisman cranes. However, if this is desirable requires more investigation.

In conclusion, the selection of energy converters for maritime applications involves trade-offs between efficiency, power density, fuel flexibility, cost, and environmental impact. The most favourable solution therefore mainly depends on the operational profile of the vessel.

3.3. Propulsion and Power Generation Architectures

Energy converters mentioned in section 3, each have their own specific advantages and limitations when integrated in the electrical grid of a marine vessel. Combining more than one means of energy with smart power management could be beneficial to optimise the electric performance and efficiency. However, this depends on the operational profile of a ship. Such a power system is called a hybrid power plant. In the maritime sector, the term hybrid most often features the combination of a power generation system and an energy storage system. The following subsections describe combinations that are considered in available literature and some practical examples.

3.3.1. ICE-battery hybrid power plant

The concept of a hybrid electric power plant, combines the conventional internal combustion engine with batteries. This is convenient for multiple reasons. First, based on the demand at any moment in time, the fuel efficiency can be higher as the system benefits from either the diesel generators or batteries. Internal combustion engines are most efficient at 85% maximum continuous rate (MCR), yet the electrical load is in general irregular. With the addition of batteries in combination with power management, described in section 2.4.5, the system is able to keep engine loading constant [Tao et al., 2023]. The load reaction time of internal combustion engines is limited by a combination of factors, such as the rotational inertia of the turbocharger. With the application of batteries, these engine reaction time limitations could be eliminated [Roslan et al., 2022]. Frequency-responsive spinning reserve with the instant load supplied by the batteries provide fast response to frequency deviations, helping to stabilize the power grid by either supplying or absorbing power. This strategy is in particular beneficial for engines running on alternative fuels, this is described in subsection 3.2.2. Batteries could also be applied to bridge a gap, whereby additional offline generators can be started and synchronized to the electrical grid [Nuchturee et al., 2020].

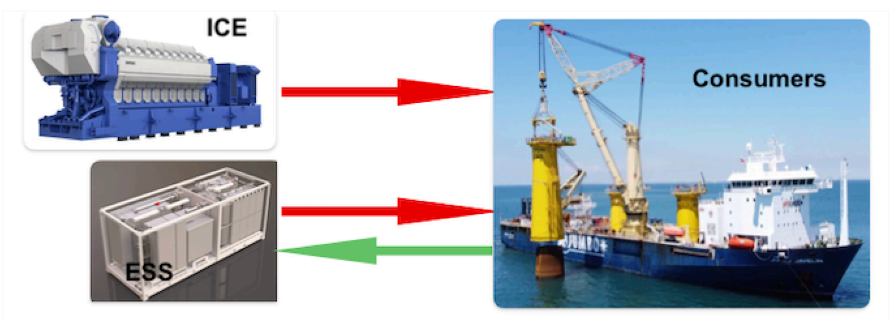


Figure 3.4: System overview of a ICE-battery hybrid system

As illustrated in figure 3.4 batteries allow for bidirectional energy flow therefore, regenerated energy from the Huisman cranes can be stored. Furthermore, engine running time is reduced, which is consequently reducing the maintenance costs. Engines running in part load have increased wear and tear of mechanical components [Panqiu et al., 2012]. Finally, batteries increase the vessel's operational redundancy because they act as a buffer if the internal combustion generators fail.

Numerous hybrid vessels are currently under development or already sailing. One example of an ICE-battery hybrid offshore vessel is the Windea Jules Verne, a battery hybrid service operation vessel for the offshore wind industry. The addition of batteries allows the vessel to manage the electrical demand of operational equipment more efficient. According to [Beveridge, 2020], overall fuel savings are expected to be between 5 to 10%. The total electrical storage capacity is 565 kWh. However, there are offshore vessels with even more battery capacity such as the North Sea giant, an offshore construction vessel with an electric storage capacity of 2034 kWh [Corvus Energy, 2023].

3.3.2. ICE-fuel cell hybrid power plant

In a fuel cell-ICE hybrid system, the fuel cell can either operate in parallel or series with the internal combustion engine, as well as a standalone unit. [Reurings, 2019] proposed the use of the SOFC-ICE hybrid because a combination of both systems, could achieve high efficiencies due to the utilisation of left-over fuel in anode off-gas and system heat recovery. In this model, the SOFC operates on a base load, while the internal combustion engine handles the transient load. Despite, that the overall efficiency heavily depend on the fuel utilization, the concept seems theoretically feasible and an efficiency of 45.7% (LHV) was achieved. However, as multiple fuels were used, the SOFC-ICE hybrid system installation volume is more than twice as large as conventional configurations.

One example of such application is the HDW's Class 212 submarine, which feature a power system based on hydrogen PEM fuel cell systems made by Siemens AG [Howaldtswerke-Deutsche Werf, 2004]. However, this example is motivated by operations, beneficial for silent underwater operations and not improving the fuel efficiency or emissions. Adding a battery to this configuration would boost the hybrid advantages described in subsection 3.3.1.

There are some examples of vessels that combine internal combustion engine, fuel cell and battery technologies. For example, the Viking Lady, is the first large scale project that integrated fuel cell technology in a merchant vessel. The Viking Lady features LNG engines, batteries, and a 320 kW molten carbonate fuel cell (MCFC) also with LNG as the fuel. At full load, a maximum electrical efficiency of 52.1% was measured [EMSA, 2017]. The project was a successful demonstration of fuel cell-ICE-battery integration. According to [Geertsma, 2019], vessels whereby the auxiliary load is a fraction of the required propulsive power, the losses associated with the electrical conversion lead to increased fuel consumption for ICE-electric hybrid propulsion systems. Nevertheless, ships that frequently operate stationary can benefit from a hybrid propulsion system. This is the case for the reference vessel in this thesis.

3.3.3. Fuel cell-battery hybrid power plant

Fuel cell technology does not allow for bidirectional energy flow. Considering that Jumbo's Huisman cranes regenerate energy, a fuel cell-battery hybrid system is considered. In this configuration, the batteries deal with the dynamic loading while the fuel cell system acts as base load and capacity extender. In figure 3.5 an example of this configuration is the MF hydra is illustrated, a double-ended ferry operating in Norway. The vessel features two 200 kW proton exchange membrane fuel cells stacks and a 1.36 MWh battery pack. The conventional internal combustion engines located on board only serve for redundancy [Balestra, 2022].

Figure 3.5: Fuel cell-battery hybrid ferry MF Hydra [NORLET,]

3.3.4. Battery-supercapacitor hybrid power plant

The downside of battery technology during high power demand is the thermal management. Accordingly, charging and discharging of the battery at high rates becomes a safety issue. Power management will protect the systems against this issue, however this means that operations are limited. To increase the system's C-rate, some studies propose a hybrid energy storage system containing a battery and supercapacitor [Sinha et al., 2022]. One example of such an application is the KwangChanwn a Chinese full electric cargo vessel [Kim et al., 2020]

3.3.5. Fuel cell-turbine hybrid power plant

The fuel cell-turbine hybrid system, is a concept that uses the fuel cell as combustion chamber for the gas turbine. The concept is illustrated in figure 3.6. Both the fuel cell and the turbine generate electricity, therefore high efficiencies could be achieved [Verda and Nicolin, 2010]. [Lunghi et al., 2003] reviewed several studies that predict the efficiency of hybrid systems featuring high temperature fuel cells (SOFC or MCFC) and gas turbines. The outcome of these studies indicate that the electric efficiency reaches beyond 75%. Main challenges include the integration of pressure ratios and mass flows and the dynamic control through start-up, shutdown, emergency [UN Climate Technology Centre & Network,]. Finally, the load-following characteristics for irregular electrical loads seems challenging due to the high temperature fuel cell.

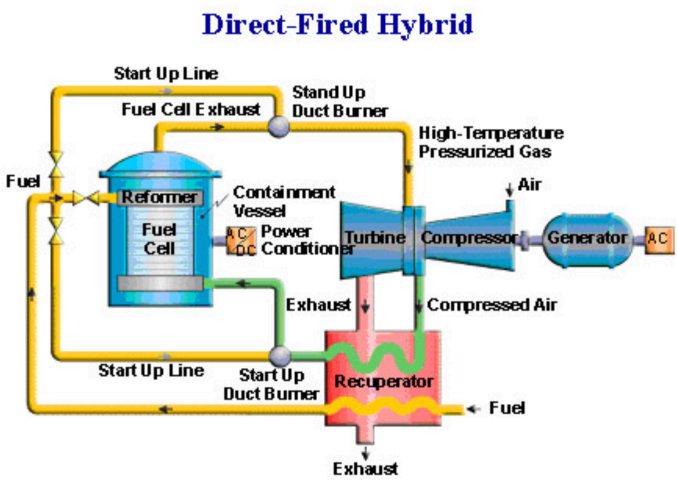


Figure 3.6: System overview of a direct FCT hybrid system [UN Climate Technology Centre & Network,]

3.3.6. Electric Propulsion

With the rapid emergence of electric cars and the fast development of more energy dense batteries, the topic of electric ships is also becoming a focal point of discussion. Despite, diesel powered applications still outperform batteries in terms of energy density, batteries have several advantages in practice. Battery powered grids offer rapid and high power response, bidirectional energy flow, low noise, no tank to wake emissions of greenhouse gasses, and low vibrations [Kim et al., 2020]. [Jeong et al., 2022] investigated if battery powered ships are the best solution for maritime environmental protection. However, the analysis concluded that battery powered ships operating in countries with high reliance on fossil-based energy resources contribute to much greater environmental impacts due to all the conversion losses well to wake. Despite, financial aspects not being the scope of this thesis, the Levelized Cost Of Energy (LCOE) of batteries become more and more comparative in terms of energy storage, due to the increase of the battery market and the use of high energy density cathodes [Vieira et al., 2022]. LCOE is a financial term used to indicate the average net present worth of the electrical energy over the system's lifetime. As of 2022 the LCOE of electrical storage was $\$153/$MWh and is expected to drop even more [Henze, 2022].

A good example of a large full electric vessel is the 120 TEU and 80 meter long, Yara Birkeland (figure 3.7). The vessel is world's first full electric and autonomous vessel without emissions, transporting container on a route of approximately 7 nautical miles. The electrical grid is feed by 20 batteries with a capacity of 6.8 MWh, which provide a range of roughly 65 nautical miles (ca. 120 km) [Yara, 2020]. The battery systems are integrated in the vessel. Therefore, recharging of the batteries has to take place during loading and discharging, increasing the time in port. In addition, there are many full electric ferries already in commission [Corvus Energy, 2023].

Figure 3.7: illustration of a full electric vessel, the 80 meter Yara Birkeland [Yara, 2020]

3.3.7. Conclusion

The first thing that was concluded when reviewing the different hybrid configurations is that the most suitable solution mainly depends on the operational profile of the vessel. The ICE-battery hybrid has some advantages over the other hybrid configurations because it has already been applied in a significant amount of new building vessels. The system has good transitional load characteristics and enables bidirectional energy flow. Therefore, the combination of a power generation system and an energy storage system is desired. This rules both the ICE-fuel cell and fuel cell-turbine hybrid out as one of the solutions to the case of this thesis.

The combination of fuel cell with batteries is not ruled out, since the transitional load could also be handled by the battery while the fuel cell load is kept constant. The characteristics of the transitional loads and if the batteries are capable to manage theses, needs to be discovered. If thermal management becomes an issue due to the high rates of discharging, the battery-supercapacitor hybrid could improve this. In conclusion the benefits for a hybrid power plant are:

- Because the base load generators are running in the range of optimal efficiency, a higher total energy converting efficiency could be achieved.
- Hybrid configuration gives a high flexibility in optimal amount of generators online.
- Hybrid power plant offers a higher level of redundancy.
- The higher efficiency and different operational modes have the potential to reduce greenhouse gas emissions
- Lower running hours which has a positive effect on the maintenance expenses.
- Noise and vibration levels are reduced.

3.4. Containerised Energy Storage Projects

Several recent projects have explored the implementation of interchangeable energy storage containers. The main objective behind such projects is to simplify bunker logistics and explore a renewable energy standardised supply chain. The novelty of the concept is that it is interesting for both shore based as waterborne application and that the integration of a renewable energy supply chain is standardised.

3.4.1. Current Direct project.

A project that is currently investigating the implementation of swappable power containers on a large scale is the Current Direct program. The project is aiming to develop innovations across all levels in the value chain, therefore not only the battery container is designed but also the supporting infrastructure to support the commercialization of the concept. The concept is called the Energy-as-a-Service (EaaS) platform. The goal of this platform is to create a system that support electric vessels by swapping their depleted batteries with fully charged ones. The empty batteries are then re-energized locally by renewable electricity. During their stay at the charging station, the batteries can also be utilized for other purposes, such as grid balancing for net stabilization. It is good to note that some companies are currently exploiting containerized batteries, either for land use or waterborne transport [Foreship, 2021]. What the Current Direct project distinguishes from these companies is that the project considers the whole value chain, while the current companies only provide a power container lease service.

According to [Scialla et al., 2022], some functionalities of the EaaS platform are; Initial infrastructure planning Fleet management, charging scheduling, regulatory framework development, Certification, route planning and determining the service fee. Limitations of the project in relation to this thesis is that the platform only evaluated batteries. Other examples of organisations that commercially supply swappable batteries or hydrogen systems include; EST-Floattech, Fleetzero, Furukawa Eco Marine Power, SEAM, Shift Clean Energy, and Zero Emission Services [Søgaard et al., 2023].

Figure 3.8 illustrates the recent build Kotug E-pusher, an electrically powered inland pusher boat featuring a modular and scalable power plant. The novelty of this specific concept is the interchangeable power source. For short trips, the vessel can use containerised battery packs. For longer distances, the batteries can be exchanged for a generator set or fuel cell. Therefore, the emission performance of this vessel can be optimized. The propulsion consist of two 300 kW azipods. Electric batteries range from 70 kWh to 6 MWh [KOTUG, 2022]. The vessel is also partial involved in the Current Direct project [Current Direct project,]

Figure 3.8: illustration of the Kotug E-pusher [KOTUG, 2022]

3.4.2. FPS Maas

On May 25, 2023, Dutch shipping company Future Proof Shipping (FPS) launched a hydrogen-powered inland container ship, the H2 Barge 1. The vessel is a 110m long and 11.45m wide and expected to reduce CO_2 emissions by 2000 tonnes annually on its Rotterdam-Meerhout route through PEM fuel cell technology. Future Proof Shipping aims to build and operate a fleet of ten zero-emission vessels. In relation to this thesis, the vessel is powered by swappable hydrogen containers of 40ft that simplify the bunkering and onboard storage of renewable fuel. Each Type II hydrogen container on the H2 Barge 1 can carry roughly 500kg of usable hydrogen, allowing for up to 1000 kg of usable hydrogen to be stored onboard the vessel.

The hydrogen containers are made up of several Type II hydrogen cylinders that will hold compressed gaseous hydrogen at 300 bar. According to [Chandrasekar and Godjevac, 2023], this project preferred hydrogen containers over fixed storage tanks because the vessel's operating range can be adjusted by adding or removing hydrogen containers, enabling operations in different locations based on the fuel cell's power capacity. As hydrogen fuelling infrastructure is limited, swappable hydrogen storage containers offer a solution. Vessels can refuel by exchanging empty containers for filled containers, and therefore the empty containers can be filled in areas where hydrogen infrastructure is available.

3.4.3. Sustainable Hydrogen Powered Shipping Project (sHYpS)

The Sustainable Hydrogen Powered Shipping Project (sHYpS) investigates the use of liquid hydrogen in swappable containers. The concept aims to update current fuel storage techniques to enable liquid hydrogen storage in containers. This also includes the connection space to reform liquid hydrogen back into gas form, for it to be used directly in the energy converters. In addition, the project also invests in arranging the supply chain infrastructure for pre-filled hydrogen containers [Busetto, 2022]. The project attempts to demonstrate its potential on one of Viking's new build vessels that is bound to sail in 2026. The liquid hydrogen containers will be coupled to PEM fuel cells with a combined power of 6 MW [Habibic, 2023]

3.4.4. Ulstein SX190

The Ulstein SX190 Zero Emission DP2 construction support vessel is a hydrogen powered offshore concept from 2019. The vessel is based on the Ulstein SX190 platform, which has a total power of 7.5 MW. In the concept, 2 MW is generated by Nedstack Proton Exchange Membrane (PEM) fuel cells. The PEM fuel cells used in the SX190 Zero Emission design are fuelled by hydrogen, which is stored in swappable containerized pressure tanks. These can be loaded and unloaded by normal cranes, eliminating complex and expensive bunker infrastructure. With this configuration, the vessel seeks emission-free offshore operations up to two weeks [Ulstein, 2021].

3.4.5. Conclusion

Containerized swappable energy projects currently focus only on hydrogen and batteries storage. This is mainly due to the bunker complications of both these storage techniques. For instance, containers for methanol exist, yet methanol is less complicated to bunker and store as described in section 3.1.4. Therefore, the storage of such fuels is more likely to take place in bunker tanks that are modified for safe methanol storage. Containerized hydrogen storage is beneficial when fuel cells are applied. The use of swappable batteries is to some extent required, since one of the design requirements is that the regenerated energy from the Huisman cranes should be utilised.

3.5. Hybrid Control Strategies

There is a fundamental difference in how hydrogen and battery storage containers could be employed to the vessel's grid. Underlying this, energy flow within batteries can be bidirectional and shows superior transitional loads over most common fuel cell systems powered by hydrogen. Furthermore, batteries do not encounter startup delays, ensuring that the electric energy is instantly available. Hydrogen, as an energy medium, undergoes an initial conversion into electricity through internal combustion engines or fuel cells, while battery energy can be used directly. With this in mind, different strategies apply for both the swappable hydrogen and battery concepts. Due to the use of fuel cell technology over internal combustion engines as of the higher energy converting efficiency, dynamic loading is considered limited. Therefore, the only strategy for hydrogen energy containers is defined as fuel storage. Battery containers on the other hand offer several additional strategies and possibilities that will be covered in the next subsection.

3.5.1. Battery control strategies

As the complexity of the system architecture increases, the degrees of freedom in control increase, which is beneficial for an offshore vessel that is intended to operate in multiple maritime markets. Operating on battery and fuel cell systems is still relatively expensive [Durmus et al., 2023]. Still, battery employment and intelligent use of DC architectures have proven that smart battery control strategies could potentially result in reductions ranging from 10 to 35% with respect to the fuel consumption and CO_2 emissions[Geertsma, 2019]. For this thesis, encompass most frequently used strategies to assess the technical and practical impact on the operations and what the strategies could potentially reduce in emissions. The strategies will be assessed independently, while in theory the highest emission reduction potential could be achieved combining different battery control strategies

Spinning Reserve

Spinning reserve is a battery strategy whereby a certain reserve capacity is used to supply power in the event of sudden increases in electricity. This strategy allows for the potential shutdown of one or more standby engines, as those engines primarily online for redundancy can be substituted by batteries that can instantly cover electrical demand in the event of a power outage.

Peak Shaving

With the peak shaving strategy, engine loading is kept constant or within a certain power envelope, whereby the specific fuel consumption of the diesel engines is most favourable. Batteries are then used to cover for the transient loads or dynamic loading outside this power envelope. During this strategy, batteries are constantly charged when the demand of the grid is below a certain level. Engines are running more constantly in with this control strategy, reducing the fuel consumption originating from engine inertia.

Enhanced Dynamic Performance

Expanding on the spinning reserve and peak shaving strategies, the enhanced dynamic performance strategy, employs batteries to cover the electrical demand for a short amount of time. The concept revolves around the notion that, during this brief interval, additional or replacement engines can be started and synchronized with the grid.

Boost Capacity

With the boost capacity, batteries are used to cover the gap between the maximum expected power and the maximum online engine's power with respect to the mean load. This strategy allows having fewer engines online with respect to the maximum expected load, therefore, the average loading of running engines is increased.

Start-stop Strategy

This approach is particularly effective at low loads, mostly regarding standby on DP and during port stays. Commonly, engines are used to charge batteries to its upper state of charge (SOC) subsequently the running engines come to a halt. After this, the vessel's power demand is supplied from the battery until the SOC drops to the lower threshold. At this point, the engine restarts, and the cycle repeated. This operating mode ensures quiet engine rooms, reduces fuel consumption, and minimizes emissions in port, standby situations, and environmentally sensitive areas. In the context of this thesis, and concerning the utilization of swappable battery containers, it's important to note that engines will not be employed for recharging the batteries. Still, this could be considered in future work.

Cold Ironing

The final strategy is called ”cold ironing”. This battery control strategy is commonly used when the vessel is connected to shore power, minimizing local emissions. It’s important to note that the onshore grid may have limited capacity for certain operations, such as heavy lifts. The battery system can then effectively manage peak demands, providing a solution to make shore power a feasible solution. With respect to the swappable energy containers scope, the concept of cold ironing, which involves utilizing onshore electricity when a vessel is at port, is not examined or explored as the focus in on offshore operations.

Energy Harvesting

With this battery control strategy, batteries can be used to store regenerated energy when braking on electric motors. Currently, the Huisman cranes onboard of Jumbo’s J-class vessels are equipped with such a system. However, in the current electric grid, this energy is dissipated in braking resistors, which are cooled with thermal oil that is then cooled by seawater. With batteries, some potential fuel could be saved as braking energy is stored, which is then later used through another control strategy. Estimating the amount of energy gained by this was not considered in this thesis.

3.5.2. Benefits and Challenges

The use of batteries offers several benefits. Firstly, they improve fuel efficiency and reduce emissions. The system will have less running hours per generator due to fewer generators online. As a result of less running engines and enhanced dynamic performance, the cost related to maintenance may be reduced. The cost of renting battery systems can be a significant challenge, and it must be carefully weighed against the potential savings and benefits. In some cases, the levelized costs of energy may not justify the expected performance improvements. Therefore, the relative environmental gains per battery container should be maximised. According to [Roslan et al., 2022] battery systems have some challenges that still need to be solved. These challenges in a hybrid power system are mainly related to the control strategy for charging and discharging the batteries. Possibly new technologies such as machine learning and artificial intelligence can help with real-time load forecasting and demand response with the most suitable hybrid control strategy. Future research should explore how these technologies can be employed.

4
Power and Propulsion Modeling and Component Quantification

This chapter introduces the physics and mathematics, used to define the emission reductions and the amount of energy containers required. The methodology ensures that all installation trips can be used as input for the proposed case study.

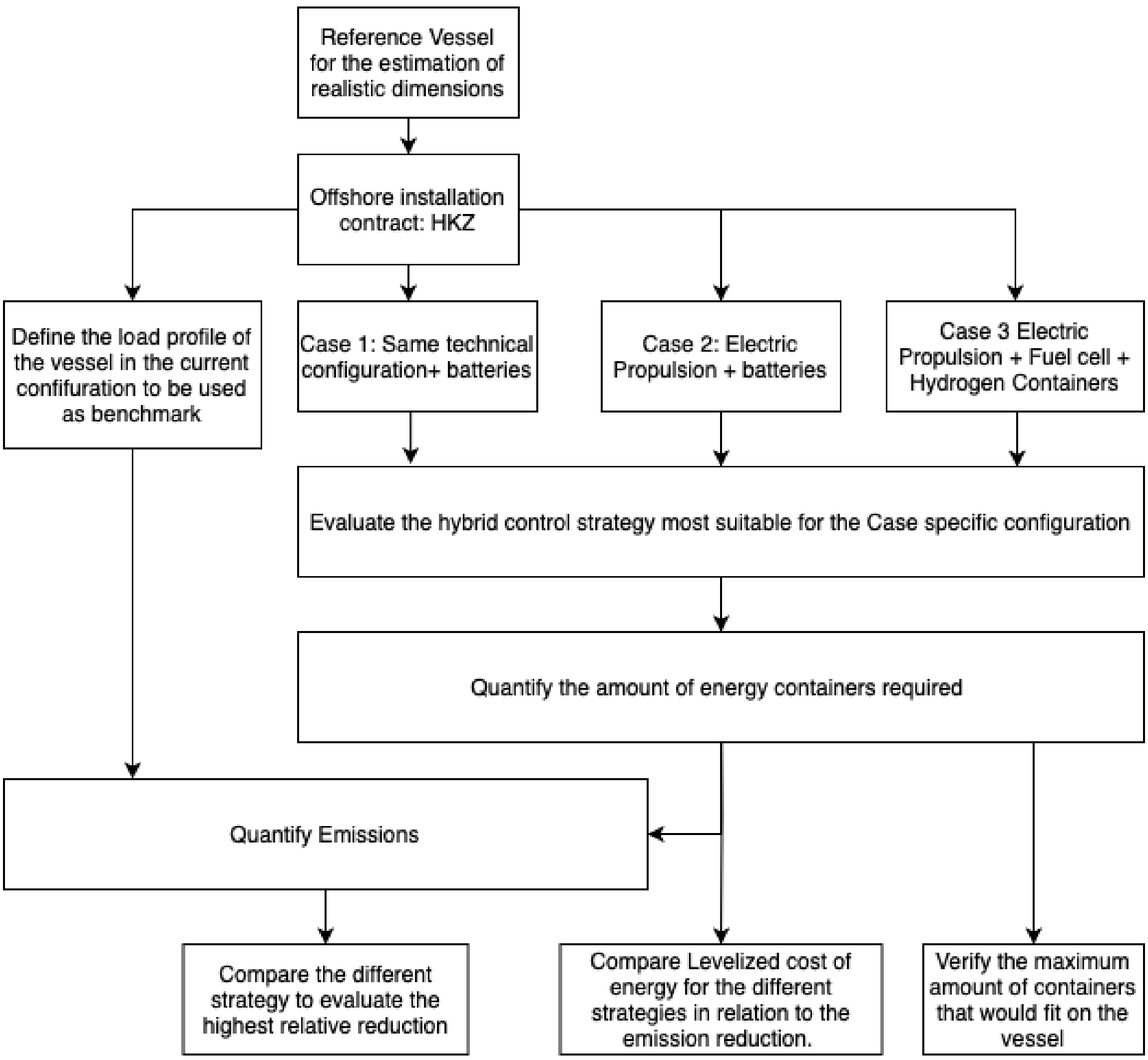


Figure 4.1: The methodology to assess the application of swappable energy containers in flow diagram

The flow diagram 4.1 schematically outlines the steps taken in this thesis to evaluate the use of swappable energy containers. Before it is possible to evaluate different strategies, the load profiles of the current operations in different architectures are defined. Subsequently, multiple energy control strategies in three different technical configurations will be evaluated, as not all hybrid control strategies apply to the current technical architecture due to DP regulations and load profile. If hypothetically one of the considered strategies emerges as a potential solution to reach the IMO's route to zero interim climate goals, a detailed follow-up study focused on the practical implementations is still required. In section 2.3 the vessel is described and all individual components as installed are defined. A stored performance date is recovered, which will be used to estimate the load profile of a certain offshore installation contract representative in regard to Jumbo's general offshore activities. For each case, a load profile is constructed from which the required storage capacity is determined. From the resulting internal combustion engines, the emissions are determined. Resulting is a variety of cases from which the emission reduction and required amount of swappable energy containers are known.

4.1. Components Definition, Architecture and Efficiencies

Various components in the power- and energy system, convert and distribute the chemical energy into the electrical power and thrust. The data available from the DP computer which is used in this thesis consist of the pitch angle (α_{pitch}) of both controllable pitch propeller, electrical output of two shaft generators and two auxiliary generators (P_e) and finally the corresponding time in reference to universal time coordinated (UTC) (t). With this variable input and some fixed conversion factors or efficiencies, it is possible to determine the brake power of the engines and the corresponding emissions. In the current technical configuration, energy flows according to figure 4.2.

