Master's thesis

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

Tor Magnus Clemens Kvinnsland Michaelsen

Sizing Optimization of a Hybrid Shipboard Power System for Low-Emission Shipping

Master's thesis in Marine Technology
Supervisor: Mehdi Zadeh
Co-supervisor: Tarannom Parhizkar
July 2019

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MASTER THESIS IN MARINE TECHNOLOGY
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TOR MAGNUS CLEMENS KVINNSLAND MICHAELSEN
"Sizing Optimization of a Hybrid Shipboard
Power System for Low-Emission Shipping"

Background

Increased attention and effort have in the last decade been directed towards reducing the environmental footprint from the shipping industry. Through regulations, IMO (International Maritime Organization) has enforced a shift towards the utilization of shipboard power system technologies that emits less anthropogenic greenhouse gases, and from January 2020, the IMO 2020 regulative takes effect, reducing the allowed sulfur content in marine fuels from 3.5% to 0.5%. A large part of the global fleet is installing exhaust gas after-treatment systems to comply with the new regulative, as to be able to still use cheaper conventional fuel oils. In some segments, alternative technologies such as fuel cells and batteries are being implemented, as the technology is showing promising features and becoming more mature. Shipowners face a complicated task when deciding on the power system on newbuildings, ensuring that they comply with current - and possible future regulations.

Operations research (OR) and optimization models are extensively adopted to solve complex problems in the industry, where an objective is to be minimized or maximized. The maritime shipping industry, being highly competitive and cost-driven, is no exception, and a decision support tool in the form of an optimization model for the selection of the shipboard power system may be crucial for shipowners.

Objective

The objective of this thesis is to develop a decision support tool in the form of an optimization model for the shipboard power system for low-emission shipping. Fuel cells, batteries, and diesel engines are to be considered, with their technological and economical considerations and implications.

Scope of work

The candidate should cover the following topics:

a) Review topics relevant to a sizing optimization problem for low-emission shipping, including technological, regulatory and economical aspects.

b) Review previous work relevant to sizing optimization problems for shipboard power systems.

c) Based on the findings from a) and b), develop an optimization model for the machinery selection for a hybrid power system, with appropriate system boundaries, assumptions and approximations.

d) Illustrate the developed model's applicability by testing it in two future scenarios with different environmental regulations.

e) Evaluate the developed model with its approximations and limitations, as well as discuss possible recommendations and extensions for further work.

Modus operandi

Professor Mehdi Zadeh will be the supervisor, and Postdoc Tarannom Parhizkar will be the co-supervisor. The work shall follow the NTNU guidelines for master's thesis work. The workload shall correspond to 30 ECTS credits.

Zadeh

Mehdi Zadeh
Professor/Main supervisor

Preface

This thesis marks the final part of my Master of Science degree at the Norwegian University of Science and Technology, with a specialization in Marine Systems Design & Logistics. The thesis corresponds to a workload of 30 credits.

The objective of the thesis has been the development of an optimization model as a decision-making support tool for the selection of the shipboard power system in a low-emission context. A cost-optimal configuration of diesel engines, fuel cells and batteries have been sought with regard to initial costs, as well as costs incurring during the vessel's life-time.

The work has been highly rewarding, giving me knowledge about important aspects connected to emission reduction measurements in the maritime sector, the increased applicability of "new" technologies such as fuel cells and batteries with their opportunities and challenges, as well as practical experience in modeling and implementation of optimization problems.

I would like to thank my supervisors, Prof. Mehdi Zadeh and Postdoc Tarannom Parhizkar at the Department of Marine Technology (IMT) for helpful guidance and feedback throughout the project. In addition, I would like to thank Prof. Stein Ove Erikstad (IMT) for valuable modeling input and rewarding problem discussions, and Research Scientist Torstein Bø, at Sintef Ocean AS for helpful understanding of battery technology aspects.

Bergen, July 31, 2019

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Abstract

The selection of the shipboard power system is in its origin a complex task. Ships are designed with a lifetime of 20-25 years in mind, and may therefore be exposed to both changing operational demands as well as fuel prices and regulations. Technological development of power electronics has enabled an increased utilization of alternative solutions to the conventional direct-drive shipboard power system. One example is hybrid diesel-electric power generation in combination with energy storage systems to reduce fuel oil consumption. Increased pressure from IMO to fulfill its commitment to reduce the emissions of greenhouse gases by at least 50% by 2050, combined with technological advances in fuel cell- and battery technology, has led shipowners in some segments to explore the possibilities for utilizing hybrid fuel cell- battery systems for the shipboard power system.

With the introduction of fuel cell- and battery technology, new aspects as replacement costs due to performance degradation of the systems need to be accounted for in the power system selection problem. The extent to which the fuel cell- and battery systems need to be replaced is dependent on how they are used. This is in contradiction to diesel engines, that are designed to last for the ship's entire lifetime, only requiring periodic maintenance. With this complex task in mind, a decision support tool in the form of a deterministic optimization model for the selection of the shipboard power system for low-emission shipping has been developed, considering fuel cells, batteries and diesel engines.

The lifetime of a vessel is modeled as consisting of two time periods lasting 10 years each. In each time-period, a typical roundtrip have been assumed and synthesized into different operational modes. Each mode can be represented with its respective load profile and ratio of total time spent to the total duration of a roundtrip in that time-period. The optimization model takes into account the power demand in the various operational modes as the governing constraints to be fulfilled. Possible variations in contract descriptions, prices on fuel and emission tax regulations are included in the time-period formulation. The model is a linear deterministic problem, where the objective function is to minimize the total costs of the vessel during its lifetime. This consist of investment costs, fuel- and emission costs subject to price and tax variations, and maintenance and replacement costs. Specific operational requirements such as fuel compliance in Emission Control Areas (ECA) and eventual electricity-only modes are also considered.

The optimization model is tested in two scenarios. In the first scenario, no increase in regulations is assumed after the IMO2020 regulative takes effect, while fuel prices are expected to increase and electricity expected to decrease. For simplicity, the same fuel price development is expected in scenario 2. However, stricter environmental regulations are assumed in the form of a global tax on carbon dioxide (CO_2) and enforced electricity modes in ECA's are introduced. Somewhat surprising, a combination of all three power systems is selected for both scenarios by the model. This may be explained, however, by the trade-offs between the cost-contributions and the fact that no restrictions on available machinery space are applied. Diesel engines need to be used with expensive fuels in ECA's, and batteries and fuel cells may therefore be more favorable in these modes. However, as fuels considered for fuel cells inhibit lower volumetric energy densities than conventional fuel oils for diesel engines, storage - and storage tanks - cannot be neglected. Increased utilization of fuel cells require more tank capacity, at an increased tank investment cost. In a similar fashion, increased utilization of electricity from batteries may rapidly require additional battery stacks to be installed to provide the required energy. Another contributing factor may be the assumed prices, in addition to the regulations themselves.

To the author's knowledge, little work has previously been done including all the aforementioned

factors in a sizing optimization study for low-emission shipping where fuel cells and batteries are included. Several factors and aspects have needed to be simplified, and assumptions have been made due to limited data and information.

Some aspects also needed to be left out due to the magnitude of the problem, and the model is subject to further expansion and development. It should also be mentioned that a nonlinear model was first developed to be utilized in a Genetic Algorithm (GA) in the optimization toolbox in the programming software Matlab. The algorithm was not able to find a solution, however, as there were too many integer variables. Therefore, a linearized version of the model had to be developed. Due to the linearization, several additional variables had to be introduced. This increases the running time, and a scale-down of the problem was needed, in addition to setting a limit for how long the model should run. In light of this, a reformulation of the problem may decrease running time and improve accuracy. Alternatively a nonlinear implementation in a different heuristic nonlinear optimization algorithm could be performed. Although several uncertainties exist, and improvements can be made, the model illustrates important aspects that need to be taken into account for the decision of the power system for low-emission shipping. Thus the model provides a foundation for the understanding of the problem as well as for further research on this topic.

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Acronyms

IMO	International Maritime Organization
OR	Operations Research
ECA	Emission Control Area
GA	Genetic Algorithm
GHG	Greenhouse gas
GDP	Gross domestic product
NOx	Nitrogen oxides
SOx	Sulfur oxides
MARPOL	International Convention for the Prevention of Pollution from Ships
EEDI	Energy Efficiency Design Index
MDO	Marine diesel oil
HFO	Heavy fuel oil
LNG	Liquid natural gas
MCR	Maximum continuous rating
AC	Alternating current
DC	Direct current
ICE	Internal combustion engines
AIP	Air Independent Propulsion
CO	Carbon monoxide
DoD	Depth of discharge
SOC	State of charge
LT-PEMFC	Low-temperature polymer membrane fuel cell
HT-PEMFC	High-temperature polymer membrane fuel cell
SOFC	Sulfur oxide fuel cell
BOP	Balance of plant
GA	Genetic algorithm
ACO	Ant colony optimization
PSO	Particle swarm optimization
Ah	Ampere-hours
SFC	Specific fuel consumption
SFOC	Specific fuel oil consumption

ULSFO	Ultra low sulfur fuel oil
EMS	Energy management strategy
SOS2	Special ordered sets of type 2
LH2	Liquid hydrogen
CH4	Methane
CO2	Carbon dioxide

Chapter 1

Introduction

1.1 Shipping and emissions

Due to the large carrying capacity for vessels, and their low fuel consumption per ton transported, shipping is considered the most energy-efficient and cost-effective means of transportation compared to road and air transport ([11]), allowing large amounts of goods and raw materials to be moved around an increasingly globalized world for a low cost. The ocean-going international trade accounts for 70% of the total world trade in terms of value, and 80% in terms of volume ([17]).

In 2012, 2.6% of the global greenhouse gas (GHG) emissions on a CO_2 equivalent basis originated from the shipping industry. This is a reduction from 3.5% of the global emissions in 2007 ([16]). The reduction can be explained by an increase in vessel size and lower operational speeds ([16]). From among the above-mentioned factors, ocean-going vessels are the preferred mode of transportation of goods from an energy-efficient and thereby emissions-efficient point of view, and its contribution to the annual anthropogenic greenhouse gas emissions may seem of minor importance. However, world trade and global gross domestic product (GDP) have had a historic relationship in growth for the last 40 years ([72]). If the the world trade increases to its triple by 2050 as expected and no emission abatement measures are implemented, future emissions are expected to increase by 150-250% by 2050, ([19]),([63]).

Recent commitment from nations signing the Paris Convention - to limit the increase in global temperatures to well below 2 degrees by the year 2100 - points toward an agreement that business-as-usual is not an option. This is also reflected in the high ambitions from IMO of emission reductions from shipping. In 2018, IMO set a goal to reduce GHG emissions from shipping by at least 50% by 2050, taking 2008 as a baseline year ([29]). The shipping industry is thus facing a complex challenge, due to the conflict between providing more of its services due to the increase in GDP, at the same time as significantly reducing emissions ([63]).

Current emission regulations already exist, covering the emittance of nitrogen oxides (NOx) and sulfur oxides (SOx). In the period 2007-2012, shipping accounted for 15% of global NOx emissions and 13% of SOx emissions, known to cause photochemical smog and acid rain ([65]), ([40]). The emissions of NOx and SOx have been subject to regulation since 1983, through the International Convention for the Prevention of Pollution from Ships (MARPOL) ([53]).

More specifically, limits on NOx emissions are regulated taking the ship's construction date, diesel engine speed and operation area into account. SOx emissions are regulated through an upper limit on the sulfur content of the marine fuel used. The extent of the regulations depends on whether the vessel is operating in ECA's (21) or not, where if a ship is passing through an ECA on its route, it needs to comply with the current emission regulations that apply there. The regulations have periodically become stricter. Outside ECA's, the cap on sulfur content was restricted to not exceed 3.5% from 2012, while inside ECA's the cap on sulfur content in marine fuels was set to 0.1%. From January 1st, 2020, a global cap on the sulfur content in marine fuels takes effect, limiting the fuels to not contain sulfur levels exceeding 0.5% (43).

1.2 Emission reduction measures

Several means are possible to reduce emission levels from shipping. We can divide between operational and technical measures (62). Operational measures can be interpreted as reducing emissions by operating a ship or a fleet of ships in an optimal way regarding speed, routing, and optimal energy management, making the best use of existing components. Technical measures will typically be engine related improvements as more efficient propulsion and power systems, more energy-efficient design or installing exhaust gas after-treatment systems (16),(73). Many of the engine improvements will have to be implemented in conjunction with each other to meet requirements and are likely to be increasing complexity, investment cost, maintenance, and fuel consumption (73). The industry is therefore to an increasingly extent investigating other alternatives for shipboard power systems, such as fuel cells and batteries.

