Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

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Modeling and Optimization of a Hybrid Electric Ship Power System

Master's thesis in Marine Technology
Supervisor: Mehdi Zadeh
June 2019

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Abstract

The maritime industry is responsible for approximately three percent of the global CO_2 emissions. The increased focus on environmental protection drives the initiative to pursue hybrid electric ships. The installation of batteries is an important step for the maritime industry towards a low-emission industry.

This master thesis aims at highlighting the advantages and potential challenges of hybrid electric propulsion for large marine vessels. As part of this thesis, thorough literature studies have been conducted in order to provide the necessary understanding of maritime batteries, hybrid electric power systems and its control systems. A simulation model of a hybrid electric propulsion system have been created, and the advantages highlighted in theory are tested through a case study analysis with real vessel operational data.

Electrical propulsion systems involve several advantages compared to conventional mechanical propulsion systems. The electrical propulsion system is more environmentally friendly, reliable and economically profitable. In addition to reducing vibration and noise levels, it may enhance operation and control in terms of maneuvering and positioning abilities. Furthermore, the electrical propulsion system also enables simple implementation of energy storage systems such as batteries. A battery may offer additional advantages such as peak shaving, load levelling, decrease harmful operation of engines, act as a spinning reserve and reduce the environmental impact. Current challenges related to maritime batteries are the high cost, low energy density, short lifetime expectancy and limited infrastructure.

In a power system with two or more energy sources it is essential to implement control systems in order to make use of the advantages that each energy source offer. Control systems can potentially have a substantial impact on a system's dynamic performance, its fuel consumption and the service life of the energy sources due to the energy sources' different capabilities and limitations. However, control systems are still novel in the maritime industry. This is mostly due to the high complexity of the propulsion systems. The complexity increases further when introducing energy storage systems, while the advantages of control systems becomes increasingly important.

A simulation model framework has been created with the intention of being used for analyzing novel power system performance, estimation of fuel consumption and emission, as well as for control system development. A case study conducted with this model indicates that the battery has ability to improve an engine's operation and reducing operational costs. However, the findings also highlight certain challenges, such as the trade-off between decreasing harmful engine operation and reducing fuel consumption.

Sammendrag

Den maritime industrien står for omtrentlig 3 prosent av de globale CO_2-utslippene. Det økte fokuset på miljøvern driver initiativet til å satse på hybrid elektriske fartøy. Installasjon av batterier er et viktig skritt for næringen mot et lavutslipps-samfunn.

Denne masteroppgaven tar sikte på å fremheve fordelene og potensielle utfordringer ved hybrid elektrisk fremdriftssystem for store marine fartøyer. Det er gjennomført grundige litteraturstudier for å gi den nødvendige innsikten og forståelsen av maritime batterier, hybrid elektriske systemer og dets kontrollsystem. En simuleringsmodell av et hybrid elektrisk fremdriftssystem er designet, og fordelene som er fremhevet i teoridelen, blir testet gjennom en case studie-analyse med virkelige operasjonsdata fra et fartøy.

Elektriske fremdriftssystemer innebærer flere forbedringer i forhold til det konvensjonelle mekaniske fremdriftssystemet. De viser seg å være mer økonomiske, miljøvennlige og pålitelige. I tillegg til å redusere vibrasjons- og støynivå, vil drift og kontroll forbedres når det gjelder manøvrering og posisjonering. Det elektriske fremdriftssystemet muliggjør også enkel implementering av energilagringssystemer som batterier. Et batteri kan tilby ytterligere fordeler som lastutjevning, redusere skadelig operasjon av motorer, fungere som balansekraft samt bedret miljøpåvirkning. Utfordringer knyttet til maritime batterier er høye investeringskostnader, lav energitetthet, begrenset forventet levetid og manglende infrastruktur.

Det er viktig for et system med to eller flere energikilder å kontrollere og optimalisere energiproduksjonen for å utnytte fordelene som hver kilde tilbyr. På grunn av ulike egenskaper og begrensninger, kan effektiv distribusjon ha stor innvirkning på systemets dynamiske ytelse, drivstofforbruk og levetid. Likevel er styringssystem fremdeles relative nytt i den maritime industrien. Dette skyldes det lave antall installerte enheter og de svært avanserte fremdriftssystemene. Kompleksiteten øker ytterligere når man innfører energilagringssystemer.

Et rammeverk som kan brukes til å analysere ytelse til nye fremdriftsssystem, estimering av drivstofforbruk og utslipp, samt for utvikling av kontrollsystem, er laget gjennom en simuleringsmodell. En case-studie utført med denne modellen indikerer at batteriet har evne til å forbedre driften av motorer, samt redusere driftskostnadene ved hjelp av midlene som ble identifisert i litteraturstudien. Funnene belyser imidlertid også visse utfordringer, for eksempel avveiingen mellom redusert skadelig motoroperasjon og redusert drivstofforbruk.

Preface

This master thesis has been carried out at the Department of Marine Technology at the Norwegian University of Science and Technology (NTNU). The thesis has been written in cooperation with Ulstein & Design AS and DNV GL. Associate Prof. Mehdi Zadeh has been the supervisor.

I would like to express my gratitude to Mehdi Zadeh for his guidance during the work on this thesis. It has been extensive work, and he has been a good discussion partner, and has followed up the work closely. I would also like to thank Daeseong Park for invaluable help on building the model used in the case study in this thesis. I am grateful for the time and effort he has spent to aid in the modeling process.

In addition, I want to thank Egil Rødskar from Ulstein Design & Solutions for providing data essential for performing the case study. I am also grateful for helpful input given from Sondre Henningsgard, Geir Dahler and Erlend Hanssen Nervold from DNV GL.

June 11, 2019

Eline Bugge Simonsen

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Abbreviations

ABS = American Bureau of Shipping
AC = Alternating Current
AVR = Automatic Voltage Regulator
BMS = Batter Management System
CAPEX = Capital expenditures
CO_2 = Carbon dioxide
CPL = Constant Power Load
DC = Direct Current
DNV GL = Det Norske Veritas and Germanischer Lloyd
DP = Dynamic positioning
ECA = Emission Control Areas
EMS = Energy management System
ESS = Energy Storage System
GHG = Greenhouse gas
GRG = Generalized Reduced Gradient
HFO = Heavy Fuel Oil
IGBT = Insulated-Gate Bipolar Transistor
IMO = International Maritime Organization
IPCC = United Nations Intergovernmental Panel on Climate Change
LCC = Life Cycle Cost
Li-ion = Lithium-ion
MCR = Maximum Continuous Rating
MDO = Marine Diesel Oil
MINLP = Mixed Integer Nonlinear Programming Model
NOK = Norwegian Krone
NOx = Nitrogen Oxide
OPEX = Operational Expenditures
OSV = Offshore Support Vessels
PID = Proportional-Integral–Derivative
PM = Particulate Matter
PMS = Power Management System
PSV = Platform Support Vessels
PWM = Pulse Width Modulation
SFOC = Specific fuel oil consumption

SLD = Single Line Diagram
SOC = State of charge
SOH = State of health
SOx = Sulphur Oxide
THD = Total Harmonic Distortion
USD = United States Dollar
VOYEX = Voyage related expenditures

Chapter 1

Introduction

1.1 Background and Motivation

The emission of greenhouse gases (GHG) from human activity is the main contributor to the observed temperature rise, states the IPCC (United Nations Intergovernmental Panel on Climate Change) in the third IMO GHG Study [1]. Despite the fact that shipping is considered as the most environmentally form of transport, being responsible for around 90 percent of the world trade, it constitutes a great source to GHGs [2], [3]. Between 2007 and 2014, maritime transport was on average responsible for 3.1 percent of the global CO_2 emissions [4]. This equals an average annual amount of a billion tons CO_2. The world transportation need is expected to increase drastically towards 2050. Forecasted scenarios presented in the third IMO GHG Study show that the emissions of CO_2 from international shipping may grow between 50% and 250%, depending on future economic growth and energy developments [1].

As we now see the emerging consequences of climate change, environmental protection receives increased attention globally. Although long in the shadow of the automotive industry, the environmental impacts contributed by the shipping industry are receiving increased attention. The international maritime organization (IMO) has set a target to reduce total emissions from shipping with 50% within 2050 [5]. The Norwegian government has set an even more ambitious target through the act relating to Norway's climate targets (Climate Change Act). The act states that the emissions of GHGs should be reduced by at least 40% by 2030 and 80-95% by 2050 compared to the levels of 1990 [6]. Domestic shipping accounts for 9 % of Norway's total CO_2 emissions, 34% of the NOx emissions and 25% of the SOx emissions. A study performed by DNV GL shows that without radical national measures, the emissions of CO_2 from Norwegian domestic shipping is expected to increase by almost 40% towards 2040 [2].

The urgent demand for sustainable and efficient energy sources drives the initiative to pursue hybrid electric ships. Batteries are identified by the Green Coastal Shipping Programme, a joint program between the Norwegian government and the industry, as one of the most important propellants that may render possible the targeted transition [7]. Battery-hybrid vessels show great potential in decreasing emissions due to reductions in fuel consumption. Batteries may also enable zero-emission operation in exposed areas.

There are additional motivational factors to utilize batteries on-board beyond the reduction in fuel consumption and the related GHGs. The battery may enable more rational loading of the connected prime movers such as diesel generators, which will reduce the need for maintenance. This is especially evident on ships with a fluctuating load demand, for example ships operating with dynamic positioning (DP). This is typically offshore supply vessels, warships and cruise ships. A battery may also help improve a system's dynamics, reliability and efficiency [8]. Furthermore, with IMO's requirement concerning low sulfur fuel, the cost of traditional fuel is expected to increase between 30 - 50 percent, making hybrid electric ships increasingly attractive for operators [9].

The effect of implementing batteries may however vary for different operations and vessel segments. As the maritime battery storage systems have a high initial cost, correct sizing and operation of these systems is therefore essential. The additional investment cost should be paid back with lower operational costs within a reasonable time. The design of hybrid electric machinery configurations are a complex and compound problem. System topology, sizing of components and control system are all important factors in the system design process [10].

1.2 Research Question and Objectives

The main research question to be answered in this master thesis is: *"What are the advantages and potential challenges of hybrid electric propulsion for large marine vessels?"*

This thesis extends the work from the specialization project written autumn 2018. The objective was then to build an understanding of different energy sources and storage systems, as well as the control systems for managing the power flow in hybrid electric vessels. The goal of this master thesis is to further develop the obtained knowledge, but with a main focus on maritime batteries as a mean for hybridization. A simulation model of a hybrid electric machinery system is created in order to test the obtained knowledge. In order to create such a model it is required to acquire an understanding of modeling, electrical systems and control mechanisms.

The main objectives of this master thesis are:

- Investigate the maritime battery through an extensive literature review. Enlighten its current status, its advantages and challenges and prospects for future development.
- Perform a simplified optimization process to determine an initial battery size.
- Create a simulation model of a hybrid electric machinery configuration.
- Conduct a comparative case study concerning the economic performance of a conventional machinery system versus a hybrid electric system with batteries.
- Discuss areas for further development in the created model.

1.3 Main Contribution

The main contribution to the field from this master thesis is three-folded.

- Provide insight and the understanding of maritime batteries, hybrid electric power systems and control systems necessary in order to create a simulation model of a hybrid electric propulsion system.
- Develop an optimization model for determining an initial battery size as input to the simulation model.
- Develop a simulation model framework that can be used for analyzing novel power system performance, estimation of fuel consumption and emission, as well as for control system development.

1.4 Thesis Outline

This remaining part of the thesis is divided into five chapters. A brief explanation of the content of each chapter is presented below.

Chapter 2 - Batteries in the Maritime Industry: introduces the maritime battery and its application onboard ships. An aim is to highlight the current status of the maritime battery, the advantages and challenges related to its implementation in a ship power system. Finally, the battery's prospects for future development and driving forces towards a battery revolution in the maritime industry is discussed.

Chapter 3 - Hybrid Electric Power Systems and Control Systems: presents the hybrid electric power system architecture. Gives an introduction to the typical prime mover in a ship power system, relevant power converters and compares the DC - and AC power system architectures. The onboard control system hierarchy is addressed where the function and purpose of the energy management system, power management system, the battery management system and the low level control system are described.

Chapter 4 - Modeling and Simulation of a Hybrid Electric Machinery: describes the designed simulation model of a hybrid electric machinery. First an overview of the system and its characteristics are given. The chapter then addresses the designed control system algorithm and the modeling of mechanical and electrical subsystems.

Chapter 5 - Case Study: presents the case study conducted for the platform supply vessel 'Blue Queen' with a main focus on economic performance.

Chapter 6 - Conclusion and Further Work: contains the concluding remarks of this master thesis. Finally, proposals for further work in relation to the topic is presented.

Chapter 2

Batteries in the Maritime Industry

This chapter investigates the maritime battery. A focus is to obtain an understanding of the maritime battery, highlight the advantages and challenges it imposes onboard ships as well as shore infrastructure. In addition, a discussion on the driving forces towards a battery revolution like the one visualized in the automotive industry in included. Parts of this chapter is taken from or based on my project thesis written autumn 2018 [11].

2.1 Maritime Batteries

This section presents the battery manner of operation and common terminology used this thesis. Then, a presentation of possible battery configurations onboard vessels are given, followed by an introduction to design and chemistry of maritime batteries and maritime regulations related to onboard batteries.

2.1.1 Manner of Operation

A battery is an energy storage system (ESS), and consist of one or more electrochemical cells that can generate electrical energy from chemical reactions. During charging of a battery, positively charged ions are forced through a separator from the positive electrode (cathode) to the negative electrode (anode). This creates an electric potential. This potential can be released as electric power by connecting a load between the two electrodes. The charge - and discharge mechanism is demonstrated in Figure 2.1 below. The battery provides the user with an operational flexibility by being able to store the electric power when it is in excess, and utilize it at a more beneficial time [9].

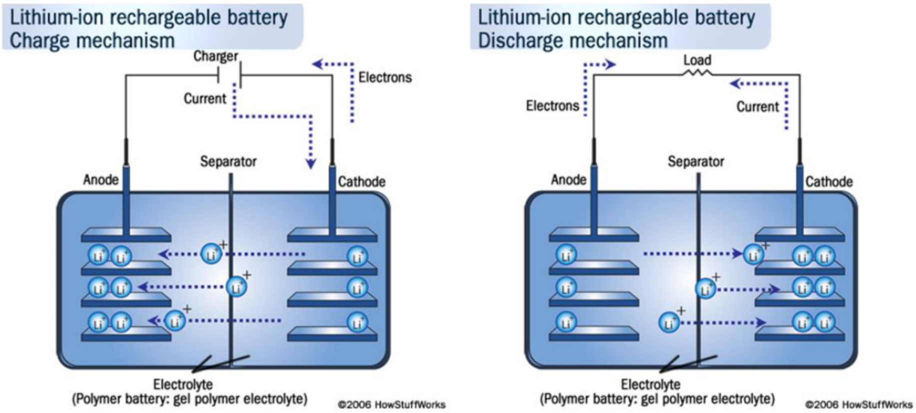


Figure 2.1: Battery charge - and discharge mechanism retrieved from [9].

2.1.2 Battery Terminology

Some terminology used to describe, compare and classify batteries are listed below [12].

Battery Terminology	
Cell	The cell is an electrochemical unit and the smallest constituent in the battery.
Module	A module consist of several battery cells that are connected in either parallel or series.

Battery pack	A battery pack is assembled in either series or parallel by several modules.
Cycle	A cycle is defined as a battery going from fully discharged, to fully charged, and then fully discharged again. Operating the battery in this manner will degrade the battery more quickly, and it is therefore usually operated in partial cycles. The partial cycles are often summed to correlate full cycles.
Cycle Life	The cycle life is the number of full cycles a battery can perform before its capacity is reduced to such extents that it is no longer able to meet specific performance requirements.
Available Energy	A battery is typically neither discharged completely, nor fully charged. The range relative to the full electochemical energy in which the battery is cycled is referred to as the battery's available energy.
State of Charge (SOC)	The state of charge expresses the present energy available for use in the battery system. The unit are percentage points, where 0% represents an empty battery, and 100% equals a fully charged battery.
Depth of Discharge (DOD)	The depth of discharge is the percentage of the battery capacity being discharged during a given partial cycle.
State of Health (SOH)	A battery's state of health reflects the ability to accumulate ions at the negative electrode, i.e. is ability to perform compared to a new battery. This ability will inevitably decline with repeated cycling.
Energy Density	The energy density is the amount of energy stored per unit volume (Wh/L). It may also referred to as the volumetric energy density.
Specific Energy	A battery's specific energy is a term that describes the energy amount per unit mass (Wh/kg). It may also be referred to as the gravimetric energy density.
Power Density	The power density is the amount of power per unit volume (W/L). It is a measure of how quickly a battery can deliver energy.
Specific Power	The specific power expresses the maximum available power in a battery per unit mass (W/kg).

C-rate	A measure of the rate in which a battery charge and discharge. It is defined as the current or power through the battery relative to the capacity.
Battery Management System (BMS)	The battery management system is the electronic control system which provide monitoring and protective functions to the battery.
Thermal Runaway	Thermal runaway occurs when an increase in temperature due to a fire or combustion causes further increase in temperature. It is also referred to as an exothermic reaction or self-heating.
Internal Resistance	The resistance within the battery. The resistance is usually different for charging and discharging and is dependent on the battery's state of charge. With higher internal resistance both thermal stability and the battery's efficiency decreases as a result of more of the charging energy is converted to heat.

Table 2.1: Relevant Battery Terminology

2.1.3 Battery Configuration Onboard Ships

There are several possible configurations of batteries onboard ships. The presently most common practice is the hybrid configuration as Figure 2.2 demonstrates. With a hybrid set-up the power may be delivered by a battery and/or from one or more other energy sources. After supplying power, the batteries will be charged from the other onboard power generating devices, such as diesel engines.

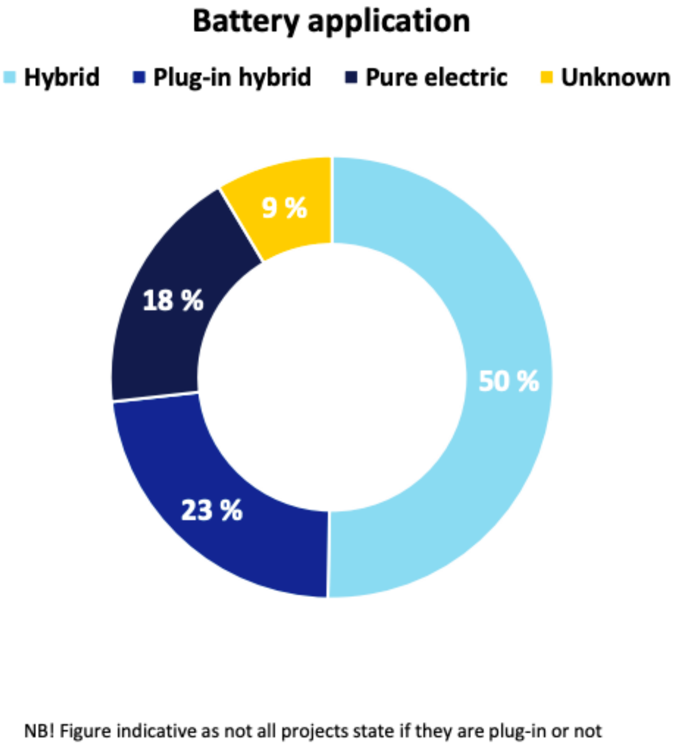


Figure 2.2: Possible battery configurations onboard ships. Graph taken from [13].

When all power stems from the battery, the vessel is called a pure-electric ship. In this configuration the batteries are charged in harbor from shore facilities through a shore-to-ship power connection. A related challenge is that the battery capacity may limit the vessel's range capability. This is the reason why vessels that are purely battery-powered today typically operate on shorter distances. A third battery configuration is the plug-in hybrid. This enables battery charging both from the other onboard power generating devices and from shore power.

Ship operation and maneuvering in harbors produces substantial pollution locally. Supplying electric shore energy to the ships while in harbor allows the vessels to turn off power generating devices, so called cold ironing. This manner of supplying power will eliminate the local emission of greenhouse gases and other harmful pollutants. Because of this, there has been an increased interest in utilizing shore power for ships in harbor.

Klimakur 2020 is an agency group established by the Norwegian Ministry of the Environment to investigate means for reducing greenhouse gas emissions. They estimate that utilizing shore power may reduce the emission of CO_2 by 198 000 tons each year within 2030. This is seen in light with a study performed by the British scientist William Hall shows that Norway is the most favourable county to produce shore power of those investigated. He estimates that the emissions form ships operating in Norway could be reduced with as much as 99.5%. His findings are presented in Table 2.2. It is also worth mentioning that utilizing shore power is not a guarantee for reducing emissions, as is the case for China. This reflects on how the electricity is produced [14].

Country	**G CO_2/kWhe (national electricity grid)**	**CO_2-emission (%)**
China	992	38.2
Japan	461	-35.2
USA	651	-9.4
Great Britain	543	-24.5
Italy	523	-27.3
South Korea	507	-29.5
Singapore	598	-16.8
Spain	447	-37.8
The Netherlands	612	-14.9
Norway	3	-99.5
Indonesia	917	27.6
Germany	612	-14.9

Table 2.2: Overview over the CO_2 effect of shore power. From [14]

2.1.4 Battery Design and Chemistry - Current Status and Future Prospects

Batteries for marine applications are mainly made of Lithium-ion (Li-ion) cells. This is due to the fact that these batteries in general have a longer lifetime expectancy and higher specific energy and -power compared to other battery configurations. Li-ion batteries can store up to two till eight times more energy per unit of weight than traditional batteries such as nickel cadmium and lead acid batteries with water based electrolytes [9]. The relation between specific power and specific energy is demonstrated in Figure 2.3. The figure also illustrate the trade-off between specific energy and specific power.