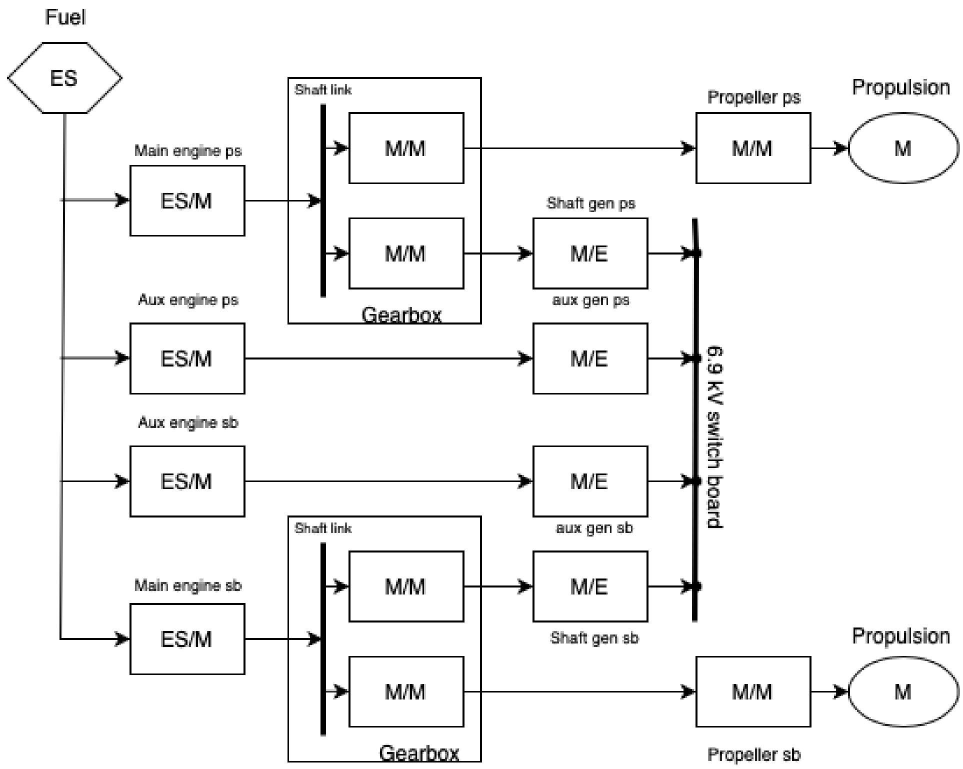


Figure 4.2: Energy flow diagram of the power system on board the Fairplayer

In this figure, we calculate the loads from right to left, with on the right side 6 outer components from which variables are known. Converting one form of energy to another results in a certain loss. These losses are expressed in efficiencies, which are used to determine the contributions of all components. Various conversion efficiencies need to be considered when estimating the load profile. In theory, estimating the engine dynamics is done via the steps proposed by [Klein wout and Stapersma, 2002], illustrated in figures 4.3 and 4.4.

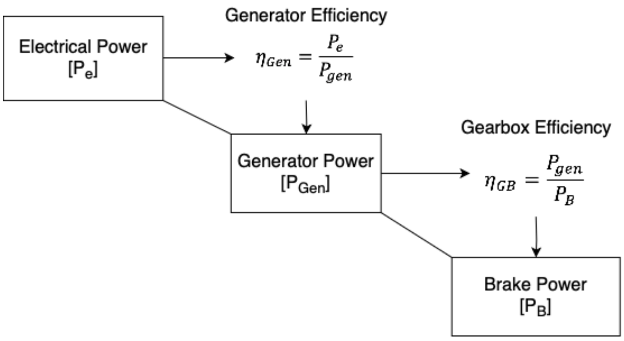


Figure 4.3: Power Chain electrical conversion

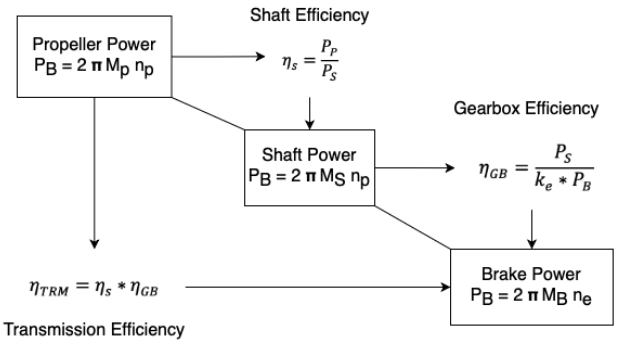


Figure 4.4: Power Chain mechanical conversion

The conversion efficiencies are defined in table 4.1. These efficiencies regarding the mechanical losses such as η_S and η_{GB} are based upon figure 2.1 which originates from the vessel handbook. Generator efficiencies were based on the difference between electrical output en rated engine power. The efficiency of internal combustion engines was based on a simple estimation using the specific fuel consumption and energy potential of MGO diesel fuel. Efficiencies with respect to the battery system are explained in subsection 4.4.1. The $SOFC_{max}$ efficiency is used in CASE 3 yet already mentioned here. Fuel cell efficiency was based on [EMSA, 2017]. It must be noted that, for both the internal combustion engine and the fuel cell, the efficiencies are variable in reality. For the solid oxide fuel cell system, the efficiency was assumed constant as the load is kept constant.

Table 4.1: Used Efficiencies throughout the calculations

Efficiency	Symbol	Quantity	Unit
Shaft	η_S	98	%
Gearbox	η_{GB}	98	%
Generator	η_{Gen}	96	%
ICE_Max	η_{ice}	44	%
DC/AC-converter	η_{cnvtr}	98	%
Battery Charge	η_{ch}	97	%
Battery Discharge	η_{dis}	96	%
SOFC_Max	η_{SOFC}	55	%

4.2. Internal Combustion Engines

To assess the impact of swappable energy containers, it is essential to estimate the emissions generated by the engines. The objective of the model for this is to combine the electrical load on the generators, in conjunction with the absorbed power on the propellers, to determine the engine power at the crankshaft. With the power at any moment in time, the fuel consumption is estimated. Subsequently, the emissions can be calculated. Section 2.3 describes that the installed generators are of two different types and purpose. Estimating the load, many differences between the auxiliary and main engines are counted for, such as appendages, specific fuel consumption and max output. In addition, the main engines are connected both to controllable pitch propellers and shaft generators. For that reason, the estimation of brake engine power differs.

4.2.1. Power estimation: MAK 9M32C, Main Engines

To estimate the power absorbed by the propeller, figure 4.5 is used. This figure illustrated the pitch angle over the required power and delivered thrust accordingly. It must be noted that this figure only holds in bollard pull conditions. Based on the logged data, it was concluded that the ship was stationary during installation, indicating that the propeller operates under bollard pull conditions. In the vessel's design process, the decision was made to prioritise optimisation for long-distance sailing, meaning that in this condition the thrust-to-power ratio does not reach its maximum potential. Despite the fact that controllable pitch propellers have enhanced bollard pull performance over fixed pitch propellers of the same dimensions, pitch is restricted to 70% due to limited water inflow. The black line power at the propeller P_p in figure 4.5 is plotted by Formula 4.1.

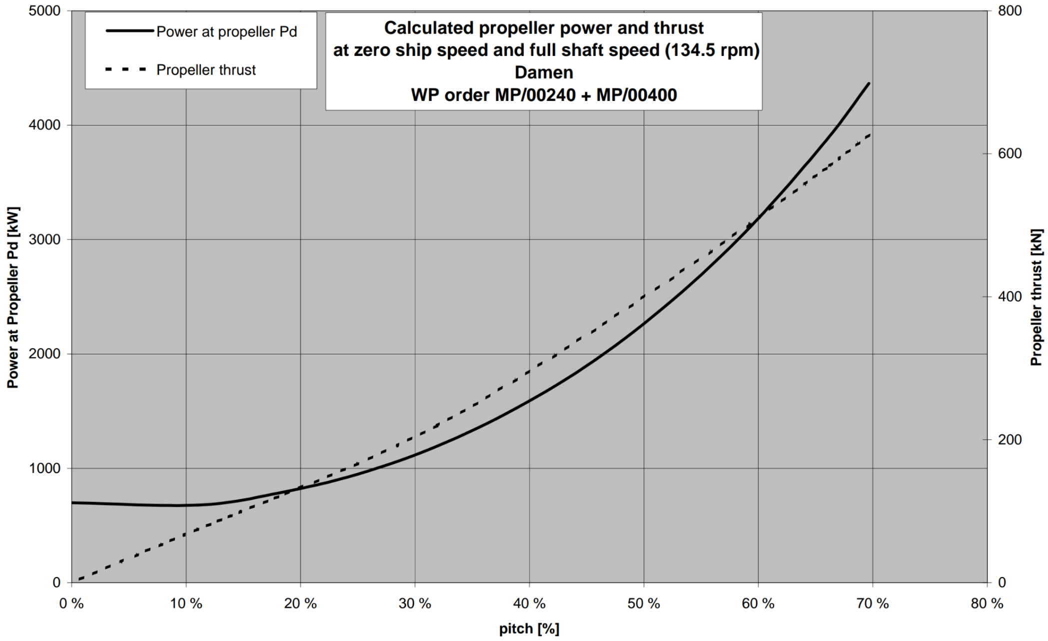


Figure 4.5: Fairplayer's thrust, power and pitch relation in bollard pull conditions

$$P_p(t) = 0.006 * \alpha^3_{\text{pitch}(t)} + 0.4 * \alpha^2_{\text{pitch}(t)} - 2.3 * \alpha_{\text{pitch}(t)} + 750 \quad (4.1)$$

Where,

- α_{pitch} is the measured pitch angle $degrees$.
- P_p is the absorbed power by the propeller at the shaft kW.

Effective power of the main engine is calculated by adding the absorbed power of the propeller to the electrical load while taking into account mechanical losses. Figure 4.6 illustrates the combinator and constant rpm load curves of the main engines. For the shaft generator to be synchronised with the grid, the engine operates according to the vertical line to maintain a proper electrical frequency. Figure 4.5 in combination with the pitch at any moment in time is used to calculate the power that the propellers absorb. This includes rotational and mechanical losses in the propeller, shaft seals, bearings and gearbox. With formula 4.2 the actual load is then determined by adding the electrical load of the 3000 kWe AEM generator to the load resulting from the propellers.

$$P_b(t) = \frac{P_e(t)}{\eta_{GB} * \eta_{Gen}} + \frac{P_P(t)}{\eta_{GB} * \eta_S} \quad (4.2)$$

Where,

- P_p is the absorbed power by the propeller at the shaft kW.
- P_e is the electrical loading of the shaft generator kWe
- η are the efficiencies defined in table 4.1

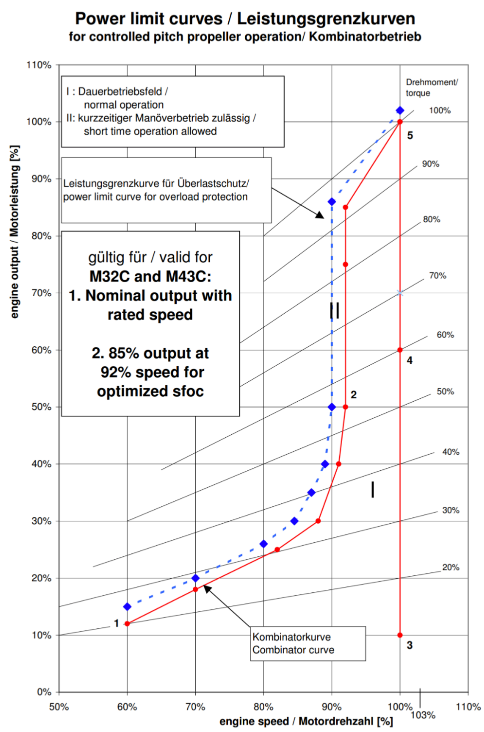


Figure 4.6: MAK 9M32C Load curve

4.2.2. Power estimation: Caterpillar 3516B, Auxiliary Engines

The power of the auxiliary engine is the electrical load divided by the efficiency of the mechanical and electrical components in the generator. In table 4.1 the mechanical and electrical losses (η_{Gen}) are assumed to be 96% when combined. The significant difference between the two generators is explained by the open busbar that separates the grid.

$$P_b(t) = \frac{P_e(t)}{\eta_{Gen}} \tag{4.3}$$

- P_b is the brake power of the auxiliary engine at the shaft kW.
- P_e is the electrical loading of the shaft generator kWe
- η_{Gen} generator efficiency defined in table 4.1

4.2.3. Specific fuel consumption

The specific fuel consumption and fuel consumption for the main engines is illustrated in figures 4.7a and 4.7b. The horizontal axis shows the delivered engine power. This number is used to quantify the amount of fuel the engines consume to produce the required amount of power.

Since Jumbo's vessels are propelled by controllable pitch propellers, the engine rpm is kept constant at 600 rpm and the delivered engine power depends on the load. This limitation also exists because the generators are not equipped with frequency converters. If they were equipped with one, the graphs would be three-dimensional, with specific fuel consumption varying depending on both the rotational velocity and the load. The vertical axis shows the brake specific fuel consumption in g /kWh. The higher specific fuel consumption at lower loads is due to lower temperatures and lower pressures, which result in lower engine efficiency. Engine data used for these graphs originates from the factory acceptance test and engine international air pollution prevention certificate. In all calculations involving these graphs, it is assumed that the load on any running and synchronized engines does not drop below 10%. This minimum load is necessary to maintain the engines operational.

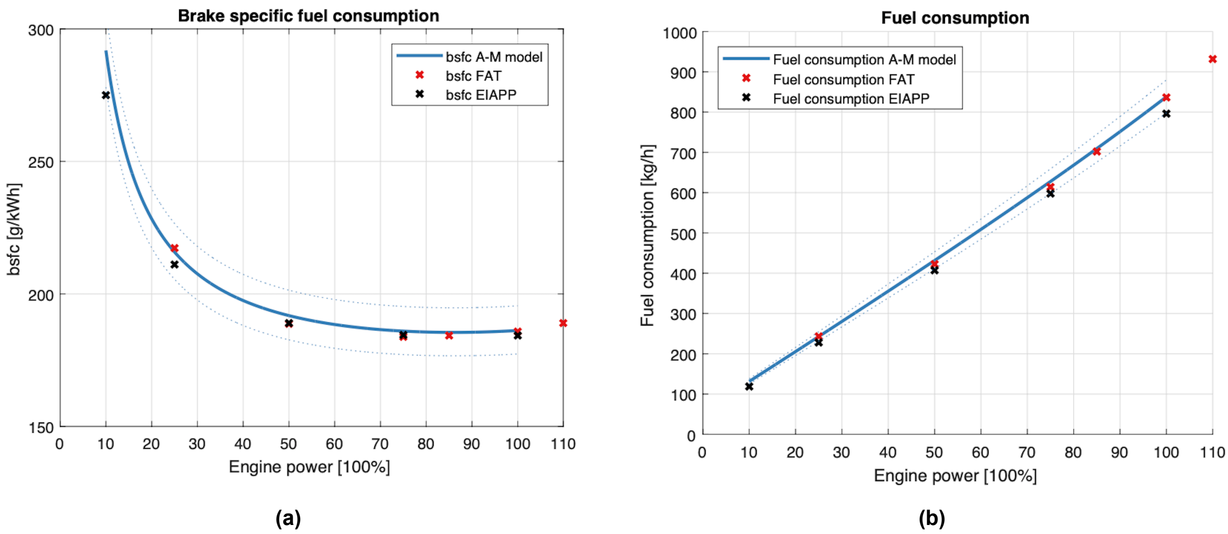
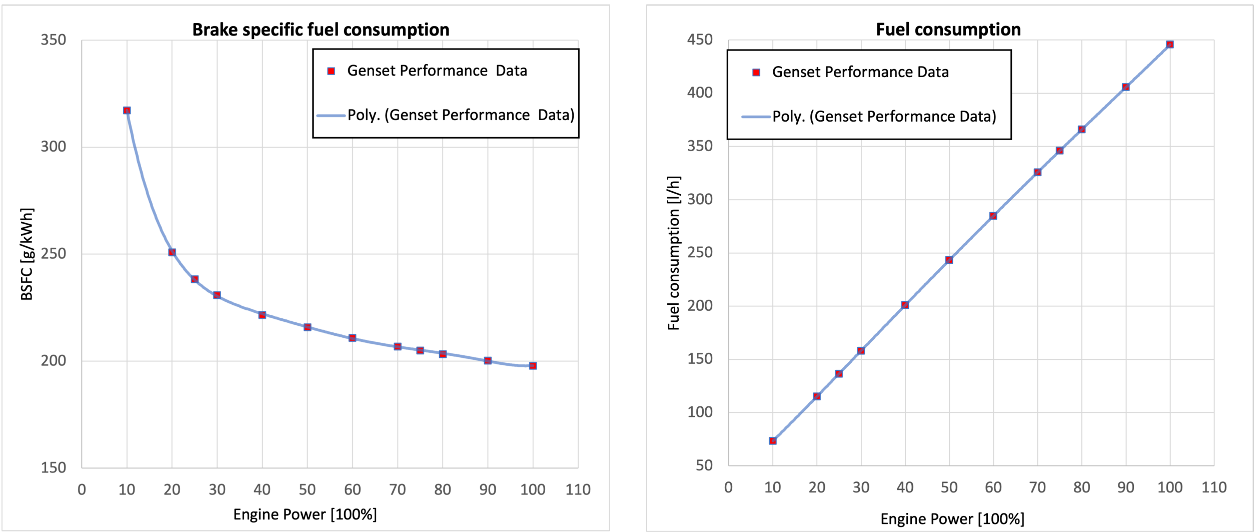


Figure 4.7: a) Brake specific fuel consumption, b) Fuel consumption, MAK 9M32C

Engine consumption graphs 4.8a and 4.8b for the auxiliary engines are similar to these of the main engine. Data originates from a factory acceptance test. While the main engines operate most efficient at 80% load, auxiliary engines are the most efficient close to their rated power.



(a) **(b)**

Figure 4.8: a) Brake specific fuel consumption, b) Fuel consumption, CAT 3516B

$$b_e = \frac{\dot{m}_b}{P_b} \quad \left[\frac{g}{kWh}\right] \tag{4.4}$$

Where,

- b_e is the specific fuel consumption $[\frac{g}{kWh}]$
- m_b is the mass of fuel ton
- P_b Is the engine's brake power, meaning the effective power at the crank kW.

4.2.4. CO_2 Emissions

Regarding the optimisation goals of greenhouse gas emissions, the initial step involves quantifying the current CO_2 emissions. Carbon dioxide emissions are the results of a reaction between the carbon in the diesel fuel and oxygen in the air during the combustion process. Accordingly, the amount of CO_2 emissions depends on the fuel consumption of the engines. Through the load profile, power estimation, specific fuel consumption and the CO_2 conversion factors, an estimation of the emitted CO_2 can be established.

$$m_b = \int_{t=start}^{t=end} \dot{m}_b(t)\, dt \quad [g] \tag{4.5}$$

Where,

- $t = start$ and $t = end$ define the duration of the trip over which the amount of fuel mass needs to be calculated.
- $\dot{m}_b$ Mass flow of fuel at any moment in time kg/s
- m_b total amount of fuel ton

Fuel-based pollutants depend on the amount of pollutant found in the fuel. Therefore, the consumed amount of fuel ($m_b[ton]$) is multiplied with a specific polluter index (SPI). To determine the CO_2 emissions, the model will use the consumption calculated with the specific fuel consumption according to section 4.2.3 and the conversion factors as given in table 4.2 The weight of carbon dioxide (CO_2) produced from burning a fuel exceeds the weight of the fuel itself. This occurs because in the process of complete combustion, each carbon atom in the fuel bounds with two oxygen atoms to form CO_2.

Table 4.2: CO_2 conversion factor, to calculate the emissions [International Maritime Organisation, 2020]

Fuel type	Conversion factor	Unit
MGO	3.206	CO_2/ ton

The conversion factor is better known as the specific pollutant index (SPI) used in formula 4.6 is derived from the specific fuel consumption formula 4.4 [Klein wout and Stapersma, 2002].

$$SPI = \frac{[m_{CO2}]}{[m_b]} \tag{4.6}$$

Where,

- SPI is the specific pollutant index.
- m_{CO2} is The pollutant mass generated.
- m_b is the Ultimate usefull product or total amount of fuel.

4.2.5. NO_X Emissions

As described in section 2.1 the NO_X emissions are catogorised as energy-based emissions which are calculated depending on the engine's power output as a percentage of the rated power using and energy-based emission factor in [g pollutant/h] corresponding to the load [%]. Accurate NO_X simulations reach beyond the scope of this thesis and depend on more parameters than this thesis has access to. For instance, combustion temperature, inlet air temperature, fuel consumption, and oxygen ratio. Therefore, the NO_X emission estimations are simplified proportional to the loading of the engine. Figure 4.9 illustrates the NO_X emission performance parameters used to determine the amount of NO_X. A detailed approach to determine the NO_X emissions for these engines accurately is examined in the thesis of M van Riet [Van Riet, 2018] on the NO_X emissions for Jumbo's Offshore vessels.

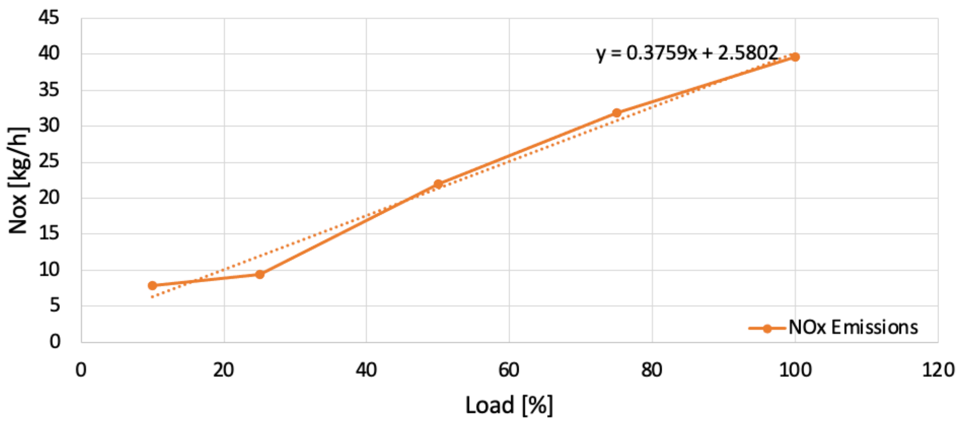


Figure 4.9: Emission performance test data 9M32C

To determine the NO_X data for the auxiliary engines, a constant number proportional to the power of the engine was used to determine the NO_X emissions of the auxiliary engines. From the factory data sheet of the Caterpillar 3516B NO_X values are not specified. It is known that the ship complies with the IMO Tier I NO_X regulations. For the constant rotational speed of 1800 rpm it is determined that the NO_X limit is 10.05 g/kWh. Accordingly, the NO_X emissions are calculated using a simplified conversion factor of 10.05 g/kWh, with a lower synchronized engine limit of 180 kW. This limit is necessary because when the load curve is matched to the running internal combustion engine's power curve, there remains a minimum power requirement to keep the engine operational. In essence, fuel is always required to keep the engines operational and online, even when the load is nearly zero.

4.2.6. Generator power

Calculating the engine power through these synchronous generators, some working principles should be accounted for. The generator consists of a stator and a rotor that rotates at a constant speed synchronized with the frequency of the alternating current (AC) power supply. In this context, maintaining a constant RPM becomes a crucial requirement, particularly when a frequency converter is not installed. For the scope of this thesis, synchronous machine theory is limited to understanding the power triangle. This triangle is a representation of the relationships between the three electrical power vectors acting within the machine: true power (P), apparent power (S) and reactive power (Q).

True power (P), is the actual power that is measured at the main switch board in watts. Apparent power (S), measured in volt-amperes (VA), is the vector sum of true power and reactive power. It represents the total power flowing in an AC circuit. In the case of a synchronous machine, apparent power accounts for both the true power output/input and the reactive power exchange with the electrical system. Apparent power is represented as the hypotenuse (the longest side) of the power triangle. Reactive power, measured in volt-amperes reactive (VAR), represents the power that oscillates back and forth between the source and the load due to the phase difference between voltage and current in AC circuits. Reactive power is represented as the vertical leg of the power triangle.

$$P(t) = S(t) * \cos \Phi \tag{4.7}$$

Where,

- $S(t)$ is the apparent power measured in kVa.
- $P(t)$ is the true power output of the generator kW.
- Φ is the Power factor or impedance angle.

Power Factor (PF): Power factor is a dimensionless quantity that describes the ratio of true power to apparent power which indicates how effectively electrical power is being converted into useful work (true power) in a circuit.

4.3. Fuel Cell Sizing

The electric power required from the fuel cell measured on the switchboard is determined according to equation 4.8.

$$P_{FC_{effective}}[kWe] = \frac{P_{required}[kWe]}{\eta_{cvtr}} \tag{4.8}$$

where,

- $P_{FC_{effective}}$ Effective fuel cell power
- $P_{required}$ The electrical load of the grid
- η_{cvtr} Efficiency of the AC/DC converter

Another factor influencing the SOFC size is the degradation of the system over time. SOFC degradation can occur due to various factors, and accounting for this is important to ensure good performance and capacity of the system throughout the 5 years of expected lifetime. Among other factors, high operating temperatures of these systems cause material degradation and thermal stresses over time. This can result in cracking and damage to the cell components. Moreover, frequent thermal cycling, where the SOFC is repeatedly turned on and off, can cause stress on the cell components and lead to mechanical failure.