Fuel cells, mainly fuelled by hydrogen only emits oxygen and water, and is a promising technology. Besides its emission reduction potential if renewable hydrogen is used, several other benefits from utilizing fuel cells exist: noise, modularity, as well as low conversion losses and thereby increased efficiency (73). Fuel cells are also attractive due to their low degree of variation of efficiency across most of their power range, in contradiction to conventional maritime power plants as internal combustion engines and turbines.

Although their range of promising features, fuel cells are not able to fulfill the requirements to ship operation to the fullest alone, due to their slow dynamics, and therefore need to be used in conjunction with energy storage systems (ESS) to be a viable option (35). Energy storage systems in the form of batteries are increasingly becoming installed in combination with conventional maritime power plants for several ship types. This is mainly attributed to the batteries positive impact on increased energy efficiency, as the internal combustion engine systems can be operating in their optimal range while the ESS can be utilized as a buffer in the case of peak demand or excess energy production. (41).

1.3 Power system selection

Jaurola et al. states that *"The different levels in the system design are choosing the system topology, sizing the components and controlling the components and they all depend on each other."*. In (20), three stages of design are defined - these are Concept design, Engineering design, and Production design.

Concept design consists of a functional analysis of the future ship, where one analyses the different alternatives at hand, regarding the major equipment. Traditionally, regarding the power system, whether to use electrical or mechanical propulsion and energy storage is decided in the concept design stage. However, limited information is available at this stage, which paradoxically is the stage where the most impactful decisions are made (7). Therefore, integrating the concept design stage with the engineering design stage may be beneficial as decisions can be made based on more information ([9]).

The selection has usually been constrained to selecting from within a small number of options. However, the emergence of alternative fuels and technology improvements offering various hybrid configurations causes the decision-making in the concept stage to become increasingly challenging ([38]).Many factors and variables need to be taken into account, and often conflicting objectives may need to be fulfilled, implying that trade-offs need to be made.

Decision-making problems such as these, with many factors and variables, can often be formulated mathematically and solved by optimization techniques to find the best feasible solution given the objectives and requirements ([32]). Shipping is, like the rest of the free market a highly cost-driven and competitive industry. Offering competitive prices is crucial to be able to stay in business. Although the green shift is needed, shipowners cannot select low-emission solutions based on idealism if this means running out of business. A framework for deciding on the cost-optimal power system is needed, and a decision support tool in the form of an optimization model is therefore suited for this problem, and the scope of this thesis.

1.4 Structure of the report

The rest of the thesis is structured as follows:

- **Literature review**

  Chapter 2 presents relevant topics that provide a foundation for the project. Environmental aspects, power system topologies, fuel cell technology, battery technology, previous work on related sizing optimization problems as well as hybrid electric power systems are covered.

- **Method**

  Chapter 3 outlines the modeling approach, with necessary assumptions, simplifications, and approximations, chapter 4 presents the developed model.

- **Case study and results**

  Chapter 5 presents the implementation of the model in two scenarios and the obtained selection of power system together with a discussion of the results.

- **Conclusion, discussion and further work**

  The optimization model is discussed in chapter 6, with the assumptions, simplifications and approximations made. Chapter 7 concludes the work done and outlines possible extensions and improvements for further work.

Chapter 2

Environmental aspects, green shipping solutions and sizing optimization

This chapter contributes to the understanding of relevant background information for the shipboard power system selection. Understanding the full picture is crucial to be able to make the right decisions about the modeling approach, i.e. what to include, system boundaries, simplifications and assumptions. First, environmental aspects are covered, followed by an introduction to current shipboard power system topologies and their aspects. Then fuel cell- and battery technology is reviewed, in addition to hybrid-electric power systems. Lastly, a literature review on sizing optimization problems is presented.

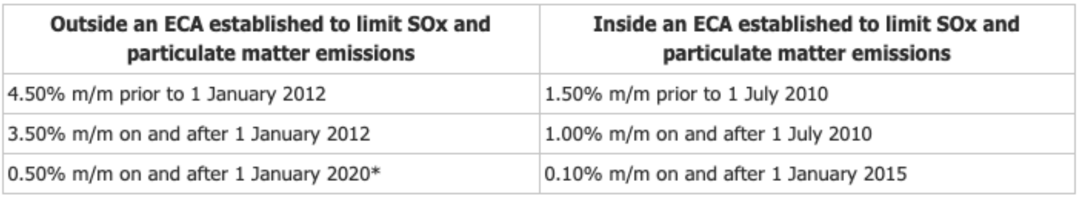
2.1 Environmental regulations

2.1.1 Marpol annex VI

The IMO's International Convention for the Prevention of Pollution from Ships (MARPOL) is an international instrument to prevent pollution of the marine environment from ships ([46]). Initially entering into force in 1983 as a response to several tanker accidents in the '70s, it has expanded to also cover pollution from normal operation, both to sea and air. There are six annexes, where Annex VI is directed towards limiting pollution of air from ships. Annex VI entered into force in 2005 and sets as mentioned in chapter 1.2 limits on the global SOx and NOx emissions from ship exhaust. In addition, certain ECA's are defined, where stricter regulations apply ([44]), ([45]).

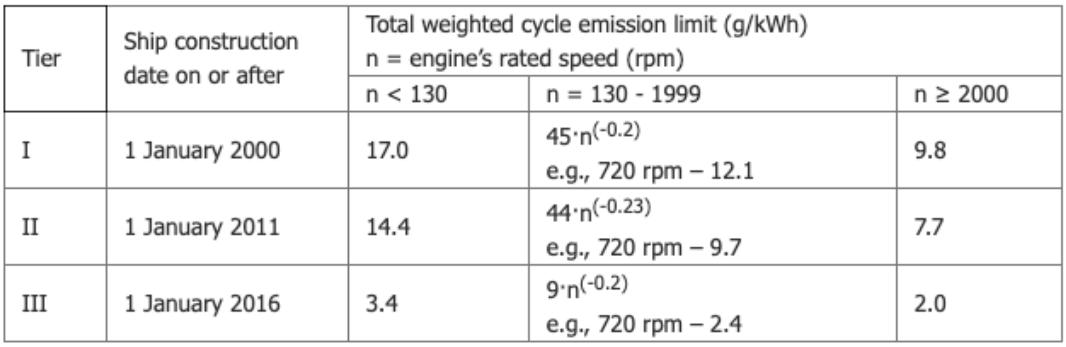
The regulations of SOx are limits on the percentage of sulfur allowed in the bunker fuel used. The regulations of NOx apply for ships with diesel engines with an output of more than 130kw. The limits are set on the weighted cycle nitrogen oxide emissions to air. In figure 2.1 regulations of sulfur content in marine fuels are shown, and in figure 2.2 the weighted cycle emission limit of nitrogen oxides are shown.

The regulations of emission of NOx are dependent on the ship's construction date – tier number – and the engine's rated speed. As can be seen in figure 2.1, a new global limit on sulfur content takes effect from January 1st, limiting the sulfur content from 3.5% to 0.5%. To comply with these regulations either the low sulfur fuel needs to be used, or appropriate exhaust gas after-treatment systems need to be installed ([27]). Figure 2.3 illustrates the implementation of ECA's and SECA's.



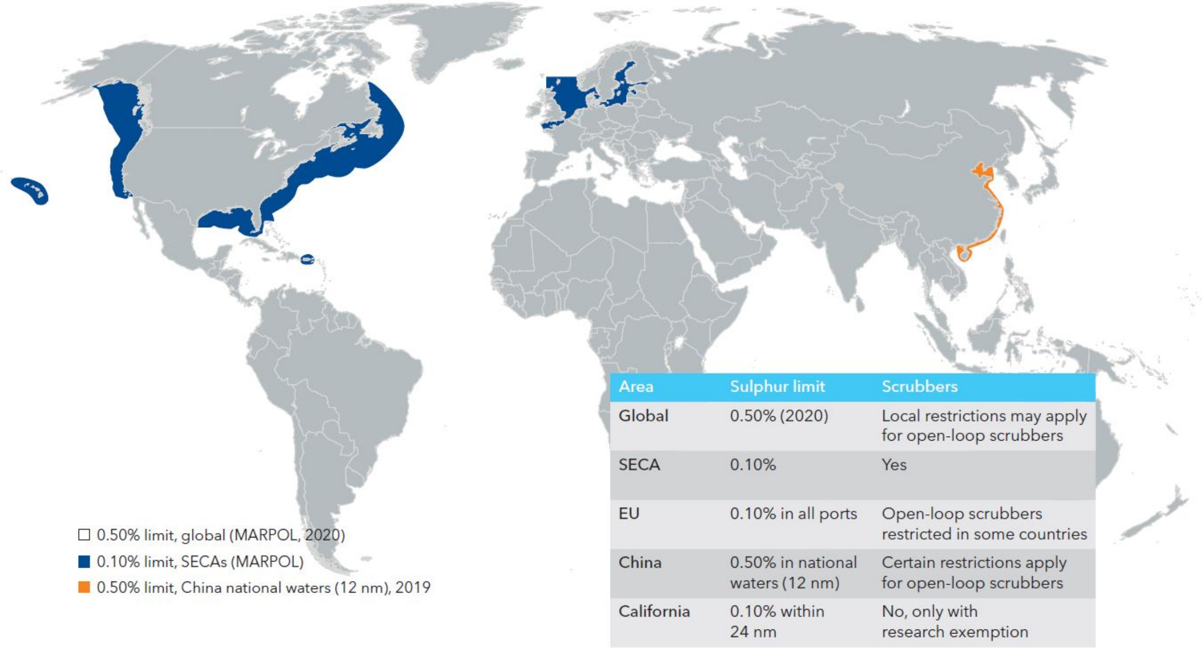
Outside an ECA established to limit SOx and particulate matter emissions	Inside an ECA established to limit SOx and particulate matter emissions
4.50% m/m prior to 1 January 2012	1.50% m/m prior to 1 July 2010
3.50% m/m on and after 1 January 2012	1.00% m/m on and after 1 July 2010
0.50% m/m on and after 1 January 2020*	0.10% m/m on and after 1 January 2015

Figure 2.1: Regulations on sulfur content in marine fuels, ([45]).



Tier	Ship construction date on or after	Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)		
		n < 130	n = 130 - 1999	n ≥ 2000
I	1 January 2000	17.0	$45 \cdot n^{(-0.2)}$ e.g., 720 rpm – 12.1	9.8
II	1 January 2011	14.4	$44 \cdot n^{(-0.23)}$ e.g., 720 rpm – 9.7	7.7
III	1 January 2016	3.4	$9 \cdot n^{(-0.2)}$ e.g., 720 rpm – 2.4	2.0

Figure 2.2: Regulations on weighted cycle emission limits for nitrogen oxides, ([44]).



Area	Sulphur limit	Scrubbers
Global	0.50% (2020)	Local restrictions may apply for open-loop scrubbers
SECA	0.10%	Yes
EU	0.10% in all ports	Open-loop scrubbers restricted in some countries
China	0.50% in national waters (12 nm)	Certain restrictions apply for open-loop scrubbers
California	0.10% within 24 nm	No, only with research exemption

Figure 2.3: Implementation of emission control areas in addition to sulfur content limitations, obtained from ([26]).

2.1.1.1 Energy Efficiency Design Index

In addition to regulations on emissions to air, an energy efficiency design index (EEDI) has been introduced in 2013, aiming at reducing the amount of GHG emissions. While this currently applies to cargo ships (container vessels, reefers, roll-on-roll-off (RO-RO) ships, etc.) and is related to the emissions produced per tonne of goods per mile, other ship types are planned to be included ([36]), ([55]). A specific figure for the ratio of the mass of CO_2 emitted to a ship's capacity-mile is calculated based on the technical design parameters for the design and is used as a basis for the EEDI. ([25]).

2.1.2 Economic incentives

Apart from legislative controls, economic incentives are also being applied to motivate industries to approach more sustainable propulsion solutions. In Norway, a tax on emissions of nitrogen oxides introduced in 2007 applies to ships, depending on the sector ([5]). The tax applies to vessels with an installed engine power of 750kW or more, and as of January 2019 the tax is 22.27 NOK/kg NOx emitted to air. Additionally, a special fund exists called the "NOx fund", in which a participating organization pays a fixed payment to the fund instead of paying the tax on NOx emissions. The intention is to create a foundation for innovation to reduce emissions. A participating organization can apply for subsidies to help to implement emission reduction measures ([6]).