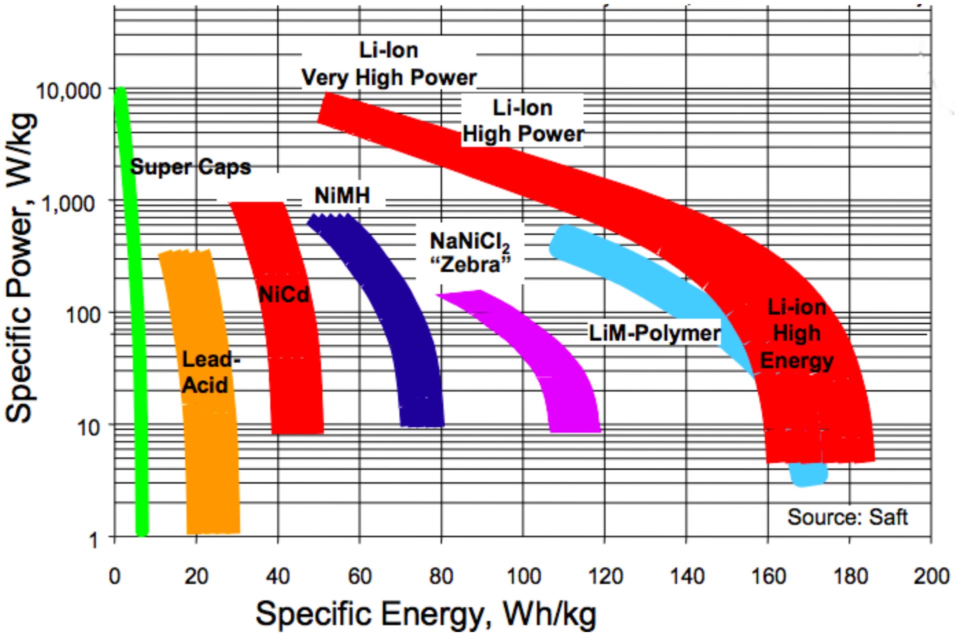


Figure 2.3: Specific energy- and power for different battery chemistries. Retrieved from [15].

There exist a wide range of Li-ion battery chemistries. The most defining feature of a battery's characteristics is the chemical composition of the cathode, i.e. the positive electrode. The battery's performance, longevity, cost and safety are highly dependent on the cathode composition. The names of the different battery technologies are for this reason often named after the cathode. Other important aspects are the porosity and thickness of the active material coating in the electrode, the anode composition, the electrolyte, the separator as well as the cell construction. Moreover, the the quality of the components and the manufacturing process may also affect the battery's performance [9].

Nickel manganese cobalt oxide (NMC) is the most widespread Li-ion cell chemistry used in maritime batteries as demonstrated in Figure 2.4. The reason for this is the high specific energy due to constituents of nickel and cobalt. Manganese contribute to stabilize the battery. However, its properties, cost and safety may be changed by altering the composition [9].

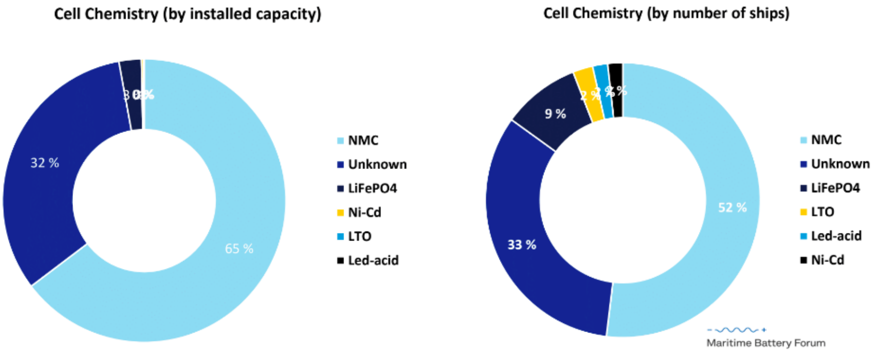


Figure 2.4: Percentual overview over installed cell chemistry on ships, from [13]

The battery design and chemistry are continuously under development where the main drivers are consumer electronics, the automotive industry and stationary systems. The focus of Li-ion research is to increase the energy density while minimizing the cost. The EMSA study on Electricity Storage on Ships recognizes two technologies as the successors of the current market leader, the NMC chemistry. The solid state electrolyte technology has come furthest in development, and is predicted to be in use by 2030. In a more long term perspective, the report points to metal-air batteries as the preferred chemistry. This technology is expected to enter the market from 2050. The design of three technologies are demonstrated in Figure 2.5, 2.6 and 2.7. Table 2.3 summarizes the findings from the EMSA study.

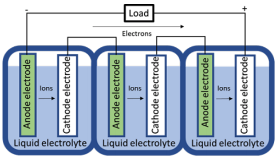


Figure 2.5: Nickel manganese cobalt oxide, from [16].

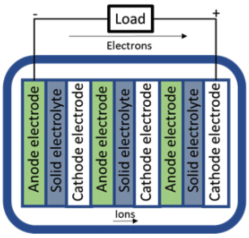


Figure 2.6: Solid state electrolyte, from [16].

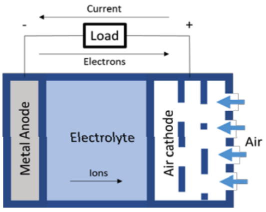


Figure 2.7: Metal-air batteries, from [16].

Battery technology	**Specific energy [Wh/kg]**	**Advantages**	**Disadvantages**
Nickel manganese cobalt oxide (NMC)	150 - 220	Power and energy density are adjustable according to the mission. Low relative cost and the safety is high.	Trade-off between power and energy density. Difficult to ensure equilibrium for key properties for stable life span.
Solid state electrolyte	200 - 400	Non-flammable and no dendrite formation increasing the safety. Higher energy density and specific energy.	Short lifetime and high production cost. Low conductivity and high interface resistance. Not good in low temperatures.
Metal-air battery	3500 (Li-air)	Potential for extremely high specific energy.	Currently no suitable electrolyte that ensures performance and safety is found. The cathode is vulnerable for CO_2 and moisture in the air.

Table 2.3: Summary and comparison of current and future battery technologies, from [16]

2.1.5 Maritime Regulations

The maritime industry is bound by standards, rules and regulations concerning all aspects from shipbuilding to safety to emission. These are imposed by different industry actors and may come in the form of classification rules, flag state regulations and industry guidelines. In order to comply with these, the complexity of the power system design process is increased. This subchapter will mainly address the regulation framework related to the implementation of maritime batteries onboard ships. However, the scope of this master thesis is not to cover all existing regulations, but is intended to give an introduction and overview of relevant regulatory framework.

A maritime battery is typically of a different dimension than the batteries used for electrical vehicles. This includes an extremely high energy content which, if not operated properly, may pose a safety threat to the battery itself, but also to property, the environment and human lives. This illustrates the necessity for regulations.

DNV GL were early to develop rules and standards regarding the use of batteries in the maritime industry with the first function based rules in 2012. Since this they have released updated versions, and also other actors such as ABS have released rules and regulations for batteries. A stated goal is that battery selection, integration and management should be performed in such manner that the risks are at least equally low as with a conventional machinery configuration [17].

DNV GL's relevant rules are found in part 6 “Additional class notations”, chapter 2 “Propulsion, power generation and auxiliary systems”. In addition, there are also rules related to the approval of Lithium batteries. Some relevant regulations for this master thesis are taken from the mentioned section, and are listed below [18].

3.2.2.2 When battery systems are used as redundant power sources for dynamic positioning, the capacity (available power and available energy) of the battery systems shall be sufficient for the planned operation.

3.2.2.3 The SOC and SOH of the battery systems shall be monitored and available for the operator.

3.2.3.1 Energy Management System (EMS) shall be installed.

3.2.3.2 For battery systems providing power to main and/or redundant propulsion or dynamic positioning, the energy management system shall provide a reliable measure of the available energy and power, taking into consideration the batteries SOH and SOC.

3.2.3.3 The EMS system shall be designed in such a way that the battery temperatures are kept within specified limits. This shall be done by limiting the:

- maximum charge and discharge current rates (C-rates).
- maximum and minimum battery voltages, i.e. over charging and excessive discharge.

4.1.2.2 The battery system shall have an integrated Battery Management System (BMS).

4.1.2.3 The battery charging equipment shall interface with and operate within the limits given by the BMS.

2.2 Incentives for Utilizing Batteries on Ships

Implementing batteries in ship propulsion systems offers numerous advantages. In a hybrid power system, the battery may smooth the engine load, so called load levelling. This is achieved by charging the battery during low power demand, and discharging when the demand exceeds the power generated by the engine as illustrated in Figure 2.8. This may reduce the wear and tear on the engine, which is increased during non-optimal operation and due to rapid fluctuations in generated power. Load leveling may also contribute to reduce the fuel consumption by operating the engine at its optimal point where the specific fuel oil consumption is minimized. Batteries can provide high power at a high response rate which makes them a good fit also for peak shaving. When used for this, the battery provide power for the load peaks. Through this the battery spare the engine from overloading with the potential of blackouts.

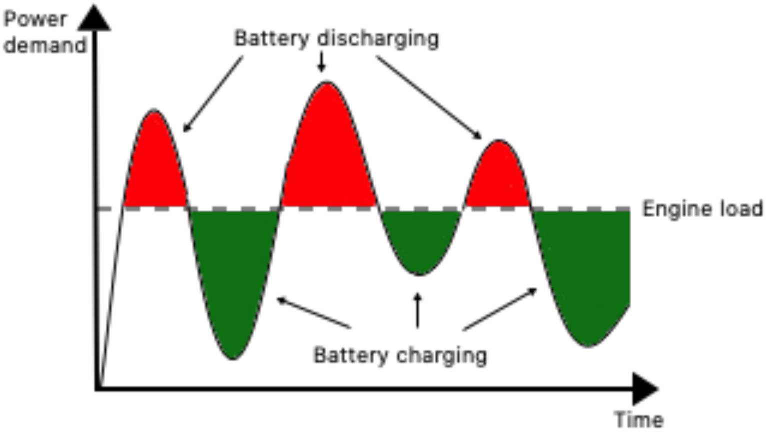


Figure 2.8: Illustration of load levelling. Battery discharging in red areas, and charging in green areas allows the generator to operate steadily at its optimal load (dotted line).

The maritime industry is a large contributor to the emission of greenhouse gases. A motivational factor to utilize batteries in ships is to reduce emissions such as CO_2, SOx, NOx and particulate matter (PM). An engine's specific fuel oil consumption (SFOC [g/kWh]) vary greatly with the percentual loading, and it is desirable to operate them at the point where SFOC is minimized. A battery may as described above enable optimal operation of the engines, which involves a large fuel saving potential. Moreover, in exposed areas, one may run the vessel solely on power from batteries, which will remove the local pollution completely.

During certain operations, maritime regulations demands that there is enough power available to cover the load demand during temporarily power loss, transients or sudden load increases. In a conventional machinery configuration this is typically solved by running a back-up generator, so called spinning reserve, at low non-optimal load as a generator is not able to start up quickly enough to provide the power necessary. Operating at these load levels can be damaging for the engines and will involve a maintenance increment. A battery with its high power density however, will deliver power much quicker and without any fuel consumption penalties. Thus, implementing a battery may increase the efficiency, reliability and robustness of a ship propulsion system. Ship types that may take especially advantage of battery hybridization will typically have a highly dynamic load profile, high redundancy requirements and low utilization of the engines in certain parts of operation [9].

Fuel cost constitutes a large percentage of a ship's total costs. It is therefore desirable for operators to decrease the fuel consumption. Moreover, with the increased focus on the climate comes stricter regulations intended to encourage to more environmentally friendly solutions. One example of this is the global sulphur cap that limits fuels to contain a maximum of 0.5% sulphur, which come into force from 2020. It is expected that this will lead to a 30 - 50 % rise in fuel cost, making battery powered ships increasingly attractive [9], [19].

The maritime industry in Norway is large, and it is one of the few industries that is considered to be large also according to international standards. As a result, Norway has the potential of, and seeks to be, in the forefront of effective and environmentally friendly shipping. A stated governmental goal is to facilitate for technological development, making the technology available and feasible for other actors in the industry. One mean to achieve this goal is the establishment of the NOx-fund. When operating at the Norwegian continental shelf, enterprises is taxed in accordance to the produced quantity of NOx emission. The enterprises may in return apply to the fund for financial support for NOx reducing measures. Furthermore, the Norwegian Parliament has adopted a resolution to implement requirements for zero emissions from tourist ships and ferries in world heritage fjords as soon as it is technically feasible, and no later than 2026. The aim is to make these fjords the world's first zero emission zone at sea [20]. The graph in Figure 2.9 may certainly indicate that the implementation of regulations and the facilitation for environmentally friendly solutions has an effect. The graph shows area of operation for vessels with batteries installed, whereupon more than 42% of these operate in Norway.

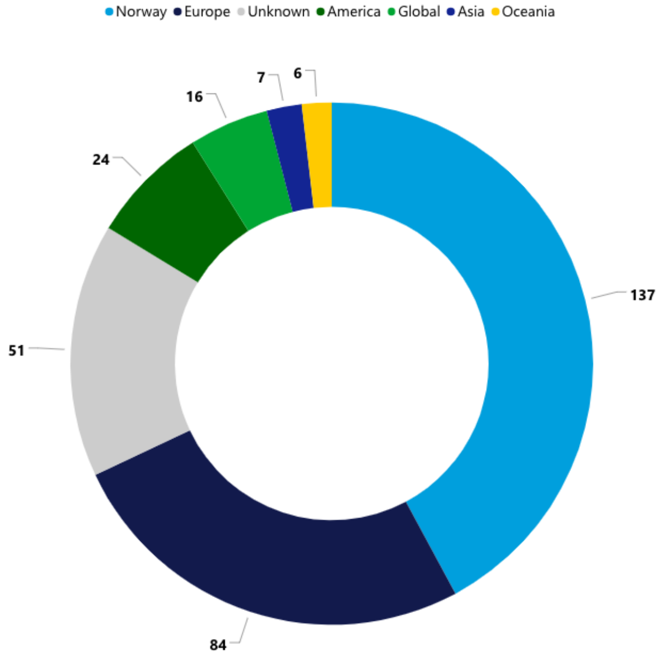


Figure 2.9: Area of operation for ships with batteries installed, from [21].

2.3 Challenges Related to Maritime Batteries

2.3.1 Battery System Cost

Battery systems for maritime use have traditionally been highly expensive. Cost drivers are maritime regulations and requirements which are stricter than for electric vehicles and consumer electronics. Higher demand to safety and more stringent requirements related to the battery performance contribute to raise the prices. Examples of decisive factors are enhanced capacity demand related to both lifetime and to energy density, as well as increased system complexity. Moreover, the economies of scale will neither have the same effect as in other industries as systems for ships are often customized and not produced in large quantities.

As manufacturing volume is increasing, the cost of battery systems is decreasing rapidly. This development is expected to sustain as the battery technology is entering new markets in the maritime industry. Market forecasts concerning the cost development are continuously surpassed as seen from Figure 2.10. However, the cost of maritime batteries vary greatly, and is dependent of chemistry, energy and power density, battery cycling, producer etc.

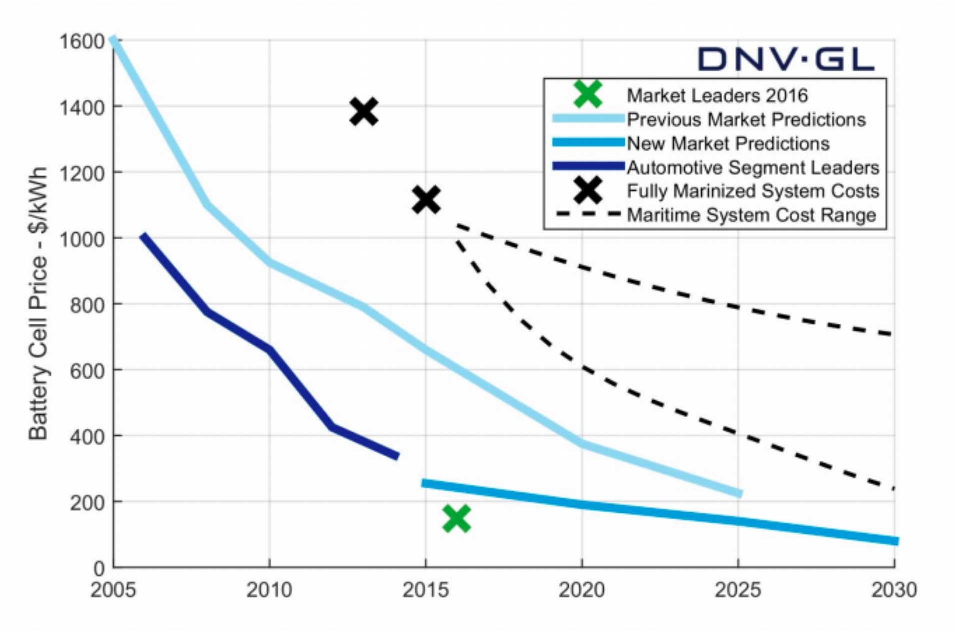


Figure 2.10: Predicted and actual costs of Li-ion batteries, [22]

2.3.2 Low Specific Energy and Energy Density

Another main challenge with utilizing batteries onboard ships is the low specific energy and energy density. This implies that batteries become both large and heavy when increasing their range capability. This restricts purely-battery driven ships to operate at shorter distances. Examples of short-distance vessels are passenger and car ferries. This is also the ship segment where there are most vessels with batteries onboard as shown in Figure 2.11.

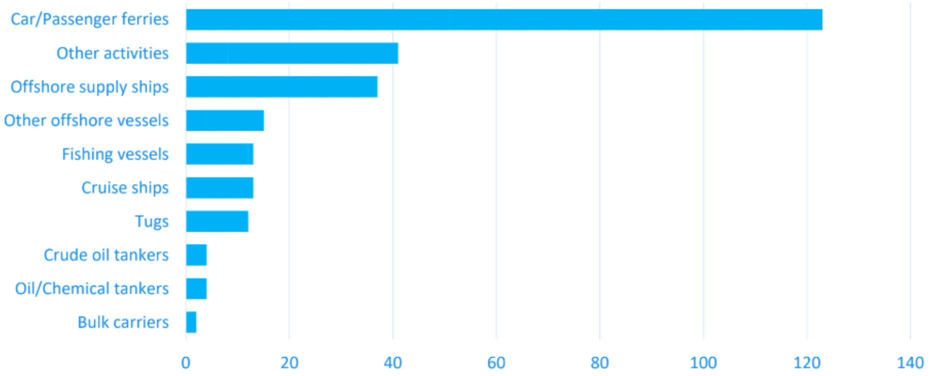


Figure 2.11: Number of ships with batteries installed by ship segment, from [13]

In a hybrid configuration, batteries may be used for other purposes than propulsion alone. An example of vessels that will benefit from a battery is offshore supply vessels, which may use the batteries for enhancing performance for the segment specific tasks. For this reason, batteries are also commonly seen onboard these types of vessels as seen from Figure 2.11.

Over the last couple of years there has been focused on enhancing the specific energy and energy density, which has led to continuous improvements. An additional, positive side effect of this is the reduction in battery cost per kWh.

2.3.3 Battery Degradation and Short Lifetime Expectations

A fully charged battery will have most of the circulating ions at the negative electrode - the anode. A battery's State of Health (SOH) reflects the ability to accumulate the ions at the anode. A battery's SOH will inevitably decline with repeated cycling and ageing effects in general, which result in a reduction in the battery capacity. Also the manner in which the battery is cycled may have a large impact on battery degradation. Moreover, the battery will also experience an increase in internal resistance. With higher internal resistance both the thermal stability and the battery's efficiency is decreased as more of the charging energy is converted into heat. A battery is typically operated between five to fifteen years as a result of loss of capacity and efficiency the battery must be replaced. The short lifetime expectancy is another reason why batteries have not yet been utilized on a larger scale in maritime applications [9].

2.3.4 Limited Infrastructure

In Section 2.1.3, the advantages of utilizing shore power for charging batteries during the stay in harbor, were highlighted. A related challenge is that plug-in charging set requirements to the shore infrastructure which has a high investment cost. Due to this, plug-in charging has up until recently mostly been relevant for vessel segments such as passenger and car ferries traversing fixed routes. This is however changing, and today, several of the bigger ports in Norway have installed charging facilities for ships, and more are to come [23].

When several ships acquire power supply from the shore power grid at the same time, certain challenges may arise. The electrical systems onboard vessels can be vulnerable to variations in voltage, and is therefore dependent on the shore infrastructure to deliver stable power. There are however few standards regarding onboard frequency. Typically frequencies will vary between 50 and 60 Hz, which may cause difficulties when several ships are supplied power from the same shore power grid simultaneously. Another challenge is related to the local shore power grid as a high amount of power is taken out during a short time window [24].

2.3.5 Complex Systems and Inefficient Operation

When implementing a battery into a machinery configuration, the system complexity increases. An example is the need for power electronics for controlling and converting electrical energy. One challenge related to this is that when errors occurs, it may be more difficult to detect its source.

The system complexity also makes the design process more difficult. A problem when designing onbaord machinery systems today is the lack of operational data. Consequently, the machinery configuration will often be optimized around one operational point or one specific load-profile time-series. The upfront estimations of the operational savings may as a consequence be incorrect. In fact, non-optimal power management may result in only minor fuel reduction or even increased fuel consumption due to losses in power conversion and energy storage.

Research performed by Sintef Energy enlightens challenges related to energy management. Results of time-domain simulation showed that by operating the generators solely at their optimum point, and making the battery provide the remaining loads, or absorb the excess during low demand, gave low fuel saving and a high number of battery cycles which accelerate the battery degradation. By optimizing the power split through energy management strategies, both the fuel consumption and battery cycling would decrease. Also the losses in energy storage were investigated where the outcome showed that there is a potentially large difference between the fuel saving potential and actual saving. This is demonstrated in Figure 2.12 [25].

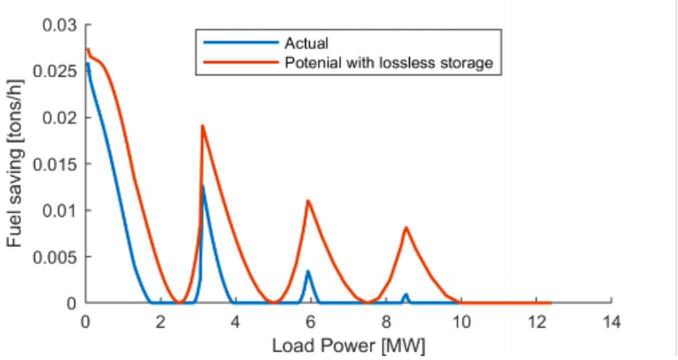


Figure 2.12: Fuel saving potential and actual savings, from [25]

2.4 Current Status of Battery Powered Ships

Both the technology and infrastructure related to electric power generation has come far in certain industries - the automotive industry in particular. The maritime industry on the other hand, has not succeeded to follow this pace. The first commercial operation of a fully electric powered car- and passenger ferry was Ampere in 2015. Since then, the maritime battery has improved substantially, and the technology is viewed as one of the most transforming developments within the maritime industry. This has led to an increase in interest towards utilizing batteries on-board ships, which is visualized in Figure 2.13. The graph shows the number of ships with batteries in operation and currently under construction. The predicted numbers from 2019 and onward are subject to change as these are only the ships presently announced, hence more ships are likely to be ordered with time.