Chemical reactions between the fuel, air, and materials within the cell can lead to degradation asswell. For example, impurities in the fuel and air streams, such as sulphur compounds or particulate matter, can poison the cell and decrease its efficiency. Finally, electrodes and electrolytes degrade over time. Nevertheless, real degradation rates of commercial SOFC systems currently on the marked are often disclosed. According to [Zarabi Golkhatmi et al., 2022], scientists of the field expect an average degradation rate of 0.5%/1000 h for commercial SOFC systems constructed after 2020, and it is therefore that this number is used to determine the required amount of power over the expected life span of five years.

$$\text{Degradation factor (DF)} = \frac{1}{1 - \left(\frac{\text{Degradation Rate}}{100}\right) \times \left(\frac{\text{Total Time Period}}{1{,}000}\right)} = \frac{1}{1 - \left(\frac{0.5}{1000}\right) \times \left(\frac{44000}{1{,}000}\right)} = \mathbf{1.78} \tag{4.9}$$

$$P_{FC_{installed}}[kWe] = P_{effective}[kWe] * DF \tag{4.10}$$

Where,

- $P_{FC_{installed}}$ Fuel cell power that is to be installed on the vessel
- $P_{required}$ The effective fuel cell power
- DF is the degradation factor

4.4. Container Sizing

4.4.1. Battery Storage Systems

As the literature study determined, renewable energy is stored in containers in the form of electricity and hydrogen. This subsection establishes the properties and characteristic of the different storage methods used for subsequent calculations. Properties of the chosen battery system are illustrated in table 4.3 assumed based on the Current Direct project [Current Direct, 2021] featuring a maximum C-rate of 1C and a maximum depth of discharge of 90%

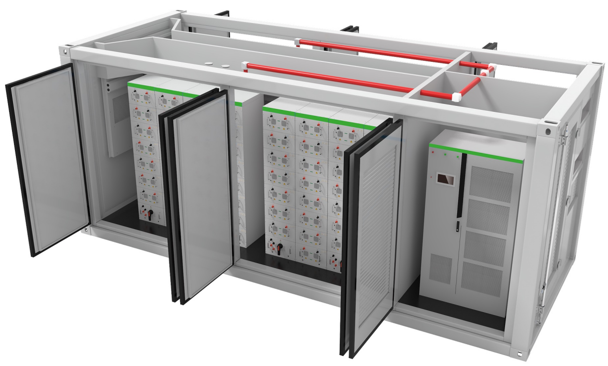


Figure 4.10: Arrangement of a 20ft containerized battery energy storage system [EVESCO, 2023]

Table 4.3: Properties of a containerised battery pack [Current Direct, 2021]

Property	**Quantity**	**Unit**
Battery cell	3.2 / 280	V / Ah
Battery capacity	2000.7	kWh
Nominal voltage	690	V
Internal resistance	50	mΩ
Dimensions	20ft	1TEU
Nominal power	2000	kW
Operating temperature	-30 $\sim$ 50	$^\circ$C

Battery characteristics focus mainly on the specific energy, charge and discharge rates, safety and lifetime. For instance, super capacitors have high intensity discharging that can be beneficial for peak shaving when combined to other systems. The specific energy is the amount of energy in MJ per kilograms. The specific energy of current high-energy batteries is still relatively low compared to that of fossil fuels. For instance, the specific energy of HFO is 40.5 MJ/kg, while a high energy marine battery system is only 0.5

MJ/kg[MAN Energy Solutions, 2019]. The specific energy for maritime batteries is lower than for car batteries. This is mainly due to operational margins and fire insulation for thermal runaway. The charge/discharge current that batteries can manage is expressed as the C-rate. This can be used to compare batteries of different sizes and types. If the C-rate is 1C, this means that the battery can completely discharge from 100 % to 0 % in one hour. In reality this charge rate is not constant as often the final 20 % is charge at a much lower rate than the previous 80 %.

Delta state of charge (DSOC) is the percentage of the total rated battery capacity that can be used. However, batteries are not ideal devises and have internal losses when charged and discharged. This energy dispatch trough thermal energy. For that reason, the correct sizing procedure cannot neglect the efficiencies of different components within the grid. For instance, electrical generator (η_{gen}), rectifier (η_{rect}), inverter (η_{invt}), bidirectional DC/DC converter (η_{conv}) and storage device. For this thesis, with reference to the battery system, two different efficiencies must be considered: discharge efficiency ($\eta_{B,DIS}$) and charge efficiency (($\eta_{B,CH}$). The real battery load then becomes:

$$p_{\text{Batt}}(t) = \frac{p_{\text{Batt}}^{+}(t)}{\eta_{\text{dis}}} + p_{\text{Batt}}^{-}(t) \cdot \eta_{ch} \tag{4.11}$$

where.

- p_{Batt} is the variable battery load in kW.
- $p_{\text{Batt}}^{+}(t)$ is charge power.
- η_{dis} is the discharge efficiency
- $p_{\text{Batt}}^{-}(t)$ is discharge power.
- η_{ch} is the charge efficiency

The charge and discharge efficiencies depend on the C-rate as more heat is developed as energy flow is increased. The temperature of the surrounding and battery also influences the efficiency. Finally, batteries in hybrid ships usually operate with variable currents both during discharge and charge. All these factors increase the complexity to evaluate the actual battery efficiency and capacity accordingly. Constant charge and discharge efficiencies of 97% and 96% were chosen respectively [Eriksen and Karlsen, 2022].

$$E_{\text{Batt}}(t) = \int_{t=start}^{t=end} p_{\text{Batt}}(t)\, dt \quad [kWh] \tag{4.12}$$

The cycle lifetime of batteries is determined by the amount of charge and discharge cycles that it can manage before the system is scrapped. Accordingly, batteries degrade over time and consequently the overall storage performance. The battery condition is referred to as the state of health.

$$Q_{batttotal}[kWh] = \frac{E_{batt-req}[kWh]}{DoD * \eta_{cvtr} * SoH_{max}} \tag{4.13}$$

Where,

- $Q_{batt-total}$ is the total capacity of the battery in kWh.
- $E_{required}$ is the required amount of energy in kWh.
- DoD is the depth of discharge
- η_{cvtr} is the DC/AC converter
- SoH_{max} is the maximum battery degradation.

$$N = \frac{Q_{batt-total}[kWh]}{Q_{batt}[kWh]} \tag{4.14}$$

Where,

- $Q_{batt-total}$ is the total capacity of the battery in kWh.
- Q_{batt} is capacity of one battery container in kWh.
- N is the number of containers required.

4.4.2. Hydrogen Storage System

Hydrogen is stored in pressurised cylinders that are packed inside a container which is illustrated in figure 4.11. For this thesis, the 350 and 500 bar(a) 40ft containers are evaluated to limit the number of dangerous lifts in port.

Figure 4.11: Arrangement of compressed hydrogen tanks inside a 40ft containers [NPROXX, 2023]

Table 4.4: Hydrogen container capacity [Abma et al., 2019]

Hydrogen Containers (Gross)	20ft	30ft	40ft	Unit
Capacity at 350 bar(a) (kg)	450	625	845	kg
Capacity at 500 bar(a) (kg)	520	815	1085	kg
Residual pressure (bar(a))	10	10	10	bar(a)
Total container weight (500bar(a))	15	23	31	mton

$$E_{SOFC} = \int_{t=start}^{t=end} p_{SOFC}(t)\, dt \quad [kWh] \tag{4.15}$$

Where,

- $t = start$ and $t = end$ define the duration of the trip over which the amount of fuel mass needs to be calculated.
- $p_{SOFC}(t)$ Power output of the fuel cell at any moment in time $[kW]$
- E_{SOFC} total amount of energy $[kWh]$

$$m_b(\text{kg}) = \frac{E_{\text{SOFC}} \times 3600s}{\eta_{SOFC}(\%) \times LHV(kJ/kg)} \tag{4.16}$$

Where,

- E_{SOFC} total amount of energy $[kWh]$
- $\eta_{SOFC}(\%)$ is the fuel cell efficiency
- m_b is the mass of fuel in this case hydrogen.
- LHV (Lower heating value) is the amount of heat released by combusting a specified quantity

Lightweight composite tanks (also called type 4 tanks for full composite) can store hydrogen at 350, 500 or even 700 bar(a) [Abma et al., 2019]. High pressure tanks require a minimum residual pressure that should be left in the tank. For the use of hydrogen containers tanks in this study, this residual pressure was 10 bar(a), indicating that these gross hydrogen capacities need to be corrected to the net weight in order to determine the correct amount of required containers. Considering the risks involved during the lifting of these hydrogen containers, it is suggested to use 40ft containers in order to minimise the amount of lifts in port. It is determined what the required amount of containers is for both 350 or 500 as availability depends on the supplier.

$$P \times V = n \times R \times T \tag{4.17}$$

Using the ideal gas law for hydrogen, it was determined that the relative density of hydrogen is 30.81 kg/m^3, 23.35 kg/m^3 and 0.81 kg/m^3 at 500, 350 and 10 bar(a) at 298.15K respectively. With the density, volume and weight, it was estimated that 28.5 kg of hydrogen in the 40ft containers cannot be used.

5
Jumbo Offshore Benchmark

In order to measure the impact of swappable containers regarding emissions, it is necessary to start by evaluating the current situation. For this purpose, an initial load profile is established, subsequently enabling the determination of emissions and consumption of a representative installation trip. Consequently, this chapter aims to answer the following sub question:

What is the load profile of Jumbo's Heavy Lift Construction vessel during an offshore installation operation, using real performance parameters?

5.1. Reference Projects Hollandse Kust Zuid

This section aims to map the load profile of the Fairplayer using a reference project, with the goal of assessing power consumption during the contract and analyzing the emission performance to establish a benchmark that can be optimized through alternative power management strategies.

The Hollandse Kust Zuid (HKZ) project was an offshore wind turbine construction contract that Jumbo was granted in 2021 and was executed in the summer of 2022. The scope of jumbo within the project was to install the boat landing, water tight seal and external work platform via an installation tool referred to as ABIT.The Hollandse Kust Zuid Wind Farm site is located in the Dutch Sector of the North Sea, approximately 22 km from the coastline. The large consumers in this project are one crane and the DP system. The project was to be completed in 27 trips, whereby 106 installations were carried out. This took Jumbo from the 12th of May 2022 to the 9th of September. From these trips, real time power data is available see figure 5.1. In figure 5.1 the installations cycles can be distinguished as all generators are online during dynamic positioning.

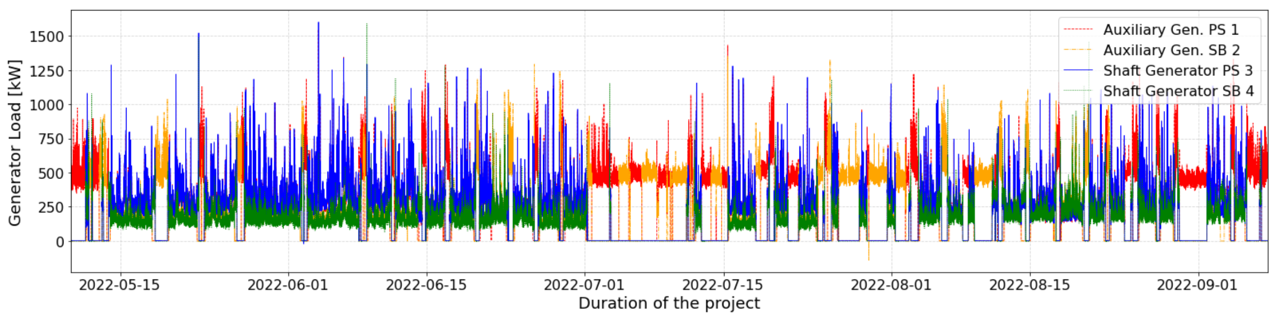


Figure 5.1: Unfiltered Load profile from the Fairplayer during the wind turbine project Hollands Kust Zuid

Combining the generator loads into one line gives the electrical demand of the vessel during the entire project. With the input from daily progress reports, it is possible to analyse the time frames on which the ship execute installation on DP. This is plotted in figure 5.2 whereby the green highlighted sections illustrate the installation trips. Despite the full electric capacity being online, the loads do not approximate the maximum capacity of the generators.

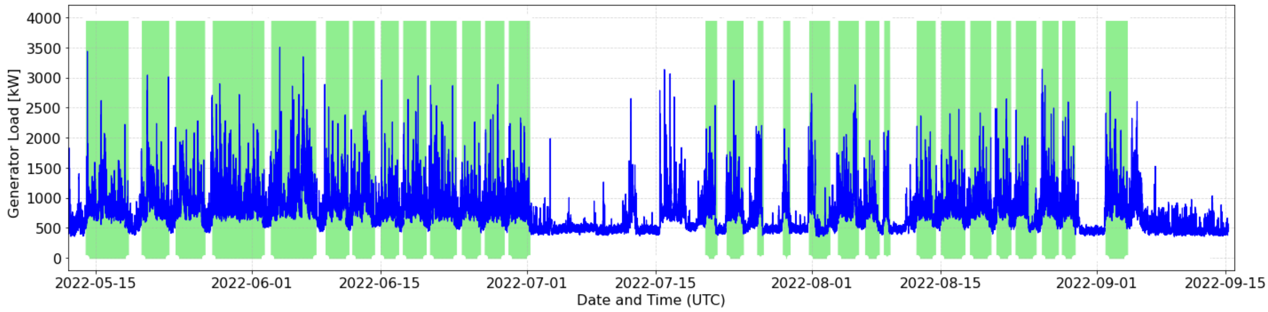


Figure 5.2: Load profile from the Fairplayer during the Hollandse Kust Zuid including time at installation

Within the Hollandse Kust Zuid project, one trip is selected to be further analysed. Despite that any change or addition to the electrical grid should hold for every trip, it is more convenient to analyse on load case in detail rather than the entire project superficial. The review of one load case will function as the benchmark used to quantify any results later in the thesis.

In order to select the most suitable trip, several factors were taken into consideration. However, the selection criteria were ultimately narrowed down to two factors that govern the required amount of energy containers later in this thesis. The first criterion was the trip duration, which directly correlated with the total energy consumption, and the second criterion was the highest average load, as illustrated in Figure 5.3. Based on the first criterion, trips 1, 4 and 5 qualified as they took the vessel significantly longer than all other installation trips. In relation to the second criterion, it was determined that trips 5 and 16 featured the highest average loading.

Considering the overlap between both criteria, trip 5 (indicated by the red bar in figure 5.3) was deemed the most relevant load case for further calculations and review. Trip 5 was notably more challenging due to the weather conditions that caused downtime and required more corrections by the dynamic positioning system resulting in a higher power demand.

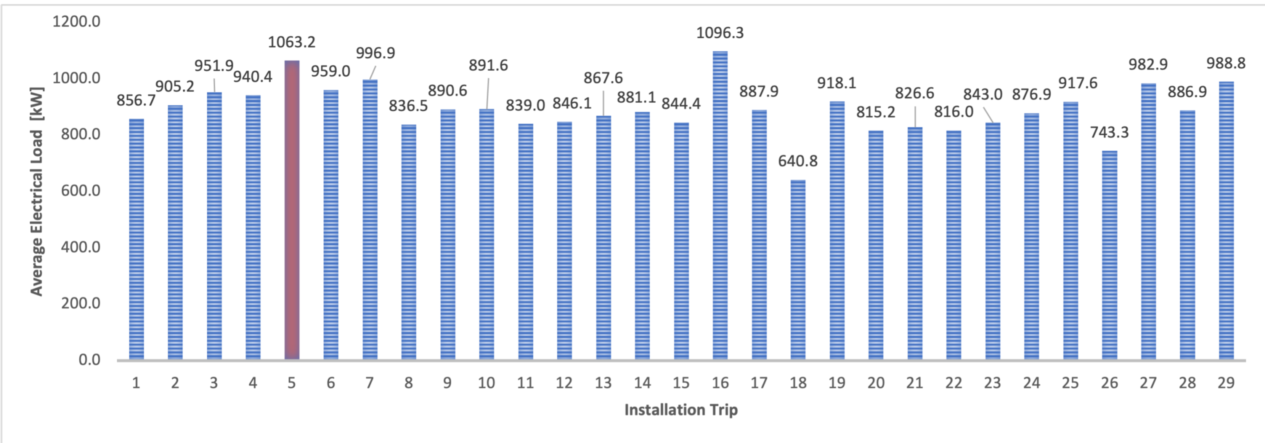


Figure 5.3: Mean electrical consumption per trip

5.2. Dynamic Load Profile, Controllable Pitch Propeller

To analyse the load profile of trip 5, first the data between the interval of '2022-06-03' and '2022-06-08' is plotted. In figure 5.4 the electrical load of the Auxiliary generators PS (1) and SB (2) and Shaft generators PS (3) and SB (4) at any moment in time are presented.

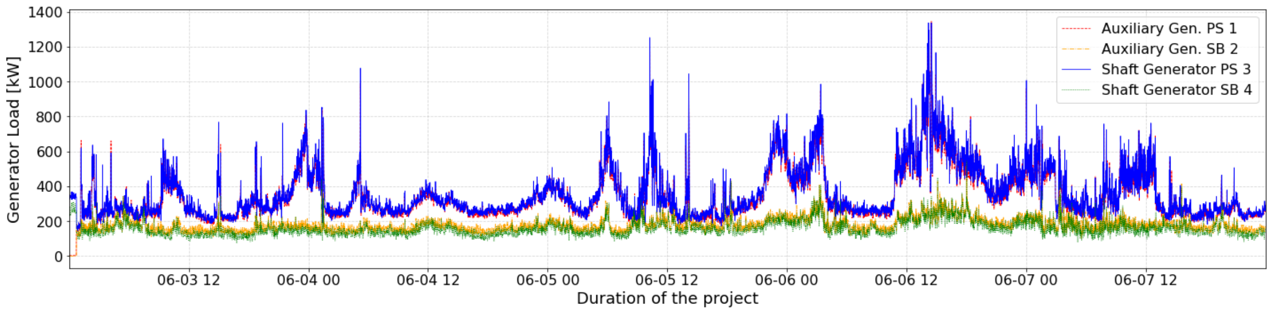


Figure 5.4: Load profile of each electric generator on the Fairplayer during the TP assembly project Hollands Kust Zuid trip 5

Figure 5.4 indicates that the electrical distribution operating philosophy discussed in section2.3 is applied during trip 5 as the electric generators 1 2 3 and 4 are online. The first abbreviation that stands out when comparing the graphs is that the load is unevenly shared between the four generators. Despite, generators 1 and 3 show load sharing behaviour that is expected from a conventional electrical grid, the load profile deviated from generators 2 and 4. The phenomenon is explained by the fact that the grid is separated by a busbar that is open during the installation campaign. Generators 2 and 4 are online for redundancy considerations only.

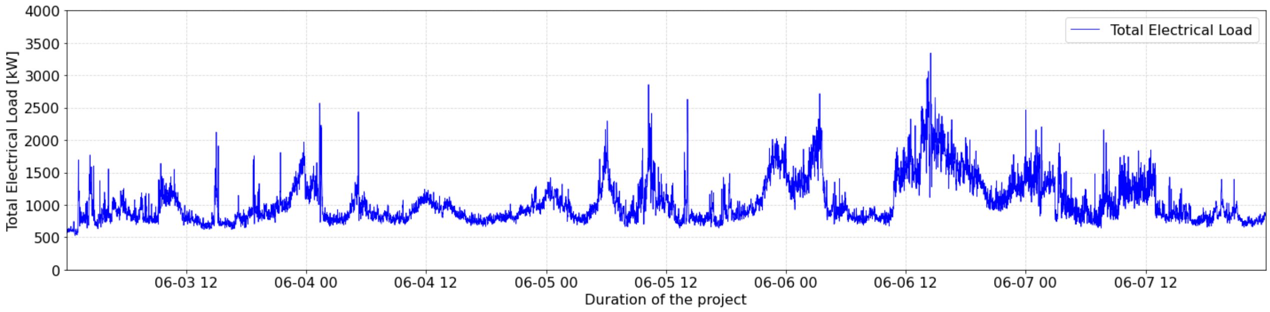


Figure 5.5: Load profile of the electric generators combined on the Fairplayer during the TP assembly project Hollands Kust Zuid trip 5

The combined curve is categorized by some characteristics that could be useful when other type of energy converters are applied to the load curve. Table 5.1 illustrate these characteristics. Noteworthy is that the peak load of, 3343 kW is below half of the 9800 kW available.

Table 5.1: Characteristics of the combined electrical load profile.

Peak load Max	Load Min	Max load increase	Power consumption	Average Load
3343 [kW]	527 [kW]	1583 [kW/min]	127584 [kWh]	1063 [kW]

For the current technical configuration, it is known that that additional to the electrical loading of the main engines through the shaft generators, the mechanically driven propellers also impose a load on the main engine. with figure 4.5 it is possible to quantify the loads imposed by these propellers on the main engines. In figure 5.6 the absorbed power by the generators is plotted.

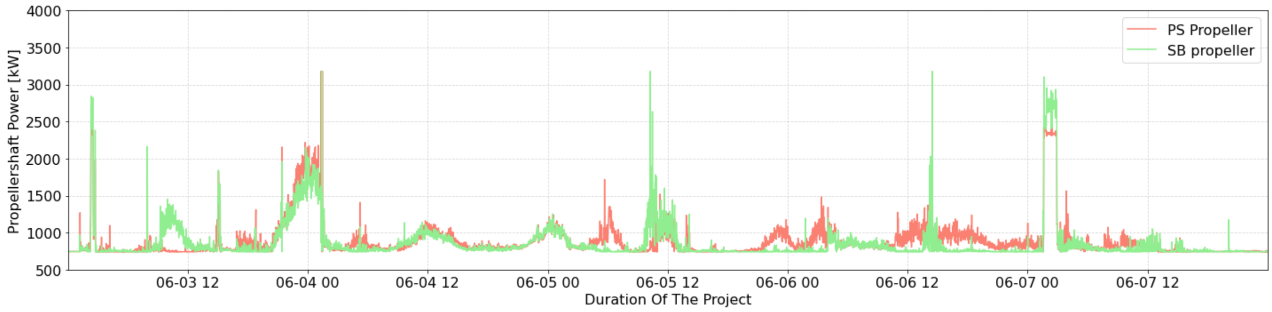


Figure 5.6: Propeller power of both controllable pitch propellers

5.2.1. Load profile: Current Technical Configuration

With the input data of all the variable load inputs filtered, it is possible to determine how the engines were loaded during trip 5. Subsequently, the emissions during trip 5 in the current configuration can be determined, which is essential to quantify the performance improvements. This thesis is limited by looking at NO_X and CO_2 emissions through the output of the diesel generators and main engines. Both emissions are the result of chemical reactions during the internal combustion process [Laursen, 2022].

Power estimation: Main engines

Estimation of the dynamic loading is defined in section 4.2. In formula 4.2, it is assumed that the propeller remained clutched in throughout the entirety of trip 5. Mechanical losses in the generator and gearbox follow from friction between the gears and disperse thermally. All mechanical losses are quantified in table 4.1. Combining both variable inputs and efficiencies, figures 5.7 and 5.8 illustrate the load curve for both the main engines.

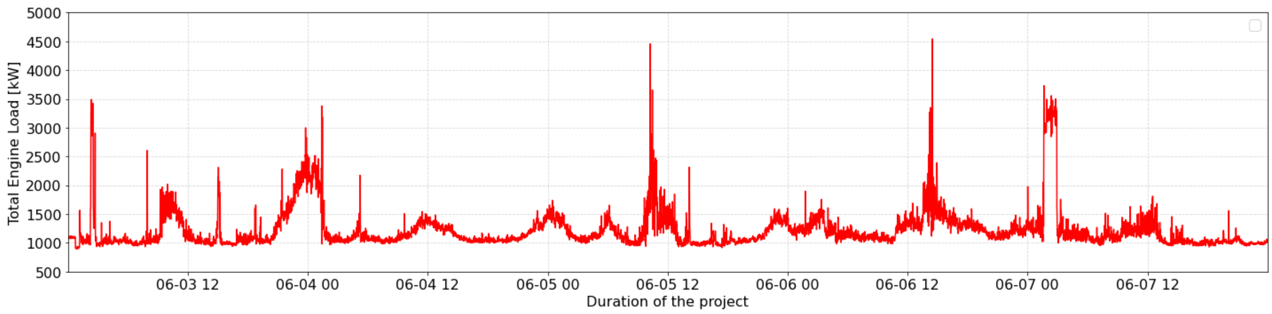


Figure 5.7: Load profile of the main engine PS on trip 5

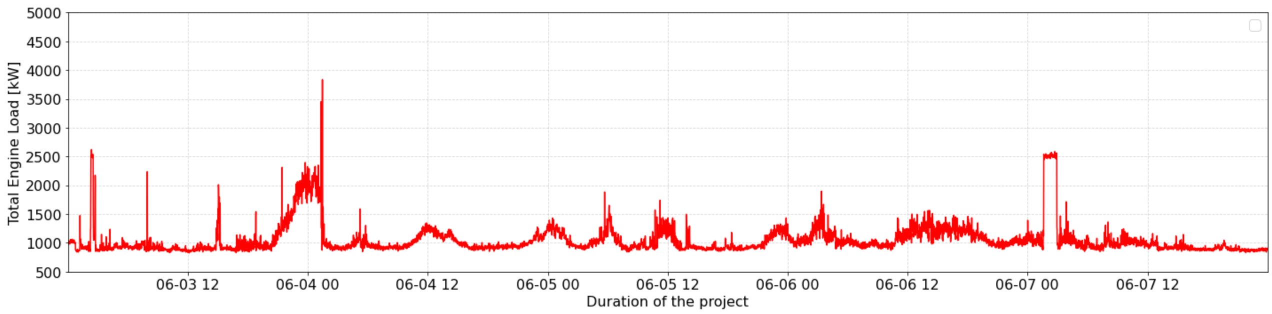


Figure 5.8: Load profile of the main engine SB on trip 5

Although the minimum load seems relatively high, both main engines frequently operate low in their power envelope. In order to gain a more comprehensive understanding of the power distribution, this power data is transformed into histograms. These histograms effectively illustrate the frequency of power data occurrences throughout trip 5. Taller bars on the histograms represent higher concentrations of data points, thereby providing insights into the characteristics of the power data. The observation is reinforced when visualized through histograms. With respect to the specific fuel consumption in Figure 4.7a, there appears to be potential for optimization as the efficiency increases when engines operate close to the rated output.

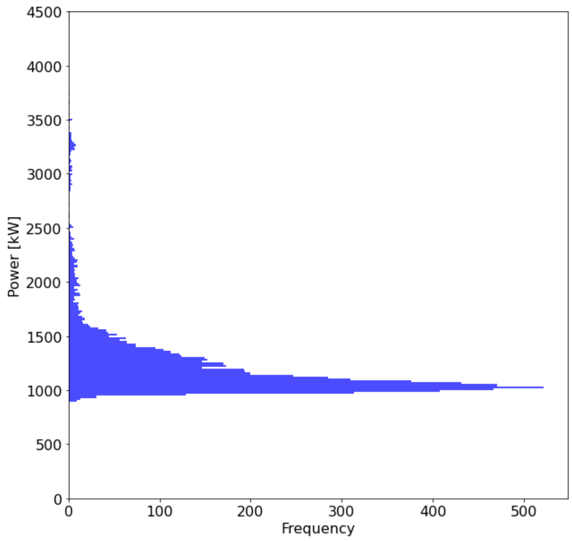


Figure 5.9: Power distribution main engine PS

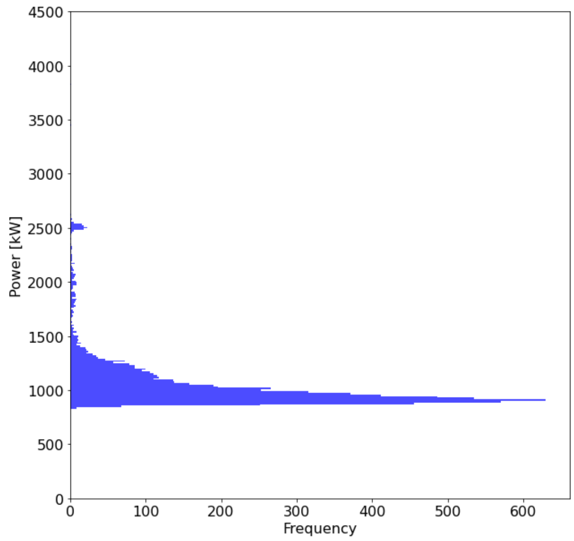


Figure 5.10: Power distribution main engine SB

Power estimation: Auxiliary engines

Figures 5.11 and 5.12 visualise the dynamic loading of the auxiliary engines. The load difference explained by the open busbar is highlighted in this representation, indicating that the starboard auxiliary engine is effectively idling. Shutting down this starboard engine would hypothetically reduce the emissions significantly.