2.2 Shipboard power systems topologies

Marine diesel engines – often referred to as a prime mover – have traditionally been coupled directly to the propellers via a shaft to provide propulsion, through a gearbox dependent on if it is a slow-speed or medium-speed engine. The prime mover converts chemical energy from an energy carrier, as marine diesel oil (MDO) or heavy fuel oil (HFO), through thermal energy to mechanical energy ([73]). Diesel engines have an optimal load range of operation where they are most fuel-efficient ([48]). This range is typically 70-100% of their maximum continuous rating (MCR). A distinction is usually made between the electrical power system for the propulsion loads and the service loads – often termed hotel loads. The power required for the hotel loads is typically produced by generator sets driven by combustion engines. Depending on the ship type, the auxiliary power demand may be a small or large fraction of the total power demand.

Direct mechanical propulsion provides high efficiencies around its design point. This is an advantage for vessels operating in most of their time in the corresponding load range. For vessels with a diverse profile however, the engines will be operated in periods with part-load with low efficiencies. Tugs for instance, with large variations in power demand from one operational mode to another, only require 20% of their installed power for transit ([48]). Lately, the development of power electronics has increasingly been applied to enable electrical propulsion to reduce efficiency losses connected to operation in part-load ([8]).

Marine diesel engines are as mentioned usually fueled by HFO or MDO. In terms of availability, both of these fuel types are commercially available worldwide and is thus a low-risk fuel option ([57]). Some engines may in addition to HFO and MDO utilize liquid natural gas (LNG), and are termed dual fuel engines. LNG is a gas mixture consisting of a variety of hydrocarbons and has been increasingly commercialized in the last decade ([57]).

In ([36]), different machinery topologies are reviewed, with their characteristics, applications, benefits and drawbacks, of which the following sections are based on, and Jafarzadeh and Schjølberg summarizes the different topologies in figure 2.4

2.2.1 Mechanical

The propeller, is as mentioned driven by the prime mover, either directly or through a gearbox. The auxiliary loads are provided by electric power distributed on a separate alternating current (AC) network, powered by auxiliary engines. Ships sailing at a single cruising speed - typically cargo ships and fast crew suppliers - are often utilizing this topology, as the fuel efficiency at their design speed is high.

Benefits

The efficiency of the system (at design speed) is high, as there are only three power conversion stages from converting chemical energy to propulsion power. These are the main engine, gearbox and propeller ([36]). The power system topology has low complexity, leading to low purchase costs

Drawbacks

The diesel engine's fuel consumption increases below 50% of their rated power, which leads to low fuel efficiency and increased emissions at sailing speeds below 70% of top speed ([36]). As the components in the drive train are directly coupled with each other, a failure of any of these components will cause loss of propulsion.

2.2.2 Electrical

In an electrical power system topology, electrical power is generated by diesel generator sets. The propulsion system and the auxiliary system draw their power from the same high voltage electrical bus. The high voltage is converted to lower voltage through a transformer, and the shaft line speed – and thus the ship's speed – is controlled by a power electronic converter. This topology is beneficial when the required auxiliary power is a large portion of the propulsion power, or if the operating profile is diverse ([36]). Typical vessels utilizing this topology are ferries, cruise vessels, ice breakers among others, and especially offshore installation vessels, due to the possibility to run redundant engines as a spinning reserve in dynamic positioning operation ([48]).

Benefits

As several engines are connected to the same bus, this topology enables running the diesel engines closer to their most fuel-efficient optimal point, reducing fuel costs and emissions ([36]). This topology also offers great flexibility in positioning the machinery spaces, as there is no shaft-line.

Drawbacks

The inclusion of additional conversion stages leads to increased losses, which may offset the fuel savings from the more optimal operation of the engines ([36]). The investment costs will in addition typically be high for an electrical propulsion topology, as several expensive electronic components are included.

2.2.3 Hybrid drive

In this topology, either a direct mechanical drive or an electric motor can be used to provide propulsion ([36]). The electric motor is connected to the main bus, in addition to being coupled to the same shaft as the direct mechanical drive – either directly or through a gearbox. At high speeds, high efficiency is obtained using the direct mechanical drive. At lower speeds the highest efficiency is obtained by using the electric motor, avoiding part load on the main engine. The electric motor can also be used to provide auxiliary power, converting mechanical energy from the main engine to electricity on the main auxiliary load network. Vessels with low auxiliary power demand relative to the propulsive power demand often choose this option, typically towing vessels, offshore vessels, naval frigates and destroyers.

Benefits

The hybrid drive topology benefits from the advantages of both the electrical and mechanical propulsion topology. As the auxiliary power is only a small fraction of the total propulsion power, this topology enables less electrical equipment compared to an electrical propulsion topology, and hence less investment cost as well as weight and size ([36]).

2.2.4 Electrical propulsion with hybrid power supply

This topology utilizes two or more power sources to generate the electrical power needed for propulsion loads and auxiliary loads ([36]). The power sources can be combustion power (diesel engines, gas turbines, steam turbines), electrochemical power (fuel cells) and stored power in energy storage systems (batteries, flywheels, capacitors). The benefits of hybrid power supply mostly arise from the usage of the ESS to obtain fuel savings, as the diesel engines can be operated closer to their optimal point. Batteries, in particular, may be used to provide backup power during a failure. Typically, in offshore operations, backup diesel engines are switched on as spinning reserve in case of failure. Other benefits are load leveling, covering power fluctuations by the ESS to reduce transient loading on the main power generators.

2.2.5 Hybrid propulsion with hybrid power supply

A hybrid propulsion with a hybrid power supply provides the choice of using either direct mechanical drive or electrical propulsion, depending on what the most fuel-efficient option is ([36]). Power can be produced from either combustion power or stored power from the energy storage system. A combination of power production from both power sources at the same time is also possible. Yachts and tugs are promising candidates for this propulsion system. *Damen* delivered the first tug with this propulsion topology in 2014 ([36]).

2.2.6 Electrical propulsion with dc hybrid power supply

Lastly, electrical propulsion with direct current (DC) hybrid power supply has recently been extensively applied to ferries and offshore vessels and is also used onboard drilling ships, research vessels and wind farm support vessels. This topology obtains increased fuel efficiency when running diesel engines in part load, in addition to reducing power conversion losses. Other benefits are reduced noise, vibration, thermal and mechanical loading. Its potential depends on whether a large amount of fixed frequency AC load needs to be fed, or if most of the load is fed through variable speed drives, where the latter gives the potential for cost reductions. Technological challenges have been the major obstacle for widespread use. Recent development in power electronics has enabled the increased application ([36]).

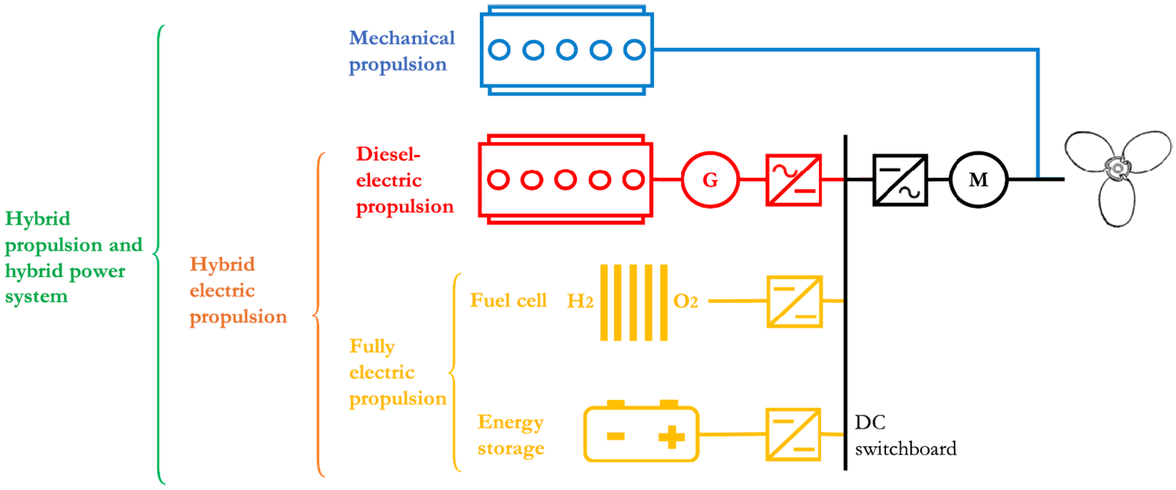


Figure 2.4: Illustration of the various power system topologies, obtained from ([48]).

2.3 Fuel cells

Fuel cells are not a new technology, already in 1842 William Grove invented fuel cells as an electricity generator ([4]). However, due to the success and efficiency of internal combustion engines (ICE), the application during the 20th century was limited to air-independent propulsion (AIP) in submarines ([71]). Lately, increased attention and effort has been applied in research on fuel cell systems for vehicle applications, and as of the beginning of September 2008, the first commercial fuel cell-powered passenger ship commenced in operation on the river in Alster in Hamburg, Germany ([74]).

2.3.1 Advantages and disadvantages of fuel cells

Compared to conventional diesel engines, fuel cells inhibit better fuel efficiency than internal combustion engines, as the chemical energy is converted directly to electrical energy without going through thermal and mechanical conversion. Based on lower heating value, the fuel to efficiency ranges from 40-60% (affected by the auxiliary components and need of reformer) ([74]). The efficiency remains mostly the same across their operating power range ([13]), and no moving parts lead to less maintenance and operation cost, compared to internal combustion engines. Drawbacks of fuel cell systems are their high initial investment costs as well as limited lifetime ([34]), often leading to a high number of system replacements dependent on the expected lifetime of the application. Fuel cells are as mentioned in 1.2 also known to have a time-delayed response ([70]), requiring them to be used in conjunction with an ESS to be able to cover large fluctuations, both providing power and absorbing excess power ([13]). The delayed dynamic response can be illustrated by figure 2.5, where the line for fuel cells shows that they are not able to provide the required power at the same rate as batteries and supercapacitors.

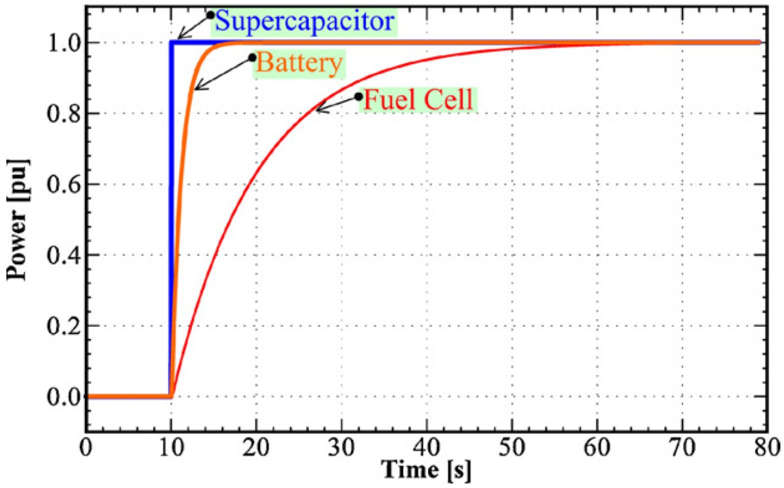


Figure 2.5: Comparison of the dynamic response to a load change between supercapacitors, batteries and fuel cells, obtained from ([70]).

2.3.2 Working principle

Several fuel cell technologies exist today, but the governing working principle is the same. Fuel cells convert chemical energy stored in an energy carrier directly to electrical energy. In a fuel cell, two electrodes – an anode and a cathode – are separated by an electrolyte, as shown in figure 2.6. In a hydrogen-fuelled fuel cell, hydrogen is supplied at the anode, where it is oxidized and releases electrons. The electrons travel through a load circuit, while the hydrogen ions travel through the membrane. Oxygen is supplied at the cathode, where it reacts with the electrons and the hydrogen ions and forms water.