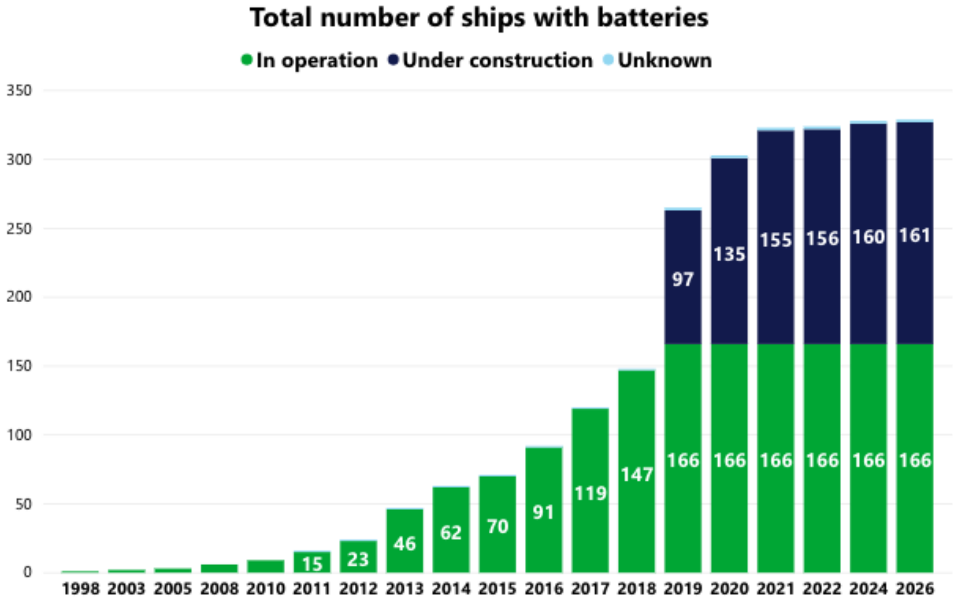


Figure 2.13: Number of ships with batteries, from [13].

2.5 Driving Forces Towards a Battery Revolution

The battery revolution that is taking place within the automotive industry has not yet reached the maritime industry. Despite a solid increase in vessels with batteries, they still represent a small minority, even within newbuilds. Three important prerequisites are identified as driving forces for the type of changes that are visualizing in the car industry:

1. Changes in regulations
2. Changes in consumer behavior
3. Technology development

Regulations from government concerning emissions have been an important driving force for the car industry to pursue electric cars. In certain countries, the government has further stimulated this process by providing the consumers with incentives to purchase electric cars, for example through the exemption from dues. This was inducted in Norway, and today more than half of all new cars are either electric or hybrid [26]. Shipping is a global industry, and it is more difficult for one country alone to induct equivalent special fees. The industry is consequently dependent on developing global regulations. The process of constructing new and binding rules are to a great extent driven by the IMO. However, it has proven to be difficult to establish common rules that are complied by all actors in the industry. Many countries act out of self-interest rather than focusing on the big picture. As a result, the common ambition level is set low, and the processes promoting environmental measures become time consuming. Moreover, the compound composition and high number of actors in the shipping industry - ship owners, design companies, shipyards to mention some - further emphasize the importance of global regulations.

Demands from the consumers are the second motive that drive change and innovation. When consumer behavior changes, producers are forced to adapt their products and production methods accordingly. Up until now consumers have to a lesser extent been engaged in emission from the shipping industry. This can be seen in context with the fact that there is no direct relationship between them and the transporter of the goods. Primarily, consumers have been interested in low prices, which does not stimulate to environmentally friendly solutions.

The third motivational factor for obtaining climate friendly solutions is connected to technology development. When environmental alternatives become equally good or better than conventional solutions with respect to both performance and price, actors will start investing in these solutions. The automotive industry is a good example where battery technology is becoming increasingly competitive compared to combustion engines. Despite substantial improvements in technology related to electric conveyance, such as prolonged battery cycle life, electric propulsion is still not a viable option for the long-haul ocean-going vessels. Regularly docking for charging is not an option as the infrastructure is not in place, nor is this an economically beneficial solution.

It is evident that the slow adoption of batteries and more environmentally friendly solutions in general has a compound explanation. The three mentioned points can be seen as main drivers, but one equally important aspect that interrelate with all three is culture. There is a need to change from compliance to a more proactive approach in the maritime industry. This means to not wait for international regulations to come into force or for others to reinvent the technology. In order for the shipping industry to join in on the battery revolution, the actors need to continuously seek to find areas to improve on. This applies for all aspects in the supply chain, from technology development to vessel operation.

Norway is a nation with long tradition within the maritime industry, and has for many years played a leading role in IMO's climate work. The country is currently taking the lead towards environmental development. Internally, the goal is to create the world's most effective and environmentally friendly fleet of coastal vessels, and show the world that it is possible to operate environmentally friendly and still make a profit. Norway's Minister for Climate and Environment, Ola Elvestuen also confirms this with his quote:

> "Zero emission shipping is possible, and Norway has started the introduction of zero emission technologies in parts of domestic shipping. I encourage development of national spearhead policies for the introduction of low- and zero emission technologies all around the world" [27].

The results of this policy are already showing as visualized in Figure 2.9 which shows that more than 40% of the vessels with batteries are operated in Norway. Within 2021, Norway will have 63 electric ferries on the waters. The same transition that has visualized within the ferry industry are now starting to show in other maritime segments; supply vessels, fishing boats, yachts and others are now being electrified with battery technology [28], [29].

Chapter 3

Hybrid Electric Power Systems and Control Systems

This chapter presents the hybrid electric power system architecture. First, an introduction to the typical prime mover in a ship power system is given. Secondary, the DC - and AC power system architectures are compared up against each other, before relevant power converters are introduced. Furthermore, the on-board control system hierarchy is addressed where the function and purpose of the energy management system, power management system and the battery management system is presented. Finally, the low level control system is described. Parts of this chapter is taken from, or based on my project thesis [11].

3.1 Hybrid Electric Power System Architecture

Electric propulsion systems utilize electrical power to drive propellers for propulsion, hotel and auxiliary loads. It offers several advantages compared to the conventional mechanical propulsion system. This is especially evident for ships which are subject to specific requirements, where it may enhance operation and control in terms of maneuvering and positioning abilities. The electric propulsion system have also proven to be more economic, environmentally friendly and reliable. Additional advantages are lower vibration and noise levels. The system is more compact and flexible in installation, and thus releases more space for payload.

A hybrid electric power system uses two or more energy sources or storage units to power a vessel's propulsion and other loads. In general, the system will consist of one primary source, a so called prime mover, which determines the vessel's range capability, and at least one secondary source. The secondary source usually complements the primary source, and with this improve the power system's performance in some way. The battery is an example of a typical secondary source. Its advantages as a secondary source is widely elaborated in section 2.2, and will therefore not be addressed any further in this section.

3.1.1 Prime Mover

The prime mover converts energy from an energy source, fuel as an example, into motive power. In marine propulsion systems, one of the most common primary power sources is the diesel engine running on heavy fuel oil (HFO) or marine diesel oil (MDO). Diesel engines are popular due to their robustness, fuel economy and simplicity. The power generated by the prime mover can either be directly applied to the propulsion unit through a driveshaft, or indirectly by supplying the mechanical power to an electric generator which generate electrical energy. The latter device is known as a diesel generator or genset.

A measure of efficiency is the specific fuel oil consumption (SFOC). The SFOC indicates how efficiently the prime mover converts chemical energy in form of fuel into mechanical energy, and is defined as the mass of fuel consumed to produce power per unit time. The SFOC is highly load dependent as demonstrated in Figure 3.1, and it is desirable to operate the engine as close to the minimum as possible in order to reduce fuel consumption and consequently the operational costs and the environmental impact.

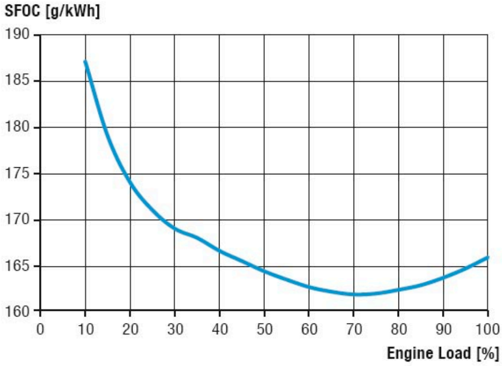


Figure 3.1: Typical SFOC curve. Retrieved from [30].

3.1.2 AC Versus DC Grid System

There is a growing trend to utilize DC grid systems rather than the traditional AC distribution systems onboard ships. One driving force for this transition is the emerging use of renewable energy sources and storage systems with DC output, such as batteries, fuel cells and supercapacitors. These devices all have DC outputs, and the integration will consequently be simplified with a DC grid.

The AC power system require synchronization of generation units. This means that the rotation of the shaft is synchronized with the frequency of the supplied current, which can be challenging to accomplish, involve energy loss and a high SFOC. DC power systems do not require this, and prime movers may consequently run at their optimal operational point with lower fuel consumption as demonstrated in Figure 3.2 [31].

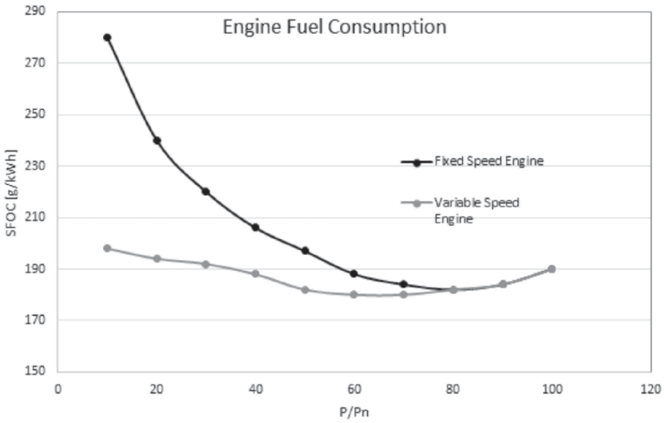


Figure 3.2: Difference in SFOC for variable and fixed speed engines. From [32].

Single line diagrams (SLD) for both AC and DC shipboard power systems are illustrated in Figures 3.3 and 3.4. Both systems have four gensets, an energy storage and the necessary power converters and transformers. As can be seen, the DC power system eliminates the need for multiple conversion- and transformation stages. This is advantageous as these converters and transformers not only represent an extra expenditure, but they also involve a power loss. Moreover, by removing the switch gears and transformers, the system weight is reduced which will have a positive effect on the fuel consumption. The DC grid system provides additional benefits such as flexible arrangement which gives more space for payload. Thus, the DC grid system will increase the overall efficiency, reduce fuel related costs and potentially increase income [33].

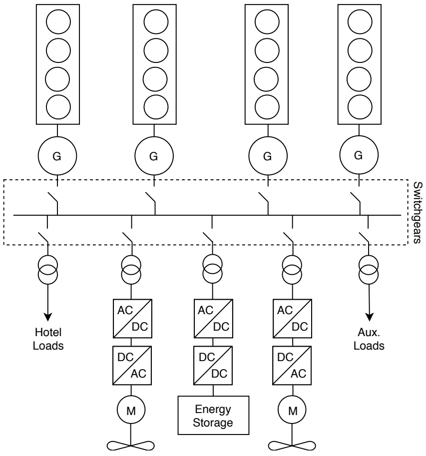


Figure 3.3: Single line diagram: AC power system.

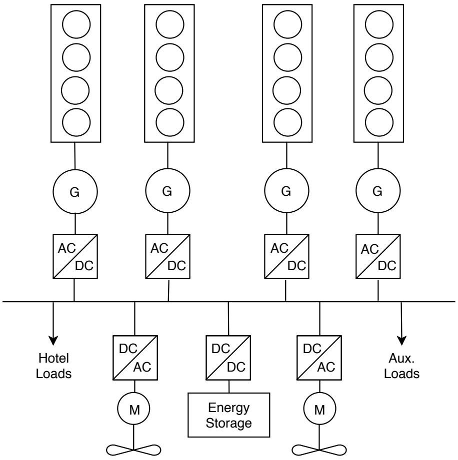


Figure 3.4: Single line diagram: DC power system.

A challenge related to DC distribution is to obtain full selectivity and equipment protection through breaking of currents. This is naturally simpler for AC currents as they cross zero twice each cycle. Even though DC circuit breakers exist, they are more complex, have a higher cost and take up more space compared to the equivalent for AC current [24], [34].

Another challenge is the lack of a standard DC power distribution system. The class societies have been slow to attribute DC distribution with a standard solution, and manufacturers are consequently using different technology and approaches [32].

3.1.3 Power Converters

DC/DC Converter

A DC/DC converter is an electromechanical device or electronic circuit that converts the voltage level of a direct current (DC) source to another voltage level. The output voltage may both be higher and lower than that of the input voltage. A battery will typically have a lower voltage level than the DC bus. The DC/DC converter may therefore be used for altering the voltage level provided by the battery before it enters the DC link and vice versa when charging [35]. There are three types of DC/DC coverters:

- Buck converter: converts high input voltage to lower output voltage.

- Boost converter: functions opposite to the buck converter, and will output a higher voltage level than that of the input.

- Buck boost converter: combines the capabilities of a buck and a boost converter, and may either step up or step down the input voltage level.

Rectifier
A rectifier is an electrical device composed of one or more diodes that converts alternating current (AC) to direct current. This imply converting a periodically reversing current to a current that flows uninterrupted in only one direction [36].

Inverter
An inverter performs the inverse process of a rectifier as described above. This device converts direct current generated by a DC source to alternating current of varying frequency. Depending on the circuit design, the inverter can produce different wave types such as square waves, modified sine waves or pulse width modulated waves [37].

3.2 Control Systems for Hybrid Power and Propulsion Systems

It is essential for a system with two or more energy sources to manage and optimize the distribution of power in order to exploit the advantages that each source and storage system offer. Due to the different capabilities, efficient distribution could have tremendous impact on a system's dynamic performance, its fuel consumption and the service life of the power sources and storage devices [38].

The main objectives of the control system is to regulate the DC bus voltage, maintain the energy storage's SOC and voltage within its safe boundaries, provide proper system dynamic during fluctuating loads and voltage, and to ensure the general stability of the hybrid system [39].

The electric hybrid system control algorithm can be divided into two levels; high level - and low level control. The high level control system determines the energy and power to be delivered from each energy source, and maintains the safety of the system. The high level consist of an energy management system (EMS), a power management system (PMS) and a battery management system (BMS) when a battery pack is installed. The lower level control system is responsible for the physical power split control in the power plant. It directs the energy source specific references to appropriate control switching functions. The interaction between the different control systems facilitates optimizing of the vessel performance. This includes higher control functionality with respect to operational availability, safety, cost effectiveness and flexibility for complex marine operations [40].

3.2.1 Energy Management System

The energy management system (EMS) is the superior control level within the high level control algorithm. Through a series of processes it monitors and has the overall control of the power generating assets and the energy flow in a power plant. Through interfacing with the lower level control systems, it determines the reference voltages and SOC that ensures reliable operation. These references are then communicated to the power management system for further distribution. The EMS seeks to optimize operation by increasing energy efficiency and reducing energy waste [41], [39].

One way the EMS ensure reliable operation is by reducing harmonic pollution. It is defined in [24] as *"any waveform with frequencies that are multiples of the fundamental frequency and is measured as total harmonic distortion (THD), which is a normalized quantity describing the relation between the amplitudes of the harmonic frequencies and the amplitude of the fundamental frequency"*. Power electronics have nonlinear behavior and is a source to harmonic pollution. With the increasing amount of electrical equipment on-board, which is either directly or indirectly dependent on power electronics, harmonic pollution is an increasing problem. Harmonic pollution lowers the system's power quality and increases the fuel cost, and as a worst case scenario, it can cause a blackout due to voltage collapse. Harmonic mitigation is therefore a necessity. The implementation of an ESS will further help the EMS to suppress and mitigate the harmonic mitigation.

In general, there exists a variety of energy management strategies with varying main objectives; some seek to reduce fuel consumption, other wish to prolong a system's or energy source's lifetime. As a consequence of the high number of interrelated energy systems on a hybrid ship, the EMS becomes a highly complex structure. This technology develops and advances in fast pace with the help of communication technology, big data and complex software. The complexity of the EMS will however vary, but highly advanced systems are able to determine the energy distribution based on past, present and predicted future events.

The use of EMS is still quite novel to the marine industry. Today, power- and energy management in marine vessels are often performed by manual interaction, occasionally with decision support from higher level control system. However, there is a growing tendency towards utilizing energy management systems on-board ships as more ships are being hybridized. The maritime industry may then learn from other industries. Advanced control systems are common in industries such as the aerospace-, automotive - and defense industry [42]. Although there exist vast scientific literature related to control systems for obtaining optimal load sharing for the different types of conveyances within these industries, these are often not directly applicable for hybrid vessels. This is due to several differences. First of all, the marine propulsion system will often consist of more than one engine, where a hybrid electric car will usually only have one. Moreover, marine auxiliary engines will often run at fixed speed whereas the hybrid car may adjust its speed to maintain high efficiency for the whole range of loads due to gearshifts etc. Furthermore will the stricter rules and regulations that apply for vessels restrict the operation of the hybrid machinery components [43].

3.2.2 Power Management System

The power management system (PMS) handles the instantaneous power distribution of the different energy sources in a hybrid system with ever changing power demands. It generates power references based on the energy related references received from the EMS. This involves determining the generated power from each energy source, and the generated or absorbed power of the ESS. The PMS' objective is to enhance the availability and reliability of the power supply through ensuring that the operational power requirements are covered at all times. It shall also reduce risk of damage to equipment by overriding the EMS when it demands operation outside of the energy sources' and storage systems' safety boundaries. The PMS is also responsible for providing the EMS with information about the system's health [24], [44]. The PMS main tasks are generalized in the list below [45].

1. Automatic start and stop of energy sources and storage units in accordance with power need.

2. Avoiding excessive load increase when operating in normal conditions.

3. Forcing quick load reduction when there is a risk of overloading.

4. Restoring the power system after a blackout has occurred.

5. Performing a redundancy and criticality assessment, checking that all components perform within its requirements.

As seen from the list, an important function of the PMS is to ensure power in critical situations. Class requirements demands that the power system can be divided in two when a fault occurs. This will minimize the chances of complete blackout and in order to keep the vessel position even if one subsystem stops working. Even though this is neither an efficient nor economical solution, it will increase the system reliability [24], [44].

3.2.3 Battery Management Systems

The battery specific electronic control system is referred to as a Battery Management System (BMS). The BMS is defined in [31] as *”a collective terminology comprising control, monitoring and protective functions of the battery system”*. In the same report it is stated that the BMS technology is as important as the energy storage technology itself. The purpose of the BMS is to ensure safe and optimal operation of the battery by forcing the battery cells to operate within specific safety and performance boundaries. This is enabled through monitoring of system voltage, current and temperature.

The complexity and consequently the capabilities of a BMS vary. The highest safety level detection systems monitor the voltage in every single cell. This is to detect unexpected - and unsafe performance and to assure balanced operation between the cells. The imbalance is a result of problems in manufacturing, temperature and cell ageing. If the voltage in one cell is substantially different from the others, there is a high risk for the cell to get overcharged or over-discharged. Undercharging may damage a battery’s chemical properties, whilst overcharging may cause the cell to explode [46]. This phenomena is demonstrated in figures 3.6 and 3.5.

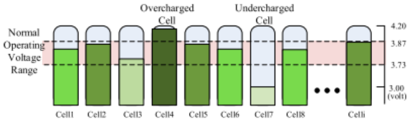


Figure 3.5: Charge imbalanced cells. Illustration from [46].

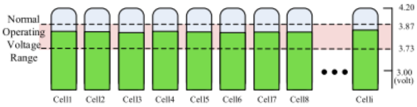


Figure 3.6: Charge equalized cells. Illustration from [46].

It is highly advantageous with a BMS that is able restore the balance in between the cells. This is done by interconnecting a circuit with a resistor to the cell with lowest self-discharge rate. This will drain the specific cell to the voltage level of the other cells. Also the voltage and power between the battery packs should ideally be monitored. This is performed by a ”Master BMS”, that will communicate with the next control level; the energy management system [9] which will adjust the power flow accordingly.

Thermal monitoring and control is also a key function of the BMS. When the battery is exposed to temperatures outside of the safety limits, the battery state of health is drastically affected and the battery's lifetime is reduced. The degradation rate of the battery lifetime will increase concurrently with the temperature rise. Unfavourable temperatures may even impose safety risks. A possible outcome is thermal runaway, which is the case where an increase in temperature causes condition changes that leads to further temperature increase. This is the result of exothermic reactions that are accelerated by the rise of temperature.

Low temperatures may also impose a threat to the battery. For instance will operation at low temperature with high current lead to the formation of lithium plating or dendrites. This will induce an irreversible capacity reduction of the battery. The severity of the capacity reduction depends on the characteristic of the over-current. Figure 3.7 illustrates the described effects that temperature variations has on a battery. The figure shows the connection between temperature, percent capacity remaining and state of charge (SOC), i.e. the available energy in the battery, after both five and ten years. This information can be used to optimize operation. The SOC is a complex calculation dependent on non-linear effects related to power level and voltage or SOC ranges. It is also highly dependent on temperature, and needs to be calibrated for the specific cell type. The complexity of this calculation confirms the demand for a BMS as it is able to enhance performance and life of batteries [9], [16].