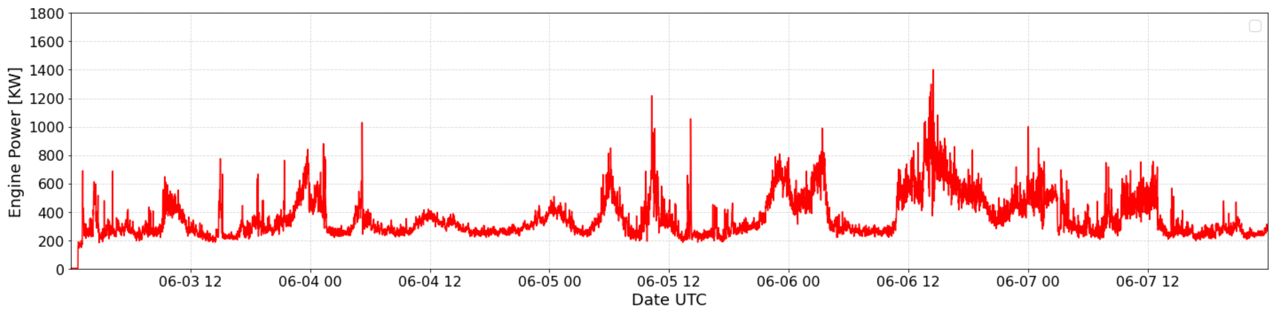


Figure 5.11: Load profile of the auxiliary engine PS on trip 5

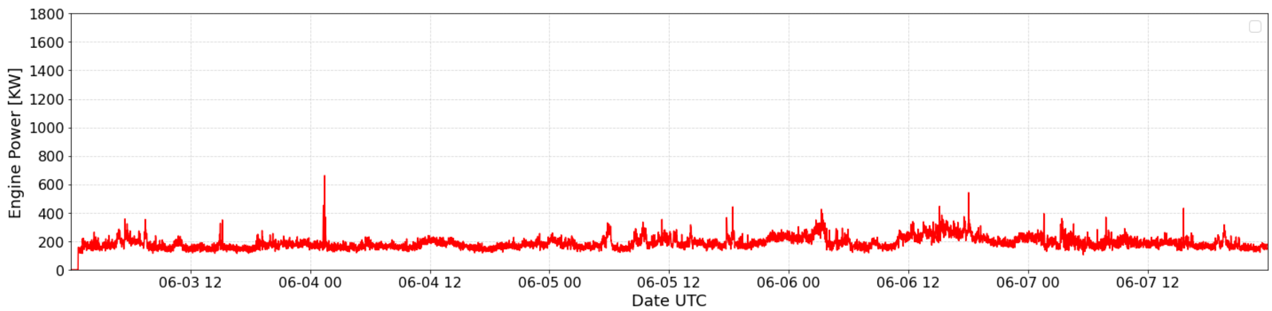


Figure 5.12: Load profile of the auxiliary engine SB on trip 5

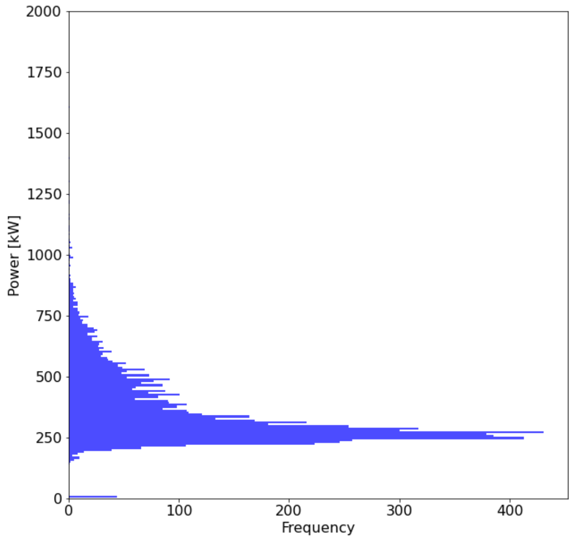


Figure 5.13: Power distribution auxiliary engine PS

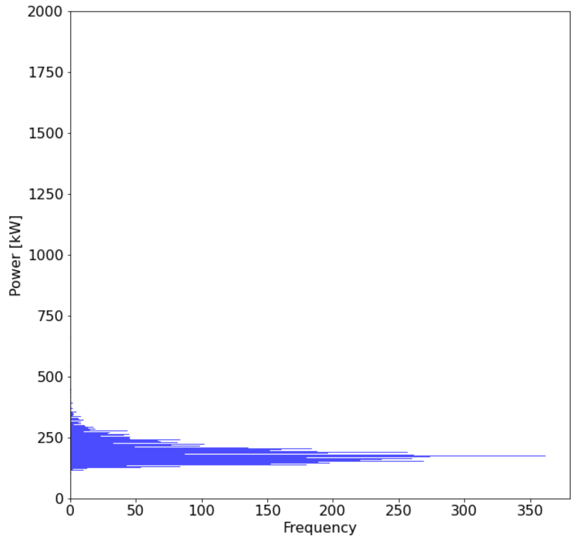


Figure 5.14: Power distribution auxiliary engine SB

Based on previous load curves, it is not immediately apparent within which region of the power envelope the port side auxiliary engine operates. Nevertheless, Figure 5.13 indicates that the port side auxiliary engine still operates low in the power envelope.

5.2.2. Applicable hybrid control strategies

With respect to the existing technical architecture, it is only feasible to implement spinning reserve and enhanced dynamic performance strategies due to the low average load and DP redundancy requirements. The DP requirements in 2.2 state that in case of a single point failure, a backup system must instantly be available. Consequently, during installation in DP a second engine is required to remain operational at all times, and the propeller must be engaged. Through the spinning reserve and enhanced dynamic performance strategies it is possible to shut down the auxiliary engines, consequently increasing the average load of the main engines enhancing the specific fuel consumption while reducing the number of engines online. Furthermore, the use of hydrogen is not viable within the current technical configuration, indicating that the utilization of hydrogen containers is impossible.

As this thesis prioritise the influence of swappable energy containers over determining the optimal solution for Jumbo's Fairplayer, an alternative technical configuration is deemed necessary. The alternative technical configurations will be based on an alternative load profile, whereby both the mechanical propeller load and electrical load by the generators will be combined to one total electrical load.

5.3. Dynamic Load Profile, Electric Propulsion

Due to the limited hybrid control strategies possible in the current technical architecture, this thesis will reevaluate the entire power generation plant, and in consequence also the propulsion plant is reconsidered. The current propulsion plant, as described in section 2.3, consists of two controllable pitch propellers which are driven by the main engines. This propulsion plant is optimised for a transport vessel sailing long distances while keeping advanced manoeuvrability. To optimise the DP operations, the type of propeller and drive are evaluated for their suitability. Therefore, the type of propellers is reevaluated. Based on the hybrid vessels described in chapter 3 the design choice is limited to azipod thrusters that are electrically driven and the directly driven controllable pitch propellers currently fitted to the reference vessel.

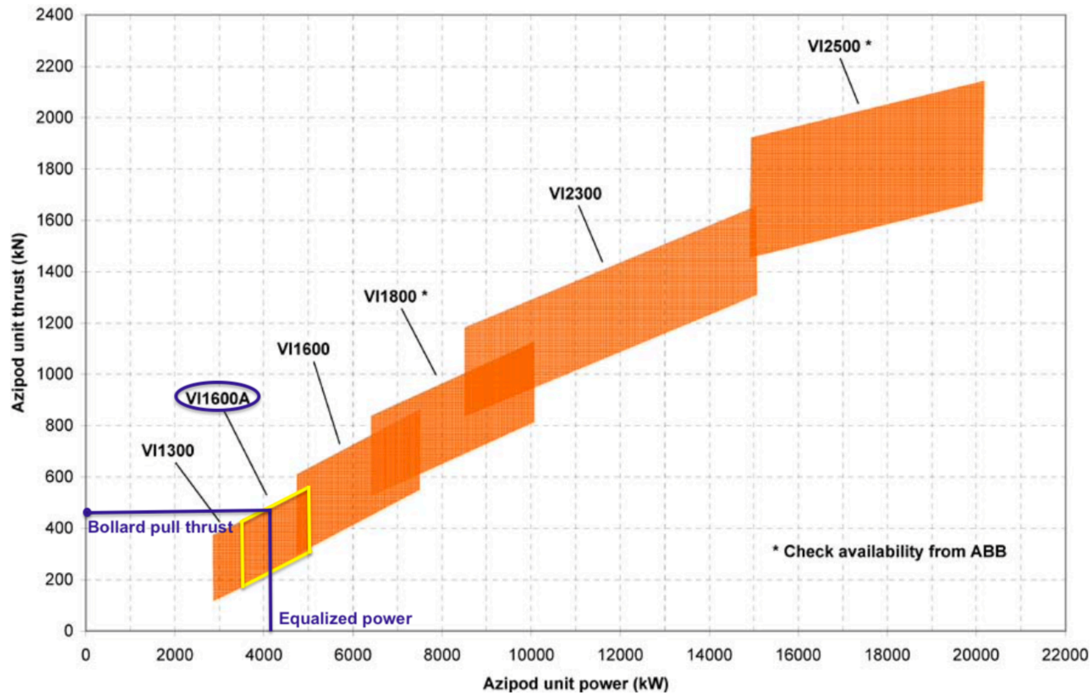


Figure 5.15: Propeller power – bollard pull thrust diagram for the different frame sizes [ABB, 2005]

Choosing the right azipod thruster regarding propeller diameter, type, rated output and number installed is a design study in itself which is beyond the scope of this thesis. Therefore, two azipod thrusters optimised for open water conditions of similar rated power are compared as design choice. It is assessed that the ABB VI1600A Azipod thruster has similar capabilities in open water as a currently installed controllable pitch propeller. The open water thrust of this thruster ranges between 600 and 840 [kN], depending on the propeller selection, and is therefore capable of delivering the required amount of thrust for 17.5 knots. Using the maximum absorbed power of the controllable pitch propeller in combination with figure 5.15, a maximum bollard pull thrust of 475 kN per azipod was determined. It is noted that azimuth thrusters which are optimised for bollard pull conditions accelerate in the thrust over power ratio over the assumed azipods during bollard pull, still the original design choices are respected and maintained by this design choice. Figure 5.16 illustrates both the power to thrust characteristics of both an azipod thruster and the currently installed propeller. The orange line is based on the CPP curve in Figure 4.5 and the grey line is fitted using propeller law and propeller data from [ABB, 2005]. Both lines intersect at 180 kN of thrust, signifying that when the mean thrust per propeller in a project exceeds 180 kN, controllable pitch propellers outperform azipod thrusters.

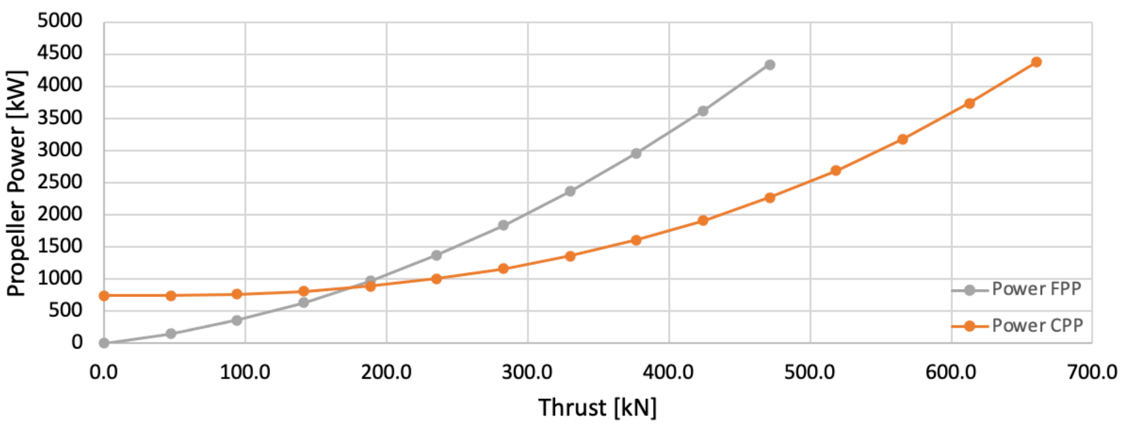


Figure 5.16: Thrust and power relation in bollard pull from both the CPP and FPP Propeller.

To determine the load of the electrically powered thrusters, the load of the controllable pitch propellers should be translated to an electric load of the electric motor for powering the propellers. As both configurations should deliver the same amount of thrust, first the thrust of the controllable pitch propellers is determined at any moment in time. This thrust data is then used to determine the power that an electrically driven propeller absorbs. To calculate the amount of thrust delivered by the controllable pitch propellers, figure 4.5 is used in combination with the pitch input plotted in figure 5.17.

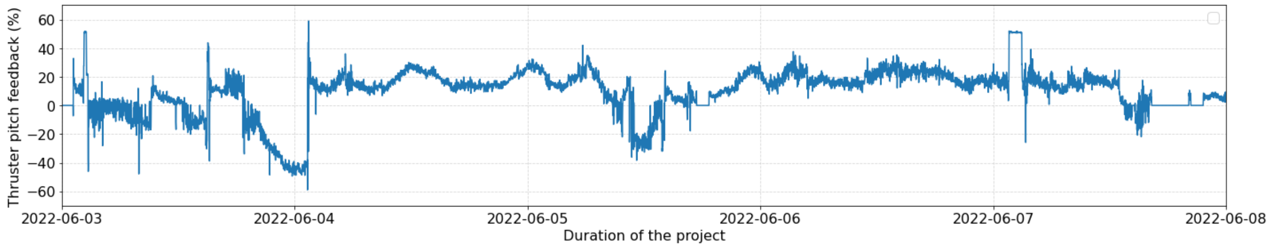


Figure 5.17: pitch angle expressed in percentages, used to calculate the corresponding thrust

Calculating the power of the main engine at any moment in time for both propeller concepts results in Figure 5.18. This figure illustrated only the load of the port side propeller, which is considered valid for the design choice. The orange line is the controllable pitch propeller load, which is the same as in Figure 5.6 while the grey line simulates the load of an ABB VI1600A Azipod thruster for the same amount of thrust. What is evident from the graph is that peak loads are considerably higher for an azipod system compared to a controllable pitch propeller, and the transient loading is significantly more challenging.

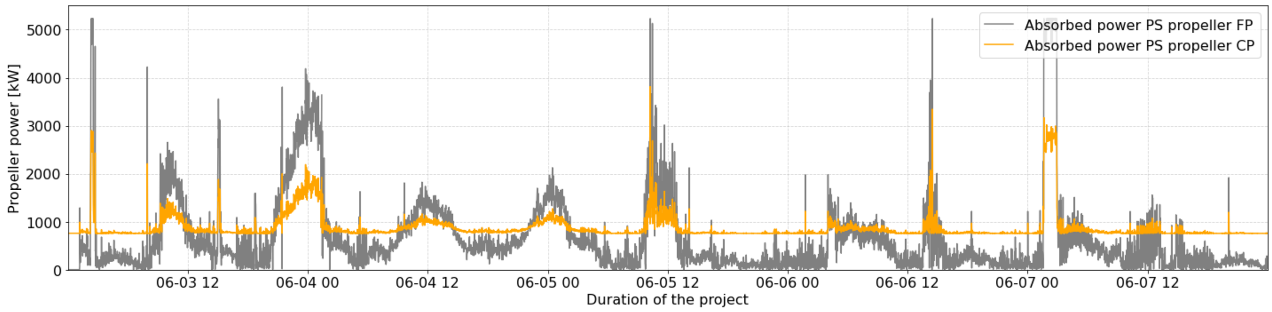


Figure 5.18: For the same amount of thrust, the absorb power by the propeller

The difference in consumed power for both concept is 4.8 and 6.3 [MWh] for the azipod and controllable pitch propeller respectively, including the total transmission loss, which is assumed equal to the converter loss for the azipod system. In must be noted that in practice, electrical losses are higher than mechanical transmission losses of the controllable pitch propeller. Changing the propulsion concept would save the vessel 24% in the power consumed for this trip with the weather conditions. Based on the estimated consumption for trip 5, the azipod thruster is more suitable for a vessel on dynamic positioning.

5.3.1. Load Profile: Combined Electrical Loading

As there are no mechanically driven load anymore, it is assumed that the electrical demand is all the loads combined. The required thrust is converted into an electric load, which is then combined with the generator load to simulate the desired load profile.

$$P_E = \sum P_{E.generators} + \frac{P_{Prop.ps}}{\eta_{GB} * \eta_S} + \frac{P_{Prop.sb}}{\eta_{GB} * \eta_S} \tag{5.1}$$

The result of this summation is plotted in figure 5.19. In Addition, this plot provides detailed information about the type of operations during trip 5, offering a deeper understanding of the load behaviour. In practice, the offshore installation cycle at sea is divided into four operational modes, which are known as transit, in-field transit, installation, and waiting on weather. In all modes except transit, the dynamic positioning system is active.

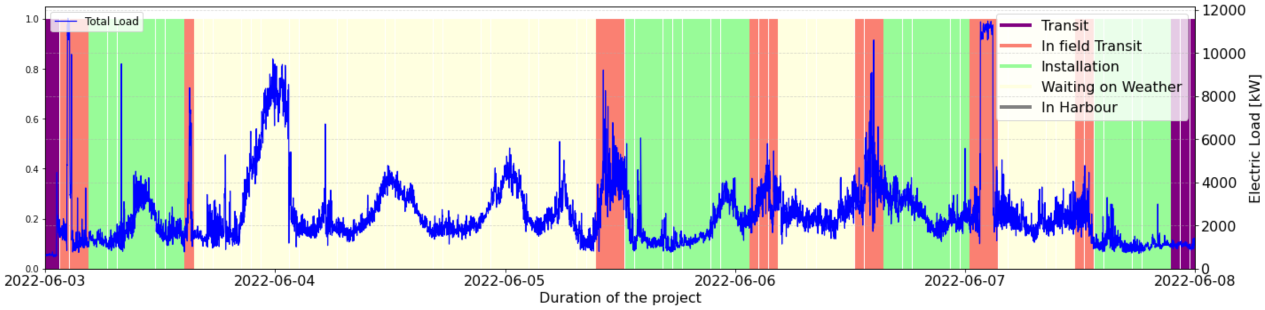


Figure 5.19: Electric load with detailed modes during trip 5

This load curve has some characteristics that are of relevance for the selection of an alternative engine room configuration. Table 5.2 illustrates these characteristics. Noteworthy is that the peak load of 11.8 [MW] is lower than the originally installed power.

Table 5.2: Characteristics of the combined electrical load profile, including thruster load.

Peak load Max	Load Min	Max load increase	Power consumption	Average Load
11816 [kW]	525 [kW]	8602 [kW/min]	294374 [kWh]	2448 [kW]

5.4. Conclusion

The effective power of the main engine was determined by combining the propeller and generator loads, taking into account all efficiencies. Similar yet different calculations were used to calculate the auxiliary engine power. Histograms were used to better understand the power data's distribution, offering valuable insights into operational patterns. The histograms revealed long-term operation significantly below engine capacity, after which it was determined that an alternative grid is essential to assess all the commonly used hybrid control strategies in which swappable energy containers can be employed.

Subsequently, multiple energy control strategies in three different technical configurations will be evaluated, as not all hybrid control strategies apply to the current technical architecture due to DP regulations and load profile. For instance, only spinning reserve and enhanced dynamic performance strategies can be applied to the current architecture due to the low average load and redundancy requirements. Also, hydrogen consumption is not feasible in the current technical configuration. For these reasons, Case 1 will evaluate these battery strategies with the current architecture, alternative management and battery containers

To evaluate other hybrid control strategies, the technical architecture is reevaluated. After an evaluation of the propulsion plant, it was concluded that azipods are superior to controllable pitch propellers during the reference project. Through the newly composed load profile, this thesis will therefore determine the impact of swappable energy containers in two additional cases. One of these cases will evaluate the usage of battery containers, while the other will assess the utilization of hydrogen containers. In total, the next chapter will evaluate the impact of swappable energy containers thought multiple hybrid control strategies in the following cases:

- Case 0: Current architecture and management serving as a benchmark.
- Case 1: Current architecture, alternative management + battery containers
- Case 2: Alternative architecture + battery containers
- Case 3: Alternative architecture + hydrogen containers

6
Case Study: Energy Containers

This chapter aims to quantify the amount of energy containers required for different technical configurations using different energy control strategies. Subsequently, the potential CO_2 and NO_X reductions are quantified, using the calculations in the methodology 4. The different cases evaluate the defined energy control strategies to explore which hybrid control strategy has the highest relative emission reduction potential while enhancing the energy efficiency of the electrical grid. Regarding this sub-questions, Table 6.1 introduces the case studies discussed in this chapter.

Table 6.1: Discussed strategies through the various case studies.

Caste study	Energy Strategy	Propulsion Architecture
Case 1.1	Spinning Reserve strategy to shut-down auxiliary generators	Diesel-Direct Propulsion + Shaft Generator
Case 1.2	Enhanced Dynamic strategy to shut-down auxiliary generators	Diesel-Direct + Shaft Generator
Case 2.1	Batteries are used for energy storage to cover the entire energy demand at sea	(Diesel)-Electric
Case 2.2	Start Stop Strategy to use electric power when average load is the lowest	Diesel-Electric
Case 2.3	Peak Shaving Strategy, whereby the engine base load is kept constant and batteries cover the dynamics	Diesel-Electric
Case 2.4	Boost Capacity covers power peaks exceeding the maximum engine capacity, considering multiple engine limits	Diesel-Electric
Case 3.1	Hydrogen containers are used for energy storage to cover the entire energy demand	Diesel-SOFC-Electric
Case 3.2	Hydrogen containers are used for energy storage to cover a share of the energy demand at sea	Diesel-SOFC-Electric

6.1. Current architecture and management, benchmark Case 0

Before estimating any improvements, it is required to determine the performance of the current technical architecture. As determined in section 2.1 greenhouse gasses can be categorised as energy-based and fuel based pollutants. To demonstrate the potential impact of energy containers on both of these categories, this thesis will evaluate one type of greenhouse gasses of each category, namely nitrogen oxides (NO_X) and carbon dioxide (CO_2). The method used to estimate these emissions is determined in section 4.2.

6.1.1. CO_2 emissions during trip 5

Thought the load profile and the emission performance data, an estimation of the NO_X emissions was established using previously determined load profiles in figures 5.7, 5.8, 5.11 and 5.12. These are used to determine the specific fuel consumption at any moment in time. For this, the load of the engine expressed as a percentage of the maximum continuous rate was derived by dividing the measured load by the maximum continuous rate. The specific fuel consumption at any specific moment in time can be derived through the evaluation of all loads with corresponding specific fuel consumption, rather than taking the mean specific fuel consumption. For this evaluation, the specific fuel consumption curves in figure 4.7a and 4.8a are used. By using formula 4.4, engine power and brake specific fuel consumption result in the mass flow of fuel. Integrating the area under the line with formula 6.2 results in the amount of fuel consumed during trip 5.

Over the course of four days, the port and starboard side main engines consumed 31.7 and 28.3 tons of fuel respectively. The process of determining the amount of consumed fuel by the main engines was repeated for the auxiliary engines. The resulting graphs indicate the fuel consumption at any moment in time, which can be used to calculate the total amount of fuel consumed during trip 5. The Auxiliary engines port and starboard side used 11.1 and 6.9 tons of diesel fuel respectively. The mass of CO_2 was determined for each individual engine as well as in total, Table 6.2

Table 6.2: Fuel consumed and resulting CO_2 emissions

Engine	Mass Fuel	Unit	Fuel type	CO_2	Unit
Main Engine ps	31.72	ton	MGO	101.69	ton
Main Engine sb	28.28	ton	MGO	90.68	ton
Auxiliary Engine ps	11.13	ton	MGO	35.69	ton
Auxiliary Engine sb	6.89	ton	MGO	22.09	ton
Total	78.03	ton	-	250.15	ton

6.1.2. NO_X emissions during trip 5

The mass flow of NO_X proportional to the engine load is plotted in figure 4.9. The power delivered by the main engines is written as a percentage of the maximum continuous rate in order to implement the emission performance data. This results in the mass flow of NO_X in kg/h at any given moment in time.The area under the curves B.5 to B.8 is the total amount of emitted NO_X in kg. Therefore, the graphs displayed are integrated over the duration of trip 5. Table 6.3 displays the total NO_X emissions of trip 5.

Table 6.3: Fuel consumed and NO_X emissions, HKZ trip 5.

Engine	Mass Fuel	Unit	Fuel type	NO_X	Unit
Main Engine ps	31.72	ton	MGO	1.54	ton
Main Engine sb	28.28	ton	MGO	1.36	ton
Auxiliary Engine ps	11.13	ton	MGO	0.43	ton
Auxiliary Engine sb	6.89	ton	MGO	0.22	ton
Total	78.03	ton	-	3.56	ton

6.1.3. Benchmark Results and Verification

Figures 5.9, 5.10, 5.13 and 5.14 indicate that during installation trip 5, all four engines are running, consequently emitting harmful greenhouse gas emissions. Furthermore, the histograms illustrate that the engines predominantly run well below their maximum capacity for extended periods. When compared with the brake-specific fuel consumption as depicted in figures 4.7a and 4.8a, it becomes clear that these low load conditions result in unfavourable fuel consumption.

Table 6.4: Benchmark verification with logged consumption

Verification	Fuel	Unit
Determined Fuel consumed	78.03	ton
Actual Fuel consumed	81.60	ton

In Table 6.4 the estimated fuel consumption of **78.03 ton** is compared with the measured fuel consumption on board, which accounts for **81.60 ton**. Subsequently, it was concluded that the proposed method yields results in the appropriate order of magnitude. The recorded fuel consumption was obtained from the daily progress reports. The difference between these two numbers can be explained by the consumption of the oil-fired boiler, for which no data is available other than its usage during this period. The results of the case studies in Chapter 6 will be evaluated with respect to **250.15 ton** of CO_2 and **3.56 ton** of NO_X

6.2. Alternative management + battery containers Case 1

The first case study evaluates the Fairplayer in the current technical architecture described in 2.3. A strategy is proposed, where emission reduction is achieved through alternative management in combination with swappable batteries, while retaining the existing technical configuration. In section 5.2 it was concluded that running on all the four generators for redundancy considerations results in unnecessary fuel consumption and emissions. Therefore, the first alternative management strategy, is reducing the amount of generators online. For the ship to operate on DP, the main engines are required, as these are the only available systems installed that could drive the propellers. Despite that the ship could maintain its positioning using only one propeller, the fact that only one propeller is then instantly available is enough to state that both main engines are mandatory. The result of this is that the shutdown of engines is limited to the auxiliary engines.

For shutting down both the auxiliary engines, the power of the auxiliary generator can be added to the PTO power as electrical load is equally shared between the two port side generators. Due to the open bus tie that separates the grid, power of the starboard side generators can also be combined. With the combined electrical power and propeller load, the theoretical load on the main engines can be derived. The resulting load profiles are illustrated in figures 6.1 and 6.2, whereby the red horizontal line indicates the maximum engine capacity.