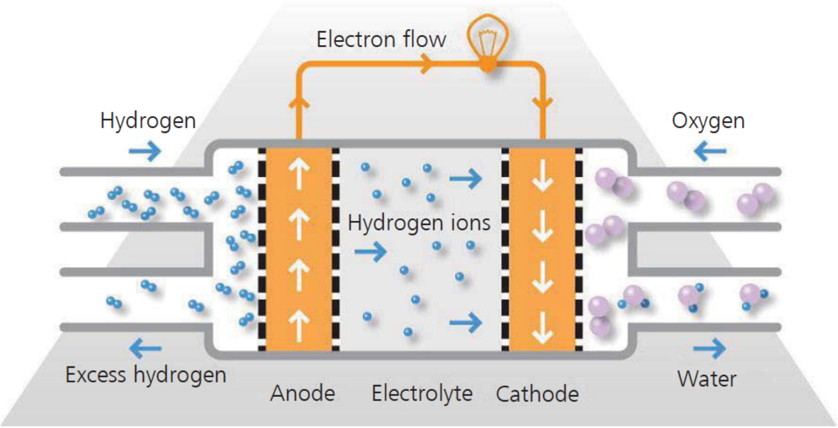


Figure 2.6: An illustration of the working principle of a fuel cell, obtained from (42).

2.3.3 Fuel cell types

The different fuel cell types are classified according to the type of electrolyte used in the system (74). These are:

- Alkaline Fuel Cells (AFC)
- Proton Exchange Membrane Fuel Cells (PEMFC)
- Direct Methanol Fuel Cell (DMFC)
- Phosphoric Acid Fuel Cells (PAFC)
- Molten Carbonate Fuel Cell (MCFC)
- Solid Oxide Fuel Cells (SOFC)

The different types of fuel cells have different operating characteristics. Typical characteristics are operating temperature ranges with corresponding transient loading capabilities, fuel options and tolerances to fuel impurities. In (23), de Troya et al. classifies fuel cells into three main groups, differentiated by their operating temperature level – these are high-temperature, low-temperature and medium-temperature fuel cells. The different fuel cell types are grouped into the main groups as in table 2.1. The most promising fuel cell technologies for maritime applications are LT-PEMFC (often only named PEMFC), HT-PEMFC and SOFC, (71).

Table 2.1: Fuel cell classification, based on ([23]).

Temperature level	Temperature	Fuel cell
Low	∼80	AFC, PEMFC, DMFC
Intermediate	∼200	MCFC, SOFC
High	650-1000	PAFC, HT-PEMFC

2.3.3.1 LT-PEMFC

The LT-PEMFC is, as can be seen in table 2.1 a low temperature fuel cell. The technology is mature and provides high power density as well as good transient performance as rapid startups and fast load changes since there is no need for heating of a large thermal mass ([73]). The low temperature, however, limits the fuel cells' tolerance to fuel impurities such as carbon monoxide (CO). At low temperatures, CO inhibits strong surface adsorption characteristics and deactivates the catalyst ([22]). Therefore, LT-PEMFC needs to be fuelled by pure hydrogen. A complex water management system is another challenge with this technology, as it is present in both liquid and gas phases ([71]), ([73]). The low temperature also leads to low quality on the excess heat.

2.3.3.2 HT-PEMFC

HT-PEMFC technology is less mature than LT-PEMFC technology. It is a promising alternative, however, as it copes with some of the challenges mentioned for the LT-PEMFC system, ([71]). Due to its elevated temperature range, water is only present in the gaseous phase, simplifying water management. The higher temperature also reduces the fuel cells' sensitivity towards fuel impurities, enabling the fuel cell to use hydrogen reformed from LNG, diesel, ethanol and methanol among others. Their operating is not too high so that transient performance is not limited. The higher operating temperature also enables waste heat recovery for heating purposes.

2.3.3.3 SOFC

The SOFC, with its high operating temperature, enables internal reforming of hydrocarbons to hydrogen within the cell and is therefore flexible concerning fuel supply ([73]). Their higher operating temperature also provides high-quality heat, enabling electricity production for service loads as for the HT-PEMFC. Drawbacks mentioned in ([23]) with this technology is less tolerance for transient loads, as well as slow startup times. The high operating temperature also leads to increased wear and corrosion of the metal stack components.

2.3.4 Fuel cell fuels

In ([73]), different fuels used as energy carriers for fuel cells are reviewed. Hydrogen and natural gas are viewed as the most applicable, while other fuels like diesel, methanol, dimethyl ether and ammonia are also possible, although not as promising due to lower efficiencies and extensive need for fuel-processing before they can be used in the fuel cells. Direct electrochemical oxidation of some fuels can be done in some fuel cells. However, hydrogen oxidation kinetics is most prominent at most practical power densities, and therefore most fuel cells effectively run on hydrogen ([73]).

If a different fuel is used, and the fuel cell technology cannot convert the fuel to hydrogen-rich gas, a separate reformer is as mentioned in 2.3.1 needed.

2.3.4.1 Hydrogen

Although hydrogen is the most abundant element in the universe, it is, for the most part, a compound in chemical connections. Coal gasification, gas synthesis from fossil feedstocks and electrolysis are common methods to produce hydrogen, while electrolysis is the only renewable method if powered by renewable energy ([33]). A benefit of using pure hydrogen in fuel cell systems is the possible high overall power densities due to hydrogen's fast electrochemical oxidation kinetics at low temperatures. This reduces the need for pretreatment of the gas and heating of the fuel cell system, which would draw a portion of the energy produced ([68]). In terms of storage, hydrogen has a low volumetric density and needs to be compressed or liquefied for most practical applications to store enough energy ([30]). For automotive applications, hydrogen is compressed to either 350 or 700 bar. To liquefy the gas, it needs to be cooled down to -253 degrees at ambient pressure, or higher temperatures at elevated pressures, usually referred to as cryo-compressed hydrogen

2.3.4.2 Liquefied natural gas

LNG, a mixture of various hydrocarbons as covered in chapter 2.2 can also be used in fuel cell systems. It offers simple fuel processing, and adsorbents can be used effectively to remove sulfur. Also, internal reforming of LNG is possible in many of the high-temperature fuel cell systems, reducing the need for external reformers ([73]). LNG is a byproduct of the production of fossil feedstocks, but biomass or synthesis from CO_2 and renewable hydrogen are production methods that are considered to be viable in the future ([59]). LNG needs to be stored at below -162 degrees at ambient pressure, and requires special storage tanks in the same way hydrogen does.

2.3.5 Operational considerations of fuel cells

2.3.5.1 Auxiliary equipment

The basic building block of a fuel cell system is the fuel cell module. It is - as its name implies - modular in nature and can be combined in numbers to increase the amount of electricity generated, making up a fuel cell stack, or system ([13]). As mentioned in 2.3.1, a number of support components are required for a fuel cell system to generate electrical power. These are commonly referred to as balance-of-plant (BOP) components ([73]). Dependent on the technology used, different support systems are needed. These may be heating of gas flows to appropriate temperatures, heating of the system if high-temperature technology is used, cooling of the system if low-temperature technology is used. Pumps, blowers, and compressors are also necessary to bring fuels and oxidant to the fuel cell. Dependent on the fuel cell − fuel combination in use, various processing equipment may also be needed. If the fuel cell type is incapable of internal reforming of the fuel, this needs, as mentioned, to be done in a separate system. The process in simple terms converts hydrocarbons to a mixture of hydrogen and CO ([73]), commonly referred to as syngas. The fuel cell system may have low tolerances for CO, and in that case, CO-clean-up is required, lowering the CO content of the syngas. Desulfurisation may also be necessary if fossil fuels are used to obtain syngas as the sulfur deactivates the catalysts ([51]).

2.3.5.2 Performance degradation

Fuel cells are as mentioned known to have limited lifetime compared to diesel engines. There are several degradation mechanisms present, affected by how the fuel cell is operated (34). Three degradation mechanisms are of significance: Catalyst degradation, membrane degradation, and gas diffusion layer degradation, briefly explained under:

Catalyst degradation

This degradation mechanism occurs when platinum catalyst particles sinter together or detach entirely from the membrane. This leads to reduced surface area and cell voltage (75). The process is accelerated under high and low loads.

Membrane degradation

Mechanical stress and/or thermal stress, occurring from high levels of heat at high loads may lead to a drop in the protonic conductivity of the membrane. This in turns leads to decreased efficiency due to increased resistance of the fuel cells (77).

Gas diffusion layer degradation

This is the least studied contribution. The mechanisms are similar to those of catalyst degradation but happen at a slower rate (34).

Summarised, to increase the fuel cell's lifetime, the fuel cell should avoid operation in high and low loads, in addition to avoiding excessive transient loading. The start-up/shut-down cycling of the fuel cell should also be limited (34),(61), (12).

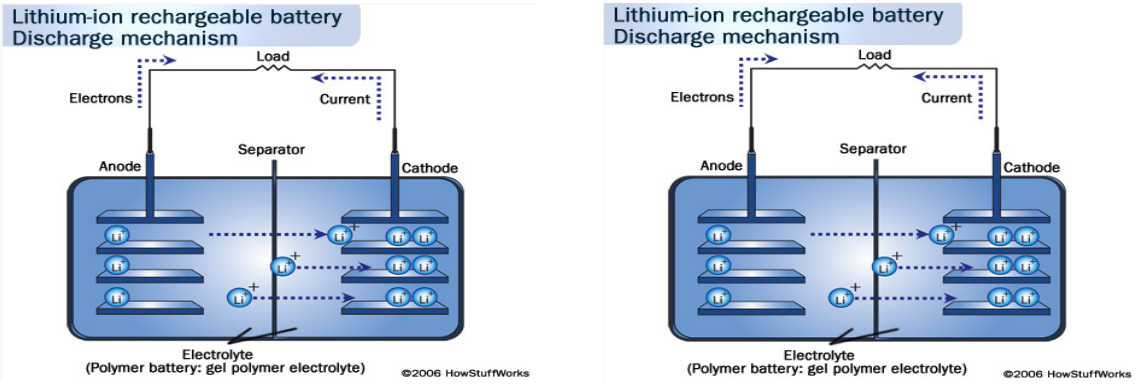
2.4 Batteries

Several energy storage systems exist. Batteries, supercapacitors, and flywheels are among the most applicable options (73). They inhibit different characteristics, as charging rates, response times, self-discharge rate and energy capacity. This thesis will exclusively focus on batteries as it is the most mature technology (38).

The increasingly technological maturity of lithium-ion batteries has enabled the widespread use of high-quality batteries in electric and hybrid-electric vehicles, as well as large-scale grid systems. The technological developments in power-to-weight ratio and increased production volumes with the following reduced costs have made batteries an attractive option for maritime applications as well, (27).

2.4.1 Working principle

A battery is made up of electrochemical cells, that transform chemically stored energy into electrical energy through chemical reactions (58), (69). The cell consists of a cathode and anode, contained in an electrolyte with a separator in between. The cathode and anode are, as for fuel cells referred to as the electrodes. Ions travel through the separator, while electrons travel through the electrodes – through an external circuit - either a load or electricity supply depending on if the battery is being discharged or charged. The working principle for the discharge and charge mechanisms for a lithium-ion battery is shown in figure 2.7. We differ between primary and secondary cells (14). Primary cells are cells that cannot be recharged and need to be recycled when discharged fully, while secondary cells can be recharged. Batteries for maritime applications are secondary batteries.



(a) Discharging mechanism **(b)** Charging mechanism

Figure 2.7: The working principle for charging and discharging a lithium-ion battery on a cell level, obtained from (18).

Battery cells are, as mentioned, the smallest component in a battery system. As a cell alone cannot provide the voltage or capacity required, they are - as for fuel cells - combined. Cells are stacked in groups and form what are called module banks, illustrated in figure 2.8. A group of module banks forms what is defined as a sub pack. The sub packs are the smallest units that can be electrically isolated and replaced, (58). To obtain the necessary system voltage, sub packs are connected in series, named strings, racks, stacks or cabinets (58). Several stacks can then be connected in parallel, depending on the amount of energy needed, to obtain the total battery system ([57]), and the components are illustrated in figure 2.9.

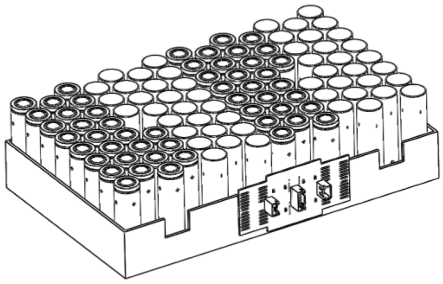


Figure 2.8: Battery cells stacked in groups to form a battery module, obtained from ([52]).