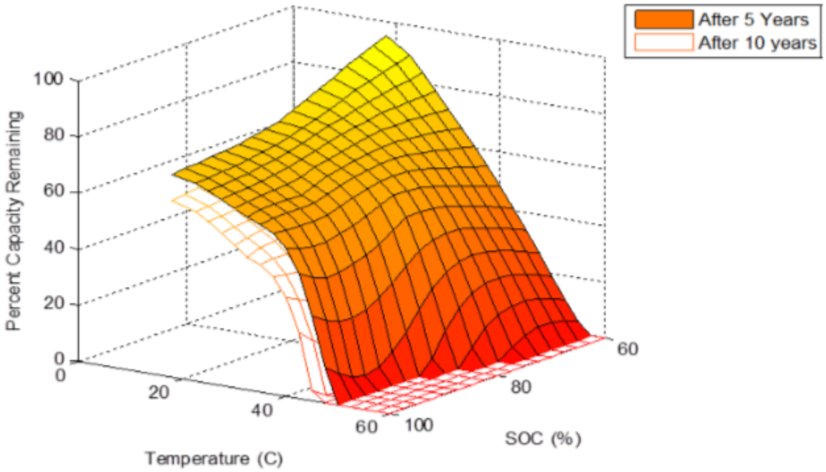


Figure 3.7: Connection between temperature, capacity and SOC. Retrieved from [9].

How a battery is cycled may also affect the rate in which it degrades. One aspect is the battery C-rate which is a measure of the rate at which a battery is charged and discharged relative to its maximum capacity. A 1C rate imply that the battery will be discharged in 1 hour. A battery with a capacity of 100 Ah will then have discharge current equal to 100 A. The C-rate varies for different batteries.

Another aspect related to cycling is variations in SOC. Large changes in SOC and high levels of current will lead to a capacity loss. Charging the battery from entirely empty to completely full may have the same effect, and it is therefore beneficial to charge and discharge in small portions. The range in which the battery is cycled relative to the full battery capacity is called 'available energy'. It is the BMS and EMS' job to ensure that the battery is operated within these boundaries. The boundaries are determined based on the desired lifetime, cell design and application. Decreasing this operational range will increase the battery lifetime. However, decreasing this range involve increasing the size of the battery in order to have the same amount of energy available. Consequently, it is necessary during the system design phase to evaluate the cost of a larger battery against the cost of more rapid replacing of the battery [9].

3.3 Low Level Control System

The low level control system is the interface to the power electronics, and it is at this level the detail power execution is handled. Through directing the energy source specific references from the PMS to appropriate control switching functions it is responsible for the physical process implementation. In other words, through the management of converters, the low level control system manages the actual power produced by the different energy sources in the hybrid power plant [42]. The converters described in Section 3.1 are typical physical components that the low level control system manages in an electric hybrid propulsion system.

A relevant low level control system algorithm used in the created simulation model presented in the next chapter, is the PID controller. A proportional-integral-derivative (PID) controller is a control loop feedback mechanism. It calculates the error between a measured value of a process variable and the desired setpoint, and applies a correction based the proportional, the integral and/or the derivative of this error.

The block diagram in Figure 3.8 is created to demonstrate the PID control process [47]. *r(t)* is the desired setpoint, *e(t)* the measured error, *u(t)* the control variable and *y(t)* the measured process value. The controller attempts to minimize the error over time by adjusting the control variable.

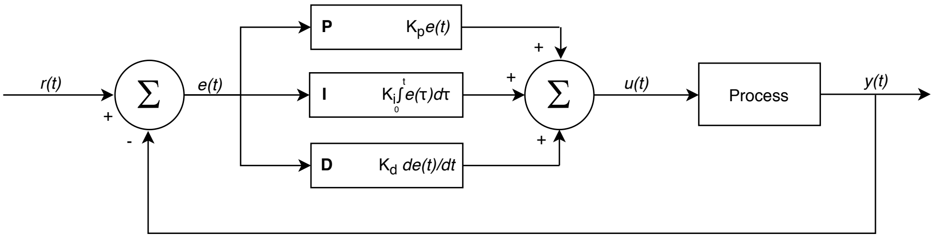


Figure 3.8: Block diagram demonstrating the PID control process.

There exists several variations of the control algorithm where one or two of the control mechanisms are left out, obtaining somewhat different control capabilities. The PI controller is an example where only the proportional and integral of the error is used to control a signal.

Chapter 4

Modeling and Simulation of a Hybrid Electric Machinery

This chapter presents the designed simulation model of a hybrid electric machinery system. Modeling and simulation is the imitation of a real life process or system's operation. Today, modeling and simulation are used in all stages of a vessel's life cycle, and may be used as tools in system design, or for understanding and predicting the response of onboard power systems. Modeling and simulation with this focus may be utilized for analyzing novel power system performance, estimation of fuel consumption and emission, as well as for control system development. Numerical simulation has the potential as a powerful tool in the design and optimization of hybrid electric propulsion systems due to the high cost of real life testing and limited amount of testing facilities.

4.1 System Overview and Characteristics

In order to obtain valuable insight related to the operation of a vessel, a simulation model of a hybrid electric machinery system is created. The model is in general intended as a framework for analyzing novel power system performance, estimation of fuel consumption and emission, as well as for control system development. In order to account for the dynamic responses of the total system, the hybrid power system is modeled in the MATLAB Simulink platform.

The goal of this thesis is to be able to indicate the effects of implementing a battery storage system in a hybrid electric machinery configuration. Chapter 5 presents a case study performed on real operational data from a particular vessel. In the case study, the original machinery configuration is compared to a hybridized version where a battery is implemented. Hence, the designed simulation model is based on the vessel's existing machinery set-up. The model may however easily be adjusted to represent any other machinery configuration. The vessel's electrical single line diagram is given in Appendix 6.2.

Due to the complexity of the vessel's machinery system, the simulation model has a long execution time. Implementing a battery with belonging power converters further complicates the model and prolongs the simulation time. Power converters are of the more time consuming components due to their fast dynamics and switching mechanisms. In order to capture their dynamic behaviour, the discrete simulation time step needs to be very short. A time step of 10^{-5} s is therefore used.

The vessel's AC power grid was in the modeling process replaced by a DC grid system for two reasons. First and foremost, it has been a goal to create a model framework for analyzing novel, hybrid power systems. As discussed in Section 3.1, there is a growing trend towards utilizing the DC architecture, and the DC grid was therefore the natural choice. The second reason is that the DC grid system contains fewer power converters which will reduce the simulation time. Each converter involve a power loss, but as the operational data input it the produced power rather than the actual power demand, the produced amount of power will be equivalent in both cases. Figure 4.1 shows a simple SLD of the modeled power system.

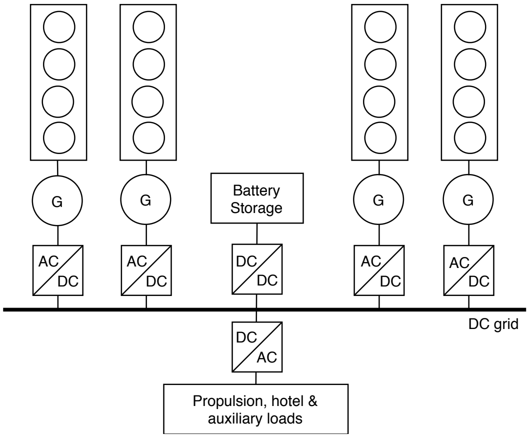


Figure 4.1: SLD of the modeled electric power system configuration.

In order to further simplify the power system, all the studied vessel's loads, i.e. propulsion, hotel- and auxiliary loads, were combined to one load as seen in Figure 4.1. However, if it is a goal to model and investigate the power consumers' behaviour rather than the power producers as is the goal in the presented case study, both the power losses and the modeling of the loads should be taken into account.

4.2 Control System Architecture

Early in the design process of hybrid electric power systems, power and energy management is often not considered. The control system is essential for optimal power sharing and operation of a hybrid machinery, as elaborated in Section 3.2.1. The result of this simplification may have consequences for the end result, with a non-optimal system which does not work as intended. A control system strategy is therefore included in the model.

A simplified block diagram is created in Figure 4.2 to illustrate the interaction between the different control levels, and the flow of power and signals in the designed model. A combined power and energy management system determines the reference powers for the different energy sources, which it communicate to the power and voltage controller for further distribution. The power and voltage controller translate these signals into source specific signals, such as current and voltage levels. The produced electric power is fed via power converters into a common DC bus which distributes it to the consumers.

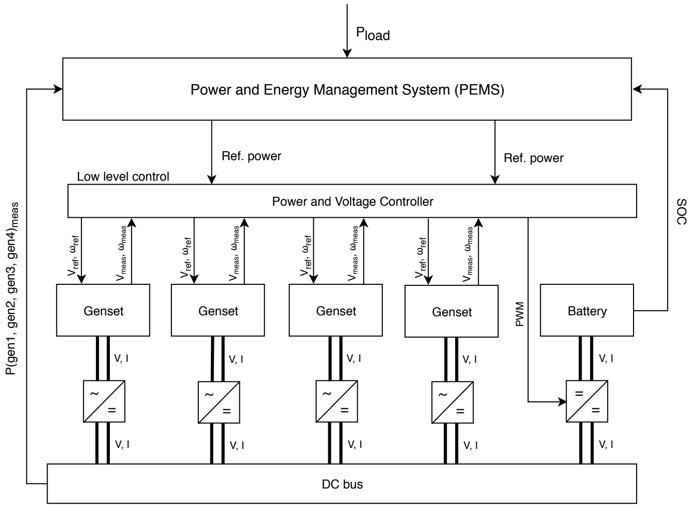


Figure 4.2: Block diagram illustrating the control level hierarchy. Arrows represent control signals, and lines represent voltage connections.

The control system does not have a battery management system (described in Section 3.2.3) in order to simplify the already highly complex model. However, extra protection mechanisms are ascribed to the power and energy management system. This elaborated in the next subchapter.

4.2.1 Power and Energy Management System

A state-based power and energy management strategy is proposed in this thesis. The state-based PEMS strategy is based on a "if/else" logic approach and determines certain states with belonging reference power for each energy source in a power plant. It offers a fairly simple and intuitive control system logic, which can be beneficial when operating with a complex system such as hybrid electric machinery configurations on ships. Due to its simplicity, it is also highly reliable.

The designed PEMS is based on 36 states that addresses different scenarios for various power demands. A MATLAB function block is used to implement the states in the model as can be seen together with the complete PEMS set-up in Figure 4.3.

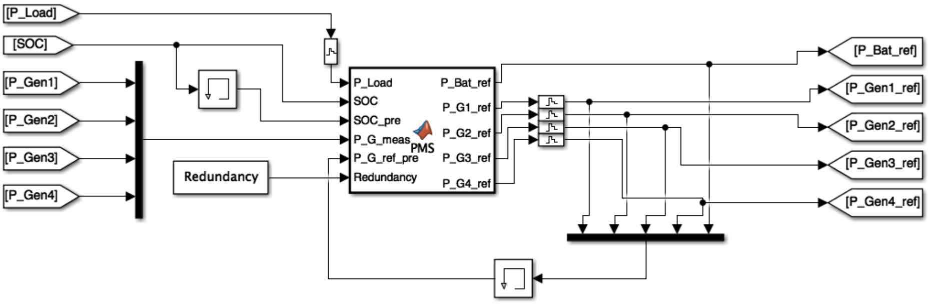


Figure 4.3: Energy management system logic.

The two most defining factors in the control system algorithm, which determines the reference powers for the different sources are the power demand and the battery SOC. These are seen as the two uppermost inputs to the PEMS MATLAB function block. In order to maintain operation within the safe boundaries of the battery, the PEMS continuously monitors the SOC and limits the battery operation between 20-80% SOC.

As the simulation model lacks a BMS and the protection mechanisms that comes with it, the PEMS is designed to restrict the C-rate. This is done by dividing the power ranges which defines the different states into several smaller ranges. The consequence of this is a more complex PEMS with a high number of states.

In general, the goal when determining a genset's reference power is to minimize the fuel consumption. Operating below 20% of maximal continuous rating (MCR) results in a high specific fuel oil consumption (SFOC), but may also cause damage to the gensets [48]. Beyond this, the gensets' fuel consumption varies as a function of percent of MCR. Optimal operating range is typically between 70-90% of MCR. The PEMS strategy is formulated so that the diesel generators operate to the greatest extent possible at the point where the SFOC is minimized. This involves charging and discharging of the battery in order to maintain the genset loading as close to its optimum as possible.

The requirement of redundant operation will also have a large impact on the reference powers. As this involve operating several gensets at low non-optimal loading, there is a need to separate redundant and non-redundant operation. This is performed by the 'Redundancy' block seen in Figure 4.3. In addition, it will alter the power split and produced power depending on the load demand. As an example, when there is a redundancy requirement, but also a low power demand, the gensets may charge the battery in order to avoid harmful operation. This is illustrated in Figure 4.4 which shows a random plotted power demand. The negative values indicate charging. This will increase the fuel consumption, but it will also reduce the wear on the gensets and reduce maintenance costs.

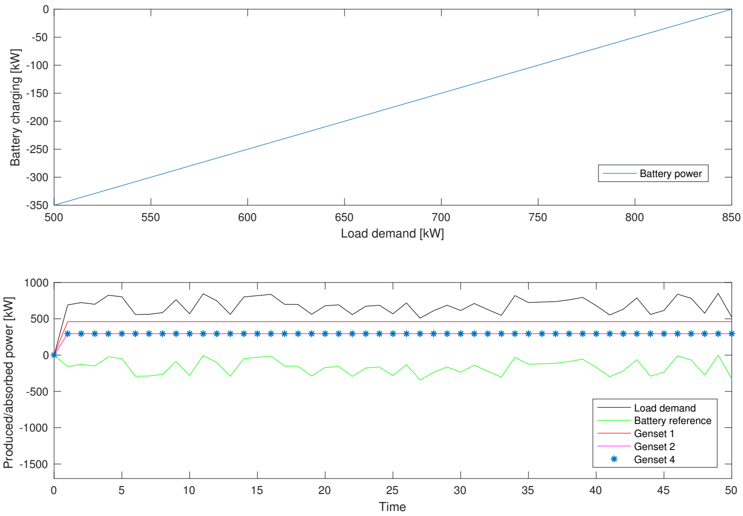


Figure 4.4: Upper figure shows battery charging as function of load demand. The lower graph illustrates load levelling with battery charging.

The diesel generator has slow dynamics, which involves slow start up. A problem then arises when one genset is switched off and another genset is switched on. The second diesel generator is not able to instantly provide the power requested, which causes instabilities in the system. In order to avoid this problem, the PEMS is formulated so that a genset will not shut down unless the power demand is covered by other means. This is performed by measuring the power currently produced (P_G_meas in Figure 4.3) and by utilizing a memory block as seen below the MATLAB function block. An additional measure performed in order to improve the system stability is to ensure that if a generator of the same size runs in two subsequent states, the power will be provided by the same diesel generator.

4.3 Modeling of Mechanical and Electrical Subsystems

In this section the modeling of the mechanical and electrical subsystems are explained in simple terms.

4.3.1 Diesel Generators

The diesel generator with its control mechanism is shown in Figure 4.5. The Simulink library's synchronous machine is used to model the diesel generators with speed (w in Figure 4.5) and voltage (Vf1 in Figure 4.5) as inputs.

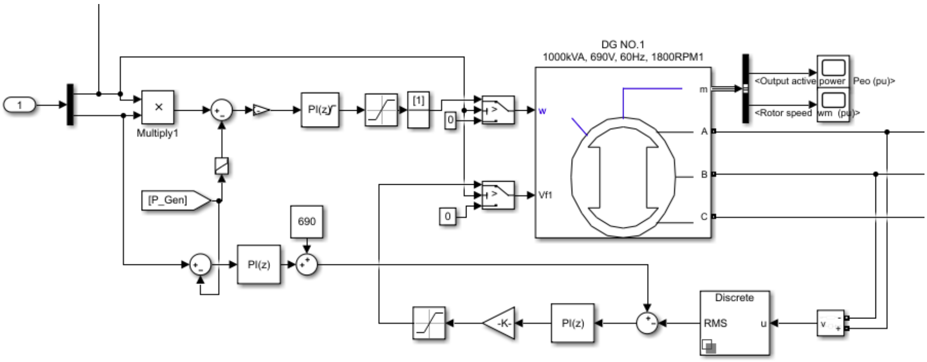


Figure 4.5: The diesel generator and its low level control mechanism.

Each genset is controlled by three PI controllers (described in Section 3.3). The PI controller is chosen as it may eliminate the steady state error while improving the relative stability.

The engine speed is controlled by a governor consisting of a PI controller which correct the error in produced power and the reference power received from the PEMS (the oval denoted '1'). Furthermore, an automatic voltage regulator (AVR), which controls the voltage level, is combined with the power error to adjust the voltage signal going into the generator.

4.3.2 Battery

The battery model from the Simulink library is used in this study. It is a generic model, parameterized to represent the most common rechargeable battery types [49]. A lithium-ion battery is chosen as they in general have a longer lifetime, high specific energy and power compared to other battery configurations as further elaborated in Section 2.1.4. Figure 4.6 shows the battery equivalent circuit. The battery is controlled by a DC/DC converter which is described in subsection 4.4.2.

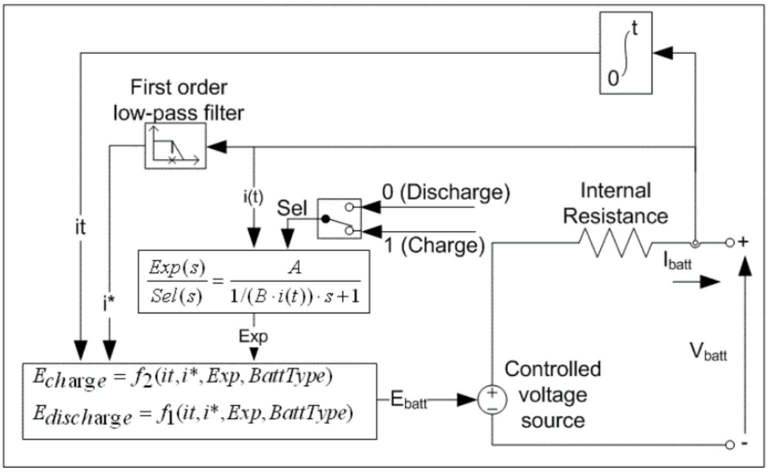


Figure 4.6: Battery equivalent circuit, retrieved from [49].

4.3.3 Load

Simulink's three phase dynamic load is used to implement the load demand. It is a complex, but robust model which showed improved stability over other tested load models. A detailed three-phase IGBT inverter is used to convert the power from AC to DC. Figure 4.7 shows the load set-up.

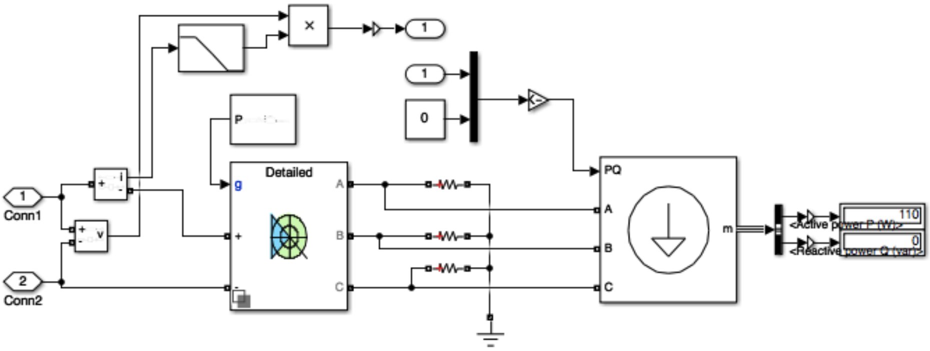


Figure 4.7: The load input and set-up.

Real life operational data may be used as input to the model. This load demand input (the lowermost oval denoted '1') is retrieved from the MATLAB workspace. The reactive power (square denoted '0') is for simplicity assumed equal to zero. 'Conn1' and 'Conn2' is the voltage connection to the DC bus. The signal output (the uppermost oval denoted '1') enters the PEMS where the reference powers are determined.

The load is divided in to two separate loads. The reason for this is that when modeling loads, common practice is to utilize constant power load (CPL). A CPL varies its impedance when the input voltage changes in order to keep the power constant. This may affect the power quality and bring instabilities to an electric system. Figure 4.8 shows an example of the relation between varying DC voltage and power and how this affects the stability of the electric system. When the system operated with only one load it fell within the unstable region, and a second load was therefore added. The load is divided equally between the two loads. Their output values are summed before entering the PEMS.

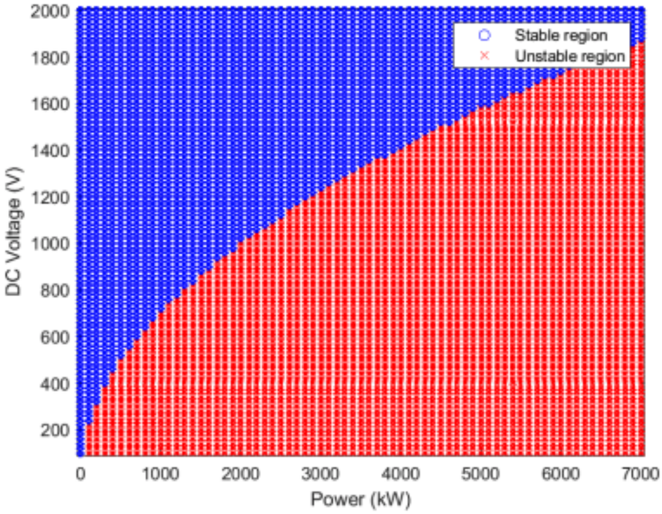


Figure 4.8: Example of stable and unstable region with varying DC voltage and power. Figure from [50].

4.4 Modeling of Power Electronic Converters

4.4.1 Rectifier

In a shipboard DC distribution system, the power supplied by the diesel generator must pass through a three-phase rectifier to convert the AC power to DC before it enters the dc grid. A simple diode is chosen to perform this task. A diode is an electric component with two terminals. The diode is a passive component with low resistance in one direction and high resistance in the opposite direction. This allows the diode to function as a switch as current is only being conducted in one direction.

Other possible options that will enable better control are thyristors and transistors. What separate the diode from the other two is that it is not possible to control the flow through the diode, i.e. it is an uncontrolled switch. A thyristor differs from the diode as it is equipped with an extra gate which allows the thyristor to be semi-controlled. If this gate receives a signal it will allow the current to pass through the component in one direction. The thyristor can however not be turned off unless the current gets below its holding current. A transistor is an active component and a controllable switch where the current can be turned on and off. The transistor may in addition function as an amplifier.

The reason why a diode is chosen is that the simulation model is highly time consuming. Choosing the simplest semiconductor can reduce the running time. The generators are otherwise controlled as described in subsection 4.3.1.