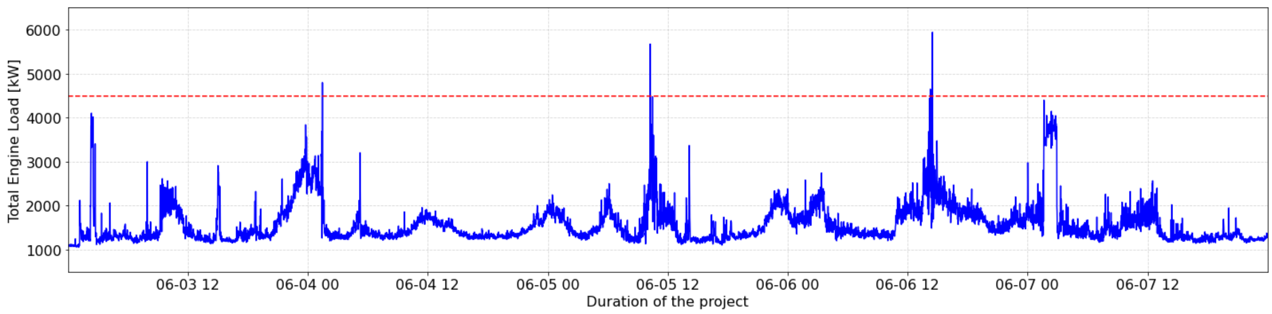


Figure 6.1: Theoretical power on main engine PS if the PS auxiliary engine were to shut down

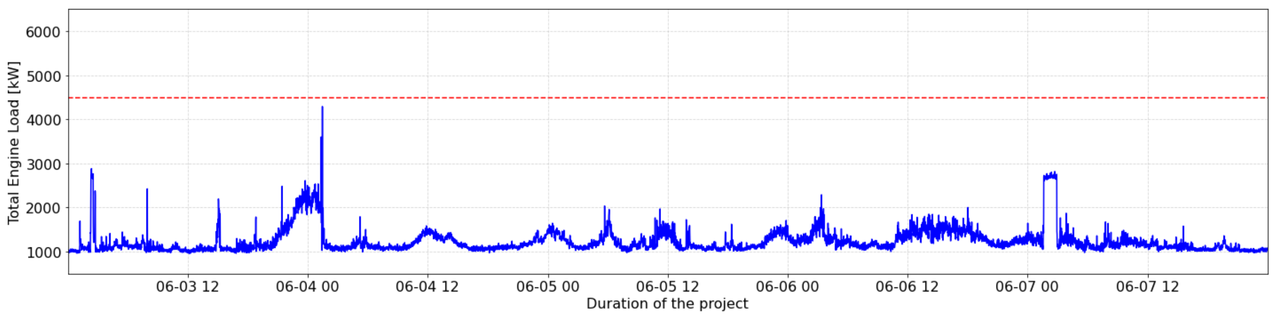


Figure 6.2: Theoretical power on main engine SB if the SB auxiliary engine were to shut down

An observation of both figures 5.13 and 6.2, indicates that the load exceeds the engine capacity. Figure 6.3 categorizes the loads during trip 5, and it is important to highlight that during the highest peaks, the vessel is in-field transit to another monopile using dynamic positioning (DP). Consequently, it is preferred to initiate an additional auxiliary engine to handle the excess electrical load during such operational modes. Furthermore, it's worth noting that even though the ground speed is slow during in-field transit, the bollard pull condition is not satisfied and the propeller loading curve in open water conditions must be used. This would lower the peaks significantly, making the real load profile less dramatic in these areas than they appear currently.

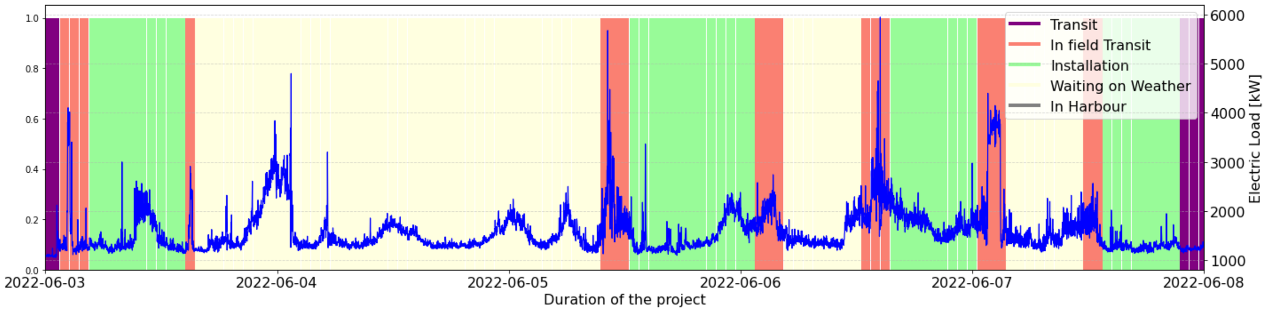


Figure 6.3: Theoretical power on main engine PS, including the operational modes

6.2.1. Case 1.1 Spinning Reserve

The Classification societies and IMO rules require that sufficient time to be available, post failure, for the safe termination of the offshore operations. Consequently, the first step in matching the correct energy storage system is determining the safe termination time. As the scope of Jumbo's offshore operations regarding transition pieces only consists of lifting operations, this safe termination time is equal to the safe DP window that Jumbo upholds. This DP window means the maximum amount of time that the lifting operations take from safe state to safe state. At Jumbo, the DP window for wind turbine transition piece, installation projects is **9 hours**. The DP window for mooring line projects or deep sea installation projects is 18 to 24 hours respectively.

DNV RU-SHIP Part 6 Chapter 3, section 2, 6.13.4 describes that when batteries are used as redundancy back-up, the calculations shall be based on the prevailing weather conditions and experienced operating pattern, e.g. mean net power consumption for the actual operation. Consequently, the calculations regarding the battery capacity is based on the actual mean net power consumption for the termination of the operation, therefore only the periods of installation for which the ship is lifting at sea are evaluated. In the case of the Fairplayer this means that in case of one gensets' power loss, batteries must supply the mean load during installation for a duration of 9 hours. The mean electrical power during installation is 1050 kW, with a load peak of 2800 kW. This results in an energy demand of 9450 [kWh]. 2800 kW with a C-rate of 1C results in a required electrical capacity of 2800 [kWh], indicating that in this case the sizing of the battery system is primarily determined by the required electrical capacity. With the safe termination time given of 9 hours, the required storage capacity and the number of energy containers is resolved. Through the battery sizing method in subsection 4.4.1 a total of 8 batteries is required to cover the safe termination time in case of the worst case failure. It is noted that determining the number of containers is rough, and classifying the ship with this concept requires a comprehensive workability study.

Table 6.5: Number of batteries required for Case 1.1

Batteries	Strategy	unit
Energy Demand	9450	kWh
Peak load	2800	kW
Battery Capacity	15066	kWh
Number of Batteries	8	-

6.2.2. Case 1.2 Spinning Reserve / Enhanced Dynamic Performance

To reduce the amount of battery capacity required, another application is reviewed. Aside from unexpected single-point power failures, spinning reserve could also denote a battery strategy whereby a certain reserve capacity is used to supply power in the event of sudden load increases, bridging a power shortage for a short amount of time. This hybrid control strategy is often referred to as enhanced reliability or enhanced dynamic performance, since it involves having additional power sources that are actively synchronised and ready to supply electricity to the grid instantly when required. In the current power configuration, this reserve or redundancy in dynamic positioning is achieved by keeping auxiliary generators idle and synchronised with the grid. Shutting down these idling generators hypothetically reduces the amount of emissions. The improvements gained by enhanced dynamic performance will result in the same amount of emission reduction with respect to Case 1.1, while the required number of batteries will decrease.

To ensure a similar level of immediate power availability when batteries are part of the backup system, specific rules are in place. Battery sizing is determined by the DNV GL Enhanced Reliability DP notations, both in terms of power and energy. In DNV RU-SHIP, Part 6 Chapter 3, Section 2, DYNPOS-ER means “Enhanced Reliability and Separation”. It is a dynamic positioning system with redundancy and a higher degree of flexibility based on utilisation of standby units and / or changeover mechanisms. It meets intentions comparable to or exceeds IMO equipment class 2 and 3 but has no direct relation to IMO MSC/Cir. 645 and improve the vessel’s flexibility, reliability, and fuel economy while reducing the environmental footprint.

These rules dictate that the required capacity of the batteries should be based on the system’s design and how it operates. When batteries are combined with standby-start generators, the batteries need to provide enough power and capacity to bridge the gap between any failure or limit and an extra online generator. This ensures that, after any combination of generators or batteries fails (but before any standby-start occurs), the system can still produce at least one-third of the power available before the failure. Additionally, the system must achieve this power level within a specified minimum time, without factoring in the contribution from the standby-start generators.

For reference vessel the Fairplayer this signifies that when running on two shaft generators with closed buss-tie, one third of the 6000 kW electric power should be installed as battery power output. The changeover time to stand-by units is set at five minutes, which seems conservative, as on board engineers claim that this is possible under a minute when remotely started and synchronised, upon asking. Nevertheless, with a C-rate of 1C the required power is governing. 2000 [kW] with a C-rate of 1C results in a total capacity of 2000 [kWh]. Resulting in 1 energy container in this thesis yet other smaller systems may also apply for this case.

Table 6.6: Number of batteries required for Case 1.2

Batteries	Strategy	unit
Energy Demand	166	kWh
Online Power	6000	kW
Power Required	2000	kW
Battery Capacity	2000	kWh
Number of Batteries	1	-

6.2.3. Environmental gains

In figures 6.4 and 6.5, red illustrates the current power distribution and blue indicates the power distribution if batteries are applied for redundancy.

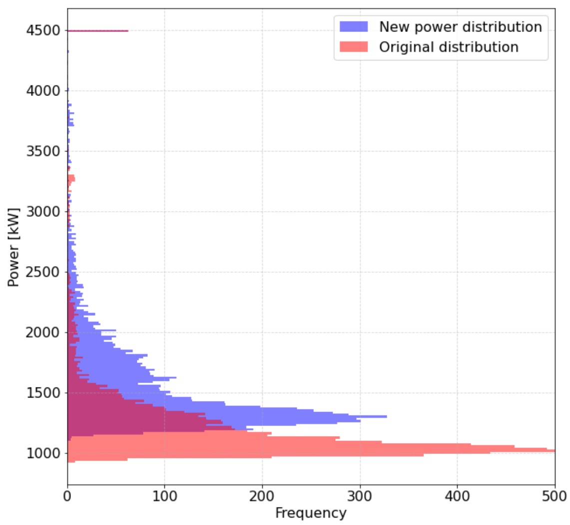


Figure 6.4: Power distribution main engine PS in both the old and new situation

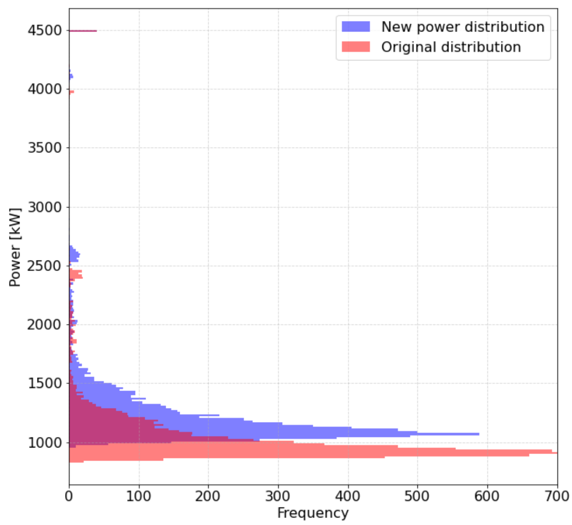


Figure 6.5: Power distribution main engine SB in both the old and new situation

Although the main environmental gains can be made by shutting off the auxiliary engines, engines that are running operate in more desirable conditions. Not only does this safe energy that is otherwise lost by running additional engines also the engines in operation run in more ideal conditions regarding the specific fuel consumption. If the proposed strategy is simulated, new fuel consumption's can be derived. With these fuel consumption, the CO_2 emissions are again calculated. Results of these approximations are displayed in table 6.7.

Table 6.7: Improved CO_2 emissions through the alternative strategy.

Engine	**Mass Fuel**	**Unit**	**Fuel type**	CO_2	**Unit**
Main Engine ps	38.61	ton	MGO	123.79	ton
Main Engine sb	31.88	ton	MGO	102.21	ton
Auxiliary Engine ps	0.00	ton	MGO	0.00	ton
Auxiliary Engine sb	0.00	ton	MGO	0.00	ton
Total	70.49	ton	-	226.00	ton
Reduction	9.65	%	-	9.65	%

Subsequently, the with the new load profiles, NO_X emissions are determined using the methodology described in 4.2.5. the results are illustrated in Table 6.8

Table 6.8: Improved NO_X emissions through the alternative strategy.

Engine	**Mass Fuel**	**Unit**	**Fuel type**	NO_X	**Unit**
Main Engine ps	38.61	ton	MGO	1.89	ton
Main Engine sb	31.88	ton	MGO	1.55	ton
Auxiliary Engine ps	0.00	ton	MGO	0.00	ton
Auxiliary Engine sb	0.00	ton	MGO	0.00	ton
Total	70.49	ton	-	3.43	ton
Reduction	9.65	%	-	3.44	%

6.3. Alternative grid + battery containers Case 2

Due to the unsuitability of the current technical configuration for all potential battery strategies, case 2 also explores how interchangeable batteries, combined with an alternative machinery room, can reduce emissions. The electrical grid could be further optimised if some components within the DP system are changed. For instance, the controllable pitch propellers are always turning during dynamic positioning operations.

6.3.1. Hybrid configuration

Case 2 explores the possibility to drive fixed pitch propellers by an electric motor, convert the main engines into diesel generators and combine with batteries to optimise the grid. The advantage of this is that the propellers are stopped when thrust is not required. Due to the high torque of electric drives, the propeller's rotational velocity is reduced, consequently lowering the frictional losses. In practice, conversion losses of 5% to 15% in additional electrical components such as, power converters transformers and electric motors are common [Geertsma, 2019]. When considering an alternative power generation architecture, the entire operational profile is employed instead of just the DP installation operations, as a configuration is optimised for all the vessel's activities. Considering this flexible configuration and the limited scope of this thesis, optimising for DP operations through performance data of trip 5 suffice. It is assumed that when the ship is in transit, additional power is activated. The proposed hybrid architecture for the Fairplayer is illustrated in figure 6.6

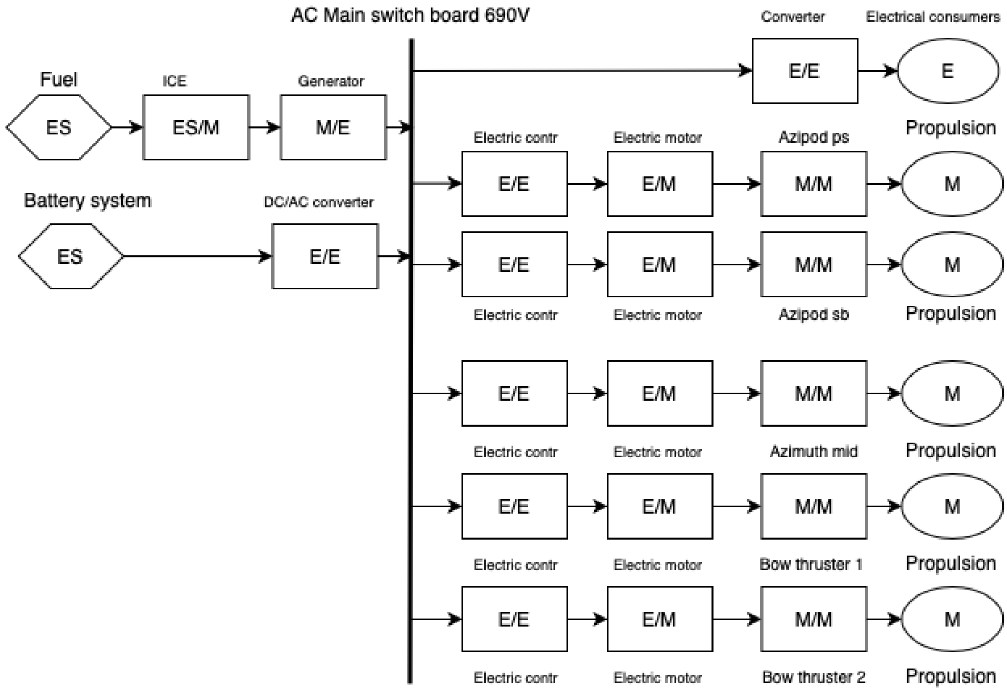


Figure 6.6: Hybrid configuration used to assess the performance of the concept

6.3.2. Considered battery control strategies

The new ICE-battery hybrid architecture increase the degrees of freedom in regard to the amount of generators and batteries that feed the grid. Consequently increasing the feasible battery control strategies. Swappable batteries open the way for renewable green energy to be stored and used at sea. The batteries are then seen as energy carriers and not to optimise internal combustion engine performance. The first strategy evaluated considered therefore how many batteries are required to fully cover the demand with electric energy. This should hypothetically result is zero local emissions as fuel- and energy-based emissions are eliminated. Figure 6.3 indicates that the required loading during the installation procedure is the lowest during the entire trip. It is therefore evaluated how a start stop strategy could be beneficial to enhance the emission performance.

Ideally, the batteries are discharged fully at sea indicating that a peak shaving strategy whereby the batteries are charged when load is below a certain fixed engine power, is not desirable. Nevertheless, the peak shaving strategy is still evaluated as this is one of the most popular battery applications in modern. For that reason, a variant to the peak shaving strategy is evaluated whereby batteries cover extensive power peaks without being recharged. This is the referred to as boost capacity.

Spinning reserve and enhanced dynamic performance strategies can also be applied in this technical configuration. Nevertheless, it was determined that the emission reductions in comparison to Case 0 and Case 1 are primarily attributed to the alternative propeller selection rather than to the more efficient operation of engines. With the addition of propeller load to the electrical demand, the amount of required battery storage capacity increases by a factor of 2.5 as the increased load increased accordingly. Despite the higher emission reduction potential, these strategies are not evaluated as these are covered in section 6.2 and this method could be applied to any other technical architecture. Case 2 assesses the application of swappable energy containers through the following battery control strategies:

- Full electric
- Start / Stop
- Peak shaving
- Boost capacity

6.3.3. Case 2.1 Full electric

In this subsection, calculations are carried out to determine the components sizing if an alternative technical configuration would be full electric. Consequently, the entire energy demand is supported by battery containers. The results will be based on the load curve of trip 5 with the azipod thruster configuration. The power demand used is plotted in figure 5.5.

The sizing of the energy storage system is based on the data of table 5.2, in which it is observed that the required amount of energy at the main switch board is 298.7 [MWh]. Calculating the battery capacity described in subsection 4.4.1, the losses in the DC/AC converter and depth of discharge should be accounted for. In this specific case, the batteries are sized according to one cycle. Once in port the energy containers are changed for fresh and fully charged units. Considering a C-rate of 1C the required capacity of **469.3 [MWh]** is governing the power of 11.8 [MW] by far. This results in a total of 235 of required battery containers.

Table 6.9: Number of batteries required for Case "Full Electric"

Batteries	Strategy Full Electric	unit
Energy Demand	294.37	MWh
Battery Capacity	469.35	MWh
Number of Batteries	235	-

6.3.4. Case 2.2 Flexible start/stop Strategy

In this subsection, the start-stop strategy was assessed, wherein the vessel is operated in a fully electric mode during periods when the average load is at its lowest. The analysis of Figure 5.19 revealed that the average load is at its lowest during installation phases. Consequently, the batteries are utilized exclusively during the installation operations, remaining idle during transit or when awaiting favourable weather conditions. With this approach in mind, the battery's load profile was illustrated in Figure 6.7.

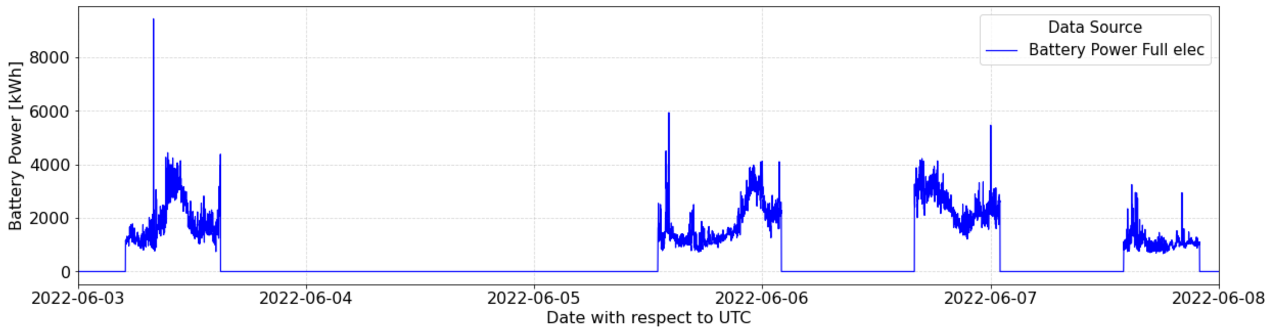


Figure 6.7: Battery power for flexible start/stop strategy

By integrating the area under this curve, we can determine that the total electric energy required accounts for 73.3 [MWh]. Considering a C-rate of 1C the required capacity of **116.8 [MWh]** is governing the power of 9.4 MW. Using the method in subsection 4.4.1, this corresponds with **59** battery containers. During in field transit and waiting on weather diesel engines cover the demand of the grid, as the duration of such modes is impossible to forecast. The amount of online engines is based on the peak demand and the load is equally shared between the engines.

Table 6.10: Number of batteries flexible start/stop strategy

Batteries	Strategy Start/Stop	unit
Energy Demand	73272	kWh
Peak load	9445	kW
Battery Capacity	116823	kWh
Number of Batteries	59	-

6.3.5. Case 2.3 Peak shaving

In this case, internal combustion engines operates at fixed speed and power in an area whereby the brake specific fuel consumption is most favourable. As described in 3.3.1 batteries are used to deal with the dynamic loading of the grid. For this case, batteries are sized in order to cover power peaks that exceed the average load, and recharged when the power is below the average load.

$$p_{\text{Batt}}(t) = p_{Load}(t) - P_{mean} \tag{6.1}$$

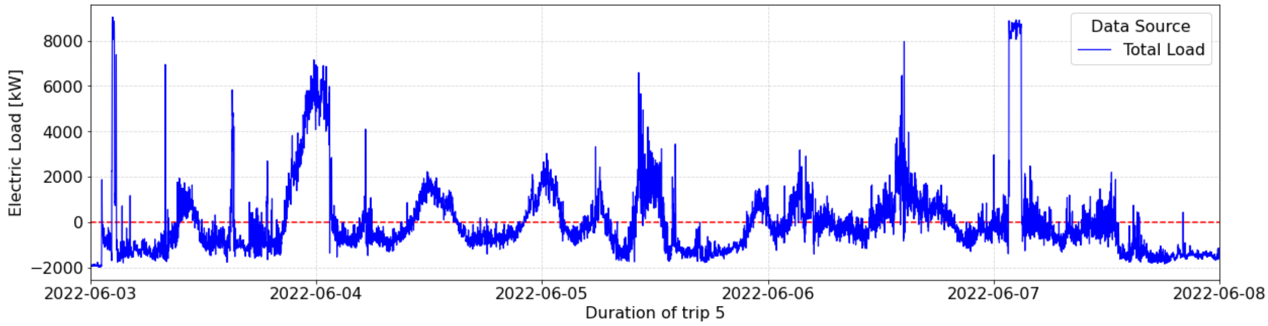


Figure 6.8: Dynamic loading on the energy storage system

The average power demand of the grid is then the power that the diesel engine is supposed to deliver, excluding transmission losses. The resulting dynamic load is illustrated in figure 6.8, whereby the load below zero means that the battery is recharged and above that the battery is discharged. The repercussion of this strategy is that the batteries are fully charged at the end of the trip. Figure 6.8 is limited to the load that the batteries are required to cover.

In equation 4.11 $P^{+}_{\text{Batt}}(t)$ are the loads in figure 6.8 where $P_{\text{Batt}} > 0$ (discharge) and $P^{-}_{\text{Batt}}(t)$ those where $P_{\text{Batt}} < 0$ (charge). According to [Del Pizzo, 2010], there is an unbalance in the charge and discharge efficiencies, therefore batteries tend to discharge more than to charge. The consequence of this unbalance is that the generator power should be suitably increased in order to include for these cycle losses. Constant charge and discharge efficiencies of 97% and 96% were chosen respectively in subsection 4.1.

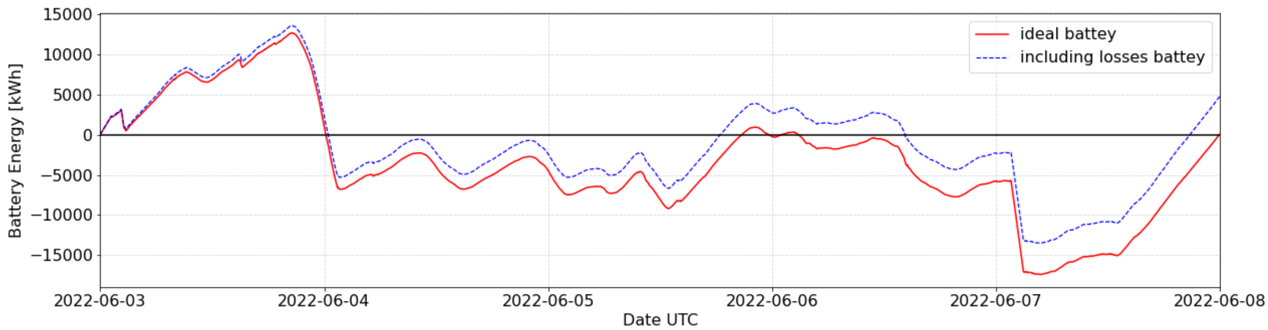


Figure 6.9: Theoretical energy flow of the battery system

In figure 6.9 the graph of figure 6.8 was integrated with formula 6.2 to get the battery energy behaviour. The red line illustrated the ideal energy behaviour of the battery is there was no difference between the charge and discharge efficiencies. The blue line that illustrates the real energy behaviour does not return to zero, indicating that the battery is not fully charged at the end of the cycle. Therefore the engine power needs to be increased. The energy difference is around 4.8 [MWh] and the cycle time of trip 5 is 120 hours, which results in a mean generator load increase of 40 kW. With figure 6.9 the minimal amount of stored energy to apply this battery strategy can be determined. The required battery capacity results from the difference between the highest peak and lowest peak. This difference indicated with $\delta E_{battery}$ is the required capacity, which in this case is 27.1 [MWh]. The electric peak power $P_{battery-Max}$ that the battery system should cover is the peak load minus the average load delivered by the diesel engine. $P_{battery-Max}$ is then 9.3 [MW]. Considering a C-rate of 1C the required capacity of **43.2 [MWh]** is governing the power of 9.3 [MW] by far. Using the method in subsection 4.4.1, this corresponds with **22** battery containers.

Table 6.11: Number of batteries required for peakshaving

Batteries	Strategy Peak Shaving	unit
Energy Demand	27070	kWh
Peak load	9328	kW
Battery Capacity	43160	kWh
Number of Batteries	22	-

Installation peak shaving

Large delta between average and dynamic loading results in quite a large required storage capacity. It is therefore also assessed if peak shaving during the installation (indicated by the green areas in figure 5.19), decreases the required capacity while still a significant impact on the emissions can be achieved.