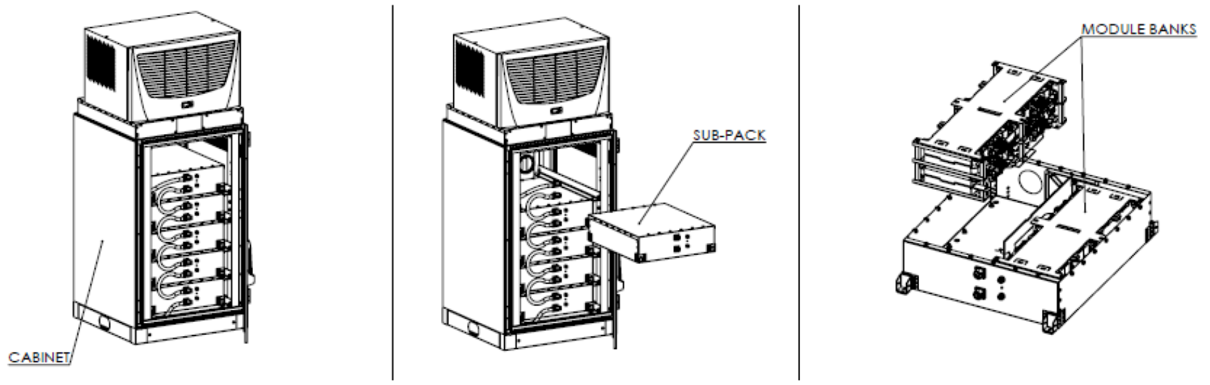


Figure 2.9: Illustration of the building blocks of a battery rack, consisting of sub packs made up of module banks, obtained from ([52]).

2.4.2 Battery chemistries

Several different battery chemistries exist, and battery technologies and hence their names are differentiated by which materials constitute the cathode. The voltage provided by each cell depends on the voltage potential across the electrode. This, in turn, depends upon which materials that constitute the electrodes as well as the composition of the electrolyte. Energy characteristics, lifetime and safety are also affected by the material choice in the cell ([57]), ([69]). The most used battery chemistries are Lithium Cobalt Oxide (LiCoO2), Lithium Manganese Oxide Spinel (LiMn2O4), Nickel Manganese Cobalt Oxide (LiNiMnCoO2) and Lithium Iron Phosphate (LiFePo4) ([58]).

Of these, LiNiMnCoO2 is the most promising alternative, and is the chemistry in which the largest portion of research effort has been put ([27]). Referring to figure 2.7, when the battery is discharging, lithium ions migrate from the anode via the separator to the cathode, forcing electrons to travel through the external circuit. When the battery is being charged, electrons are supplied at the anode, and li-ions migrate to the anode from the cathode ([69]).

2.4.3 Operational considerations

As for fuel cells, batteries experience degradation, in the form of increased internal resistance and loss of capacity. The degradation mechanisms will happen due to numbers of cyclic charging and discharging, as well as calendar effects as time goes. The ability to withstand these two mechanisms are referred to as cycle life and calendar life ([57]).

Secondary batteries are usually discarded when their capacity shrinks to 80% of initial capacity, a state termed end-of-life (EOL) ([28]). Factors contributing to the aging mechanisms are among the following:

- **Temperature**

  The temperature of which the battery system is both stored at and operated at affects the rate of degradation. However, no concise relationship between the extent of performance degradation and temperature have been found in ([28]), where batteries from different manufacturers showed different characteristics.

- **State-of-charge**

  State-of-charge (SOC) - defined as the ratio of residual capacity to the total capacity of the battery ([28]) - at a specific point in time showed similar characteristics as for the storage temperature. The most beneficial average SOC differed between the batteries from different manufacturers.

- **Calendar aging**

  As mentioned under *Temperature*, the battery performance degrades independently of usage, a term named calendar aging ([28]). As for the aforementioned factors, different chemistries inhibit different characteristics.

- **Cycle depth**

  The amount of energy discharged relative to the battery's rated capacity is the cycle depth. A full cycle is a 100 % discharge, while a smaller depth of discharge (DoD) may be converted to an equivalent full cycle. A discharge of 10% of the rated capacity of a battery is equal to a tenth of an equivalent full-cycle However, the term cycle is not always unambiguous as the definitions often are used about another ([28]). It is also discovered that a deeper depth-of-discharge - for instance 80% - increases the performance degradation relative to two DoD events of 40 % each ([2]).

- **SOC range**

  In addition to the average SOC of the battery system, the range of which the battery is utilized affects performance degradation. As for previously mentioned factors, batteries from different manufacturers inhibit different characteristics ([28]).

- **Current rate - rate of discharge** Another characteristic of batteries is their rated C-rate, the rate of charge/discharge of energy relative to one hour. A 1000kWh battery system delivering its full capacity in one hour provides a C-rate of 1. Higher C-rates implies faster charging and discharging, and leads to more heat development and accelerated degradation if the battery is not designed for withstanding elevated rates ([28]).

Despite all the aforementioned factors, battery vendors only provide a datasheet projecting the projected cycle life ([27]). Actual battery life is therefore difficult to estimate with certainty ([28]), and depends on the usage.

2.5 Hybrid shipboard energy systems

As covered in 2.2, a distinction is made between hybrid propulsion and hybrid power supply. In the remainder of the thesis, hybrid systems will refer to a hybrid power supply, where an energy storage system is included. In (13), hybrid power supply *"...aim to make the best use of the power sources..."*, to achieve a more flexible, economical and reliable system. Challenges of such systems are higher complexity and investment costs. In addition, with the inclusion of several power sources, an appropriate energy management strategy, (EMS) is needed to share the load between the power sources in such a way that the fuel cost, maintenance costs and emission costs are minimized (36). Especially, since there is an upper and lower limit on the amount an energy storage module can hold, the energy flows to and from this must be accounted for. The inclusion of several power sources may also end up weighing more, and take up space, an aspect that may need to be addressed.

2.5.1 Battery applications in hybrid energy systems

The inclusion of energy storage systems - in this case, batteries - may provide enhanced performance through different applications as covered in (41):

Strategic loading

The batteries can be used as a load compensation device, letting engines run at their most optimal point, to minimize the cost of producing energy.

Zero emission operation

In certain operation modes, emissions are not allowed, as in harbors. The battery system may then be used to produce the necessary energy, enabling compliance with regulations.

Enhanced dynamic performance

For slower engines, like fuel cells and dual-fuel/LNG engines, sudden load changes may be unfavorable and lead to increased wear and tear. In some instances the necessary load change is not even possible. In a hybrid energy system, batteries can absorb the sudden load changes and then transfer these load changes over to the main engines, both for increasing loads as well as decreasing loads.

Peak shaving

This is a variant of enhanced dynamic performance, where the load variations in the network are absorbed by the ESS so that the running engines only see the average system power.

Spinning reserve

For dynamic positioning operations, regulations require that enough capacity is ready for instantaneous use in case of a failure on the system (27). This is called spinning reserve and is obtained by running multiple diesel engines at very low load, which leads to lower fuel efficiencies. Using batteries as spinning reserve reduces the need for the number of engines running - reducing running hours, as well as the number of engines needed to be bought may be reduced. If generating capacity is lost, the battery steps in to cover for the load.

2.5.2 Vessels suited for hybridization

In (48), an assessment was done to investigate which vessels that are most suited for hybrid propulsion systems, based on their operational profile in Norwegian waters. It was found that offshore and passenger ships have the greatest potential of fuel savings from hybridization, diesel-electric propulsion or other electric concepts (batteries and fuel cells), as they spend a significant fraction of their total operational time in part-load where the fuel efficiency is sub-optimal. A ranking of the different vessels was performed, reproduced in table 2.2, where 4 and 1 correspond to the most and least potential for fuel savings in the inter-ranking.

Table 2.2: Ranking of potential for hybridization for various ship types, based on (48).

Ship type	**Rank**
Offshore vessels Passenger vessels	4
Containter ships Ro-Ro vessels	3
Tankers Bulk carriers General cargo ships	2
Reefers	1

In (57), additional vessels are also mentioned as viable candidates for hybridization with high potential fuel savings: Special vessels, tugboats, icebreakers, lifting vessels and research vessels.

2.6 Sizing optimization

As mentioned in 1.3, formulating mathematical models suited for optimization techniques is a widely used approach to obtain the best solutions to complex real-world problems, where the problems typically are subject to specific constraints, and also apply to ship design-related problems. The problem to solve is represented by an objective function, a function of several decision variables, which the optimal values for must be found. In addition, technological and operational constraints must be fulfilled for a solution to be valid, these are expressed through various equations. A generalized minimization problem definition is shown in figure 2.10, ([32]). X is the design vector, with the variables that are subject to optimization, while $g_j(x)$ and $l_j(x)$ are functions of x describing equality and inequality constraints that must be fulfilled for the solution to be valid.

$$\text{Find } X = \begin{Bmatrix} x_1 \\ x_2 \\ . \\ . \\ x_n \end{Bmatrix} \text{ which minimizes } f(X)$$

subject to the constraints

$$\begin{aligned} g_j(x) &\leqslant 0, \quad j = 1, 2 \ldots, m \\ l_j(x) &= 0, \quad j = 1, 2 \ldots, p \end{aligned}$$

Figure 2.10: General optimization formulation, based on ([32]).

Optimization is a wide field, and there are several approaches to solving mathematical optimization problems. Several high-level programming commercial solvers exist, in which the problem can be formulated in, to then be solved by an appropriate generalized optimization technique available in the software. The distinction between the problems is often made on whether the problem is linear or nonlinear, and if it includes only continuous decision variables or integer decision variables, or both combined.

In linear problems, the objective function and constraints are formulated so that the decision variables are not multiplied or divided by each other in the objective function or the constraints. In nonlinear problems, on the other hand, multiplication and division of decision variables is possible, at a cost. Complexity and implementation effort quickly increases, in addition, the number of solvers possible to use becomes limited ([49]).

Nonlinear features of a problem may be linearized by piecewise linearization if applicable. Another option is to apply artificial intelligence approaches such as heuristic optimization techniques. While linear solutions are global solutions, solutions found by a heuristic algorithm does not guarantee to be a global optimum, but it has a high probability of being close within some error ([32]).

Evolutionary heuristic algorithms are widely applied in complex energy systems due to the nonlinear features and high problem dimensions ([32]). The heuristics find the best solutions by – as the name implies – eliminating the poorest solutions. Genetic algorithms (GA), particle swarm optimization (PSO) and ant colony optimization (ACO) were reported to be among the most used algorithms in the literature. GA is the most applied, used in 63% of the problems studied by ([10])

2.6.1 Optimization cases in literature

Several studies have looked into optimization problems related to the vessel's power system, with different focus, objective, approaches, scope, and weighting of aspects. This section presents the relevant literature that has been used as supporting material for the reasoning and approaches developed in chapter 4.

In ([66]) the problem of deciding on the diesel generators of an anchor handling vessel is studied. The vessel's load profile is represented by a set of operational modes the vessel operates in, with fixed power demands and respective duration in the fraction of total duration in a time-period. Different operational circumstances as fuel prices, taxes on emissions and fuel compliance in different contract models are included in the operational modes and time-periods. The problem is solved as a deterministic linear optimization problem, implemented in the Xpress solver. To include the nonlinear fuel consumption curve of the diesel engines, special ordered sets of type 2 (SOS2) are applied for a piecewise linear approximation.

In ([24]), the sizing optimization of the power generating components in a hybrid electric system is explored, through an exhaustive search method. Two design-methodology approaches for the hybrid system are proposed, and validated through a case study on the Venice water buses. The first approach assumes a fixed speed and power for the main power system for it to operate at its highest efficiency point. The main power system is sized to generate the mean load power, while the battery system is sized to be able to cover the additional power needed to supply the electric motor during peak power demand, where the magnitude and duration of the maximum peak is used as a basis. In the second approach, power ranges delimited by maximum and minimum power for in which the main power system is allowed to operate in - to partially cover the load variations - is subject to optimization. The second approach allows for a smaller size of the battery system, however decreasing overall efficiency, an aspect needed to be taken into account in a cost-benefit-analysis.

In ([67]) a PSO algorithm is used to optimize the sizing of the machinery of a hybrid electric vessel. A time-step simulation of a typical maritime driving cycle of 600 seconds is used as the basis for the optimization. A thermostat control strategy based on the SOC is employed to take into account the energy flow between the main components. The operational requirements are included by using penalties for violation of acceleration and velocity requirements of the vessel in the constraint function, while the objective function is based on the fuel consumption of the system. Compared with the baseline system, a 40% reduction of fuel consumption is obtained, although investment and replacement costs from degradation are not included in the model.