4.4.2 DC/DC Converters

The DC/DC converter is the PEMS' interface to the energy storage system, and is the component that physically controls the battery power flow. When implementing an energy storage system in an electric power system, it is common practice to utilize bidirectional DC/DC converters. This is because the battery voltage level is usually lower than that of the DC bus, therefore the converter steps up (boosts) the voltage when discharging the battery, and steps down (bucks) the input voltage level when charging the battery. A combined buck and boost DC/DC converter is created to model the battery charge/discharge functions.

Figure 4.9 shows the signal flow in the DC/DC converter. Pulse width modulation (PWM) is used to interpret and translate the error in current, voltage and power relative to their references. This is done by converting the digital signals to analog signals. These signals are then sent to the appropriate switching functions for the physical execution. Two insulated-gate bipolar transistors (IGBT) were the chosen switches, which will direct the current in DC/DC converter in Figure 4.10 on different routes depending on whether the battery is charging or discharging.

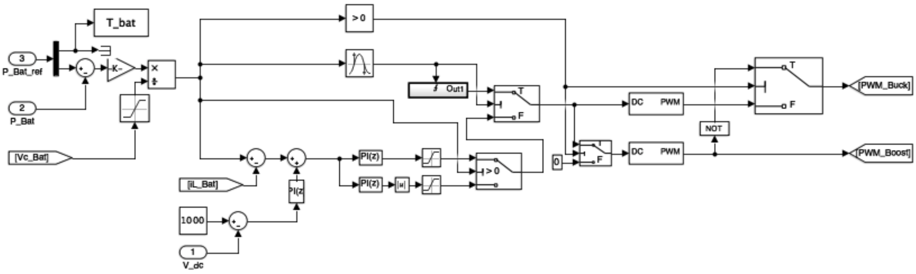


Figure 4.9: The DC/DC converter signal scheme.

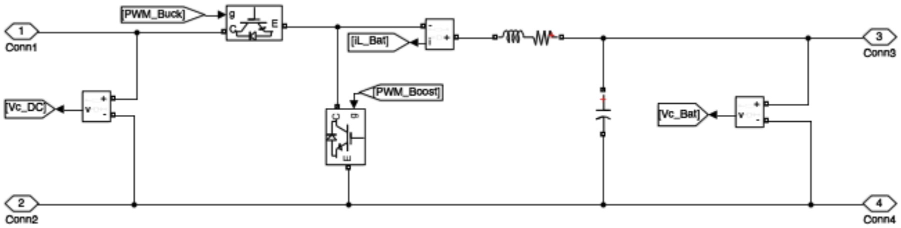


Figure 4.10: The DC/DC converter physical switching mechanisms ensuring bidirectional behaviour.

Chapter 5

Case Study: platform supply vessel

5.1 Introduction and Motivation

The conducted literature study established that the battery hybrid propulsion system has a theoretical potential to improve a vessel's operation related to technical, economical and environmental aspects. Identified means are load levelling, peak shaving, preventing prime movers from operating at damaging load levels and to serve as a spinning reserve as described in Section 2.2. The purpose of this case study is to evaluate the economic feasibility of the battery hybrid propulsion system within the boundaries of the specific operation of a platform supply vessel. Operational data from a real life vessel is basis for comparison. The operation of the hybrid vessel is determined by the help of the designed simulation model described in the previous chapter.

The case study process is illustrated in the flow chart in Figure 5.1. Before running the simulations, an optimization process to determine a sensible battery size is performed. The optimization process is further described in 5.4. The simulation model determines the loading of each genset, from which the fuel consumption may be calculated. Maintenance costs are calculated as a function of running hours as elaborated in section 5.2.2. Finally, a life cycle cost analysis (LCC) is performed based on battery size determined from optimization, the fuel consumption and genset running hours. As seen from the figure, the calculations are performed after the simulations. This is done in order to reduce simulation time. This is made possible by writing operational data to the MATLAB workspace for every discrete simulation time step throughout the simulation period.

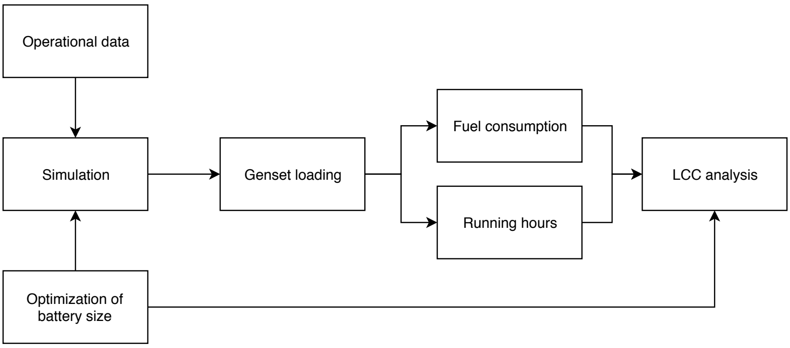


Figure 5.1: Case study flow chart

5.1.1 Technical Background

The case study focusing on economical performance is executed for the platform supply vessel (PSV) 'Blue Queen' as depicted in Figure 5.2. She was delivered from Ulstein ship yard February 2015. In 2017 she changed name to Kasteelborg as a result of a 6-year contract signed with Wagenborg Offshore. The case study is based on operational data from operation under the name Blue Queen.

Figure 5.2: Blue Queen, retrieved from [51].

Blue Queen has an Ulstein X-bow hull that together with a diesel electric propulsion system ensures sensible fuel consumption, speed and stability. The machinery configuration consists of four diesel generators. It is equipped with two smaller and two larger diesel generators that deliver power for propulsion, hotel and auxiliary loads. Blue Queen has five propulsion units. The vessel's specifications are shown in table 5.1. Blue Queen's electrical single line diagram is found in Appendix 6.2.

Feature	**Value**
Ship specifications	
Length	83.4 m
Breadth	18 m
Machinery:	
2 × Diesel engine	2350 kW
2 × Diesel engine	994 kW
Propulsion system:	
2 × Azipull	2200 kW
2 × Tunnel thruster	880kW
1 × Azimuth	880 kW

Table 5.1: Specifications of Blue Queen. Data is retrieved from Ulstein Design & Solutions AS.

5.2 Economic Basis

A vessel's lifetime costs are normally divided into three main elements: capital expenditures (CAPEX), operational expenditures (OPEX) and voyage related expenditures (VOYEX). The cost elements included in this study are elaborated in this section.

5.2.1 CAPEX

The CAPEX is the initial system investment cost. In the model it is calculated as the sum of the cost of the battery system and the diesel generators. The battery investment cost is dependent on its available energy, measured in kWh. The investment cost related to the engines are dependent on the size and the number of engines.

The engine investment cost is assumed to be 350 USD/kWh [52]. The gensets used in this study are similar to the ones in the Blue Queen machinery system. As seen in Figure 2.10, the cost of maritime battery systems is predicted to range between 650-950 USD/kWh. For the purpose of these calculations a battery cost of 800 USD/kWh has been used for the battery cells bought in present time. Including power electronics, a total system cost of 1200 USD/kWh is used.

The battery is affected by wear and tear and needs to be replaced after a period of time, usually ranging between 5-15 years. In this analysis a lifetime of ten years is used. Figure 2.10 indicates that the cost of a maritime battery system in 10 years from now will range between 250-700 USD/kWh. Power electronics are assumed not replaced, and the replacement cost is therefore set to 550 USD/kWh. After ten years, the cost reduction rate on the graph in Figure 2.10 declines, and a 20% reduction is assumed from this point. The cost of the battery in 20 years are therefore set to 440 USD/kWh.

It is believed that by reducing the wear on the engine, one can prolong its lifetime. However, in this study it is assumed that the benefits of implementing a battery will take effect in reduced maintenance costs. The engine replacement costs are therefore are left out of the study.

5.2.2 OPEX

The OPEX are in this model related to maintenance, which constitutes a large part of a vessel's expenditures. The cost of maintenance performed on the diesel generators is calculated as the product of installed power, MCR, and number of hours in operation. The cost is set to 3.2 USD/MWh based on discussions with experts.

By installing a battery, the wear and tear may be reduced through fewer engine running hours and by avoiding operation at low load which is damaging for the engine. Furthermore, the battery may also absorb the load peaks which may be stressful for the gensets. These means will in turn reduce the maintenance costs. This maintenance cost factor is therefore reduced to 2.8 USD/MWh for the hybrid case.

In order to account for the plug-in hybrid case where the battery is charged with shore power, an electricity price of 0.304 NOK/kWh (0.036 USD/kWh) is assumed. This price is based on statistics in the period between 2001 and 2016 from Statistics Norway [53].

5.2.3 VOYEX

The VOYEX are the expenditures related to voyage, such as the cost of fuel. The MDO fuel price is based on international prices and is set to 600 USD/ton [54]. The total fuel cost is calculated for each engine as the product of the fuel price, engine load and the specific fuel oil consumption (SFOC) function.

The SFOC function for the engines onboard Blue Queen are not known, and a similar, standard engine is therefore used. In [55] numbers for percent of MCR and SFOC are given. These are used to create a polynomial, which enables the calculation of the gensets' specific fuel oil consumption. This curve is plotted in MATLAB and is shown in Figure 5.3. The two engine types considered in this analysis are assumed to follow the same specific fuel consumption curve.

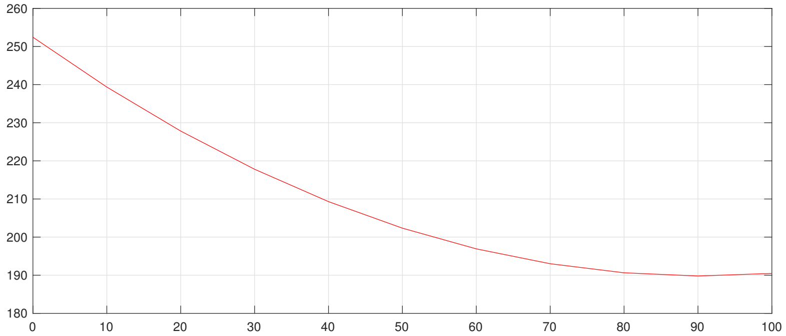


Figure 5.3: Specific fuel consumption curve plotted in MATLAB.

In addition to fuel cost, fuel related taxes is included in the VOYEX calculation. Through the Gothenburg Protocol of 1999, Norway is committed to curtail its emission of nitrogen oxides (NOx). In order to stimulate to the reduction of NOx emissions and to reach this target, the Norwegian parliament has implemented a tax on the emission of NOx that applies for the entire Norwegian continental shelf. The vessel Blue Queen is assumed to operate solely in this area, and will be taxed accordingly.

The NOx tax is calculated as the product of the fuel consumption. The tax rate in 2019 is 22.27 NOK per kg emitted NOx, corresponding to 2.615 USD/kg with a dollar cost equal to 8.52 NOK (18.03.19) [56], [57]. The relation between NOx and fuel is 51.8 kg NOx per ton fuel for supply ships [58].

5.2.4 Inflation

The Norwegian Government has set a target to maintain a low and stable inflation rate in Norway. The monetary policy is oriented towards adjusting the base rates so that the increase in consumer prices is as close to 2% as possible over time [59]. The maintenance - and battery cost is set to follow the 2% inflation rate.

Fuel costs will typically vary greatly over time, and are dependent on several factors. Forecasts indicate that the world oil demand will increase in the future with an increment in fuel costs as a probable result [60]. One may also assume that the implementation of the IMO 2020 Sulphur Cap, which come into effect in 2020, will affect the fuel prices in the same way. However, speculating in the development in fuel prices is a complex task and a time consuming process, with possibly misleading results. For simplicity, the fuel price and electricity price inflation level used in this analysis is set to 3%.

A fourth cost item that may be subject to change is the NOx taxes as discussed in 5.2. The increase to 2019 from 2018 was 1.48%. In this analysis it is assumed that the NOx tax will increase at the same rate in the years to come.

5.3 Operation of Platform Supply Vessels

The Blue Queen is a PSV, which is specifically designed for servicing offshore structures such as platforms, wind farms and subsea installations. The PSV can be seen as a multipurpose vessel that can conduct a range of different offshore operations. Tasks typically include logistic support such as transportation of supplies, equipment and personnel, but also operations involving maintaining position in close proximity to offshore structures by the help of dynamic positioning (DP). DP is a computer controlled system that continuously controls and adjusts the main propulsion and thrusters to maintain a set position regardless of currents, waves and wind. This position may be relative to a moving object or locked to a fixed point over the sea floor. DP operation is illustrated in figure 5.4. The external forces are shown as red arrows, degrees of freedom in yellow arrows and DP adjustments are represented by the green arrows.

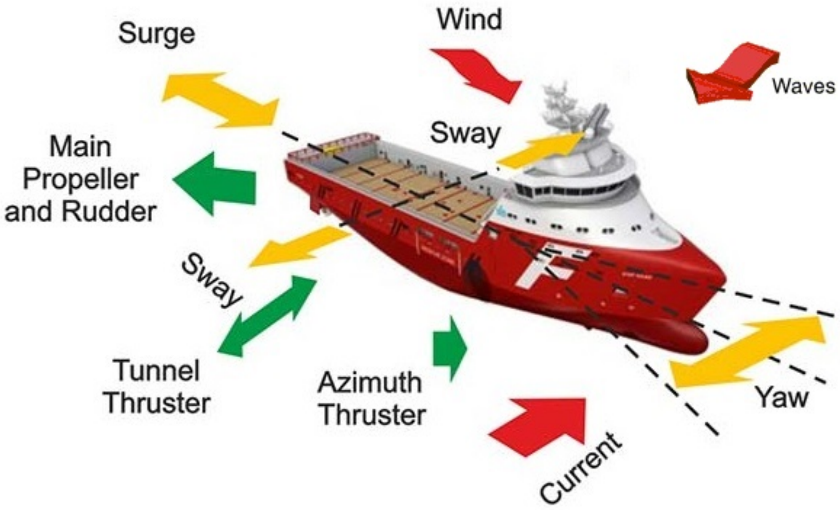


Figure 5.4: Illustration of DP operation. DP adjustments (green arrows) as response to external forces (red arrows) with different degrees of freedom (yellow arrows). Figure from [61].

Failures in the power system when operating in the proximity to offshore structures may involve substantial economical, environmental or health and safety related consequences. A PSV therefore needs to have enough power available so that if one engine fails, the machinery may still cover the load demand necessary to perform a certain operation. This is especially important when operating in DP, but it is also often the case for transit and stand-by operation, even though this is not a requirement. This involve running more engines than necessary at low, non-optimal load with high specific fuel consumption. This is because most generators are not able to start up quickly enough to provide the power necessary. Another option to running the redundancy generators is to install a battery that serves as a spinning reserve. The battery can respond extremely quickly, and does not demand energy while in stand-by.

5.3.1 Operational Input Data

An operational profile is the quantitative characterization of how a system is utilized. In regards to Blue Queen, it shows how the total power demand varies with time and is found as the total power generated by the four gensets. They are summed in order for the PEMS to determine the power split based on the current load demand and SOC as described in section 4.2.1.

The simulation model has a long execution/running time, and it is therefore desirable to introduce measures to reduce the duration. The input data to the model is quite extensive, and a means to decrease the running time is to run the simulation for smaller sections of the data, and adjust the results accordingly afterwards. In order to accomplish this, there is a need to further discretize the load data. A vessel's operating cycle can be defined as a set of operational states. With use of the operational data from Blue Queen together with additional PSV operational data obtained form Ulstein Design & Solutions AS these states can be estimated reasonably well. The different operational states are described in Table 5.2 and the duration of each state is presented in Table 5.3.

A challenge (discussed in Section 2.3.5) is that the design of power systems are often are based around either one operating point or one specific load-profile time-series. A possible result of this is that the upfront estimated savings are less than the actual savings. The Blue Queen data is collected over a time period of around one and a half month. In order to be sure to account for variations in weather conditions and operational requirements, the Blue Queen data is seen in light of a wider range of operational data.

The different operational states are identified in the Blue Queen operational data, and the simulation model is run for a section of each state. It is essential that these sections are representative for its state, and include load fluctuations. This data is then multiplied to account for the full duration spent in the relevant state over the vessel lifetime. A ship will typically have an operational lifetime ranging between 20 - 30 years. For the purpose of this analysis the vessel lifetime is set to 25 years.

Operational state	**Description**
Harbour	While in harbor the vessel is loading and unloading cargo, performing maintenance, change of crew and bunkering. The power demand is low, and the duration of this operational state is usually quite long.
Manoeuvring at quayside	Upon arrival and departure from harbour the vessel will perform manoeuvring at the quayside. The power demand is medium high and duration is short.
Transit low	The vessel is sailing between harbour and offshore locations. Duration is quite high due to fuel economic sailing, so called slow steaming at significantly lower speed than maximum speed.

Transit high	Transit with high speed, typically ranging between 10-15 kn. Involves a very high power demand. The vessel will mainly operate in this state in special cases and due to urgent matters. Hence, this state constitute a small part of the total operational time as seen in Table 5.3.
DP low	The vessel is in stand-by while awaiting go-ahead signal to approach offshore installation and operates on DP outside a 500 m safety zone. Medium duration and power demand.
DP high	Position movement into the 500m safety zone and during dynamic positioning operation. This operational state constitute a large part of the PSV operation, and has a quite high power demand.

Table 5.2: Explanation of PSV operational states.

Operational state	Percent of time [%]	Duration [h/yr]
Harbour	23	2014.8
Quayside	1	87.6
Transit low	25	2,190
Transit high	2	175.2
DP low	15	1,314
DP high	32	2,803,2
Off-hire	1	87.6

Table 5.3: Duration of PSV operational states.

Another means performed in order to reduce the simulation running time is to decrease the amount of input data. This is performed by so called averaging of the operational load data. This is performed by taking replacing two subsequent data points with their average value. This will reduce the number of data points by half while the sampling time is doubled.

The Blue Queen load demand raw data has a sampling time equal to 5 seconds. Through averaging the new sampling time becomes 40 seconds, meaning there is a data point for every 40^{th} second of real time. The upper graph in Figure 5.5 shows the raw data and the lower graph shows the same data averaged three times. As the power demand will remain the same for 40 seconds, there will be no change in the dynamic behaviour either. This makes it possible to simulate that every data point has a 5 seconds interval, and multiply afterwards to account for the 40 seconds. By doing this one may significantly reduce the simulation time.

In order to get comparable results, the related cost for the non-hybrid machinery configuration is calculated for the same averaged data selection. The code retrieving this data is found in Appendix 6.2.

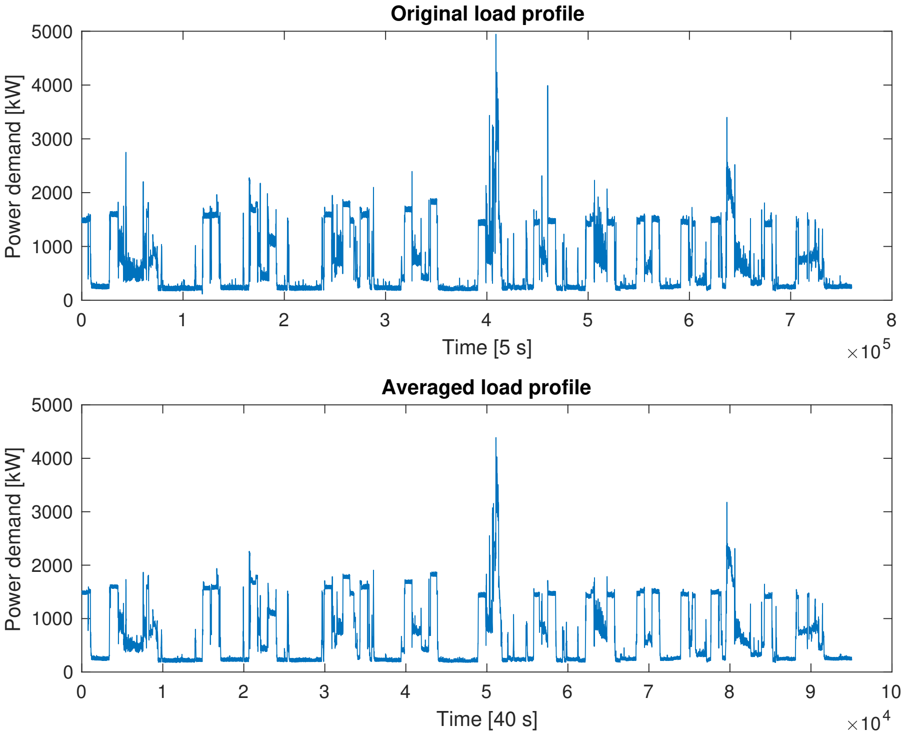


Figure 5.5: Original versus averaged load profile.

What becomes apparent from the two graphs is that the larger peaks are decreased somewhat in magnitude. Performing this type of data processing makes it even more important to select representative sections of the operational data. Moreover, the peaks with short duration are effaced with the data averaging as can be seen around $4.5 \cdot 10^5$ in the upper graph.

5.4 Optimization for Initial Battery Sizing

This chapter presents an optimization process related to the determination of a battery size. Mathematical optimization involves seeking the best possible solutions to complex issues subject to specific limitations and requirements.

5.4.1 Background and Motivation of Optimization

It is desirable to find a reasonable and feasible initial value for the size of the battery system as input to the simulation model. A simple mixed-integer nonlinear programming model (MINLP) is therefore formulated for decision support and to get an idea of the effect of installing a battery pack. MINLP refers to optimization problems where the objective function and/or the constraints contain nonlinear functions, and the variables are both discrete and continuous.

The objective of the optimization is to find the battery size that minimizes the total costs related to the integrated system over the vessel lifetime. It is the specific fuel consumption function which is non-linear demanding the MINLP model. The optimization model and process are presented and described in the following sections.

5.4.2 Operational States for Optimization Calculation

For the purpose of this optimization process an average power demand for each operational state is used. These are identified with the use of the data from Blue Queen and with input form Ulstein Design & Solutions AS. The findings are summarized in Table 5.4

Operational state	Power demand [kW]
Harbour	200
Quayside	580
Transit low	1,730
Transit high	4,500
DP low	550
DP high	2,200
Off-hire	0

Table 5.4: Operational states

5.4.3 Optimization Model Assumptions

Some assumptions have been made in order to perform the MINLP optimization process.

- For this analysis the fuel consumption that goes to charging of the battery is set to 0.08465 kg/kWh. This is based on discussions with experts. The battery is assumed charged every 4th hours.
- The battery is allowed to range between 0-1000kWh.
- Space restrictions are not accounted for.
- The engine loading is set to range between 20-100% of MCR.