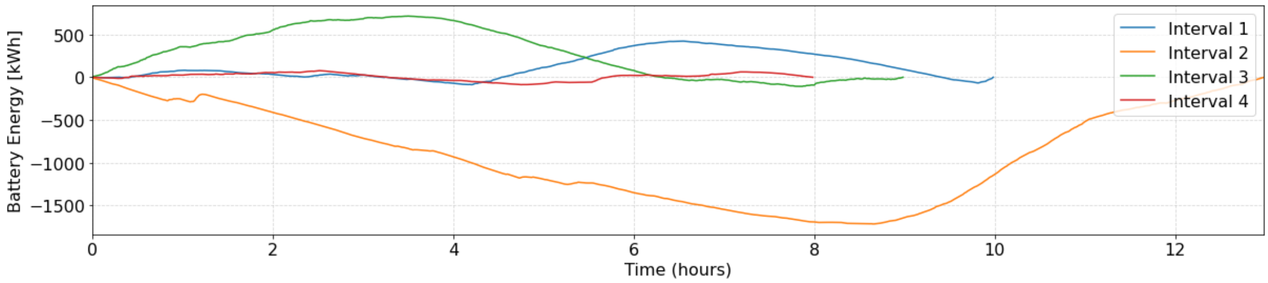


Figure 6.10: Battery energy flow for peaks shaving at each interval

If this strategy is applied, the required battery behaviour can be simulated with figure 6.10. This figure is similar to Figure 6.9, indicating that the estimation of required storage capacity is identical. The required capacity for each interval is found in Table 6.12.

Table 6.12: Required energy storage capacity for each offshore lift

Installation	Interval 1	Interval 2	Interval 3	Interval 4	unit
Average Load	1900	1772	2490	1104	kW
Required capacity	2700	3765	1999	461	kWh

Despite the resulting required storage capacity being much lower as anticipated, the average load turns out to be unpredictable and not in the same order of magnitude for the same installation scope. In addition, the batteries are fully charged at the beginning of each interval, which is not desirable considering the advantage of swappable battery containers over integrated systems is to bring green electric energy offshore. Similar results over the entire trip 5 can be achieved if the online engines are operated in a certain dynamic power envelope with upper and lower limits. Batteries act when the electrical load exceeds these limits. Nevertheless, the peak shaving strategy is not satisfying the requirements regarding interchangeable energy storage units.

6.3.6. Case 2.4 Boost Capacity

The next battery strategy being evaluated in the thesis is referred to as "boost capacity." This strategy employs batteries to provide additional power support when the electrical load exceeds a certain upper limit. In other words, when the power demand exceeds the capacity of the online generators, the batteries cover the peak load. The key idea behind the boost capacity strategy is to optimize the use of batteries that cover temporary spikes in electricity demand, thereby decreasing the need for additional generator capacity and potentially improving overall system emission performance.

$$E_{\text{Boost}} = \int_{t=start}^{t=end} p_{\text{total.load}}(t) - P_{\text{upper.limit}}\, dt \tag{6.2}$$

For the entire duration of trip 5 we can determine the required battery capacity at certain engine limits. The results of these calculations are plotted in figure 6.11. The lower the internal combustion engine limit, the higher the required capacity. Orange results indicate the amount of batteries based on the amount of energy consumed in kWh and the blue results flow from the required battery power based on a C-rate of 1C.

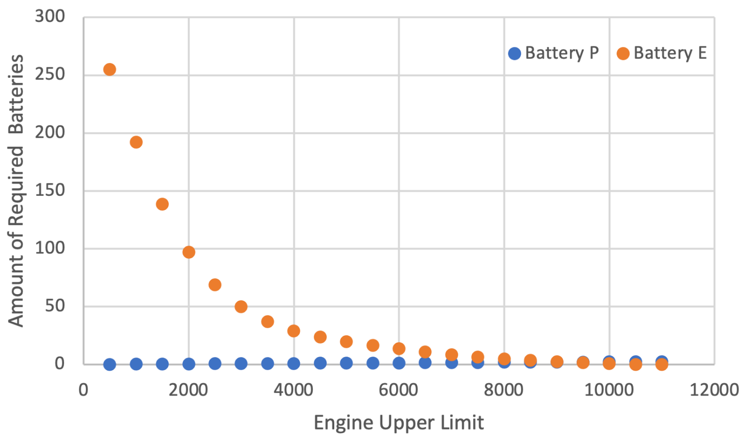


Figure 6.11: Required batteries for the corresponding engine limit

Both the sizing for power and capacity are plotted, since the design choice is dominated by either. For a maximum discharge rate of 1C the tipping point for the capacity dominance is around 8.5 [MW] of battery power. Figure 6.11 indicated that for the boost capacity at the engine limit of 8.5 [MW] or more does not change the amount of required batteries. For this reason, a 9.1 [MW] limit is the maximum power engines should make for this comparison which is the equivalent of 5 generators. Since data of the caterpillar 3516B engine is available in combination with the engine power limit of 8 [MW] The environmental gains are determined using four of these engines installed.

Table 6.13: Required energy storage capacity for each upper engine limit

Upper limit	Case 2.4a	Case 2.4b	Case 2.4c	Case 2.4d	Case 2.4e	Unit
3516B Cat Running	1	2	3	4	5	-
Generator Power	1825	3650	5475	7300	9125	kW
Required Capacity	97644	29793	14254	5733	9125	kWh
Battery Capacity	159479	48172	22702	9608	2682	kWh
Units	80	24	12	5	2	-

Figures 4.7a and 4.8a indicate is the brake specific fuel consumption at loads above 50% are in the same order of magnitude. Consequently, it is acceptable to operate engines in these areas of power curve. Therefore, an assessment was conducted to determine the emission reductions of the hybrid power plant with the configurations illustrated in Figure 6.6.

6.3.7. Environmental gains

In Case 2 we assessed some strategies that can utilise battery containers in combination with alternative technical configurations. Through electric azipod propulsion delivering the same amount of thrust and combining the electric load of the generation input, a new electrical load curve was defined. Despite the full electric option was taken into account, most battery strategies used conventional engines, which are still common electric generators currently used. For this thesis, the focus is on the emission reduction through energy containers therefore, less on the use of alternative low carbon fuels. However, it is acknowledged that the adoption of such fuels could potentially eliminate the emissions completely.

For the proposed strategies involving combustion engines, new fuel consumptions can be derived. With these fuel consumption, the CO_2 emissions are again calculated using the method described in subsection 4.2.5 using the Caterpillar 3516B engines. Results of these approximations are displayed in table 6.14.

Table 6.14: CO_2 emission reductions through the different hybrid strategies

CO_2 **Emissions**	**gen1**	**gen2**	**gen3**	**gen4**	**gen5**	**gen6**	**total [ton]**	**Reduction**
Case 2.1	0	0	0	0	0	0	0.00	100.00%
Case 2.2	30.17	30.17	30.17	30.17	30.17	30.17	181.00	27.64%
Case 2.3	102.47	102.47	0	0	0	0	204.94	18.07%
Case 2.4a	39.18	0	0	0	0	0	125.42	49.86%
Case 2.4b	27.90	27.90	0	0	0	0	178.60	28.60%
Case 2.4c	20.64	20.64	20.64	0	0	0	198.25	20.75%
Case 2.4d	16.58	16.58	16.58	16.58	0	0	212.28	15.14%
Case 2.4e	14.00	14.00	14.00	14.00	14.00	0	224.15	10.39%

Finally, the new load profiles are used to determine the NO_X performance. With the method described in subsection 4.2.5 using the Caterpillar 3516B engines, the NO_X reductions are approximated. Results of these approximations are displayed in table 6.15. The NO_X emissions are calculated using a simplified conversion factor of 10.05 g/kWh, with a lower synchronized engine limit of 180 kW.

Table 6.15: NO_X emission reductions through the different hybrid strategies

NO_X **Emissions**	**gen1**	**gen2**	**gen3**	**gen4**	**gen5**	**gen6**	**total [ton]**	**Reduction**
Case 2.1	0	0	0	0	0	0	0.00	100.00%
Case 2.2	0.39	0.39	0.39	0.39	0.39	0.39	2.37	33.36%
Case 2.3	1.18	1.18	0	0	0	0	2.36	33.65%
Case 2.4a	2.05	0	0	0	0	0	2.05	42.40%
Case 2.4b	1.39	1.39	0	0	0	0	2.79	21.54%
Case 2.4c	0.99	0.99	0.99	0	0	0	2.97	16.65%
Case 2.4d	0.76	0.76	0.76	0.76	0	0	3.06	14.09%
Case 2.4e	0.62	0.62	0.62	0.62	0.62	0	3.11	12.67%

6.4. Alternative grid + hydrogen containers Case 3

As the current technical configuration is not able to consume pure hydrogen, the final configuration determines the impact and use of hydrogen storage containers, for the reference project. For this, the current technical configuration is altered to utilise the hydrogen as a fuel.

6.4.1. Hybrid configuration

Similar to case 2 it is assumed that the propellers are driven electrically. The literature study concluded that hydrogen can be used in both suitable internal combustion engines and fuel cell technology. For this thesis, the hydrogen is used in fuel cell technology as these systems have a higher efficiency, thus consuming less hydrogen for the same amount of electrical power with respect to hydrogen powered engines. Subsequently, reducing the number of required containers. In the literature study subsection 3.2.1 it was determined that the solid oxide fuel cell was most suitable for this vessel as the fuel flexibility of these systems are beneficial for worldwide operations.

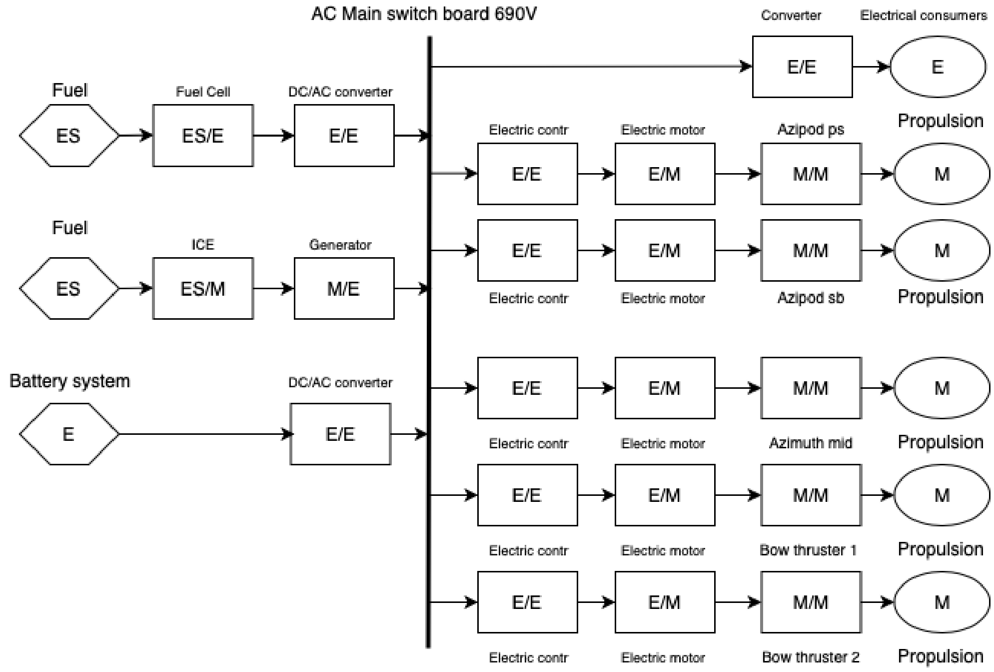


Figure 6.12: Energy diagram alternative grid case 3

Fuel Cell sizing

To appropriately size the fuel cell system, it is important to quantify the fuel consumption used to determine the amount of required hydrogen containers. As the fuel cell system employed for these calculations is integrated in the engine room layout, sizing the weight and dimensions is not important. The amount of required hydrogen containers that power the fuel cell system depend on several assumptions such as stack size, consumption and degradation. The load on the fuel cell system is assumed to be constant for this case. As described in 3.2.1 fuel cells are most efficient when the load is kept constant. Moreover, high temperature fuel cells are attractive due to their high efficiency. Electrochemical reactions in the SOFC respond almost instantly to the dynamic load, but the inertia of heat, mass, and momentum in the stack and appendages limits the actual load response. Assuming that the ship is powered by other means during transit, the peak shaving strategy described in Section 6.3.5 is utilized to determine the necessary amount of hydrogen containers required for the reference project.

Applying this strategy, the continuous power requirement for the fuel cell system is calculated to be 2448 kW. The electrical output of fuel cell systems is similar to that of batteries, producing direct current (DC). Consequently, the integration of an SOFC system with the electrical grid required the use of a DC/AC converter. Losses in this converter are assumed to be the same as for the battery system. This results in a total installed power of 2498 kW. With the required power of the fuel cell system over the total duration of trip 5 the consumption of hydrogen can be determined. Considering that the loading of the SOFC system is constant, a constant efficiency of 55% is assumed. In reality, this efficiency is dependent on several factors such as used fuel and loading.

Battery sizing

As was described in the literature study, the dynamic loading of fuel cell systems is limited and therefore the dynamic loading is covered by an integrated battery system. The average power demand of the grid is then the power that the fuel cell system is supposed to cover regardless of online units. With figure 6.9 the minimal amount of stored energy to apply this battery strategy can be determined. The required battery capacity results from the difference between the highest peak and lowest peak. This difference indicated with $\delta E_{battery}$ is the required capacity, which in this case is 27.1 [MWh]. The electric peak power $P_{battery-Max}$ [kW] that the battery system should cover is the peak load minus the average load delivered by the diesel engine. $P_{battery-Max}$ is then 9.3 [MW].

6.4.2. Case 3.1 Hydrogen powered SOFC

In the first hydrogen case, we will evaluate how many hydrogen containers are required if the entire energy demand was powered by hydrogen. Due to the limited dynamic loading a peak shaving strategy is assessed whereby the entire, average load of 2498 kW is covered by a SOFC system. Utilizing the model in subsection 4.4.2, it has been determined that the required amount of hydrogen is 15.6 ton, which can be stored in standard-sized containers. With the density, volume and weight, it was estimated that 28.5 kg of hydrogen in the 40ft containers cannot be used. With these, the required amount of containers was determined at 15 for 500 bar(a) and 19 for 350 bar(a) storage containers. Since there are no other energy converters besides the SOFC in use, emissions are effectively reduced to zero.

Table 6.16: Reduced emissions for 2498 kW Fuel Cell.

Hydrogen	**H2 Fuel**	**Unit**
Hydrogen amount,	15552	kg
Storage units 500 bar(a)	15	-
Storage units 350 bar(a)	19	-

6.4.3. Case 3.2 Hydrogen powered SOFC + ICE

In addition to this, another strategy involving one of the conventional generators is reviewed, to reduce the fuel cell size. In this configuration, the diesel engines operate alongside the battery system and fuel cell system. Therefore, one of the generators is feeding the grid with 1825 [kW] meaning that 635 [kW] is required from the SOFC system. Utilizing the model in subsection 4.4.2, it has been determined that the required amount of hydrogen is 4220 kg. As a result, this case requires 4 hydrogen containers at 500 bar(a) and 6 at 350 bar(a).

Table 6.17: Number of hydrogen containers

Hydrogen	**H2 Fuel**	**Unit**
Hydrogen amount	4220	kg
Storage units 500 bar(a)	4	-
Storage units 350 bar(a)	6	-

6.4.4. Environmental gains

Assuming the ship is powered in transit by other means, the peak shaving strategy 6.3.5 and subsection 4.4.2 are used to size the required amount of hydrogen containers to employ the vessel for zero emission offshore installation. With the hydrogen demand mapped, the resulting load separated between the battery system and the internal combustion engine, can be determined. The resulting CO_2 emissions are presented in table 6.19

Table 6.18: Reduced CO_2 emissions.

CO_2	**Generator**	**total ton**	**Reduced** CO_2
Case 3.1	0	0.00	100.00%
Case 3.2	144.14	144.14	42.38%

The NO_X emissions are calculated using a simplified conversion factor of 10.05 g/kWh, with a lower synchronized engine limit of 180 kW.

Table 6.19: Reduced NO_X emissions.

NO_X	**Generator**	**total kg**	**Reduced** NO_X
Case 3.1	0	0.00	100.00%
Case 3.2	2291	2291	35.58%

6.5. Results combined

In this chapter, several strategies are discussed that utilize the concept of swappable energy containers during trip 5. The objective is to explore the potential improvements in overall emission performance of the vessel that can be achieved through the proposed strategies. The focus is on determining the required quantities of containers and online engines for the successful implementation of these strategies. The utilization of energy containers was not restricted to the existing technical configuration. This because incorporating energy containers through standard hybrid strategies on the current layout had implications, primarily due to the requirement that both main engines must operate with the controllable pitch propellers engaged necessary for dynamic positioning redundancy purposes while there is still enough capacity to cover the electrical demand. As the histograms 6.4 and 6.5 prove, the main load for peak shaving is considered slightly too low. Boost capacity is not possible as engines have enough capacity and finally other strategies are not possible due to the redundancy considerations.

To investigate the application of energy containers beyond the existing technical configuration while maintaining the same vessel performance (electrical load and required thrust), it became essential to match the thrust/load curve of an azipod thruster with the thrust/load curve of a controllable pitch propeller and convert the mechanical load into an electrical load. It must be concluded that in the bollard pull condition this already made quite a significant improvement of 24% on the consumed energy for driving the propellers. Replacing the controllable pitch propellers with azipod thrusters enables the utilization of battery containers and indirectly also hydrogen containers for vessel's propulsion, consequently opening up several other possible strategies for harnessing energy containers in innovative ways. Table 6.20 provides an overview regarding all the discussed cases with the applied energy strategies and technical configuration.

Table 6.20: Combined Results including applied strategy and technical architecture

Caste study	Energy Strategy	Propulsion Architecture	Containers	Reduced CO2	Reduced NO_X
Case 1.1	Spinning Reserve	Diesel-Direct	8	9.65%	3.44%
Case 1.2	Enhanced Dynamic	Diesel-Direct	1	9.65%	3.44%
Case 2.1	Energy Storage	Diesel-Electric	235	100.00%	100.00%
Case 2.2	Start Stop	Diesel-Electric	59	27.64%	33.36%
Case 2.3	Peak Shaving	Diesel-Electric	22	18.07%	33.65%
Case 2.4a	Boost Capacity	Diesel-Electric	80	49.86%	42.40%
Case 2.4b	Boost Capacity	Diesel-Electric	22	28.60%	21.54%
Case 2.4c	Boost Capacity	Diesel-Electric	12	20.75%	16.65%
Case 2.4d	Boost Capacity	Diesel-Electric	5	15.14%	14.09%
Case 2.4e	Boost Capacity	Diesel-Electric	2	10.39%	12.67%
Case 3.1	Energy Storage	Diesel-SOFC-Electric	15	100.00%	100.00%
Case 3.2	Energy Storage	Diesel-SOFC-Electric	4	42.38%	35.58%

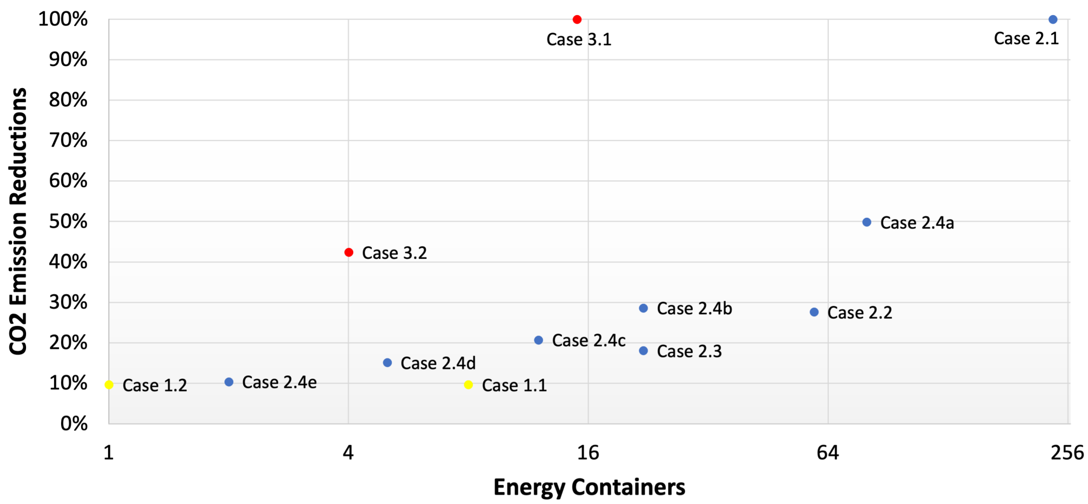


Figure 6.13: Combined results CO_2, on a logarithmic scale

The CO_2 related reductions are the most significant with respect to the IMO's route to zero climate goals. Figure 6.13 combines all the case's into one graph with on the y-axis the required amount of containers and on the x-axis the emission reduction. In figure 6.13 Case "2.1" and "3.1" are identified as the most obvious cases. In these cases, the entire energy demand is covered by renewable sources, resulting in the anticipated 100% reduction in emissions compared to the current operation. Furthermore, a notable observation is that for the cases which use batteries, there appears to be a correlation between the quantity of containers required and the extent of emission improvement for each case. However, further investigation is required to prove this theory. It seems that for the strategies considered, a hybrid configuration with minimal one diesel engine online the highest potential emission reduction is 50%.

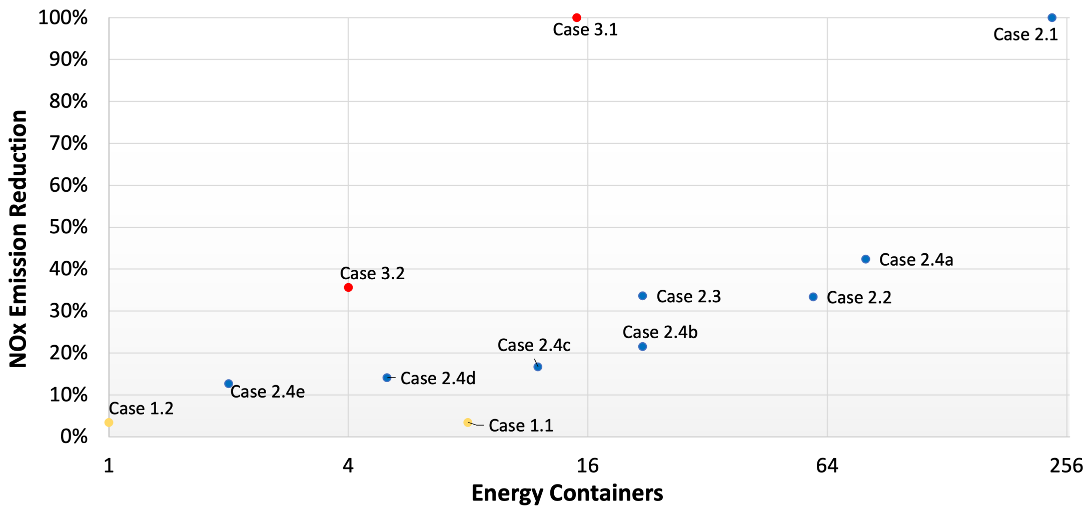


Figure 6.14: Combined results NO_X, on a logarithmic scale

For the NO_X emissions, Figure 6.13 combines all the case's into one graph, with on the y-axis the required amount of containers and on the x-axis the emission reduction. Compared to the CO_2 emission reduction that have a direct relation with the fuel consumption, the NO_X reductions are shifted to the left, indicating a lower impact. Despite the lower NO_X emissions in g/kWh for higher loads, this difference in relation is most likely explained through the increase of combustion temperature of engines operating on higher average load.

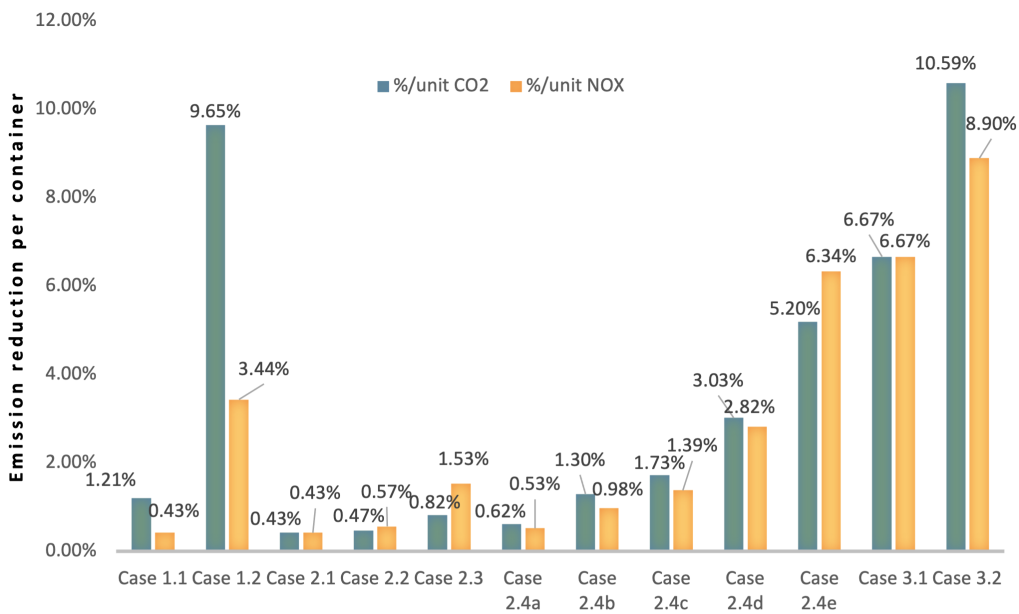


Figure 6.15: Combined results, reductions per energy container

To see which strategy has the highest potential in the short term, it is relevant to see what the most effective strategy is in terms of improvements per used energy containers is. In figure 6.15 the different strategies are expressed as gains per energy container. The most complex case 3.2 in which the diesel engine integrated batteries for peak shaving and SOFC fuel cell technology powered by hydrogen containers. It appears that partly covering the load by hydrogen and fuel cells has a large boost on the emission performance, while the relative amount of containers required is limited. Critical note is that the amount of energy in kWh in 40ft hydrogen containers is 13 times higher than in the 20ft battery containers.

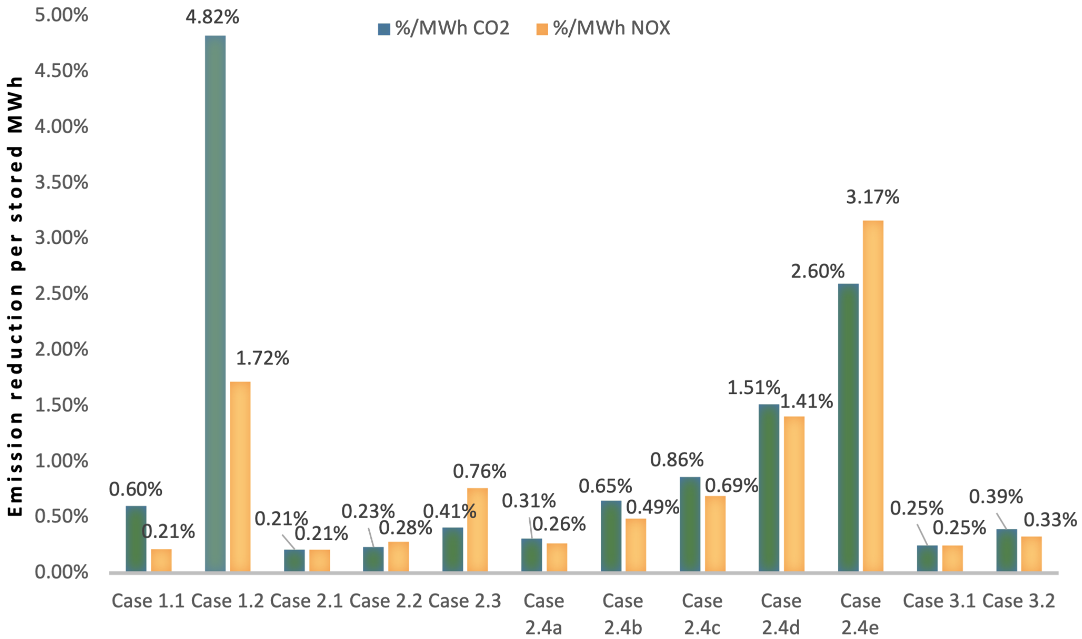


Figure 6.16: Combined results, reductions per stored MWh

Figure 6.16 illustrates the improvement per stored [MWh] of renewable energy. This figure puts the impact of hydrogen in perspective, as the impact per stored [MWh] of energy is similar to the fully hydrogen powered case. The Key takeaways from these figures are that the relative initial gains are the highest for the lowest quality of energy containers.