In ([17]), an algorithm for the optimum sizing and management of general energy storage systems is developed. It is aimed at reducing both fuel oil consumption, emissions, and management costs of integrating energy storage systems into already operating power systems. The SFOC is considered through a piecewise linear function, The algorithm developed is applied to two case studies, a ferry and a platform supply vessel through a time-step simulation, where a typical cycle profile is the basis for simulation. The results are extrapolated to calculate total costs over the vessel's lifetime. Both the energy management problem and optimal sizing problem is considered, by dividing the problem into two sub-problems. The first problem solves the optimal sizing problem of the ESS. The resulting size of the ESS is fed into a mixed-integer linear problem (MILP) formulation, where the optimal scheduling and dynamic dispatch for the diesel generators are solved. Compared to baseline total costs, 5.64% savings are obtained for the ferry, while 32% savings are obtained for the PSV.

In ([37]) the combined power management and design optimization is explored for a fuel cell-battery plug-in hybrid electric road vehicle (PHEV) through a time-step model. A constrained multi-objective optimization problem is formulated, where fuel costs and investment costs are considered. The energy flow between the fuel cell- and battery system is accounted for by a charge-depleting and charge-sustaining energy management strategy (EMS). To protect the PEMFC stack, constraints are put on the power transitions through the maximum change in power delivered over a specific time step. Compared with a benchmark solution, the resulting optimal size and EMS performs better, however, aging and degradation are not considered.

In ([54]), a component sizing optimization is done for optimal energy management for a plug-in hybrid electric vehicle. A deterministic multi-objective optimization problem is formulated, minimizing drivetrain cost (investment and replacement of batteries) and voyage expenditures, by weighted equivalent fuel consumption and weighted exhaust emissions. A fuzzy logic controller is applied as the EMS. PSO is used as the optimization algorithm, and a Pareto-optimal solution is sought as the problem is solved by a multi-objective model. The problem is applied in predefined driving cycles in the time-domain and compared with default component sizes. The optimal solutions are reported to perform better than default component sizes considered.

In ([76]), a multi-objective component sizing problem, based on optimal EMS is developed for a fuel cell/battery hybrid electric vehicle. A two-step optimization approach is utilized, where a dynamic programming algorithm for energy management is combined with a Pareto-optimal principle, to find a quasi-optimal solution. The Pareto optimal solution is chosen based on the tradeoffs between fuel costs and system durability in terms of performance degradation. The optimization problem is solved for a time-domain problem with time-steps of 1 second.

In ([78]) a hybrid electric propulsive system for an anchor handling tug supply vessel (AHTS) is considered, with the inclusion of batteries in conjunction with existing machinery. An optimal trade-off with respect to fuel consumption, GHG emissions and lifecycle costs is sought, and the problem is formulated as a nonlinear multi-objective optimization problem. A Rule-based EMS for controlling the energy flow of the system, and a non-dominated sorting genetic algorithm, (NSGA-II) is developed for this case. The degradation mechanisms are not included, however. A tug boat is used as a representative vessel, and an example velocity profile is obtained from real operation data and used as the load profile, with a duration of 5000 seconds. The performance of the resulting hybrid electric propulsive system is tested on a real-time hardware-in-the-loop platform. The results are compared with results obtained from single-objective optimization of reducing fuel consumption only. The developed algorithm indicates 7.34% less emission of GHG and a reduction in life-cycle costs of 21.75%.

A two-stage stochastic optimization model to optimize the machinery system selection for diesel-electric systems is developed and solved in the Xpress solver in ([50]). A medium-sized container vessel is used as the case study, and different scenarios with different price projections of HFO, MGO and LNG from 2020 to 2030 are considered. The installation and operational costs of the systems over the vessel's lifetime are included as cost contributions.

In ([15]), a methodology for optimized sizing of energy storage in hybrid systems with diesel or gas generators is developed to support battery investment decisions. Different vessel operation modes are considered, with their technical and safety constraints, as closed vs open bus-tie breaker operation and spinning reserve requirements. A constant C-rate is assumed for the batteries, and a linear approximation for the SFOC in the diesel engines is done. The cost contributions are investment costs and fuel costs, as well as replacement costs of batteries, dependent on the amount of energy throughput through the vessel's lifetime.

2.6.2 Resulting modeling aspects needed to be taken into account

Diesel engines are designed to operate for the ship's entire lifetime and only need periodic maintenance (3). Batteries and fuel cells, however, are as mentioned subject to degradation both dependent on how they are used, as well as calendar aging for batteries, (34),(27). Fuel cells and battery systems installed on a vessel will therefore have to be replaced a certain number of times during the vessel's lifetime.

2.6.2.1 Batteries

As covered in 2.4.3, several mechanisms affect battery performance degradation. However, no accurate parameterized lifetime prediction addressing the influence of the different aging mechanisms have been developed, (64), (31), and different batteries from different manufacturers show a diverse influence of the mechanisms (27). Depth-of-discharge has as mentioned been reported to affect the capacity degradation of the battery, meaning that deeper discharge cycles cause stronger aging compared to smaller cycles (64), (1). Accelerated testing was done on LiNiMnCO cells of 2.05Ah on a cell level, designed for automotive applications in (31). When discharging cells 100%, in average 440 cycles were allowed until the rated capacity was decreased to 80% of the initial rated capacity. In comparison, cycling between 47.5 and 52.5 %, only discharging the batteries 5% of their rated capacity allowed for 8500 equivalent full cycles, although a proper mathematical description was not clear.

In (17), the number of battery replacements is modeled as a function of the average depth of discharge of the batteries, where this value is pre-defined from the EMS. Bordin and Mo uses lifetime energy throughput as a measure of the lifetime of the battery. This is defined as the total amount of energy in kWh that is available for usage over the battery's lifetime before it has degraded to the point where the lost capacity and increase in internal is of such nature that the battery is no longer fit for its purpose (EOL). A single value for lifetime throughput is calculated for every depth of discharge, and the total lifetime throughput is then calculated by averaging all the value of lifetime throughputs.

2.6.2.2 Fuel cells

Limited amount of literature is found where fuel cell degradation is taken into account in the optimization formulation. Several mechanisms are as mentioned contributing: Transient loading, start/stop cycling and load level. In (34), a fixed performance drop at nominal operating power represents the end-of-life for the fuel cell stack. A constant degradation rate for low power and high power operation is considered, in addition to a transient loading and start/stop cycling of the fuel cells. The same approach was used in (76), and it seems as this is the most applicable way to model performance degradation for fuel cells at the current level of research.

Chapter 3

Modelling approach and methodology for the sizing optimization problem of a hybrid power system

3.1 Choice of modeling approach

A model is, in general, a representation of a real-life system. In this context, system boundaries need to be defined, modeling considerations and assumptions need to be made and the relevant physical laws and relations need to be approximated. Some aspects also need to be excluded, as it is not possible nor practical to model the full system. This chapter aims to outline the modeling considerations that provide the baseline for the modeling approach that has been used.

In the literature reviewed, some projects include the energy management system in the optimization problem, while others do not. For diesel-electric propulsion as in ([66]) and ([50]), this is not necessary due to the absence of energy storage systems. When including energy storage systems, however, the power flow needs to be considered ([17]). Another aspect is the assumptions of future operations. Most of the literature reviewed assumes a non-changing operational profile, this is included only in ([66]) and ([50]). This may be a fair assumption for automotive applications, however for a ship, where the lifetime spans over a quarter of a century, different operational modes may change. Prices on fuels and regulations may also be subject to changes, arguing that this should be considered. It was therefore chosen to try to create an optimization model that takes future developments into account, and the model developed by Solem et al. was decided to be used as a basis for the approach, with appropriate modifications for the inclusion of a fuel cell battery hybrid configuration. Due to the nonlinear features of the problem reported in the reviewed literature, a genetic algorithm in the Matlab optimization toolbox was first tried out. However, due to a large number of integer variables (over 200), it did not manage to find any feasible solution. A linear problem variant therefore had to be developed instead.

3.2 Operational breakdown

As described in Solem et al., a vessel's lifetime can be "*. . . defined as a set of operational profiles, where an operational profile can be defined as a set of operational states, for example as transit, loading and standby. . .*". Further, each operational state has a corresponding power demand

and duration. A ship is usually designed to be in operation for about 20-25 years, and the operational profiles may be subject to change depending on the type of ship, the ship owner's business strategy and the market situation ([66]).

The vessel's power profile is assumed known, with different load profiles in different operational modes. The load profile can be divided into an average load and a fluctuating profile around this average, illustrated by figure 3.1.

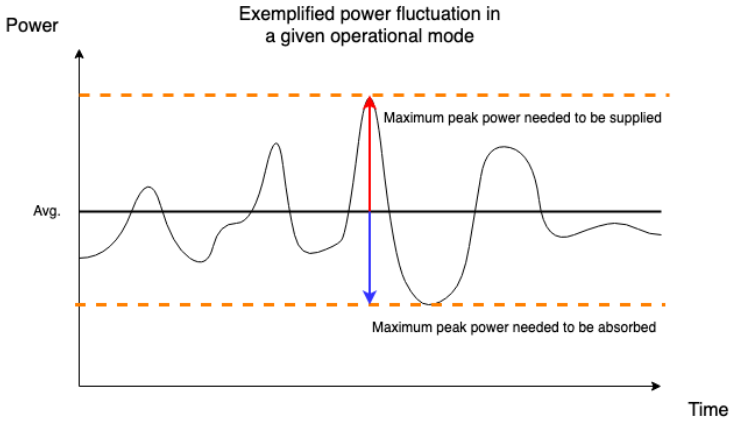


Figure 3.1: Illustration of a vessel's power profile in a specific operational mode, with average load and a fluctuating part.

In a hybrid system, batteries may cover for rapid increase or decrease in load and gradually hand this change over to the main machinery if this is not capable of handling rapid load changes (fuel cells and dual-fuel engines) ([41]). However, including this dynamic behavior requires an optimization of the load sharing for each time step considered as was done in the second approach in ([24]). However, this increases the complexity of the model drastically. An assumption is therefore made that the batteries cover all fluctuations and that the main machinery only sees the average power in an operational state, as for in the first approach in ([24]). The fluctuating power demand around the average demand can be represented by a statistical distribution of peaks and troughs in the different operational states in a roundtrip. This means that a typical operational mode will have a typical pattern and that each peak and through can be assumed to be enumerated and have its distinct place in a vector of peaks and troughs.

Batteries should be allowed to be used for the average base load as well. To reduce complexity, it is assumed that shore power is used to recharge the batteries in that case. It is also assumed that the energy lost due to efficiency loss during charging and discharging will be replaced by charging by shore. It is assumed that batteries cover all fluctuations, i.e. the amount of energy supplied for this application is not subject to optimization. Therefore the cost of the lost energy is not taken into account.

3.3 Cost breakdown

From a cost perspective, the total cost of a ship consist of capital expenditures (CAPEX), voyage expenditures (VOYEX) and operational expenditures (OPEX). Related to the ship power system, capital expenditures are the initial investment costs of the machinery, voyage expenditures are fuel costs and emission costs, and operational costs can be seen as maintenance and replacement costs.

3.3.1 Capital expenditures

The initial investment costs consist of the costs of the fuel cell-, battery and diesel engines systems, with their auxiliary equipment if applicable. Batteries are both a power source and energy source in the same module, and the only auxiliary component included in this model is a power inverter. Fuel cells may need as covered in section 2.3.5 a fuel reformer if a specific fuel is used. BOP components - pumps, blowers, dryers etc. - are assumed to be an already integrated part of the fuel cell cost. As special tanks are required for storage of liquid and gaseous hydrogen, the cost of these should be included. As exhaust gas after-treatment is not included in this model, diesel engines are assumed to not need any auxiliary equipment.

3.3.2 Voyage expenditures

Voyage expenditures consist of the cost of fuel and electricity used on a round trip. It is assumed that batteries are charged by shore if used for base-load. The cost of lost energy due to efficiency losses from peak shaving and load shedding is not included in the model since the load-compensation pattern is pre-defined. As it is assumed that the lost energy is replaced by shore, the batteries must be sized accordingly so they do not run out of energy.

3.3.3 Operational expenditures

The fuel cell- and battery systems inhibit certain degradation mechanisms as covered in section 2.6.2. During the vessel's lifetime, these systems will need to be replaced a given number of times, dependent on their usage. In addition, as for conventional diesel engines, these systems are subject to periodic maintenance (13). These two factors should be taken into account when developing the model.