5.4.4 Solver and Solver Method

The problem has been solved using the Excel GRG Nonlinear Solving method, where GRG is short for generalized reduced gradient. The solver uses the gradient i.e. the slope of the objective function. It finds the optimal solution by changing the decision variables and finding the solution where the partial derivatives are equal to zero.

The GRG nonlinear method is chosen as it finds a solution very quickly. The drawback of this is that the solution is dependent on the initial conditions. This implies that the found solution may be a local optimum. This means that there is no set of variable values in the proximity of those chosen that will provide a lower objective function value. However, the found solution might not be the global optimum as demonstrated in Figure 5.6. Nonetheless, as this is a fairly simple model, it is assumed that this is close to the optimal solution for the formulated model. The spreadsheet is found in Appendix 6.2.

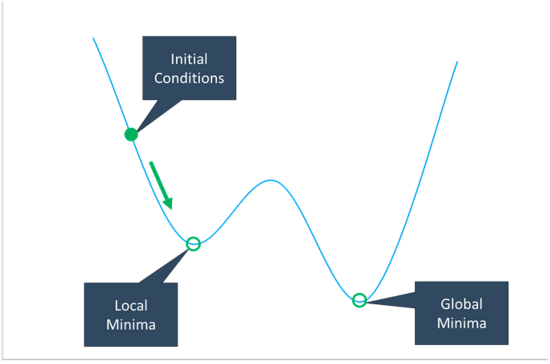


Figure 5.6: Illustration of local vs. global optimal solutions, from [62].

5.4.5 Mathematical Optimization Model

Before the mathematical optimization model is presented, an introduction to the model notations is given.

Notations

Sets:

O	Operational states, indexed by o
J	Engines, indexed by j
O^R	Operational states where redundancy is required

Parameters:

C	Total cost
C^I	Total investment cost [USD]
C^B_0	Investment cost for battery per kWh in year 0 [USD/kWh]
C^B_{10}	Investment cost for battery per kWh in year 10 [USD/kWh]
C^B_{20}	Investment cost for battery per kWh in year 20 [USD/kWh]

C_j^G	Investment cost for engine *j* [USD]
C^O	Total operational cost over a year [USD]
C^F	Fuel cost [USD/ton]
C^{NOx}	NOx tax [USD/ton]
C^M	Total maintenance cost over a year [USD]
C_j^m	Specific maintenance cost for engine *j* [USD/kWh]
L_j^U	Upper load limit for engine *j* [%]
L_j^L	Lower load limit for engine *j* [%]
L_{batt}^U	Upper load limit for the battery [%]
L_{batt}^L	Lower load limit for the battery [%]
P_o^D	Power demand in operational state *o* [kW]
T_o	Time spent in operational state *o* [hrs]
T^L	Vessel lifetime [yrs]
$SFOC_{jo}$	Specific fuel oil consumption for engine j in state o [g/kWh]
Variables:	
x^B	Battery size [kWh]
α_{jo}	Binary variable equal to 1 if engine *j* is in operation in state *o*, 0 otherwise
y_j^G	Binary variable equal to 1 if engine *j* is selected in the machinery configuration, 0 otherwise
P_{jo}	Engine load for engine *j* in operational state *o*
β_o	Battery load in operational state *o*

Table 5.5: Optimization model notations

Objective function

The objective function aims at minimizing the total costs which is the sum of the investment costs, the operational costs and the voyage related costs over the vessel lifetime, T^L. It is defined as follows

$$MinC = C^I + \left(C^O + C^M\right) \cdot T^L \tag{5.1}$$

where the investment cost is formulated as follows:

$$C^I = \sum_{j \in J}(C_j^G \cdot y_j^G) + (C_0^B + C_{10}^B + C_{20}^B) \cdot x^B \tag{5.2}$$

and the operational costs:

$$C_O = \sum_{o \in O} \bigg(\Big(\sum_{j \in J} \big((C^F \cdot \alpha_{jo} + C^{NOx}) \cdot SFOC_{jo} \cdot P_{jo}\big) \Big) \cdot T_o \bigg) \tag{5.3}$$

and lastly the maintenance costs:

$$C^M = \sum_{o \in O} \Big(\sum_{j \in J} C_j^m \cdot L_j^U \cdot \alpha_{jo} \cdot T_o \Big) \tag{5.4}$$

Constraints:

$$\sum_{j \in J}(P_{jo} \cdot \alpha_{jo}) + \beta_o \geq P_o^D \quad o \in O \tag{5.5}$$

$$\sum_{j \in J}(L_j^U \cdot \alpha_{jo}) \geq 2 \cdot P_o^D \quad o \in O^R \tag{5.6}$$

$$P_{jo} \in \{0, [L_j^L, L_j^U]\} \quad o \in O, j \in J \tag{5.7}$$

$$\beta_o \in \{[L_{batt}^L, L_{batt}^U\} \quad o \in O \tag{5.8}$$

$$y_j^G \in \{0, 1\} \quad j \in J \tag{5.9}$$

$$\alpha_{jo} \in \{0,1\} \quad j \in J, o \in O \tag{5.10}$$

Constraint 5.5 make sure that the power demand is met at all times. 5.6 only applies for the non-hybrid case, and makes sure that there are redundant engines available in the operational states where this is considered necessary. Constraints 5.7 and 5.8 sets limitations for upper and lower load output for the engines and the battery. 5.9 and 5.10 are binary constraints that ensures that the engines are in the machinery configuration and in operation respectively.

5.5 Analysis of Results

5.5.1 Optimization Results

The result of the optimization process gave an optimal battery size equal to 200kW or 800kWh. The load demands coinciding quite well with the optimal generator loading points. The result of this is that the battery is only supplies load in harbor. The resulting investment and operational costs are summarized in Table 5.6.

Cost	Non-hybrid	Hybrid
Battery installation cost yr 0 [USD]	0	960,000
Battery installation cost yr 10 [USD]	0	536,367.5
Battery installation cost yr 20 [USD]	0	523,053.5
Engine installation cost [USD]	2,340,800	2,340,800
Total installation cost [USD]	2,340,800	4,360,211
Fuel cost [USD/year]	1,446,665.6	1,334,070.95
NOx taxes [USD/year]	326,484.8	301,074.3
Maintenance [USD/year]	90,520.9	37970.34
Total yearly operating costs [USD]	1,863,671.4	1,673,115.6
Difference CAPEX, OPEX and VOYEX [USD]	69,560,251.3	64,861,240.8

Table 5.6: Optimization results

The hybrid system has a substantially higher initial system cost due to the battery investment cost. Additional investments to replace the battery is necessary after 10 and 20 years, which further increase the difference in investment costs for the two machinery configurations. Nevertheless, the operational costs constitutes 93.3% of the total lifetime costs and reducing these are highly desirable. With the implementation of a battery system, there is an annual 10.2% reduction in costs related to fuel, maintenance and NOx taxes. This gives the battery a payback period of 5 years. The cost development over the vessel lifetime is illustrated in Figure 5.7.

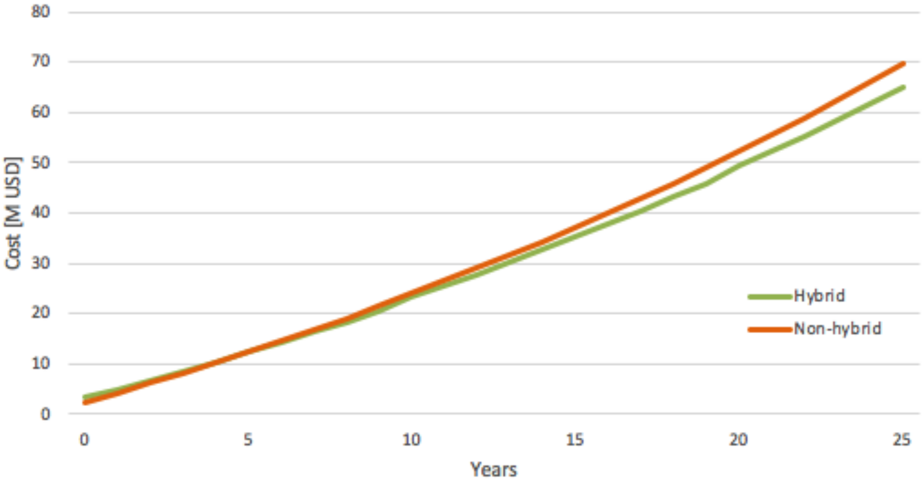


Figure 5.7: Cost development over the vessel lifetime

The economical benefit of removing one of the smaller generators in the hybrid configuration is weighed up against the cost of running one large generator at non-optimal conditions in the states where this is relevant. This results in a somewhat higher fuel consumption and consequently also a higher NOx tax. The larger diesel engine will also require more maintenance during operation than the two smaller engines together. On the other hand, the investment cost is naturally higher for the case with the two smaller engines. The difference over the vessel lifetime between the two cases is 76.650 USD in favor of the larger engine. This result will however be different for the simulation model that will distribute the power differently, and where load variations are accounted for.

It is also worth mentioning that it is usually desirable to operate the engines in such a manner that the need for maintenance is aligned. The results show that the smaller and larger engines will not run simultaneously for the hybrid case as the battery covers the redundancy demands. Having two smaller engines may therefore align the maintenance need with the two larger engines, which may have positive effects on cost.

5.6 Simulation Results

This section presents the results from the simulation process. First a system verification is presented, before the economic results for each operational state are given. The results are compared against the Blue Queen raw data which constitutes the non-hybrid system. A summary of the operational savings concludes this section. All numbers are rounded as the results merely can give an indication of a potential operational cost rather than an exact sum.

In order to simplify the reading of this section the four gensets are called by numbers. Genset 1 and 2 are the two larger gensets, while 3 and 4 are the smaller gensets. Moreover, due to the averaging process explained in Section 5.3.1, the x-axis will not give a correct perspective. In addition, the genset and battery plots are color coded where orange indicates the reference value received from the PEMS, and the yellow is the produced/absorbed power.

5.6.1 Model and PEMS verification

In order to verify the model and PEMS strategy, the model is tested with a highly fluctuating load profile. The relevant profile is plotted in Figure 5.8.

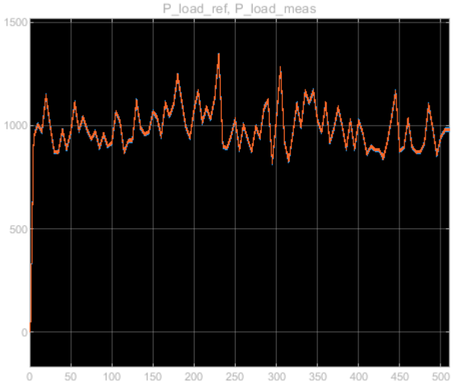


Figure 5.8: Simulated load profile used to verify the model.

The hybrid system is able to exploit the battery, which is used for load levelling through charging (negative values) and discharging (positive values) during load variations. This can be seen from Figures 5.9, 5.10 and 5.11.

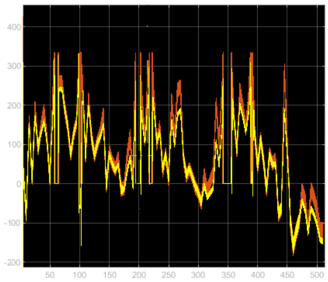


Figure 5.9: Reference and absorbed power by the battery.

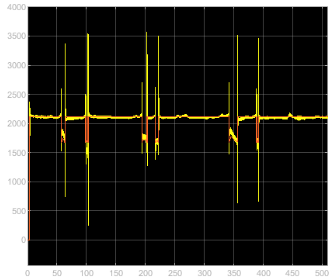


Figure 5.10: Reference and delivered power by genset 2.

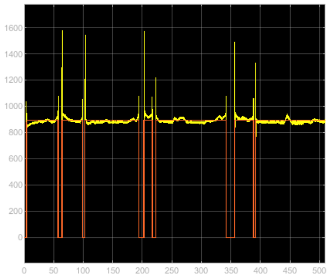


Figure 5.11: Reference and delivered power by genset 3.

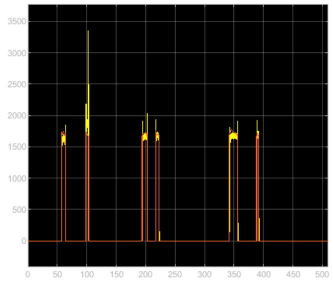


Figure 5.12: Reference and delivered power by genset 1.

On six occasions the load level exceeds the limits of the current PEMS state, which causes a switch in power supply. The battery is shut down in order to limit the c-rate. The smaller genset (genset 3) is also shut down, while the second large genset (genset 1) is swiched on. The reference sent to genset 2 is lowered in value. This is seen in Figures 5.10, 5.11 and 5.12.

5.6.2 Transit Low

The operational profile during 'transit low' which is plotted in Figure 5.13 remains steady around 1600 kW. Due to the designed PEMS in the simulation model, the power distribution in this operational state is different for the hybrid case compared to how the Blue

Queen is operated. In the non-hybrid case Blue Queen is operated with one large diesel generator at relatively low load, while in the hybrid mode the vessel is operated with the two smaller gensets. The battery is in stand-by, and this way the available power corresponds to that of the non-hybrid case. The battery is neither charged nor discharged during the simulated load range, and the two gensets share the load equally as demonstrated in Figures 5.14 and 5.15. The orange lines are the references from the PEMS, while the yellow lines are the produced power.

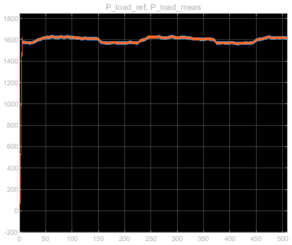


Figure 5.13: Load demand during transit low.

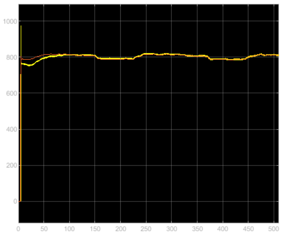


Figure 5.14: Produced and reference power for genset 3.

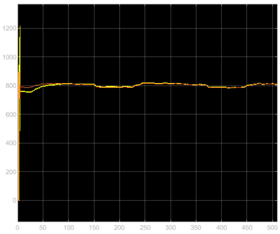


Figure 5.15: Produced and reference power for genset 4.

By changing from one large to two smaller gensets, the relative loading is changed from 68% of MCR to close to optimum at 80%. This results in a small reduction in fuel consumption and a corresponding reduction in NOx taxes. Nevertheless, the largest saving potential is related to the maintenance costs. It is calculated as a function of installed power and hours in operation, and by reducing the installed power from 2350 kW to 2x 994 kW the maintenance costs are reduced significantly. Lowering the maintenance factor from 3.2 to 2.8 also has an effect on the generated costs, and a total 27% reduction in maintenance related costs is obtained.

Through its function as stand-by power, the battery has an indirect positive economic effect on the operation. In total, the savings incurred over the vessel life time in this operational state is close to 450,000 USD. The data from both the hybrid and non-hybrid case during transit low operation are presented in Table 5.7.

Cost [USD]	**Non-hybrid**	**Hybrid**
Fuel cost	15,204,500	14,950,500
NOx taxes	2,781,500	2,735,000
Maintenance	538,000	395,500
Lifetime operational costs	18,524,000	18,081,000

Table 5.7: Costs generated during transit low over the vessel lifetime.

5.6.3 Transit high

The load demand during transit high fluctuates moderately around the capacity of one large genset as seen in Figure 5.16. Whereas the non-hybrid machinery system has to operate with one large and one small genset, the hybrid configuration will operate one large genset at optimal loading with the battery providing the remaining power demand.

As can be observed from Figure 5.17, the battery is able to follow the dynamics of the load demand, but produces slightly less power than requested by the PEMS. The genset tries to compensate during the peaks as seen in Figure 5.18. This error is due to the local PID-controllers which are not tuned perfectly.

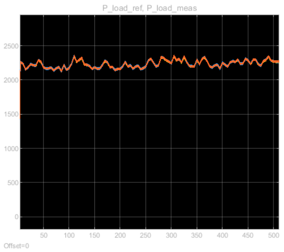


Figure 5.16: The load demand during transit high.

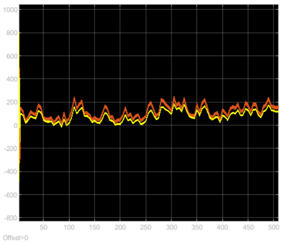


Figure 5.17: Reference and produced power by the battery.

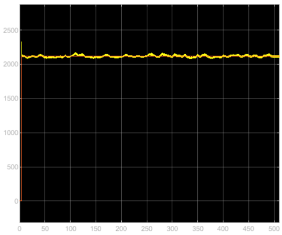


Figure 5.18: Produced and reference power for genset 2.

The economic results from this operational state are presented in Table 5.8. By removing one genset, the maintenance costs are as can be seen decreased substantially. Operating only one large genset allows optimal loading, which contribute to reduce the SFOC and consequently the fuel related costs. The fuel reduction is also due to the fact that the battery provides some of the power. The fuel necessary to charge the battery is however not accounted for. This is further discussed in Section 5.7. Optimal loading will also indirectly reduce the maintenance need through the maintenance cost factor.

Cost	Non-hybrid	Hybrid
Fuel cost [USD/year]	1,703,000	1,577,000
NOx taxes [USD/year]	312,000	288,500
Maintenance [USD/year]	61,000	37,500
Lifetime operational costs [USD]	2,076,000	1,903,000

Table 5.8: Operational costs generated from operation in transit high state over the vessel lifetime.

5.6.4 DP low

The load demand during DP low, which is plotted in Figure 5.19, is kept steady around 650-700 kW. Operation with dynamic positioning sets high demands to redundancy regardless of the actual load demand. As is usual during these operations, the load demand is lower than the available power. The power generation in the non-hybrid configuration is provided by the two large gensets. This implies that if one engine fails, there is still 2350 kW available. The two gensets share the load equally, which involve operating the gensets at around 14% of MCR. This way of operating may substantially increase maintenance and in worst case damage the gensets.

In order to reduce the impact of the above mentioned problem, several measures have been performed for the hybrid case. One of the large gensets have been replaced by two small. Should the larger diesel generator fail, the two smaller may provide 1988 kW together, and with the battery in stand-by, one obtains the same power level as in the non-hybrid case. In addition to supplying the load, the gensets will also charge the battery as the described example in Section 4.2.1. This implies load levelling of the gensets as seen in Figures 5.21, 5.22 and 5.23. This also allow the gensets to operate at 20% of MCR, which is the recommended lower limit [48].

As is evident from the plots there is a shift in the power flow in the system at time equal 225. The gensets which have been producing somewhat below the requested amount, now overproduces. The excess produced energy goes to charging of the battery which is visualized in Figure 5.25. This is once again due to the PID controllers which regulates each energy source, which is further discussed in the Section 5.7.

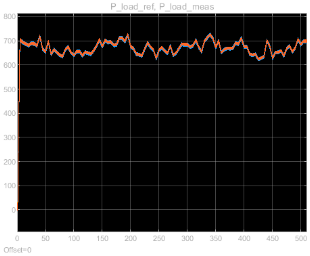


Figure 5.19: Load demand during low dynamic positioning.

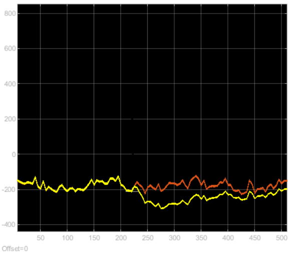


Figure 5.20: Reference and absorbed power by the battery.

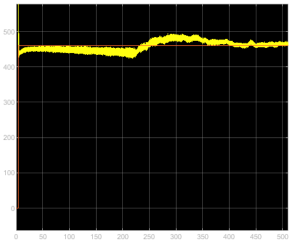


Figure 5.21: Produced and reference power for genset 1.

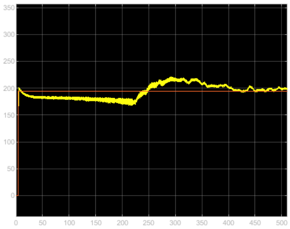


Figure 5.22: Produced and reference power for genset 3.

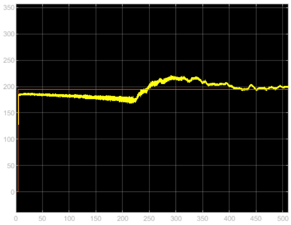


Figure 5.23: Produced and reference power for genset 4.

In the hybrid charging case, the gensets will produce an excess of power and this way increase the fuel consumption. Despite lower maintenance costs, the total operational costs are increased by 18% for this case. It should be mentioned that the production of excess power will only last until SOC reached its upper limit. This is however not accounted for in the simulation. Overproduction of energy, as visualized in the figures above halfway into the operation, may also help drive the costs up.

As producing an excess of power will increase the fuel related costs substantially, the model is also run for the same three gensets without battery charging. The results of both simulations are shown in Table 5.9 together with calculated results from the Blue Queen operation. The case where the battery is charged in order to avoid harmful operation is referred to as ’hybrid charging’ in the table.

The other hybrid case, without battery charging, will have substantially lower fuel related costs compared to the hybrid case with charging. Due to more optimal loading, this configuration is also able to decrease the fuel costs to some extent compared to the non-hybrid case. The maintenance costs are similar for the two hybrid cases. Whether this is realistic is discussed further in 5.7.

Cost [USD]	Non-hybrid	Hybrid charging	Hybrid
Fuel cost	4,633,000	5,669,000	4,579,000
NOx taxes	848,000	1,037,000	837,500
Maintenance	646,000	517,500	517,000
Lifetime operational costs	6,127,000	7,223,500	5,934,500

Table 5.9: Costs generated from DP low operation over the vessel lifetime.

5.6.5 DP high

The machinery configuration of this operational state is similar to the DP low set-up with two small gensets and one large. However, as the load level is higher (shown in Figure 5.24), the battery is no longer needed to avoid the gensets from operating at harmful load areas. Three times during the simulated period the power demand gets below this critical limit. These low load areas causes a switch in PEMS states, in which the battery will absorb power as seen in Figure 5.25.

From Figure 5.25 it can be seen that the battery deviate from the reference received from the PEMS after a certain point. This coincide with the inconsistency in power produced by the gensets. This is especially evident for genset 3 and 4, which produce less power up until the same point. This can be seen from Figures 5.26, 5.27 and 5.28. This is once again related to the PID controllers which regulates each energy source.