To answer this chapter's sub question:

Which hybrid control strategy has the highest relative emission reducing potential while enhancing the energy efficiency of the electrical grid?

It can be concluded that Case 1.2 for the current grid has the highest potential, as the gained improvements relative to the required amount of containers is largest. For the diesel-electric hybrid with an upper limit of 9125 kW, the boost capacity (Case 2.4e) strategy has the highest relative improvement as you combine mean load increase and engine shutdown. For the hydrogen containers, it is concluded that combining batteries fuel cell and diesel engines has the highest relative improvement. However, these strategies alone are not enough to meet the IMO's climate goals for 2030 which strive for a reduction of at least 40% CO_2. If this climate goal meant that the vessel must reduce its CO_2 emissions with 40% only the strategies of Cases "2.1", "2.4a", "3.1", and "3.2" in itself would be enough to meet these goals.

7

Overall Impact Assesment

After finding the technical configuration that has the highest emission reducing potential, it is possible to assess the second objective of this thesis. This is to evaluate if a swappable power extension is a technically feasible solution. Construction of previous heavy lift vessels resulted in limited space for accommodating the machinery spaces. Installing energy storage that is more spacious than diesel oil seems problematic. In this chapter, the cases described previously will be assessed to answer the following subsection:

To what extent can the electricity demand of a Heavy Lift Construction Vessel be made with interchangeable power containers without compromising the offshore operations?

7.1. Technical Assessment

Assessing the technical feasibility of swappable energy containers, the first and most obvious design criteria is how well does such a system fit on deck and what is the maximum amount of containers the ship can accommodate. According to DNV RU-ships Chapter 3, specific cable route and location requirements must be respected in order to ensure safety in regard to collision impact and crew accommodation. Consequently, it has been determined that the energy containers should be placed within a single area on the deck, as opposed to being scattered over the entire deck and hold. Therefore, it is determined that placing the energy containers on the aft deck, in proximity to the engine room and at a distance from the crew accommodation, is the most appropriate design choice. This decision minimises electrical impedance due to excessive cable lengths and enhancing fire safety measures. The container location is indicated in blue in figure 7.1.

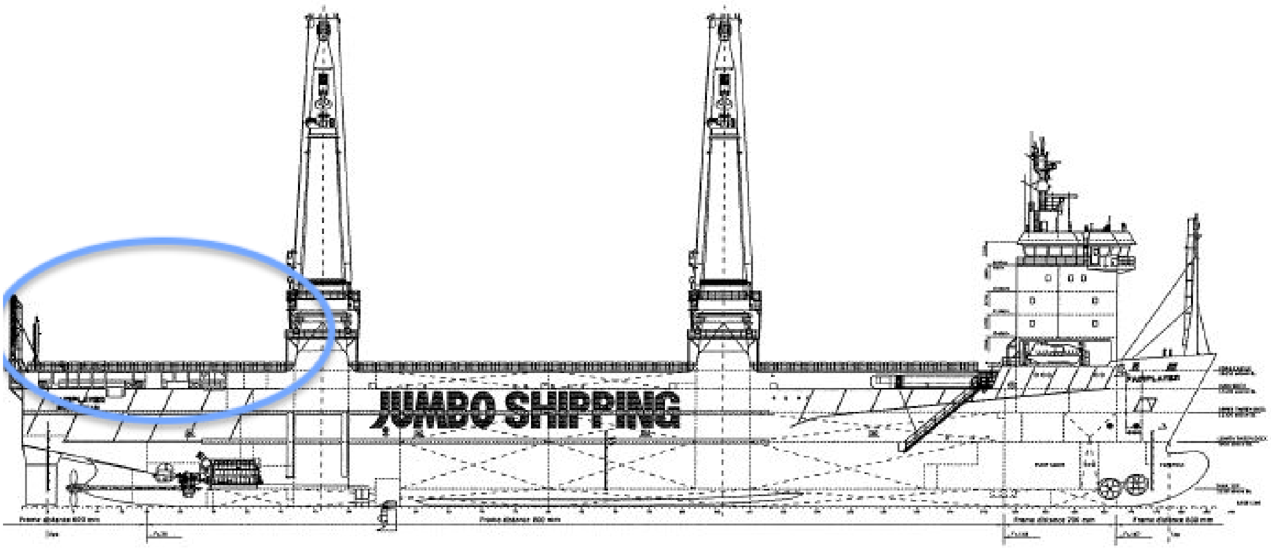


Figure 7.1: Proposed location of the swappable energy containers onboard J-class vessel

To estimate the maximum number of energy containers that can be placed on the aft deck of the J-class vessels, it is crucial to determine the maximum allowable stack height, which is governed by the maximum allowable deck load. It must be noted that for any specific project, twist locks are welded onto the deck and these are not standardized onboard. The deck load capacity for a single point load is specified as 10 tons per square meter (ton/m^2). For the 20ft batteries it is given that the total weight is 26 tons, which equates to 6.5 tons per twist lock, it is deemed not feasible to stack multiple containers on top of each other. Similarly, when examining the 40ft hydrogen containers, their weight is documented as 31 ton [Abma et al., 2019]. This translates to a load of 7.8 tons per twist lock, indicating that stacking hydrogen containers is also not feasible. In Figures 7.2 and 7.3, the layout of the most aft section of the Fairplayer's deck during the case project Holland Kust Zuid is illustrated. Within these visual representations of the real situation, precise container positions indicated by the use of black rectangles. Container locations were established through the collaboration of Jumbo's AutoCAD department, that verified the feasibility of the current representation of container locations.

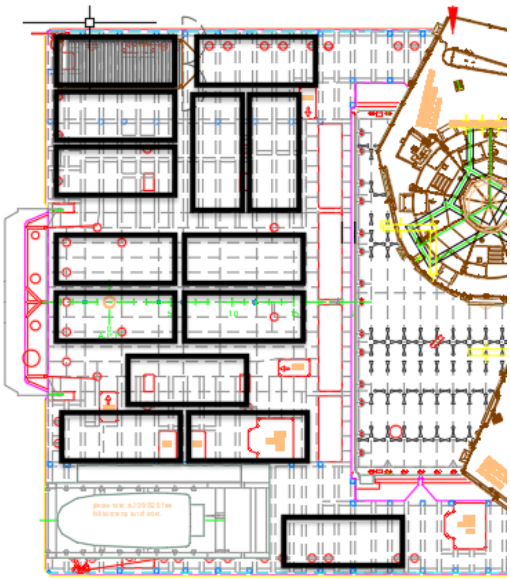


Figure 7.2: Maximum 20ft container fitment on the aft deck

Figure 7.3: Maximum 40ft container fitment on the aft deck

With regard to the maximum stack height, figures 7.2 and 7.3 prove that a maximum of 14 20ft containers and 6 possibly 7 40ft containers are technically feasible on board Jumbo's J-class offshore vessels. The maximum container weight governed by batteries result in a total weight of 370 ton. As the J-class deadweight is 13270 ton, energy containers should not give any issue regarding the vessel's installation capabilities.

Table 7.1: Technical feasibility of energy containers.

Case	Containers	Containers max	Feasible
Case 1.1	8	14	Yes
Case 1.2	1	14	Yes
Case 2.1	235	14	No
Case 2.2	59	14	No
Case 2.3	22	14	No
Case 2.4a	80	14	No
Case 2.4b	22	14	No
Case 2.4c	12	14	Yes
Case 2.4d	5	14	Yes
Case 2.4e	2	14	Yes
Case 3.1	15	6	No
Case 3.2	4	6	Yes

7.2. Financial Evaluation

The financial feasibility of the proposed storage systems is based upon renting a fully charged system every cycle start. Despite multiple container renting concepts can be found, the two most dominant concepts are leasing energy containers and a pay-per-use concept. Leasing doesn't seem to have much potential in the transition to zero-emission. According to [Ministry of Infrastructure, 2021] leasing energy containers is hardly used in the sector due to large financial barriers. Nevertheless, leasing will not be used in this thesis.

Pay-per-use financing seems more promising. It fits well with the trend of offering flexible energy supply services instead of owning a large amount of energy containers. This financial model charges shipowners who want to switch to an emission-free energy supply nothing more than the cost of renewable energy consumed, and a rental fee for the battery container [Ministry of Infrastructure, 2021]. The renting price of the energy is based on the current prices of renewable energy in 7.2. In addition to these energy costs in €$/kWh$ prices, a certain fee for renting a suitable and classified storage container is added to the price of a full energy container. In the energy sector, such a model is often referred to as "Energy as a Service" or "EaaS" which is described in 3.4.1. Examples of organisations that commercially supply swappable batteries or hydrogen systems include; EST-Floattech, Fleetzero, Furukawa Eco Marine Power, SEAM, Shift Clean Energy, and Zero Emission Services [Søgaard et al., 2023].

The downside of this infrastructure is that as of 2023 there is currently no up-to-date financial data publicly available which could be used to make a financial comparison between conventional fuel expenditures and pay-per-use financing of green energy. The result of this is that financial figures are assumed numbers based upon other battery rental companies that publish their renting rates.

Since energy containers are rented through the pay-per-use concept, it is assumed that there is no capex required for the utilisation of the required green energy indication the financial feasibility is limited to the operational expenditures. The cost of renewable energy is expressed in levelized cost of energy (LCOE) which calculates the costs of one available kWh. In addition the storage costs are evaluated which are expressed in levelized cost of storage (LCOS).

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + R_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{7.1}$$

where,

- $E_t =$ Total energy consumption over the full cycle
- $F_t =$ Fuel expenditures
- $I_t =$ Renewable energy expenditures
- $R_t =$ Renting Fee including maintenance expenditures and transport costs.
- $r =$ Discount rate

The LCOS is calculated similarly, however this excluded the energy that originates from the diesel fuel.

$$LCOS = \frac{\sum_{t=1}^{n} \frac{I_t + R_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_{str}}{(1+r)^t}} \tag{7.2}$$

where,

- $E_{str} =$ Energy stored in the batteries over the full cycle
- $I_t =$ Renewable energy expenditures
- $R_t =$ Renting Fee including maintenance expenditures and transport costs.
- $r =$ Discount rate

Table 7.2: Parameters used for LCOE and LCOS

Energy form	Price [€/kWh]	Rental fee [€/unit/hour]	Source
MGO	0.07	-	[Ship&Bunker, 2023]
Hydrogen	0.14	20	[Schippers, 2019]
Electricity	0.06	45	[EUenergy,] / [Ministry of Infrastructure, 2021]

Table 7.3: Levelized cost of energy and storage for the pay-per-use concept

Example Case	Consumed [kWh]	Diesel [ton]	Containers	Energy Containers	Diesel	LCOS [€/kWh]	LCOE [€/kWh]
Case 0	925080.00	78.00	0.00	€ -	€ 64,754.72	0.000	0.07
Case 1.1	837365.37	70.60	8	€ 58,560.34	€ 58,614.78	3.659	0.14
Case 1.2	837365.37	70.60	1	€ 7,320.04	€ 58,614.78	3.659	0.08
Case 2.1	470164.50	0.00	235	€ 1,720,209.87	€ -	3.659	3.66
Case 2.2	759320.49	64.02	59	€ 431,882.48	€ 53,151.71	3.659	0.64
Case 2.3	508722.70	39.18	22	€ 161,040.92	€ 32,529.07	3.659	0.38
Case 2.4a	821779.66	55.79	80	€ 585,603.36	€ 46,320.02	3.659	0.77
Case 2.4b	778550.79	61.93	22	€ 161,040.92	€ 51,416.78	3.659	0.27
Case 2.4c	810530.94	66.32	12	€ 87,840.50	€ 55,055.83	3.659	0.18
Case 2.4d	840485.77	70.02	5	€ 36,600.21	€ 58,132.97	3.659	0.11
Case 2.4e	674623.08	56.54	2	€ 14,640.08	€ 46,942.88	3.659	0.09
Case 3.1	404415.00	0.00	15	€ 92,618.10	€ -	0.229	0.23
Case 3.2	641899.80	45.03	4	€ 24,698.16	€ 37,383.40	0.229	0.10

The LCOS of the Cases 1.1 1.2 and 2.3, is arguably only correct for the first cycle as at the start of a second cycle containers do not have to be swapped with full batteries as they are still full at the end of each cycle. Therefore, the LCOS and LCOE will be lower for longer cycle period as only the unit rent is continuous while the required energy is not being consumed. The organisations that commercially supply swappable batteries or hydrogen containers and working with the pay-per-use concept operate mostly locally, resulting in a price deviation globally. The techno-economic analysis of [Siddique, 2019] determined that the transport costs of battery containers have a large impact on the renting fee, since this encompass all the operational expenses of the energy containers companies. The result of this is that the economic feasibility of energy containers in general heavily depends on the port location with respect to the charge station.

7.3. Maintenance

For Trip 5 the online running generators hours are mapped, as this is a direct link to the maintenance intervals of each technical layout. Real maintenance costs are rather specific and depend on multiple factors, such are thermal and dynamic loading, component age, fuel quality and much more. In addition, it is assumed that for the renting of energy containers maintenance of those systems is part of the scope of any supplier, as the costs for this are included in the renting price.

Table 7.4: Running hours of engines in the cases

Running hours	ME PS	ME SB	gen1	gen2	gen3	gen4	gen5	gen6	total	Improvement
Case 0	120	120	120	120	-	-	-	-	480	0%
Case 1.1	120	120	0	0	-	-	-	-	240	50%
Case 1.2	120	120	0	0	-	-	-	-	240	50%
Case 2.1	-	-	0	0	0	0	0	0	0	100%
Case 2.2	-	-	80	80	80	80	80	80	480	0%
Case 2.3	-	-	120	120	0	0	0	0	240	50%
Case 2.4a	-	-	120	0	0	0	0	0	120	75%
Case 2.4b	-	-	120	120	0	0	0	0	240	50%
Case 2.4c	-	-	120	120	120	0	0	0	360	25%
Case 2.4d	-	-	120	120	120	120	0	0	480	0%
Case 2.4e	-	-	120	120	120	120	120	0	600	-25%
Case 3.1	-	-	0	0	0	0	0	0	0	100%
Case 3.2	-	-	120	0	0	0	0	0	120	75%

Table 7.4 illustrates that the various cases exert a considerable influence on the running hours of the installed engines. According to [Laursen, 2022], there is a direct relation between the wear and tear of mechanical components and engine running hours. Therefore, operational costs with respect to maintenance are positively influenced by the application of swappable energy containers in most of the cases. Besides, it is acknowledged that there is a difference in maintenance requirements for electric and mechanical propulsion architectures. Mapping the exact impact of swappable energy containers through different hybrid control strategies in three different architectures on the operational expenses is a consideration for future research.

7.4. Conclusion

The technical assessment has shown that it is feasible to place a few energy containers on the aft deck of J-class vessels, and the total combined weight does not pose an issue for the vessel's installation capabilities. The maximum number of energy containers that the vessel can accommodate is 14 20ft containers and 6 to possibly 7 40ft containers.

With respect to the financial feasibility, the pay-per-use concept appears to be a more promising option compared to container leasing. It aligns with the trend of offering flexible energy supply services rather than owning a large amount of energy containers and arrange battery charging and hydrogen refuelling under own management. Unfortunately, insufficient financial numbers for a basis fee as of 2023 has led to assumptions based on other battery rental companies' published rates. Therefore, swappable container strategies are not assessed ”not feasible” on the basis of the assumed rental fee. The Levelized Cost of Energy (LCOE) and Levelized Cost of Storage (LCOS) calculations indicate that, in some cases, the pay-per-use model with swappable energy containers can be cost-competitive with conventional fuel expenditures. For instance, ”Case 1.1” and ”Case 2.5” show promising results, with an LCOE of €0.08/kWh and €0.09/kWh, respectively. It's worth noting that the financial feasibility is highly dependent on factors such as energy source prices, rental fees, and transport costs, which may vary by location, making such estimates for a vessel operating worldwide even more complex.

Taking into account the maximum capacity for both battery and hydrogen containers that can be accommodated on board, it is observed that the highest potential for CO_2 reductions for batteries and hydrogen, are reaching 21% and 42% respectively. This underscores that competitiveness of swappable hydrogen containers surpasses batteries in terms of emission performance. Moreover, the levelized cost of energy for Case 3.2 is only half of that in Case 2.5. Moreover, it's worth noting that Case 3.2 aligns with the International Maritime Organization's (IMO) ”Route to Zero” goals for the year 2030 in terms of emissions reduction.

8 Discussion

This chapter aims to interpret the key findings of this thesis and discuss their implications in the context of the existing literature and current developments with respect to the energy transition.

8.1. Key Findings

The literature study revealed that the energy as a service concept could enhance the overall efficiency of an offshore vessel without the need for initial capital cost required to retrofit an existing vessel. The main advantage of such a system is that the distribution and bunkering of renewable energy is simplified, making such a concept also an interesting consideration for new-build projects. Energy containers currently used in such concepts are limited to battery and compressed hydrogen storage.

Multiple energy control strategies were evaluated to investigate how these energy containers could be integrated effectively. With the load profile of the current technical layout during the Hollandse Kust Zuid reference project, hydrogen can not be utilised and only two battery control strategies qualify for employment. This straight forward outcome only provides a satisfactory outcome for the current vessel yet with the main research question in mind the research was not limited by the current technical architecture. Subsequently, it was considered valuable to evaluate multiple hybrid control strategies to investigate the impact of both energy as a service concepts on the overall emission performance. Consequently, two other technical configurations were reviewed.

In relation to the Hollandse Kust Zuid project, the study revealed that the Azipod system outperforms conventional controllable pitch propellers in terms of energy consumption during dynamic positioning. Consequently, the alternative grid will distribute the power for thrust and operational equipment electrically. The composed load profile was used to simulate different technical layouts. Different hybrid control strategies were used to quantify the required number of units and resulting emission reductions with respect to the current emission performance.

The technical assessment determines that placing energy containers on the aft deck is feasible, with a maximum of 14 20ft containers and 6 to possibly 7 40ft containers. Financially, the pay-per-use concept is considered promising, with respect to the concept of flexible energy supply services for inland vessels. Levelized Cost of Energy (LCOE) calculations indicate that in some of the cases, swappable containers could be cost-competitive with conventional fuel expenditures.

The case study results indicate that the lower the required amount of storage, the higher the relative impact. Full energy coverage will result in a large amount of energy containers, which considering the technical assessment is not feasible. For the cases which employ battery containers, there appears to be a correlation between the quantity of containers required and the extent of emission improvement for each case. With the current assessed strategies, only three cases will satisfy the IMO's route to zero climate goals of 2030. The study has revealed that a small amount of battery or hydrogen containers can have a relative high impact on the emission performance of a vessel.

8.2. Assumptions

This section gives an overview of the assumptions that were mandatory to reach results, yet further research is required to eliminate these assumptions and make results more accurate. The assumptions are listed below:

- The measured generator load is the actual electrical output of each generator.
- The pitch set point value is the actual pitch angle of the controllable pitch propeller, and there is no offset between these.
- For the fuel cell, efficiencies are variable in reality. For the solid oxide fuel cell system, the efficiency was assumed constant as the load is kept constant.
- Trip 5 was selected the most challenging installation cycle. With this in mind, it is assumed that the required amount of containers for this trip are sufficient for the entire project and therefore similar contracts.
- Propellers operate in bollard pull conditions throughout trip 5
- It is assumed that the electrical loads can be combined, without the correction for unsynchronised loading.
- The charge and discharge efficiencies depend on multiple factors, such as the C-rate. For higher C-rates, more heat is developed as energy flow is increases. Nevertheless, these efficiencies are assumed constant.

8.3. Implications and Limitations

This thesis gives insight into the application of swappable energy containers. The findings provide implications for understanding the impact of these energy containers on the emission performance of offshore installation vessels working on dynamic positioning. The reference vessel and current load profile highlights the need for efficiency enhancing methods and renewable energy without the need for large capital expenses.

Nevertheless, in this study several limitations are acknowledged. The amount of data which was suitable and representative was limited. Since Jumbo's offshore activities are diverse, the initial aim was to analyse multiple contracts to give a comprehensive overview of the different hybrid strategies through different offshore operations. However, the proposed method with minor modifications can analyse large sets of installation trips, to optimise the required amount of energy containers.

Different hybrid control strategies were individually evaluated, while in practice multiple strategies are combined by smart energy management systems. Hypothetically, such systems improve the overall energy efficiency, consequently reducing emissions.

Regarding the location of the energy containers on the aft deck, there are generally equipment containers and workshops located on the aft deck. These would have to be relocated, which seems difficult on an already full deck. In addition, the containerised energy system should be class approved, and measures have to be taken to ensure safety with respect to cable routing and fire fighting precautions.

Spinning reserve and enhanced dynamic behaviour strategies could also be applied to the second and third case. However, it was decided to leave this disregarded as the impact of these strategies is already evaluated in case 1

Financial aspect of this thesis was limited to the operational expenses of fuel and renting costs of energy container systems, while the levelized cost of energy could also include the capital expenses or maintenance costs of the corresponding technical architecture. Significant differences in initial investments to be expected between the current technical layout and, for example, an ICE-fuel cell-electric configuration.

9 Conclusion

The share of greenhouse gas emissions of the shipping industry is currently marginal in the context of global greenhouse pollution. However, this should not be viewed as a reason for doing nothing, as the share would inevitably increase if business as usual continues. Nonetheless, the quantity of emissions remains substantial, and significant gains can be realized by enhancing the efficiency of individual sectors. Undoubtedly, every effort should be made to replace fossil fuels with renewable and sustainable alternative energy sources in the long run, meeting IMO's 2050 goals. Until that time, enhancing the overall efficiency and emission performance of the current vessels seems like the way forward to meet intermediate targets.

Before addressing the main research question, it is necessary to answer the foundational sub-questions, which will ultimately contribute to formulating an answer to the main research question. The literature review partly solves the first subsection, whereas current low emission technologies, swappable power extensions and hybrid control strategies are reviewed.

1, What are relevant technologies that could reduce the greenhouse gas emissions resulting from current diesel generators?

With respect to the IMO's route to zero emissions timeline, the outcomes of the literature study primarily encompass an interim solution that at best improves overall efficiency and emission performance. Consequently, the thesis focused on reducing the emissions through renewable energy, which is stored in containers that can be exchanged in port. Swappable energy projects, involving energy as a service, currently focus only on hydrogen and battery storage. This is mainly due to the bunker complications of both these storage techniques. Therefore, the suggested technical approach involves the use of containers filled with batteries or hydrogen, which will be managed in port for recharging. Containerized hydrogen storage is beneficial when fuel cells are applied. The Literature study revealed that a solid oxide fuel cell system the most preferred choice to utilise the hydrogen, given that the fuel flexibility of these systems is beneficial for global operations.

In order to measure the impact of swappable containers regarding emissions, it is necessary to start by evaluating the current situation. For this purpose, an initial load profile is established, subsequently enabling the determination of emissions and consumption of a representative installation trip. This resulted in the second sub-question.

2, What is the load profile of Jumbo's Heavy Lift Construction vessel during an offshore installation operation, using real performance parameters?

It was decided that the Holland Kust Zuid would be used for this case study and the result will be based on a particular trip, namely Trip 5. This 120-hour installation trip was chosen to serve as a benchmark for subsequent investigation. The chosen load case was determined by assessing the mean electrical load and consumption of all the 27 trips. The load profile of Trip 5 gave insight on the distribution of electrical load among generators 1, 2, 3, and 4. While generators 1 and 3 displayed load-sharing behaviour, generators 2 and 4 operated on much lower electrical load due to the open busbar.

The effective power of the main engine was determined by combining the propeller and generator loads, taking into account various losses. Similar yet different calculations were applied to calculate auxiliary engine power. Histograms were employed to better understand the distribution of power data, offering valuable insight into operational patterns. Histograms revealed that long-term operation significantly below engine capacity results in unfavourable fuel consumption rates. To determine CO_2 emissions, the study employed load profiles, power estimations, specific fuel consumption, and a CO_2 conversion factor to estimate the emitted CO_2. Similarly, NO_X emissions were estimated based on load profiles and emission performance data. When comparing the actual consumption with the determined fuel consumption, it was concluded that the proposed method yields results in the appropriate order of magnitude.

These two previous sub-questions serve as the foundation that required to assess different alternative strategies and application of these energy containers. Simulating the different strategies in python result in required amount of energy containers and resulting emission reductions.

3, Which technical configuration has the highest emission reducing potential while enhancing the energy efficiency of the electrical grid?

With respect to the existing technical architecture, it is only feasible to implement spinning reserve and enhanced dynamic performance strategies due to the low average load and DP redundancy requirements. As this thesis prioritise the influence of swappable energy, alternative technical configurations were deemed inevitable. To assess the impact of both hydrogen and battery energy containers, it is necessary to evaluate multiple energy control strategies in three different technical configurations. After an evaluation of the propulsion plant, it was concluded that azipods are superior to controllable pitch propellers during the reference project. The newly composed load profile was used to determine the impact of swappable energy containers in two additional cases. One of these cases evaluated the usage of battery containers, while the other will assess the utilization of hydrogen containers.

It can be concluded that Case 1.2 for the current grid has the highest potential, as the gained improvements relative to the required amount of containers is largest. For the diesel-electric hybrid with an upper limit of 9125 kW, the boost capacity strategy (Case 2.4e) has the highest relative improvement when one combines the average load increase, improving the specific fuel consumption and engine shutdown. For the hydrogen containers, it is concluded that combining batteries fuel cell and diesel engines has the highest relative improvement. However, these strategies alone are not enough to meet the IMO's climate goals for 2030 which strive for a reduction of at least 40% CO_2. To achieve this climate goal, the vessel must reduce its CO_2 emissions with 40%, and the strategies of Case "2.1", "2.4a", "3.1", and "3.2" would be sufficient to meet this goal.

After finding the technical configuration that has the highest emission reducing potential, it is possible to assess if a swappable power extension is a technically feasible solution. Construction of previous heavy lift vessels resulted in limited space for accommodating the machinery spaces. Installing energy storage that is more spacious than diesel oil seems problematic. Moreover, when faced with the current energy density trends of, for example batteries, it is plausible that the state-of-the-art systems age quickly over the 25-year lifetime of a vessel. Consequently, making the application of energy containers appealing.

4, To what extent can the electricity demand of a Heavy Lift Construction Vessel be made with interchangeable power containers without compromising the offshore operations?

The technical assessment has shown that it is feasible to place a few energy containers on the aft deck of J-class vessels, and the total combined weight does not pose an issue for the vessel's transport and installation capabilities. The maximum number of energy containers that the vessel can accommodate is 14, 20ft containers and 6 to possibly 7, 40ft containers. Taking into account the maximum capacity for both battery and hydrogen containers that can be accommodated on board, it is observed that the highest potential for CO_2. Reductions for batteries and hydrogen, are reaching 21% and 42% respectively. This underscores that the competitiveness of swappable hydrogen containers surpasses batteries in terms of emission performance. Moreover, the levelized cost of energy for Case 3.2 is only half of that in Case 2.4e. It is worth noting that Case 3.2 aligns with the International Maritime Organization (IMO) "Route to Zero" goals for the year 2030 in terms of emissions reduction.