3.4 System modeling and assumptions

Considering the various operational modes, the selection of the machinery system will be subject to a trade-off between minimizing the three contributions to the total costs. Going back to the formulation of operational states and operational profiles, the governing requirement for the ship power system is to be able to deliver the required power in all operational modes in all time periods. The optimization problem is then to minimize the total cost while doing so, in addition to fulfil other technical constraints imposed.

3.4.1 Fuel cell system

3.4.1.1 Fuel cell costs

The investment cost of fuel cells are based on information from (13) and (23). As HT-PEMFC and SOFC are of low technological maturity, estimates are found only for SOFC, and a price on HT-PEMFC is assumed to lie in between that of LT-PEMFC and SOFC. The following investment costs are then as summarized in table 3.1.

Table 3.1: Nominal investment costs for the considered fuel cell types.

Fuel cell type	**Investment cost [$/kW]**
LT-PEMFC	235 (13)
HT-PEMFC	493
SOFC	750 (23)

3.4.1.2 Reformers

For the scope of this thesis, it is assumed no differences between reformers for different fuel cell types and fuels. In (59), a reformer cost of 44 $/kW for a LT-PEMFC is assumed, based on (47). For modeling purposes and due to uncertainties, it is assumed that the size of the system can be a continuous variable and not constrained to a specific number of reformer modules as it is for fuel cells.

3.4.1.3 Tanks

Finding prices and capacities for hydrogen tanks fitted for maritime purposes is also challenging, due to the limited application of this technology. In (56), hydrogen storage for maritime usage is discussed. 1200kg tanks for liquid hydrogen are used as an example, whereas for gaseous hydrogen a 5000 psi system (about 350 bar) with 60kg capacity is considered. However, prices are not revealed. In (60), cost predictions for tanks for light-duty vehicles are made for 2020 and 2025. For 700 bar storage systems, a cost of 333$ per kg is stated. Due to the lack of information on liquid hydrogen storage cost, some assumptions need to be made. As light-duty vehicles carry smaller tanks than larger consumers such as ships, the 700 bar storage cost is assumed to be valid for storage of liquid hydrogen (LH2), with a 10% lower cost due to economy-of-scale factors. It is also assumed that for gaseous storage, 700bar is most realistic due to area and volume limitations. It is assumed that the tank costs of gaseous hydrogen (700bar) is 10% less than for liquid hydrogen.

Limited information was found regarding LNG, and an assumption is made that the storage cost per kg LNG can be approximated to be 10% less than for gaseous hydrogen stored at 700bar. For simplification and due to uncertainties, storage tank sizes are considered a continuous variable.

3.4.1.4 Fuel consumption

As the fuel cell efficiency can be assumed constant within its power range, specific fuel consumption (SFC) can be calculated on the basis of fuel to energy efficiency of different fuels in a fuel cell, based on (59) and (39). The total fuel consumption is then the product of the SFC, the power provided and the duration in hours of the power provided. It is assumed that efficiency losses from the fuel cell system are already included in the product sheet provided by the manufacturer.

Table 3.2: Specific fuel consumption of the considered fuels in fuel cells, based on ([59]) and ([39]).

Fuel	**Specific fuel consumption [g/kWh]**
Hydrogen	46
LNG	173

3.4.1.5 Emissions

Emissions from fuels utilized in fuel cells is based on ([59]) and ([39]), where a specific emission factor in grams emitted per kWh energy provided is stated. The emission parameters are summarised in table 3.3.

Table 3.3: Emission factors in [g/kWh] for the fuels considered, based on ([59]) and ([39]).

Fuel	**CO_2**	**CH_4**	**Sox**	**Nox**
H2	0	0	0	0
LNG	412	3	0.003	1.17

3.4.1.6 Maintenance

Based on ([13]), an annual maintenance cost of 50$/kW installed fuel cell power is assumed for LT-PEMFC. This is for simplicity also assumed for both HT-PEMFC and SOFC.

3.4.1.7 Performance degradation

It is assumed that the lifetime in a defined number of hours provided by the manufacturer can be converted to a constant performance degradation factor when in use. By this, the usage-dependent performance degradation and hence replacement cost can be included in the model. A fuel cell system may, for instance, have a lifetime of 20 000 hours guaranteed by the manufacturer. The allowed degradation before the fuel cell system needs replacement can for simplicity be set to 80% as for batteries. Voltage degradation is often used as a measure for the performance degradation ([34]), ([76]), and the allowed voltage performance degradation is then 20% of the rated voltage. The constant voltage degradation per hour in use can then be calculated as

$$J_e^N = \frac{\text{Allowed performance drop in \% * Rated voltage}}{\text{Lifetime guaranteed by manufacturer}} \tag{3.1}$$

In the lack of certain numbers for the accelerated performance drop in high or low load regions, a 30% increase in performance degradation is taken as an assumption.

3.4.2 Battery system

3.4.2.1 Capacity and power

Battery capacity is usually given in ampere-hours (Ah) by the manufacturers. To get the capacity in kWh, ampere-hours is multiplied with the number of battery cells/modules and the rated voltage and divided by 1000. Power is calculated as the product of the current delivered by the battery and the voltage. The current is dependent on the C-rate of the battery. For simplification, the C-rate is assumed to be 1, and the current is then multiplied by 1.

3.4.2.2 Investment costs

Investment costs of batteries are based on ([13]) and set to 1000 \$/kWh. The LiNiMnCoO2 chemistry is the only chemistry considered, different manufacturers should be possible to include, however.

3.4.2.3 Electricity consumption

Battery efficiency is considered constant, and the electricity consumption is calculated similarly as for fuel cells, directly as the product of power delivered, duration in hours and battery efficiency. A battery efficiency of 95% is assumed.

3.4.2.4 Performance degradation

Battery life is as mentioned dependent on the number of charge-discharge cycling, operational temperature and calendar time among others ([64]), ([31]), ([17]) and ([15]). For simplification, available lifetime energy throughput is used as the basis for performance degradation. It is assumed that the battery's performance is constant until a point in time where the performance drops momentarily ([64]). The total available lifetime energy throughput can be calculated as the number of cycles guaranteed times the number of batteries installed. The number of cycles guaranteed is assumed to be 2000 and the replacement costs are set to 27.63 \$/kWh, ([13]).

3.4.2.5 Maintenance

Annual maintenance cost for batteries is based on ([13]), and set to 21 \$/kW.

3.4.3 Diesel engines

3.4.3.1 Investment costs

The investment costs of diesel engines are approximated to be a function of installed power and are set to 52\$/kW, based on ([13]).

3.4.3.2 Fuel costs

As the nonlinear relationship between fuel consumption and percentage loading of MCR is omitted, the specific fuel oil consumption stated by the manufacturer is used, and the fuel costs will therefore be an optimistic estimate. As HFO is non-compliant with the IMO 2020 regulative, only MDO and ULSFO are considered as alternatives, with less than 0.5% and 0.1% sulfur content respectively.

3.4.3.3 Emissions

As for fuel cells, emission factors for diesel engines are based on (59) and (39), summarised in table 3.4.

Table 3.4: Emission factors in [g/kWh] for the fuels considered for diesel engines, based on (59) and (39).

Fuel	**CO_2**	**CH_4**	**Sox**	**Nox**
MDO	524	0.01	0.32	14.8
ULSFO	320	0.01	0.15	10

3.4.3.4 Maintenance

In (13) the cost of periodic maintenance is set to 10 % of the investment costs, which also is used here.

Chapter 4

Optimization model

This chapter presents a walk-through of the developed model, covering the logic of how variables, cost functions and restrictions are defined. The resulting mathematical formulation in compact form, with the defined sets, parameters, variables, objective function and constraints is presented at the end of the chapter, in 4.5

The vessel's life-time can as covered in 3.2 be expressed by time periods and operational modes the vessel takes on. We can define T as the set of time-periods the ship will operate in, and O as the set of operational states that a vessel can take on. Each operational state will have a power demand, P^D_{ot}. The governing requirement is that power demand shall be met in all operational states in all time-periods. In an operational state, this means that the sum of power produced from all the power generating sources shall be equal to the power demand. The total system cost will have the contributions as explained in 3.3.

4.1 Contribution from fuel cells

As fuel cells are modular in nature, they can be combined together to provide the required power rating, where each module is delivering the same amount of power. It should be mentioned that stacks, modules and racks are often used about one another, and for the rest of this thesis, a fuel cell stack and battery stack is defined as several modules combined together to form a total system.

There are several ways to incorporate the power supply from fuel cells. One way is to assign a variable to represent the power supplied from fuel cells. However, we need to assess the load in a percentage of rated power as the load level affects the rate of degradation ([34]). If a designated variable for the amount of power supplied from fuel cells is used, this variable needs to be divided by the installed fuel cell power to obtain the percentage. However, this introduces a nonlinear expression which is not possible in a linear modeling approach. Another way to model the power delivered from fuel cells is be to assign a variable for the percentage load of a fuel cell, and then multiply this percentage with the installed power. This would also introduce nonlinear expressions however as the installed power is the multiplication of the nominal power of the fuel cell modules and the number installed which would have to be a decision variable.

A final approach is to create a set of fuel cell stacks. This can be illustrated by a vector ranging from 1 to n, where the index represents how many fuel cell modules are stacked together. From this pool of combinations, n stacks will exist. Each stack's power rating is the nominal power rating of one module, times the number of modules stacked together. The underlying logic is that the model "sees" the pool of fuel cell stacks possible to use and if a specific fuel cell stack is used in an operational state, this needs to be installed, with the corresponding costs associated with this. By this approach, a pre-defined maximum size possible of the fuel cell system is defined. We need to consider that the fuel cell system may provide the base-load alone, without having to operate in regions where accelerated degradation is present, so a margin of 50% is used. The operational mode with the highest power demand has to be used as a basis, and the relation can be expressed as follows:

$$\text{MaxNumberOfFCStacks} = \left\lceil \frac{1.5 * \max(\text{PowerDemand}}{\min(\text{fcPower})} \right\rceil \tag{4.1}$$

where *PowerDemand* is the matrix of the different power demands in the different operational states and time-periods, and *fcPower* is the array of the rated power of each fuel cell type.

Referring to the available fuel cell stacks, these stacks may be of different types, i.e. LT-PEMFC, HT-PEMFC or SOFC. This means that there will exist three vectors of length n, where e refers to the type. Using i as the index for the fuel cell stack number in the available vector of fuel cell stacks, we can now introduce the variable φ_{eot}, representing the load in MCR of fuel cell stack i of type e in operational state o in time period t, taking on a value between 0 and 1. However, the different fuel cell types may as covered in 2.3.4 use different fuels, which need to be accounted for. For the same reasons different fuel cell stacks had to enumerated due to the linearity requirements, a fuel cell type using a fuel type need to be enumerated. This can be done by extending the variable φ_{ieot} to φ_{iefot}, the load on fuel cell stack i of type e in operational state o using fuel f in time-period t. With this approach, the entire pool of fuel cell stacks will be able to take on a value between 0 and 1 for each operational state considered.

4.1.1 Contribution to voyage expenditures from fuel cells

The voyage related costs of using a specific fuel cell stack i of type e, fed by a specific fuel f is made up of the fuel costs and emission costs.