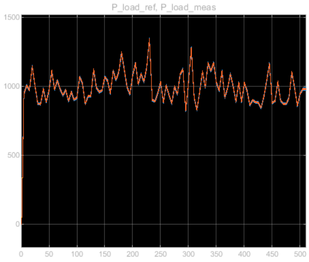


Figure 5.24: Load demand during DP high operation.

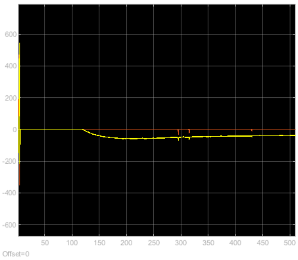


Figure 5.25: Reference and absorbed power by the battery.

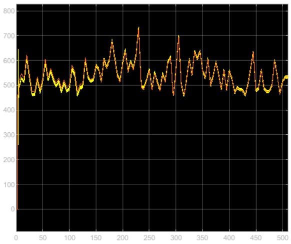


Figure 5.26: Produced and reference power for genset 1.

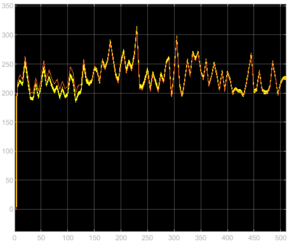


Figure 5.27: Produced and reference power for genset 3.

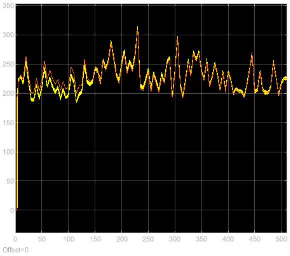


Figure 5.28: Produced and reference power for genset 4.

The vessel in the non-hybrid case is powered by the two larger gensets. By replacing one of these with the two smaller gensets, one obtains a small reduction in fuel consumption, which decreases both the fuel cost and NOx tax. The modification of the machinery configuration also result in a larger retrenchment in maintenance costs as visualized in Table 5.10.

Cost [USD]	Non-hybrid	Hybrid
Fuel cost	14,078,500	13,966,000
NOx taxes	2,575,500	2,555,000
Maintenance	1,378,000	1,105,000
Lifetime operational costs	18,032,000	17,626,000

Table 5.10: Costs during DP high operation over the vessel lifetime.

5.6.6 Harbor

The power demand during the stay in harbor is related to hotel loads and for loading/unloading cargo when the vessel is fitted with cranes. The required power during this state is around 200 - 300 kW for the Blue Queen, which might suggest that batteries should supply the load as this is an unfavorable load level for the gensets. However, the duration of this operational state is usually quite long, and the load demand will therefore exceed the battery's capacity. This imply an alternating operation where the battery supply the load as long as the SOC allows it, before a generator will start up and supply the load demand while charging the battery. As the time spent in harbor constitute a quite large percentage of the vessel's operational cycle, this involves starting up and shutting down the generator numerous times which will escalate the need for maintenance. Hence, a vessel will usually not be operated in this manner. In addition, the effect of repetitive start-up is not a measurable unit in the current model, and this way of operating is therefore not considered in this analysis. There are however two other options for power generation during the harbor operation.

Option 1: diesel generator supplying load

The first option is to let one small generator supply all the load. This imply similar operation for the hybrid and the non-hybrid case. It should for the same reasons also be assumed that the factor used to calculate the maintenance cost is equal for the hybrid and non-hybrid case. As a result, the operational costs in harbor are equivalent for the hybrid and the non-hybrid machinery configurations.

Option 2: plug-in hybrid with shore power

The second option is to connect to shore power as described in Section 2.1.3. As the cost of electricity in Norway is cheap, this is as seen from Table 5.11 a by far more economic favorable option. A total 78.6% reduction in operational costs are obtained with shore power. This will however demand that the infrastructure is in place in the relevant ports.

Cost [USD]	Non-hybrid/Hybrid opt. 1	Hybrid opt. 2
Fuel cost	2,515,500	-
NOx taxes	460,000	-
Maintenance	209,500	-
Lifetime operational costs	3,185,000	681,500

Table 5.11: Costs generated from operation in harbor over the vessel lifetime considering shore power and use of genset.

5.6.7 Manoeuvring at Quayside

Due to redundancy demands, the Blue Queen is originally operated with two small diesel generators despite a low power demand. The hybrid configuration however, derive advantage from having the the battery in stand-by, and can operate with one small genset. The load demand and the produced power are seen in Figures 5.29 and 5.30 respectively.

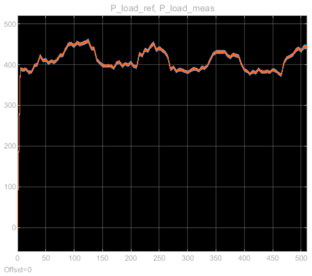


Figure 5.29: Load demand during manoeuvring at quayside.

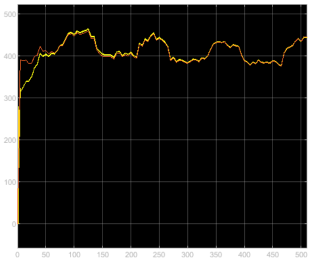


Figure 5.30: Reference and generated power by genset 4.

The alteration in power generation performed for the hybrid case involve a 13.86% reduction in both fuel costs and NOx taxes. The greatest expenditure cut is however related to the maintenance cost, which obtains a 57.2% reduction. This is due to the reduction in running hours as one genset is removed, and indirectly due to the fact that the remaining genset operational point is closer to the optimal level. The latter is takes effect through a lower maintenance factor. The results from maneuvering at quayside is presented in Table 5.12.

Cost [USD]	**Non-hybrid**	**Hybrid**
Fuel cost	183,000	158,000
NOx taxes	33,000	29,000
Maintenance	18,000	7,800
Lifetime operational costs	234,000	194,800

Table 5.12: Costs generated by manoeuvring at quayside over the vessel lifetime.

5.6.8 Summary of Simulation Results

The results from the comparative study are presented in Table 5.13. Negative numbers imply a reduction due to the implementation of the battery. Two cases for hybrid power generation are considered. The difference between the two are related to the power supply in the two operational states DP low and harbor which are combined in this summary.

In the first case the harbor operation is assumed to be powered by one small genset. This is the same set-up as the non-hybrid configuration, and consequently no expenditure cuts are obtained. In order to avoid harmful genset operation during DP low, the gensets produce an excess of power used to charge the battery. The results indicate a substantial increase in fuel related costs. This case where costs during DP low are increased, and costs in harbor remains the same, obtains a minimal increment of 0.07% in the total operational costs. Hence, the investment in a battery system is not justified with lower operational costs.

In the other case considered, the harbor operation is powered by shore power and the battery is not charged during DP low operation. This way of operating indicates a operational saving potential of 3,76 million USD. Considering the battery system prices as presented in Section 5.2, this case justifies the investment of batteries.

Operational state	**Difference [USD]**	**Difference [%]**
Transit low	-443,000	-2.4
Transit high	-172,500	-8.3
DP low	1,097,000 / -192,500	17.9 / -3.1
DP high	-406,000	-2.3
Harbor	0 / -2,503,500	0 / -78.6
Maneuvering at quayside	-39,800	-17
Total operational difference	35,600 / -3,757,000	0.07 / -7.8
Total cost difference	2,055,000 / -1.738,000	4 / -3.5

Table 5.13: Operational difference between hybrid and non-hybrid operation over the vessel lifetime.

It is the duration of an operational state which to a large extent determines the saving potential rather than the percentage in which the costs in the state is reduced. This is especially evident for transit low which is only able to reduce the costs with 2.4%, but as this state constitutes 25% of the vessel operation the total savings is close to 450,000 USD. On the other hand, maneuvering at quayside which reduces costs with 17%, generates a saving potential of less than 40,000 USD as it only constitute 1% of the total operation.

The cost development over the vessel's lifetime is plotted in Figure 5.31.

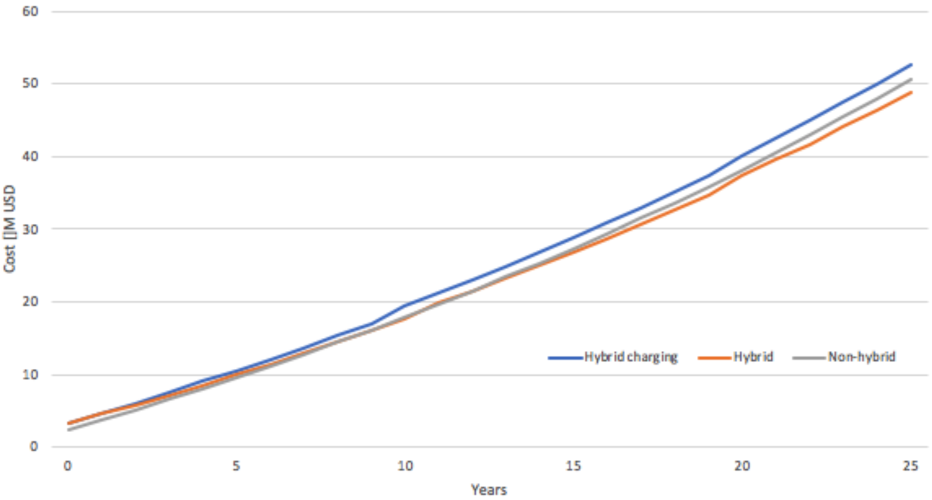


Figure 5.31: Cost development over the vessel's lifetime.

Extensive research has been performed as a part of this master thesis in order to highlight the advantages a battery may bring to a hybrid electric machinery. The benefits involve peak shaving, load levelling, spinning reserve, avoiding harmful genset loading and also to pose a propitious effect on the environment. The simulation results may give an indication of the impact a battery may have in a PSV.

Operation in transit low as well as maneuvering at quayside shows that utilising the battery as spinning reserve may improve the economic performance. During DP high, its ability to deliver power during stand-by is tested. The battery responds quickly, and is able to provide the requested power

In DP low the battery is used to avoid harmful operation of the gensets. However, this will incur a substantial increase in operational costs compared to the non-hybrid configuration, resulting in a increased fuel costs and negative environmental effects. On the other hand, by utilizing shore power when in ports one may substantially reduce the local emission of GHGs while simultaneously avoiding the damaging genset loading area.

The battery's peak shaving and load levelling abilities are tested during DP low and transit high. The battery responds quickly and is to a great extent able to absorb the load fluctuations. The observed deviations from the references are due to controller tuning, not the battery itself.

During the fluctuating load section tested in model and PEMS verifiction it is observed that it is not quite able to supply the highest peaks, but this is due to the PEMS restricting its c-rate. It is however able to reduce the load peaks imposed on the gensets considerably.

5.7 Discussion

The results of the optimization model gave a battery size of 200 kW, which is used in the in the simulation model. A weakness of the optimization model is that it is very sensitive to the set charging intervals. The size is optimized in order to meet a certain power demand in kW, while the battery cost is measured per energy amount provided in kWh. Altering the charging interval will consequently result in large variations in investment costs of the battery. Moreover, the results may be misleading as the relation between power and energy is not necessarily linear. This relation is not considered in this optimization model.

The results from the optimization process are considerably higher than those obtained from the simulation model. The main reason to this is that the power demands used in the optimization are averaged data based on general PSV data, while the simulation data is an extract from the operation of one particular vessel. The optimization data exceeds the power demands used in the simulations for most operational states, resulting in higher fuel operational costs. A relevant question is whether the simulated ranges really fall in under the states they are supposed to represent. Based on input from the industry the load demand observed during transit high is considerably lower than what can be expected during this state. It may be explained by the fact that it is rather an exception than common practice for a PSV to operate in this operational state, and this state might not have been captured in the Blue Queen raw data.

A drawback with the state-based PEMS is that the states, which are essential for the efficiency of the control system, are set based on empirical or heuristic data. The quality of the PEMS is consequently dependent on the designer's familiarity with the system's operation. The model may as a result provide an improved and satisfactory solution, but it is not necessarily the optimal solution. Several PEMS strategies should be tested in order to determine the solution that optimizes the machinery's performance.

As mentioned in Section 5.6, it is observed a deviation in the reference and the produced or absorbed power. The energy sources are however able to follow the fluctuations of their references, which might suggest that the error can be fixed by tuning of the local PID controllers. The integral term is used to correct steady-state errors. This was attempted without success. Tuning of PID controller may in many cases be highly time-consuming process, and is suggested for further work.

In order to capture the dynamics of the system the simulation time becomes highly extensive. Due to time constraints, the model was only run for short, averaged load data sections. The drawback of this solution is that the effect of the battery is not correctly accounted for. As the duration of the simulation is not sufficient in order to either charge or discharge the battery fully, the calculated fuel consumption corrected for the entire operation will therefore not be correct. The operational states where the battery is charged will therefore obtain a higher fuel consumption, while discharging will have the opposite effect. The battery is charged during DP low operation, and discharged during transit high. The duration of these states is 15% and 2% respectively, which indicates that the battery is charged substantially more than it is discharged. This will produce conservative results concerning the potential savings generated from hybrid operation. This may however not be the case for other operational profiles. As the effect of the battery is not accounted for properly, the benefit of an optimization model is also reduced.

An alternative that could decrease the time consumed to perform an analysis on fuel consumption during dynamic load, is to create an efficiency model based on algebraic expressions. This was however considered to constitute a much smaller work load with a lesser learning outcome and was therefore disregarded. Another option could be to develop a simplified simulation model where the time-consuming Simulink components are left out and modeled otherwise. This was not performed due to time constraints.

A large part of the saving potential is observed within maintenance related costs. This is to a large extent a result of the battery's ability to decrease the number and/or size of running gensets. The maintenance cost used in this study is measured as a function of installed power and running hours. The value is obtained from the industry, yet it could be interesting for further studies to investigate whether the ratio between installed power and maintenance really is strictly linear. Furthermore, a reduction in maintenance cost from 3.2 to 2.8 USD/kWh was assumed for hybrid operation. However, in the operational state DP low, two hybrid cases are tested. One involves operation below 20% of MCR, while the other case avoids this by charging the battery. It is then probable that the latter will decrease the maintenance costs. Whether this is able to balance the increased fuel related costs are not assessed.

Chapter 6

Conclusion and Further Work

The research question of this master thesis have been: *”What are the advantages and potential challenges of hybrid electric propulsion for large marine vessels?”* This section summarizes the main findings of the work performed in order to answer this question. Finally, some proposals for further work in relation to the topic is presented.

6.1 Conclusion

This thesis is motivated by the desire to highlight the advantages and potential challenges related to the implementation of batteries into hybrid electric propulsion systems. Another objective has been to develop a simulation model framework that may be used for analyzing hybrid electric propulsion systems. A case study has been conducted with this model to assess the feasibility of this propulsion system in a PSV.

The hybrid electric propulsion system offers a more economic, environmentally friendly and reliable operation than the conventional machinery system. This propulsion system is especially suitable for ships with demanding operations such as dynamic positioning as it may enhance control in terms of maneuvering and positioning abilities. Passenger and crew comfort may also be improved as noise and vibration levels are substantially reduced. Furthermore, the electrical propulsion system enables simple implementation of storage systems such as batteries, which offer additional advantages. Examples of battery advantages highlighted in the conducted literature study are reduced fuel costs and emissions and enhanced operation of gensets through peak shaving and load levelling. Prevailing challenges related to maritime batteries are expensive systems, low energy density, short lifetime expectancy and limited infrastructure.

The ship's control system manages and optimizes the distribution of power in a hybrid system. These systems are vital in order to exploit the advantages that each energy source and storage system offer as they often complement each other. Further development of the maritime power and energy management systems are necessary for optimizing the operation of complex hybrid propulsion systems. Efficient operation and power distribution can have a tremendous effect on a system's dynamic performance, its fuel consumption and the service life of the different energy sources.

This master thesis has contributed to the field by providing a simulation model that can be used for analyzing novel power system performance, estimation of fuel consumption and emission, as well as for control system development. It has a long running time, but the high detail level of the model is also what makes it valuable for system analysis and educational purposes. The model may be helpful for understanding and predicting the response of onboard power systems.

As part of this master thesis, a case study has been performed to verify the battery's ability to improve an engines operation and reducing operational costs. The results indicate that the battery has potential to reduce emissions and improve the operation of the prime movers in a hybrid electric power system. The case study also enlightens challenges related to optimal control and power flow related to the trade-off between reducing fuel consumption and consequently emissions, and decreasing harmful engine operation and the accompanying maintenance.

6.2 Future Work

This section provides a short description of some suggested topics for further work related to the research in this master thesis.

- Find measures to make model less time consuming. Suggestions include to develop an efficiency model based on algebraic equations or model the most time consuming components differently. This has the potential of increasing quality of the results as the effect of the battery will be better accounted for.

- Conduct a comparative study related to different control strategies in order to propose a method for optimal operation with respect to fuel consumption, battery cycling and engine maintenance.

- Include the effect of battery cycling and degradation for better estimation of the replacement time and cost of battery systems.

- Perform an analysis on the effect on maintenance of frequent start-up and shut down of gensets as a result of the implementation of batteries. This was not relevant to the present model as the simulation time was not sufficient to account for this effect.

- Investigate the relation between percentual loading of gensets and maintenance need.

- Improve optimization model in order for it to function as a tool for decision support in the design of hybrid propulsion systems.

- Perform laboratory tests to further investigate and verify the theoretical advantages of a hybrid electric propulsion system compared to a conventional propulsion system.

Bibliography

[1] J. s. Thongam, M. Tarbouchi, A. F. Okou, D. Bouchard, and R. Beguenane. *Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge - United Kingdom, 2013.

[2] DNV GL. *Sjøkart for grønn kystfart*. Grønt Kystfartsprogram, 2016.

[3] International Chamber of Shipping. *Shipping and World Trade*. [Online; accessed 08.10.2018]. URL: `http://www.ics-shipping.org/shipping-facts/shipping-and-world-trade`.

[4] IMO. *Third IMO GHG Study 2014*. [Online; accessed 06.10.2018]. URL: `http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Greenhouse-Gas-Studies-2014.aspx`.

[5] IMO. *Low carbon shipping and air pollution control*. [Online; accessed 19.02.2019]. URL: `http://www.imo.org/en/MediaCentre/HotTopics/GHG/Pages/default.aspx`.

[6] Lovdata. *Act relating to Norway's climate targets (Climate Change Act)*. [Online; accessed 19.02.2019]. URL: `https://lovdata.no/dokument/NLE/lov/2017-06-16-60`.

[7] G. M. of Climate and Environment. *Norway's climate target for 2030*. [Online; accessed 19.02.2019]. URL: `https://www.regjeringen.no/en/aktuelt/innsending-av-norges-klimamal-til-fn/id2403782/`.

[8] A. M. Bassam et al. "*Sizing optimization of a fuel cell/battery hybrid system for a domestic ferry using a whole ship system simulator*". 2016 International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC). 2016.

[9] DNV GL. "*DNV GL Handbook for Maritime and Offshore Battery Systems*". 2016.

[10] L. Guzzella, A. Sciarretta, et al. *Vehicle propulsion systems*. Vol. 1. Springer, 2007.

[11] E. B. Simonsen. *Hybrid Electric Ships: Energy Management and Optimal Design*. 2018.

[12] MIT Electric Vehicle Team. *A Guide to Understanding Battery Specifications*. [Online; accessed 08.04.2019]. URL: `http://web.mit.edu/evt/summary_battery_specifications.pdf`.

[13] Maritime Battery Forum. "Status of batteries on Ships". Maritime Battery Forum 06-07 March 2019. Bergen, Norway, 2019.

[14] O. A. Opdal and E. H. Steen. "Landstrøm i Norge. En studie av mulighene for landstrøm i Norge. Case: Hurtigruten". 2012.

[15] H.-M. Heyn. *TMR4290 – Marine Electric Power and Propulsion Systems*. 2019.

[16] H. Helgesen. "Electrical Energy Storage for Ships - Emsa Maritime Battery Study". Maritime Battery Forum 06-07 March 2019. Bergen, Norway, 2019.

[17] DNV GL. "*DNV GL Handbook for Maritime and Offshore Battery Systems*". 2016.

[18] DNV GL. "RULES FOR CLASSIFICATION: Part 6 Additional class notations. Chapter 2 Propulsion, power generation and auxiliary systems". In: (2015).

[19] DNV GL. *Global Sulphur Cap 2020 - extended and updated*. [Online; accessed 08.03.2019]. URL: `https://www.dnvgl.com/maritime/publications/global-sulphur-cap-2020.html`.

[20] Stortinget. *Klimastrategi for 2030 - norsk omstilling i europeisk samarbeid*. [Online; accessed 08.10.2018]. URL: `https://www.stortinget.no/no/Saker-og-publikasjoner/Vedtak/Vedtak/Sak/?p=69170`.

[21] Maritime Battery Forum. *Alternative Fuels Insight: overview over the uptake of batteries for ships*. [Online; accessed 24.03.2019]. URL: `https://afi.dnvgl.com/Statistics?repId=3`.

[22] Maritime Battery Forum. "*Batteries in Ships*". Landstrømsforum 12 April 2018. Oslo, Norway, 2018.

[23] T. Stensvold. *Disse 20 havnene får landstrøm-støtte fra Enova*. [Online; accessed 04.02.2019]. URL: `https://www.tu.no/artikler/disse-20-havnene-far-landstrom-stotte-fra-enova/396612`.

[24] E. Skjong et al. "Past, Present and Future Challenges of the Marine Vessel's Electrical Power System". In: (2016).

[25] E. B. Mehammer and O. Mo. "SINTEF Energy: A glimpse of maritime battery related research activities". Maritime Battery Forum 06-07 March 2019. Bergen, Norway, 2019.

[26] Z. Rodionova. *Half of all new cars in Norway are now electric or hybrid*. [Accessed 11.12.2018]. URL: `https://www.independent.co.uk/news/business/news/norway-half-new-cars-electric-hybrid-ofv-vehicle-registrations-a7615556.html`.

[27] M. Hand. *Norway seeking zero emissions from shipping*. [Accessed 11.12.2018]. URL: `http://www.seatrade-maritime.com/news/europe/norway-seeking-zero-emissions-from-shipping.html`.

[28] T. Stensvold. *I 2021 vil Norge ha 60 ferger med batterier. Nå må Vegdirektoratet finne en standardløsning for lading*. [Accessed 11.12.2018]. URL: `https://www.tu.no/artikler/i-2021-vil-norge-ha-60-ferger-med-batterier-na-ma-vegdirektoratet-finne-en-standardlosning-for-lading/414997`.