This research explored the opportunity to use energy container infrastructures, originally intended for inland cargo and tug vessels, on offshore installation vessels owned by Jumbo Offshore as a means to mitigate greenhouse gas emissions. Currently, there is limited public research focussing on the use of such application for large seagoing vessels, as most research, established regulations, commercial infrastructure and available systems focus on inland vessels or integrated systems. Consequently, the following research question has been formulated for this study:

How can swappable energy containers be effectively integrated into offshore installation vessels to reduce greenhouse gas emissions and enhance the energy efficiency, considering real load profiles?

This thesis assessed whether energy containers can significantly improve the total emission performance for offshore installation vessels, if not, make such a vessel comply with the IMO's climate targets for 2030. However, the required number of batteries has a significant impact on the levelized fuel cost, therefore the most effective solution can be found with the largest relative emission reductions. The highest relative reductions can be achieved through a small number of batteries, as Cases "1.2" and "2.4e" prove. In the end, eliminating greenhouse gas emissions can be achieved by replacing fossil fuels with renewable and sustainable alternative energy sources as this has the largest improvements on the emission performance, as described in 3. A significant enhancement of the fuel efficiency through a marginal number of battery containers with strategies similar to Case "1.2" and "2.4e" could then contribute to the cost-effectiveness of these renewable fuels.

9.1. Recommendations

This section start with the key findings that Jumbo, as the participating company and the primary contributor to this research, can utilize to further investigate practical implementation on board. In the context of current offshore vessels, a dynamic positioning system with redundancy and a higher degree of flexibility based on utilisation of standby units and / or changeover mechanisms (DYNPOS-ER), subsection 6.2.2, presents an opportunity to enhance the operational efficiency with relative little impact on the levelized cost op energy. Future research should point out the specific alterations required to the vessel's power management system and certification requirements.

In the context of this thesis as academic writing, the strategies are evaluated independently, while a higher potential emission reduction could be achieved by combining different battery control strategies. However, future research is required to prove this theory. A notable observation in Figures 6.13 and 6.14 is that there appears to be a linear relationship between the amount of battery containers required and the extent of emission improvement for each case. Nevertheless, further investigation is required to prove this theory. Which could be beneficial to determine the required amount of storage required for a desired emission reduction.

A novel feature of the cranes currently installed on board is their ability to regenerate energy. Due to limited data on crane movement, this was not considered during this research. Consequently, future research should evaluate the integration of this feature, as it has the potential to positively affect the required amount of battery containers.

With the application of containers filled with renewable energy sources such as green hydrogen and electricity, future research should focus on developing energy management and control solutions that can seamlessly integrate these swappable containers in existing energy grids through multiple hybrid control strategies. Possibly new technologies such as machine learning and artificial intelligence can help with real-time load forecasting and demand response with the most suitable hybrid control strategy. Future research should explore how these technologies can be employed.

One aspect missing in this research in the context of commercial feasibility, which could involve conducting cost-benefit analyses. With respect to carbon tax, swappable battery could offer an opportunity as it improves the overall system performance on multiple levels. In addition to the lower fuel consumption and implementation of certain hybrid control strategies could have a favourable impact on maintenance costs, given a reduction in running hours.

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A

Engine Data

The following pages show the Acceptance Test Record and the EIAPP report of the parent engine of the 9M 32 C marine diesel engine from Caterpillar Motoren GmbH & CO. KG which where used to simulate the installed engine performance.

Emission Test Report **No. M32C-LE**

Engine Information

Engine		
Manufacturer	Caterpillar Motoren GmbH	
Engine type	6 M 32 C	
Group identification	M32C-LE2	
Serial number	38729	
Rated speed	600	rpm
Rated power	3000 / 2880	kW
Intermediate speed	-	rpm
Max. torque at intermediate speed	-	Nm
Cylinder number and configuration	6,8,9 inline	
Bore	320	mm
Stroke	480	mm
Mean effective pressure at ratet power	25,9 / 24,8	bar
Max. cylinder pressure at ratet power	204	bar
Auxiliaries	2 pumps	

Specified ambient conditions		
Max. Seawater temperature	38	°C
Max. Charge air temperature, if applicable	45	°C
Cooling system spec., intermediate cooler	yes	
Cooling system spec., charge air stages	2 stage	
Low / high temp.cooling system setpoints	30 / 90	°C
Maximum inlet depression	25	mbar
Maximum exhaust backpressure	30	mbar
Fuel oil specification	Gas oil	
Fuel oil temperature	40	°C
Lubricating oil specification	see engine documentation, chapter "Operating Media"	

Application / Intendet for	
Customer	
Final application/ installation, Ship	
Final application/ installation, Engine	main

Emissions test results				
Cycle		D 2	E 2	
NOx	600 1/min	9,8	9,6	g/kWh

Figure A.1: Test Data Report M32C Engine Family

MaK

Diesel Engine Acceptance Test Record

Sheet 2 of 2
Order No.: 261223-1
Engine No.: 39162

Run time (min.)	Fuel (mm)	Output Speed (rpm)	Output Pe (kW)	Load (kN)	Load (%)	Air press P0 (bar (a))	Air Temp. T0 (°C)	Mean eff. press pme (bar)	Fuel Oil Consumption (g/kWh)	Fuel Oil Consumption (kg/h)	Lubricating oil Press. (bar)	Lubricating oil Temp. in (°C)	Cooling water Press. (bar)	Cooling water Temp. In (°C)	Cooling water Temp. Out (°C)	Charge air cooler Water HT In (°C)	Charge air cooler Water HT Out (°C)	Charge air cooler Water LT In (°C)	Charge air cooler Water LT Out (°C)	Charge air cooler Air In (°C)	Charge air cooler Air Out (°C)
30	27,0	600	1125	18,8	25	1,020	23,5	6,48	216,2 ISO 217,3	243,2	4,7	58	2,8	87	89	86	87	38	39	72	41
30	37,0	600	2250	37,5	50	1,020	24,0	12,95	187,7 ISO 188,7	422,4	4,8	58	2,8	86	89	82	86	38	40	136	41
30	43,0	600	3375	56,3	75	1,020	24,3	19,43	182,8 ISO 183,8	617,0	4,8	58	2,8	85	89	75	85	37	42	190	42
30	46,0	600	3825	63,8	85	1,020	24,9	22,02	183,5 ISO 184,3	702,0	4,7	59	2,8	85	88	71	85	38	42	208	42
60	49,0	600	4500	75,0	100	1,020	25,1	25,90	185,8 ISO 186,8	836,3	4,7	58	2,8	84	88	67	84	38	43	230	43
30	[illegible]	600	4950	82,5	110	1,020	25,4	28,49	188,2 ISO 189,0	931,8	4,8	59	2,9	84	89	84	84	38	43	246	44

Load (%)	Exhaust gas temperature °C Cylinder 1	2	3	4	5	6	7	8	9	aft. Turb.	bef. Turb. 1	bef. Turb. 2	bef. Turb. 3	Turbocharger Charge air pr. bef. cool. (bar)	Charge air pr. aft. cool. (bar)	Diff. press (mbar)	Speed (rpm)
25	362	378	372	352	401	359	394	348	372	378	439			0,490	0,475	15	12313
*	360	375	370	349	395	356	391	345	368	375							
50	350	350	346	332	371	339	364	332	342	328	439			1,513	1,490	23	18876
*	347	348	343	329	367	336	358	327	339	324							
75	366	370	360	350	385	359	380	350	362	296	457			2,670	2,640	30	23250
*	363	366	358	348	382	357	375	347	359	294							
85	382	388	378	366	407	377	404	370	384	300	477			3,093	3,060	33	24500
*	379	385	374	363	400	374	398	366	381	298							
100	414	424	408	396	447	411	452	404	424	318	518			3,635	3,600	35	26125
*	411	421	405	394	441	407	444	400	420	316							
110	448	456	436	424	483	441	492	428	454	338	550			3,939	3,900	39	27125
*	439	451	433	419	476	436	483	425	450	335							

witnessed

Indicator : LEHMANN & MICHELS
Type : LEMAG PREMET LS

Combustion pres. (bar)	1	2	3	4	5	6	7	8	9
	203	203	201	203	202	204	204	203	203

Notes:

Specific fuel consumption including 1 lubricating oil pump and 1 cooling water pump.
Engine elastically mounted.

*) Readings from control panel.

Caterpillar Confidential: green

20 is basic value for crankweb deflection 1/100 mm

Example 18 (-) Example 23 (+)

Cylinder		1	2	3	4	5	6	7	8	9
B.D.C.		20	20	20	20	20	20	20	20	20
Exhaust side	cold	18,5	19	19,5	20	19	19,5	20	19,5	18,5
	warm	17,5	18,5	19,5	19,5	18,5	18,5	19	19	18
T.D.C.	cold	18	18,5	20	20	20	20,5	20,5	19	17
	warm	15,5	17	18	17,5	17	18	18	18	16
Camshaft side	cold	20,	20,5	20	21	19,5	20,5	21	20	19,5
	warm	19	19,5	19,5	19,5	18,5	19,5	19,5	20	19

Measured on test bed and coupled to hydraulic brake.

Measured with overhung flywheel.

Follow MaK instructions for installation.

ISO) Calculated to ISO 3046
(a) absolute

Exhaust gas back pressure at full load 0,026 bar

Lloyd's Register EMEA Acceptance
LR/EMEA
MN LR QAM 042
Kiel Office HAM 1241432

Mechanic
Plambeck / 24.10.2012

Engineer
Viereck / 24.10.2012

Approved
/ 24.10.2012

DICARE f. Windows / Version 2.0 / 22.10.2012

Approval No. 68508-13 HH
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Figure A.2: MAK 9M32C Acceptance Test Record

Emission Test Report M32C LE Ambient and Gaseous Emissions Data

Mode			1	2	3	4	5
Power / Torque		%	100	75	50	25	10
Speed		%	100	100	100	100	100
Time at beginning of mode			14:28	14:47	15:08	15:28	15:47
Ambient Data							
Atmosph. pressure		mbar	1021	1021	1022	1021	1021
Intake air temp.		°C	30,7	31,9	32,4	32,3	31,5
Intake air humidity		%	19,4	18	17,5	17,5	18,4
Atmospheric factor (fa)			1,013	1,018	1,021	1,020	1,016
Gaseous Emissions Data							
NOx	conc. wet	ppm	875,9	898,7	913	681,6	822,3
CO	conc. dry	ppm	43,4	38,9	39,5	87,4	132,5
CO2	conc. dry	%	5,84	5,63	5,66	5,48	4,11
O2	conc. dry	%	12,92	13,20	13,16	13,41	15,31
HC	conc. wet	ppm	143,2	152,2	215,1	264,9	266
NOx hum.corr.factor			0,959	0,966	0,971	0,973	0,969
Dry/wet corr.factor			0,948	0,95	0,95	0,951	0,963
NOx	mass flow	kg/h	26,383	21,199	14,653	6,319	5,20
CO	mass flow	kg/h	0,787	0,55	0,377	0,482	0,507
CO2	mass flow	kg/h	1664	1249,5	850	475,2	247,2
O2	mass flow	kg/h	2675	2129,2	1437	845	669,3
HC	mass flow	kg/h	1,358	1,122	1,074	0,762	0,524
SO2	mass flow	kg/h	-	-	-	-	-
NOx	specific	g/kWh	9,55	10,157	10,479	9,018	18,634

Figure A.3: Emission Test Report M32C Ambient and Gaseous Emissions Data

Emission Test Report No. M32C LE Engine Test Data

Mode		1	2	3	4	5
Power / Torque	%	100	75	50	25	10
Speed	%	100	100	100	100	100
Time at beginning of mode		14:28	14:47	15:08	15:28	15:47
Engine Data						
Speed	rpm	600	600	600	600	600
Power	kW	2880	2160	1440	720	288
Mean eff. pressure	bar	24,87	18,65	12,43	6,22	2,49
Fuel rack	mm	48,4	44,3	39,8	31,7	25,1
Uncorr.spec.fuel cons.	g/kWh	184,3	184,5	189	211,1	275
Fuel flow	kg/h	530,7	398,5	271,5	152,0	79,2
Air flow	kg/h	-	-	-	-	-
Firing pressure	bar	201	-	-	-	-
End of needlelift (Noz)	° CA	-	-	-	-	-
Charge air pressure	bar	3,51	2,48	1,4	0,51	0,14
Turbo speed	rpm	31040	27520	22400	15280	10040
Exhaust flow (gexhw)	kg/h	19800	15392	10421	6006,5	4115
Exhaust temp.	°C	291	294	321	335	259
Exhaust backpress.	mbar	25				
LT Coolant temp. in	°C	37	37	38	38	38
LT Coolant temp. out	°C	40	39	39	38,5	39
HT Coolant temp. in	°C	75	80	84	87	87
HT Coolant temp. out	°C	87	87	87	87	87
Cyl.Coolant pressure	bar	3,7	3,7	4	3,6	3,7
Temp. intercooled air	°C	43	41	40	39	38
Lubricant temp.	°C	56	54	54	56	53
Lubricant pressure	bar	4,4	4,4	4,4	4,5	4,5
Inlet depression	mbar	-	-	-	-	-

Figure A.4: Emission Test Report M32C Engine Test Data

GEN SET PERFORMANCE DATA

AUGUST 10, 2012

For Help Desk Phone Numbers Click here

Performance Number: DM6954 **Change Level:** 02

Sales Model: 3516BDITA **Combustion:** DI **Aspr:** TA

Engine Power:
1825 W/O F EKW **Speed:** 1,800 RPM **After Cooler:** SCAC
1,901.0 KW

Manifold Type: DRY **Governor Type:** ADEM3 **After Cooler Temp(C):** 30

Turbo Quantity: 2 **Engine App:** GS **Turbo Arrangement:** Parallel

Hertz: 60 **Application Type:** MAR AUX ENG **Engine Rating:** MA **Strategy:**

Rating Type: PRIME **Certification:** IMO 2000 - EPA TIER-I 2004 - 2007 EPA TIER-I 2000 - 2005

General Performance Data

GEN PWR EKW	PERCENT LOAD	ENGINE POWER BKW	ENGINE BMEP KPA	FUEL BSFC G/BKW-HR	FUEL RATE LPH	INTAKE MFLD TEMP DEG C	INTAKE MFLD P KPA	INTAKE AIR FLOW M3/MIN	EXH MFLD TEMP DEG C	EXH STACK TEMP DEG C	EXH GAS FLOW M3/MIN
1,825.0	100	1,889.2	1,825	197.900	445.7	43.7	192.1	152.3	577.1	464.7	391.0
1,642.5	90	1,699.0	1,641	200.300	405.7	41.9	168.1	140.3	569.1	464.6	360.9
1,460.0	80	1,509.8	1,459	203.300	365.9	40.4	144.2	128.4	561.1	467.2	331.0
1,368.8	75	1,415.5	1,368	205.100	346.1	39.7	132.1	122.3	557.1	469.6	315.9
1,277.5	70	1,321.1	1,276	206.900	325.8	39.0	119.1	115.2	552.8	473.2	298.8
1,095.0	60	1,133.1	1,095	210.900	284.9	37.7	93.2	100.9	543.1	480.3	264.2
912.5	50	945.6	914	215.900	243.4	36.6	67.4	86.6	531.6	487.2	228.9
730.0	40	761.2	735	221.600	201.0	35.9	44.5	74.0	505.1	476.3	193.5
547.5	30	574.5	555	230.900	158.2	35.3	23.7	62.7	463.9	449.1	157.7
456.3	25	480.3	464	238.400	136.5	35.1	14.1	57.4	437.7	429.2	139.7
365.0	20	385.4	372	251.000	115.3	34.9	6.3	53.3	402.9	398.5	123.9
182.5	10	193.9	187	317.200	73.3	34.6	6.0	47.0	315.6	315.8	94.9

Figure A.5: Caterpillar 3516B-1825kW Engine Test Data)

B
Additional Model Results

B.1. Mass flow Fuel

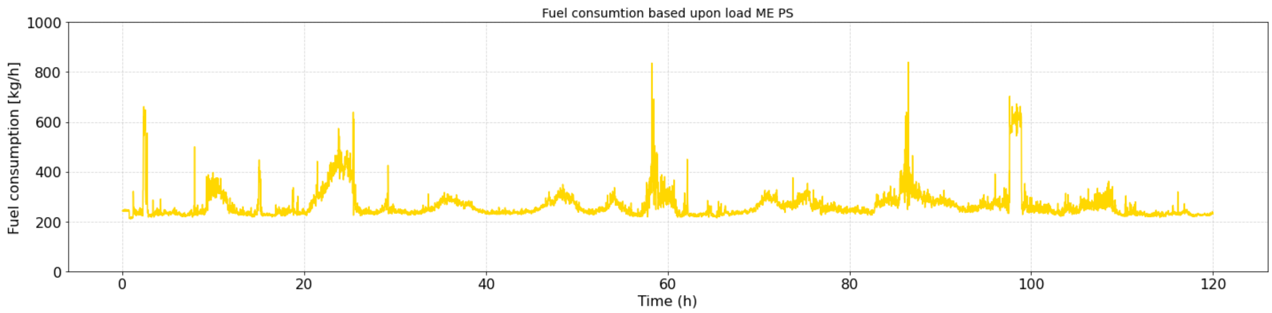

Figure B.1: Fuel consumption of the main engine PS

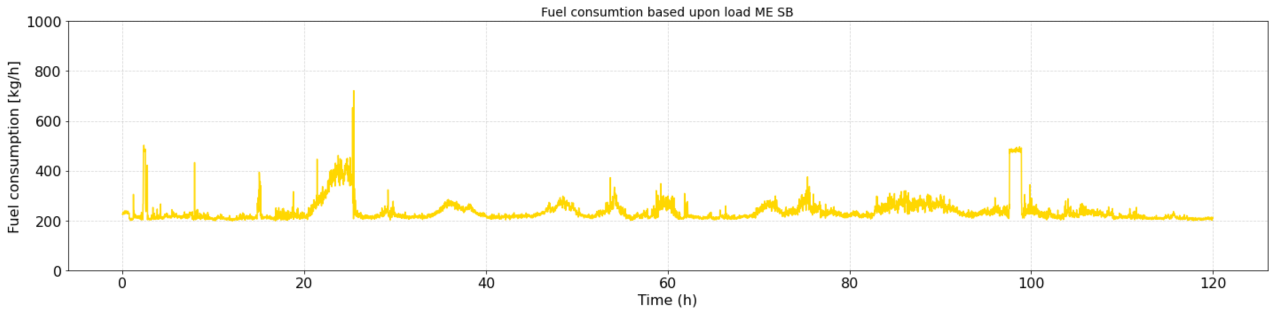

Figure B.2: Fuel consumption of the main engine SB

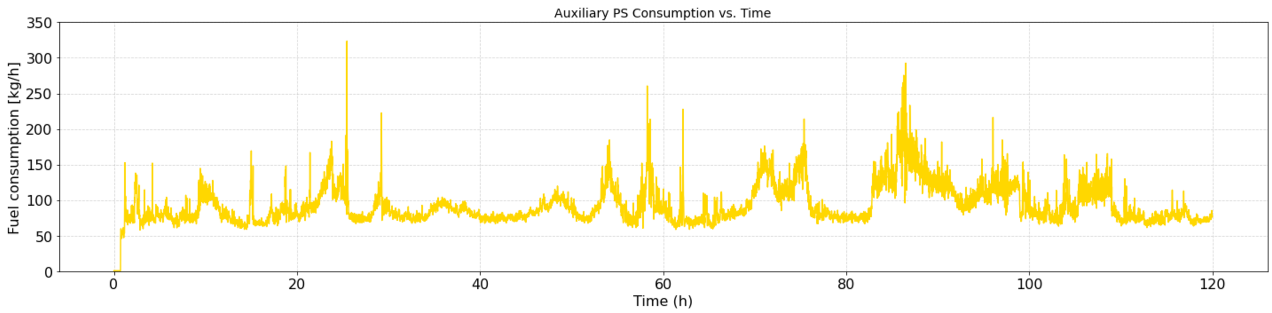

Figure B.3: Fuel consumption of the auxiliary engine PS

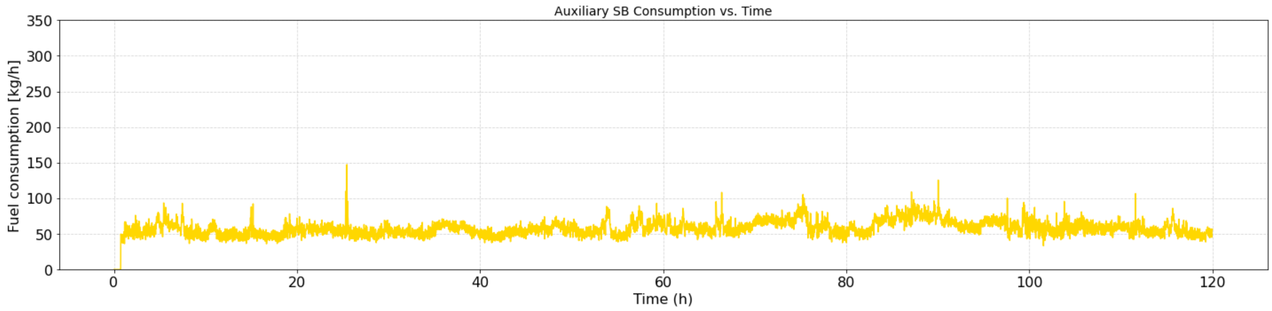

Figure B.4: Fuel consumption of the auxiliary engine SB

B.2. NO_X Emissions

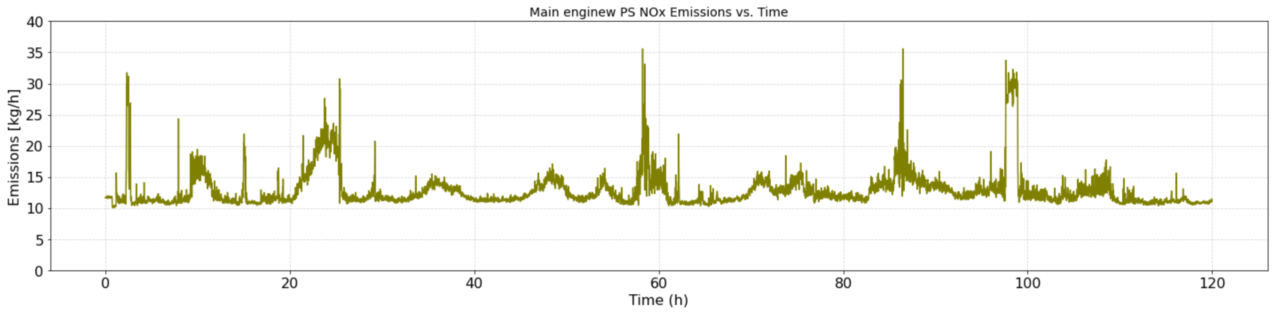

Figure B.5: NO_x emissions of main engine PS any moment in time

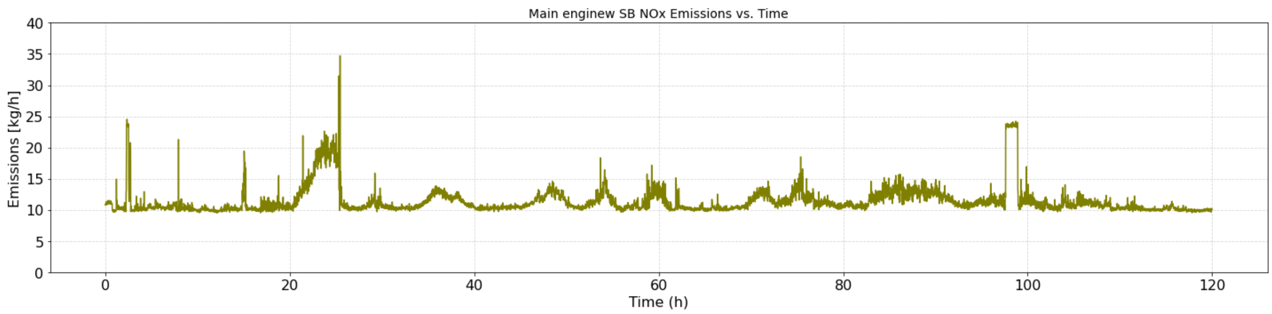

Figure B.6: NO_x emissions of main engine SB any moment in time

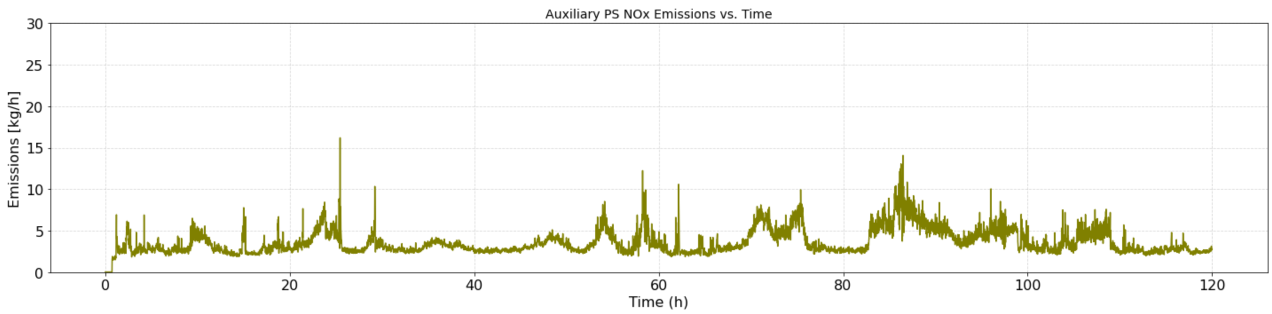

Figure B.7: NO_x emissions of auxiliary engine PS any moment in time

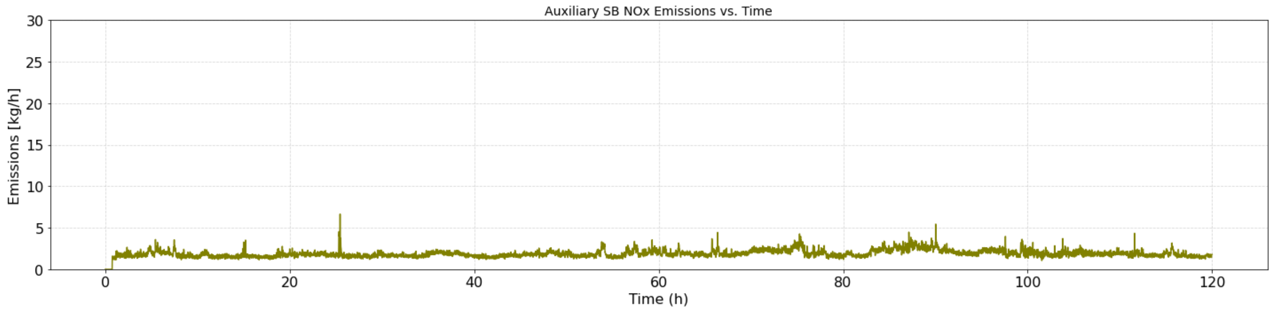

Figure B.8: NO_x emissions of auxiliary engine SB any moment in time