[29] Safety 4 Sea. *Are electric vessels the future of shipping?* [Accessed 11.12.2018]. URL: `https://safety4sea.com/are-electric-vessels-the-future-of-shipping/`.

[30] V. Shipping. *Efficiency Improvements to Main Engine Auxiliary Systems*. [Online; accessed 13.03.2019]. URL: `http://www.veus-shipping.com/2017/08/efficiency-improvements-to-main-engine-auxiliary-systems/`.

[31] DNV GL. *The future is hybrid*. 2015.

[32] R. Prenc, A. Cuculić, and I. Baumgartner. "*Advantages of using a DC power system on board ship*". In: *Pomorski zbornik* 52.1 (2016), pp. 83–97.

[33] B. Zahedi, L.E. Norum, K.B. Ludvigsen. "Optimized efficiency of all-electric ships by dc hybrid power systems". In: *Journal of power sources* 255 (2014), pp. 341–354.

[34] ABB. *Onboard DC Grid - The step forward in Power Generation and Propulsion*. 2011.

[35] Rohm Semiconductor. *DC-DC Converter*. [Online; accessed 08.11.2018]. URL: `https://www.rohm.com/electronics-basics/dc-dc-converters/what-is-dc-dc-converter`.

[36] Technopedia. *Rectifier*. [Online; accessed 08.11.2018]. URL: `https://www.techopedia.com/definition/681/rectifier`.

[37] Technopedia. *Power Inverter*. [Online; accessed 08.11.2018]. URL: `https://www.techopedia.com/definition/8597/power-inverter`.

[38] J. Han, J.-F. Charpentier, and T. Tang. "An energy management system of a fuel cell/battery hybrid boat". In: *Energies* 7.5 (2014), pp. 2799–2820.

[39] M. K. Zadeh. "*Stability Analysis Methods and Tools for Power Electronics-Based DC Distribution Systems, Applicable to On-Board Electric Power Systems and Smart Microgrids*". 2016.

[40] M. K. Zadeh et al. "Stability analysis of hybrid AC/DC power systems for more electric aircraft". In: *Applied Power Electronics Conference and Exposition (APEC), 2016 IEEE*. IEEE. 2016, pp. 446–452.

[41] K. Caird. *Energy Management Systems (EMS) Introduction*. [Online; accessed 03.11.2018]. URL: `https://web.stanford.edu/class/archive/ee/ee392n/ee392n.1116/Lectures/EE392n_Lecture5GE.pdf`.

[42] P. L. L. Rosario. "*Applying management methodology to electric vehicles with multiple energy storage systems*". In: *Machine Learning and Cybernetics, 2007 International Conference*. Vol. 7. IEEE. 2007, pp. 4223–4230.

[43] O. Mo and G. Guidi. "*Design of Minimum Fuel Consumption Energy Management Strategy for Hybrid Marine Vessels with Multiple Diesel Engine Generators and Energy Storage*". In: *2018 IEEE Transportation Electrification Conference and Expo (ITEC)*. IEEE. 2018, pp. 537–544.

[44] M. K. Zadeh. *TMR4290 – Marine Electric Power and Propulsion Systems*. 2018.

[45] D. Radan. *Integrated control of marine electrical power systems*. 2008.

[46] M. A. Hannan et al. "State-of-the-Art and Energy Management System of Lithium-Ion Batteries in Electric Vehicle Applications: Issues and Recommendations". In: *IEEE Access* 6 (2018), pp. 19362–19378.

[47] Control Solutions Minnesota. *Anatomy Of A Feedback Control System*. [Online; accessed 11.04.2019]. URL: `https://www.csimn.com/CSI_pages/PIDforDummies.html`.

[48] Wärtsilä. *Wärtsila 26 product guide*. [Online; accessed 27.03.2019]. URL: `https://www.wartsila.com/docs/default-source/product-files/engines/ms-engine/product-guide-o-e-w26.pdf?utm_source=engines&utm_medium=dieselengines&utm_term=w26&utm_content=productguide&utm_campaign=msleadscoring`.

[49] The MathWorks, Inc. *Implement generic battery model*. [Online; accessed 20.02.2019]. URL: `https://se.mathworks.com/help/physmod/sps/powersys/ref/battery.html`.

[50] D. Park and M. Zadeh. "Dynamic Modeling and Stability Analysis of Onboard DC Power System for Hybrid Electric Ships". 2019 IEEE Transportation Electrification Conference and Expo (ITEC). 2019.

[51] U. S. AS. *BLUE QUEEN (KASTEELBORG)*. [Online; accessed 06.02.2019]. 2018. URL: `https://ulstein.com/references/blue-queen`.

[52] M. J. Heian. "Factors Influencing Machinery System Selection for Complex Operational Profiles". MA thesis. Norwegian University of Science and Technology. Department of Marine Technology, 2014.

[53] S. Norway. *Priser på kraft og nettleie. Øre/kWh*. [Online; accessed 01.04.2019]. URL: `https://www.ssb.no/300119/priser-pa-kraft-og-nettleie.ore-kwh-sa-246`.

[54] Bunkerworld. *Fuel prices*. [Online; accessed 19.02.2019]. URL: `http://www.bunkerworld.com/prices/`.

[55] Wärtsilä. *Wärtsilä 26 - Product Guide*. [Online; accessed 14.02.2019]. URL: `https://www.wartsila.com/docs/default-source/product-files/engines/ms-engine/product-guide-o-e-w26.pdf?utm_source=engines&utm_medium=dieselengines&utm_term=w26&utm_content=productguide&utm_campaign=msleadscoring`.

[56] Sjøfartsdirektoratet. *Utslipp til luft*. [Online; accessed 20.03.2019]. URL: `https://www.sdir.no/sjofart/fartoy/miljo/forebygging-av-forurensning-fra-skip/utslipp-til-luft/#NOx_-_nitrogenholdige_oksider`.

[57] Skatteetaten. *NOx-avgift*. [Online; accessed 20.03.2019]. URL: `https://www.skatteetaten.no/bedrift-og-organisasjon/avgifter/saravgifter/om/nox/`.

[58] K. Flugsrud, B. Hoem, and K. Aasestad. "*Utslipp til luft av NOx fra innenriks sjøfart og fiske*". 2010.

[59] H. Jordheim. *Prishopp på klær løftet inflasjonen*. [Online; accessed 19.02.2019]. URL: `https://e24.no/makro-og-politikk/inflasjon/sterkere-prisvekst-enn-ventet/24461701`.

[60] B. D. Solomon and K. Krishna. "The coming sustainable energy transition: History, strategies, and outlook". In: *Energy Policy* 39.11 (2011), pp. 7422–7431.

[61] Offshore Engineering. *Introduction to Dynamic Positioning*. [Online; accessed 19.02.2019]. URL: `https://www.offshoreengineering.com/`

education/dynamic-positioning-dp/what-is-dynamic-positioning.

[62] Engineer Excel. *Excel solver: which solving method should I choose?* [Online; accessed 24.04.2019]. URL: https://www.engineerexcel.com/excel-solver-solving-method-choose/.

Appendix

Appendix A - Data for non-hybrid case

```
data = dlmread('Blue_Queen_data_1.csv',';');
gen = data(:,1:4);

%10 sec
j=1;
A1 = zeros(4,(length(gen)-1)/2)';
for i = 1:2:(length(gen)-1)
    A1(j,:) = (gen(i,:) + gen(i + 1,:))/2;
    j = j + 1;
end

%20 sec
j=1;
A2 = zeros(4,(length(A1)/2))';
for i = 1:2:(length(A1)-1)
    A2(j,:) = (A1(i,:) + A1(i + 1,:))/2;
    j = j + 1;
end

%40 sec
j=1;
A3 = zeros(4,(length(A2)-1)/2)';
for i = 1:2:(length(A2)-1)
    A3(j,:) = (A2(i,:) + A2(i + 1,:))/2;
    j = j + 1;
end

%------------input operational state------------
state = A3();


Gen1 = state(:,1);
Gen2 = state(:,2);
Gen3 = state(:,3);
Gen4 = state(:,4);

Time1=0;
```

```
Time2=0;
Time3=0;
Time4=0;

for k = 1:length(Gen1)
        if Gen1(k) <= 0
           Gen1(k) = 0;
        end
        if Gen1(k) ~= 0
            Time1=Time1+1;
        end


        if Gen2(k) <= 0
           Gen2(k) = 0;
        end
        if Gen2(k) ~= 0
            Time2=Time2+1;
        end


        if Gen3(k) <= 0
           Gen3(k) = 0;
        end
        if Gen3(k) ~= 0
            Time3=Time3+1;
        end


        if Gen4(k) <= 3
           Gen4(k) = 0;
        end
        if Gen4(k) ~= 0
            Time4=Time4+1;
        end
end
```

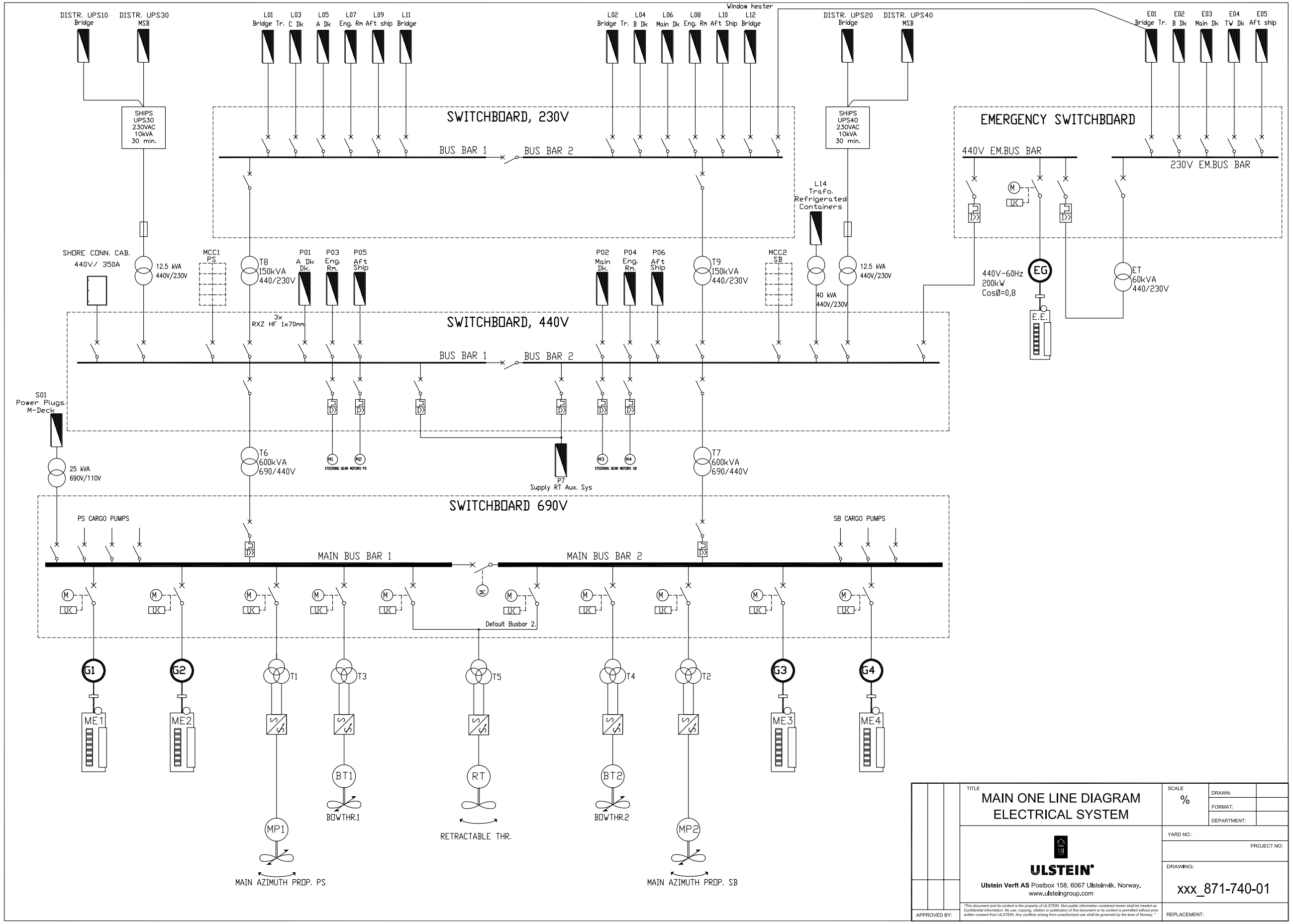
Appendix B - Calculation of hybrid case

```
%--------------Fuel consumption--------------
FuelPrice = 600; %USD/ton
Gen1r = 2350; %kW
Gen2r = 994;  %kW


%-------Time factor: hybrid or non-hybrid----------
if exist('Time1','var') == 1  %non-hybrid
    tf = 40; %(sampling time = 40s)


SFC1 = (tf/3600).*(0.007641992882562400.*((100.*Gen1)/Gen1r).^2 ...
     - 1.383733096085400000.*((100.*Gen1)/Gen1r)+252.433185053380000000);
SFC2 = (tf/3600).*(0.007641992882562400.*((100.*Gen2)/Gen2r).^2 ...
     - 1.383733096085400000.*((100.*Gen2)/Gen2r)+252.433185053380000000);
SFC3 = (tf/3600).*(0.007641992882562400.*((100.*Gen3)/Gen2r).^2 ...
     - 1.383733096085400000.*((100.*Gen3)/Gen2r)+252.433185053380000000);
SFC4 = (tf/3600).*(0.007641992882562400.*((100.*Gen4)/Gen1r).^2 ...
     - 1.383733096085400000.*((100.*Gen4)/Gen1r)+252.433185053380000000);


else

tf = 8*10^-5; %(sampling time =10^-5 s, 5s*8->40s)
for i=1:length(Gen1)
        if Gen1(i) <= 1
        Gen1(i) = 0;
        end
        if Gen2(i) <= 1
        Gen2(i) = 0;
        end
        if Gen3(i) <= 1
        Gen3(i) = 0;
        end
        if Gen4(i) <= 1
        Gen4(i) = 0;
        end
    end

SFC1 = (tf/3600).*(0.007641992882562400.*((100.*Gen1)/Gen1r).^2 ...
     - 1.383733096085400000.*((100.*Gen1)/Gen1r)+252.433185053380000000);
SFC2 = (tf/3600).*(0.007641992882562400.*((100.*Gen2)/Gen1r).^2 ...
     - 1.383733096085400000.*((100.*Gen2)/Gen1r)+252.433185053380000000);
SFC3 = (tf/3600).*(0.007641992882562400.*((100.*Gen3)/Gen2r).^2 ...
     - 1.383733096085400000.*((100.*Gen3)/Gen2r)+252.433185053380000000);
SFC4 = (tf/3600).*(0.007641992882562400.*((100.*Gen4)/Gen2r).^2 ...
     - 1.383733096085400000.*((100.*Gen4)/Gen2r)+252.433185053380000000);



end


```

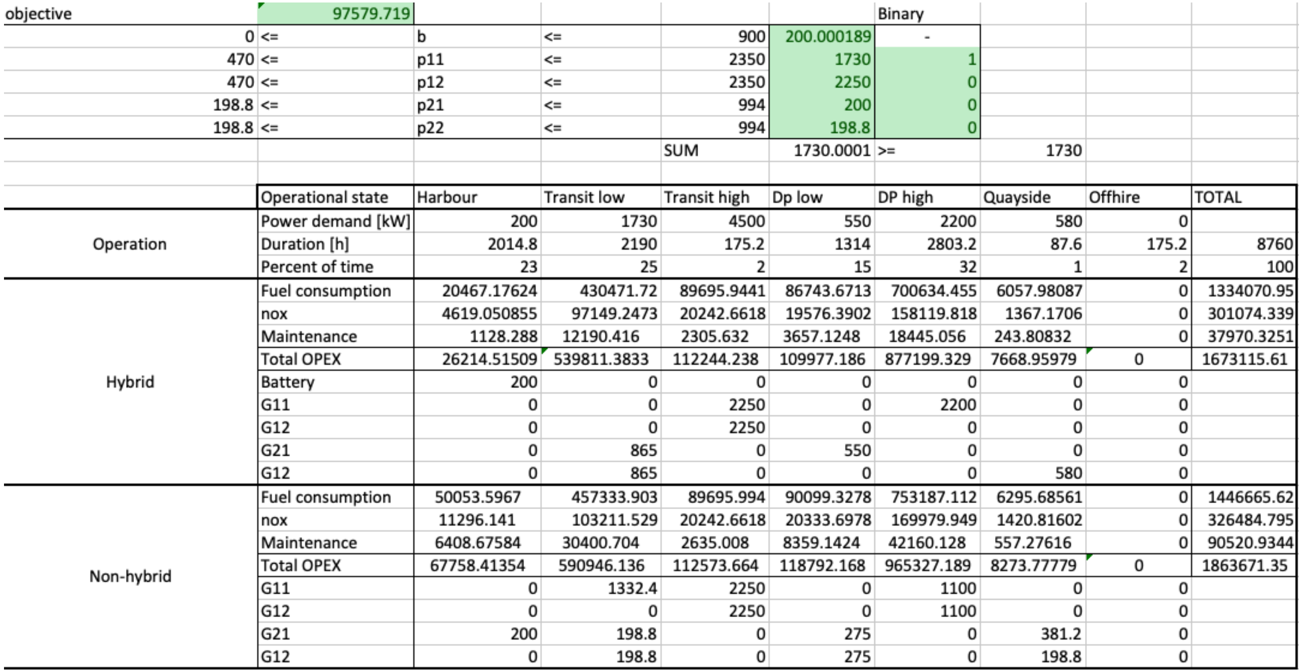
```
f1 = Gen1 .* SFC1;
f2 = Gen2 .* SFC2;
f3 = Gen3 .* SFC3;
f4 = Gen4 .* SFC4;

FC1 = sum(f1) * (1/10^6) * FuelPrice;
FC2 = sum(f2) * (1/10^6) * FuelPrice;
FC3 = sum(f3) * (1/10^6) * FuelPrice;
FC4 = sum(f4) * (1/10^6) * FuelPrice;

TOTFuel = FC1 + FC2 + FC3 + FC4;

%--------------NOx taxes--------------
Tax =  2.615; %USD/kg
NOxFuelRel = 0.0518;

NOx1 = sum(f1) * NOxFuelRel * Tax * (1/10^3);
NOx2 = sum(f2) * NOxFuelRel * Tax * (1/10^3);
NOx3 = sum(f3) * NOxFuelRel * Tax * (1/10^3);
NOx4 = sum(f4) * NOxFuelRel * Tax * (1/10^3);

TOTNOx = NOx1 + NOx2 + NOx3 + NOx4;

%--------------Maintainance--------------

%For hybrid case. (Duration already calculated for non-hybrid case)
if ~exist('Time1','var') == 1
    Time1 = 0;
    Time2 = 0;
    Time3 = 0;
    Time4 = 0;
    for i = 1:length(Gen1)
        if Gen1(i) >= 1
        Time1 = Time1 + 1;
        end
        if Gen2(i) >= 1
        Time2 = Time2 + 1;
        end
        if Gen3(i) >= 1
        Time3 = Time3 + 1;
        end
        if Gen4(i) >= 1
        Time4 = Time4 + 1;
        end
    end
    Time1 = Time1 * tf/3600;
    Time2 = Time2 * tf/3600;
    Time3 = Time3 * tf/3600;
    Time4 = Time4 * tf/3600;
    mCost = 0.0028; %USD/kWh
    Maint1 = Time1 * Gen1r * mCost;
    Maint2 = Time2 * Gen1r * mCost;
    Maint3 = Time3 * Gen2r * mCost;
    Maint4 = Time4 * Gen2r * mCost;
else
    Time1 = Time1*tf/3600;
    Time2 = Time2*tf/3600;
```

```
    Time3 = Time3*tf/3600;
    Time4 = Time4*tf/3600;
    mCost = 0.0032; %USD/kWh. Non-hybrid
    Maint1 = Time1 * Gen1r * mCost;
    Maint2 = Time2 * Gen2r * mCost;
    Maint3 = Time3 * Gen2r * mCost;
    Maint4 = Time4 * Gen1r * mCost;
end

TOTmaint = Maint1 + Maint2 + Maint3 + Maint4;
```

Appendix C - Electrical SLD



Appendix D - Initial optimization excel sheet



objective	97579.719					Binary			
0	<=	b	<=	900	200.000189	-			
470	<=	p11	<=	2350	1730	1			
470	<=	p12	<=	2350	2250	0			
198.8	<=	p21	<=	994	200	0			
198.8	<=	p22	<=	994	198.8	0			
				SUM	1730.0001	>=	1730		
	Operational state	Harbour	Transit low	Transit high	Dp low	DP high	Quayside	Offhire	TOTAL
Operation	Power demand [kW]	200	1730	4500	550	2200	580	0	
	Duration [h]	2014.8	2190	175.2	1314	2803.2	87.6	175.2	8760
	Percent of time	23	25	2	15	32	1	2	100
Hybrid	Fuel consumption	20467.17624	430471.72	89695.9441	86743.6713	700634.455	6057.98087	0	1334070.95
	nox	4619.050855	97149.2473	20242.6618	19576.3902	158119.818	1367.1706	0	301074.339
	Maintenance	1128.288	12190.416	2305.632	3657.1248	18445.056	243.80832	0	37970.3251
	Total OPEX	26214.51509	539811.3833	112244.238	109977.186	877199.329	7668.95979	0	1673115.61
	Battery	200	0	0	0	0	0	0	
	G11	0	0	2250	0	2200	0	0	
	G12	0	0	2250	0	0	0	0	
	G21	0	865	0	550	0	0	0	
	G12	0	865	0	0	0	580	0	
Non-hybrid	Fuel consumption	50053.5967	457333.903	89695.994	90099.3278	753187.112	6295.68561	0	1446665.62
	nox	11296.141	103211.529	20242.6618	20333.6978	169979.949	1420.81602	0	326484.795
	Maintenance	6408.67584	30400.704	2635.008	8359.1424	42160.128	557.27616	0	90520.9344
	Total OPEX	67758.41354	590946.136	112573.664	118792.168	965327.189	8273.77779	0	1863671.35
	G11	0	1332.4	2250	0	1100	0	0	
	G12	0	0	2250	0	1100	0	0	
	G21	200	198.8	0	275	0	381.2	0	
	G12	0	198.8	0	275	0	198.8	0	

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