4.1.1.1 Fuel costs from the usage of fuel cells

Fuel costs depend on fuel price and fuel consumption as covered in 3.4.1.4. Assuming a constant efficiency for the fuel cells, the total fuel consumption depends on the specific fuel consumption (SFC) – g/kWh - and the amount of energy supplied. The energy supplied is the product of the time spent in an operational state and the power delivered, which again is the product of the load on the fuel cell stack and the rated power of that specific stack of type e. Defining the duration of time periods in years as the parameter D^T, and the relative time spent in operational state o in time period t as R_{ot}, the fuel cost contribution from using a fuel cell stack with a fuel f in a specific operational state o in time period t can be defined as:

$$\text{Fuel cell fuel cost} = H^Y D^T R_{ot} C^F_{ft} G_{fe} \varphi_{iefot} P^R_{ie} \tag{4.2}$$

Here H^y is the number of hours in a year, G_{fe} is the specific fuel consumption of fuel f [g/kwh] of fuel cell type e, C_{ft} the fuel cost of fuel f in time period t, and P_{ie} is the rated power of fuel cell stack i of type e. The model decides which fuel cell stacks to use with the different fuels. From a cost perspective, only one fuel cell stack should be used in a combination with one fuel at a time, as the alternative will be to have to install multiple fuel cell stacks, increasing costs. This, in turn, means that the fuel costs must be calculated as the sum of all fuel costs contributions, which leads to the following equation:

$$\text{Total fuel cell fuel cost} = \sum_{t\in T}\sum_{o\in O_t}\sum_{f\in F^{FC}}\sum_{e\in E^{FC}}\sum_{i\in I^E} H^y D^T R_{ot} C^F_{ft} G_{fe} \varphi_{iefot} P^R_{ie} \tag{4.3}$$

4.1.1.2 Emission costs from fuel cells

Ignoring emissions from production, using fuel cells with hydrogen produces no emissions. LNG utilized in a fuel cell will have both CO_2 emissions and NOx emissions, either from the reformer if a fuel cell requiring pure hydrogen is used, or from internally reforming the fuel if a fuel cell capable of this is used ([39]). We can define R^{FC}_{wf} as the specific emissions to air in [g/kwh] of the emission type w using fuel in fuel cells, and the tax on emission type w in time-period t as C_{wt}. Then, from the same modeling approach as for the fuel costs, the total cost of emissions can be expressed as:

$$\text{Total fuel cell emission cost} = \sum_{t\in T}\sum_{o\in O_t}\sum_{w\in W}\sum_{f\in F^{FC}}\sum_{e\in E^{FC}}\sum_{i\in I^E} H^y D^T R_{ot} C^F_{wt} R_{fw} \varphi_{iefot} P^R_{ie} \tag{4.4}$$

4.1.2 Contribution to capital expenditures from fuel cells

To assess the costs of the fuel cell system, the decision of buying fuel cell stacks, auxiliary equipment and fuel tanks need to be considered. We can define the binary variable λ_{ie} as 1 if fuel cell stack i of type e is bought, and 0 if not. This decision variable needs to be connected to the variable defining the load on the fuel cell stack, so that a fuel cell stack does not have any load if it is not included in the final selection. The investment costs of fuel cells will then be the product of the nominal cost of fuel cell type e, the rated power of fuel cell stack i of type e and whether the fuel cell stack is bought or not:

$$\text{Fuel cell investment costs} = \sum_{e\in E^{FC}}\sum_{i\in I^E} C^I_e P^R_{ie} \lambda_{ie} \tag{4.5}$$

The cost of tanks also needs to be accounted for. This will as for the investment costs of fuel cells be connected to the fuel usage. Several tank types might be considered, for the different fuel types - here hydrogen and LNG. As liquid hydrogen and gaseous hydrogen require different tank types, they are also defined as two different fuel types. A variable z_{hf} can then be defined, as the size of tank-type h for fuel f installed, with the corresponding investment cost C^I_{hf} in \$/kg. The total investment cost of the tanks will then be:

$$\text{Cost of fuel tanks} = \sum_{f\in F^{FC}}\sum_{h\in H} C^I_{hf} z_{hf} \tag{4.6}$$

It is assumed that the BOP components are included in the price of the fuel cells so that the only auxiliary equipment for a fuel cell system will be the reformers. As covered in 3.4, only one type of reformer is considered. A variable q can then be defined as the size of the reformer system required, and the total investment cost of reformers will then be the product of the nominal cost of reformers C^A and q:

$$\text{Cost of fuel reformers} = C^A q \tag{4.7}$$

4.1.3 Contribution to operational expenditures from fuel cells

As covered in 3.4, the fuel cells will need annual maintenance, in addition to being replaced when their performance drops below a certain limit.

4.1.3.1 Maintenance costs of fuel cells

The annual maintenance costs are dependent on the size of the system installed and can be expressed as:

$$\text{Maintenance cost of fuel cells} = \sum_{t \in T} \sum_{e \in E^{FC}} \sum_{i \in I^E} C_e^M P_{ie}^R \lambda_{ie} D^T \tag{4.8}$$

4.1.3.2 Replacement costs of fuel cells

The total cost of the replacements of the system will be the number of replacements of the system multiplied with the nominal replacement cost and size of the fuel cell system. The number of replacements can be approximated as the total performance degradation of the system divided by an amount of allowed performance degradation.

As mentioned, no simplified parameterized model have been found for fuel cell degradation. Therefore, an approximation has been made in this thesis. An assumption can be made that the lifetime provided by the manufacturer is valid for steady-state operation in a load region with the lowest degradation (worst-case approximation) and that a constant voltage-degradation takes place during operation. If we refer to the performance drop in percentage voltage loss, an amount of allowed voltage loss V_e for fuel cell type e can be calculated as the product of the performance loss in percent and the rated voltage as specified by the manufacturer:

$$V_e = \text{performance drop in } \% * \text{Rated voltage} \tag{4.9}$$

The constant voltage degradation can then be calculated by dividing the allowed voltage drop by the number of hours guaranteed by the manufacturer, and represented by the parameter J_e^N for a fuel cell type e:

$$J_e^N = \frac{\text{Allowed performance drop}}{\text{Lifetime guaranteed by manufacturer}} \tag{4.10}$$

For simplification, it is assumed that the voltage drop happens instantaneously as for batteries.

The number of replacements of a fuel cell stack i of type e can then be calculated as the product of the duration of operation of that fuel cell stack i of type e, and the voltage degradation factor for fuel cell type e, divided by the allowed amount of degradation for fuel cell type e before replacement. The number of hours a specific fuel cell stack i of e is switched on in a time-period t can be calculated as:

$$\text{Total hours of operation} = \sum_{o\in O_t} \sum_{f\in F^{FC}} H^Y D^T R_{ot}\theta_{iefot} \tag{4.11}$$

where θ_{iefot} is a binary variable indicating if fuel cell stack i of type e is switched on in operational state o in time-period t using fuel f.

The total cost of replacements will then be:

$$\text{Cost of fuel cell replacements} = \sum_{e\in E^{FC}} \sum_{i\in I_e} C_e^R P_{ie}^R \sum_{t\in T} \sum_{o\in O} \sum_{f\in F^{FC}} \sum_{e\in E^{FC}} \sum_{i\in I^E} \frac{H^Y D^T R_{ot}\theta_{iefot} J_e^N}{V_e} \tag{4.12}$$

As high load and low load accelerates the voltage degradation, this need to be incorporated in the function. An approximation to the characteristics has been made, by introducing a binary variable for if the load on fuel cell stack i of type e using fuel f in operational state o in time period t is high, represented by δ_{eifot}^H. Due to modeling challenges, low load accelerated degradation has not been included. The variable indicating high load will be "activated" depending on if the load is under or above a threshold, and will be multiplied with the increased degradation factor J_e^H The total costs of replacements of the fuel cell system will then be:

$$\sum_{e\in E^{FC}} \sum_{i\in I_e} C_e^R P_{ie}^R \sum_{t\in T} \sum_{o\in O} \sum_{f\in F^{FC}} \sum_{e\in E^{FC}} \sum_{i\in I^E} \frac{H^Y D^T R_{ot}(J_e^N \theta_{iefot} + J_e^H)\delta_{eifot}^H}{V_e} \tag{4.13}$$

4.2 Contribution from batteries

As mentioned, batteries are modular and provide the same amount of power when combined. The depth of discharge with the corresponding energy throughput will be used as the factor affecting the degradation behavior, and will therefore be used in calculating the power supplied. As for fuel cells, the total number of battery stacks need to be defined due to the linearity of the model. We can define ρ_{ibot} as the depth-of-discharge of battery stack i of type e in operational state o in time-period t. The power produced can be calculated as the product of DoD and rated battery capacity K_ib, divided by the time of which the energy is supplied – the product of fraction of time in operational state o in time period t and the duration of a roundtrip in time period t, D_t^R:

$$\text{Power supplied in an operational state} = \frac{K_{ib}\rho_{ibot}}{R_{ot}D^R} \tag{4.14}$$

4.2.1 Contribution to voyage expenditures from batteries

The cost contribution to voyage expenditures from a battery stack i of type b providing base load will be the sum of the product of cost of electricity and the energy supplied in a roundtrips, times the number of roundtrip the vessel will be expected to take on during its lifetime, which can be calculated as the following:

$$\text{Electricity cost} = \sum_{t\in T}\sum_{o\in O}\sum_{b\in B}\sum_{i\in I_b} C_t^E K_{ib}\rho_{ibot}\frac{H^Y D^T}{D_r} \tag{4.15}$$

4.2.2 Contribution to capital expenditures from batteries

Similar to fuel cells, binary variables can be introduced for if a battery stack i of type b is bought or not, π_{ib}. The cost corresponding to batteries is as covered in 3.4 based on \$/kWh, the capacity installed. The cost of the needed power inverter also needs to be included, based on the rated power of the battery system. The total capital expenditures from the battery system can then be expressed as:

$$\sum_{b\in B}\sum_{i\in I_b}\pi_{ib}(C_e^I K_{ib} + C_b^A P_{ib}^R) \tag{4.16}$$

Where C_b^A is the nominal cost of the power inverter, and C_b^I is the nominal cost of battery type b.

4.2.3 Contribution to operational expenditures from batteries

4.2.3.1 Maintenance costs of batteries

As for fuel cells, the annual maintenance costs are dependent on the size of the system. The cost can be expressed as:

$$\text{Maintenance cost of batteries} = \sum_{t\in T}\sum_{b\in B}\sum_{i\in I_b} C_b^M P_{ib}^R \pi_{ib} D^T \tag{4.17}$$

4.2.3.2 Replacement costs of batteries

The same way as covered for fuel cells, batteries will need to be replaced several times, dependent on their usage. As mentioned, no concise mathematical relationship is defined in the literature reviewed, and both linear and nonlinear dependencies are suggested. As covered in section 2.4.3, the deeper the DoD, the more prevalent the aging effects. A slope could be calculated based on the relationship between the number of cycles possible at different average DoD's, however, assumptions would be needed to make about the approximation. Therefore, an approach as in (15) is used. An available energy throughput U_{ib} for the battery system can be defined as the product of the number of cycles guaranteed by the manufacturer and the rated capacity of the battery stack:

$$U_{ib} = \text{Number of cycles} * K_{ib} \tag{4.18}$$

The number of replacements can then be expressed as the total energy throughput - amount of energy - provided during the vessel's lifetime, divided by the available energy throughput U_{ib} in the battery system - as stated by the manufacturer. The total amount of energy provided from base load is defined as the following, where $\frac{H^Y D^T}{D_r}$ is the total amount of roundtrips performed in a time period:

$$\text{Total base energy provided} = \sum_{t \in T} \sum_{o \in O} \sum_{b \in B} \sum_{i \in I_b} K_{ib} \rho_{ibot} \frac{H^Y D^T}{D_r} \tag{4.19}$$

The number of battery replacements from providing base power can be defined as:

$$\text{Number of replacements} = \sum_{t \in T} \sum_{o \in O} \sum_{b \in B} \sum_{i \in I_b} \frac{K_{ib} \rho_{ibot} \frac{H^Y D^T}{D_r}}{U_{ib}} \tag{4.20}$$

Then, the cost of replacements from providing base power can be calculated as:

$$\text{Cost of battery replacements} = \sum_{t \in T} \sum_{o \in O} \sum_{b \in B} \sum_{i \in I_b} C_b^R K_{ib} \frac{K_{ib} \rho_{ibot} \frac{H^Y D^T}{D_r}}{U_{ib}} \tag{4.21}$$

Energy throughput from peak shaving can be calculated based on the amount of energy needed to be supplied, from a pre-defined load-compensation pattern. The load-compensation pattern could be results from simulation or measured from a load profile, where a number of N peak shaving instances can be defined, each with its necessary power and duration, E_n^{PS}. The total energy throughput required from peak shaving can then be calculated as:

$$\text{Peak shaving energy throughput} = \sum_{t \in T} \sum_{o \in O_t} \sum_{n \in N_{ot}} E_n^{PS} \frac{H^Y D^T}{D_r} \tag{4.22}$$

A simplification to avoid introducing a variable defining the amount of energy provided for peak shaving from a specific battery stack i of type b is done. This is connected with the constraints limiting the number of battery types installed to one. Then the product of the binary variable indicating if a battery stack i of type b is bought, multiplied with the total energy throughput, defines the total amount of energy throughput of this battery stack. Multiplying this with the cost of replacement of battery type b, C_b^R gives the total cost of replacements for the battery stack of this type. Summing over all possible battery stacks and types, the total cost will be obtained, since only one binary variable π_{ib} will be non-zero. This can be expressed as:

$$\text{Battery replacements cost from peak shaving} = \sum_{t \in T} \sum_{o \in O_t} \sum_{n \in N_{ot}} C_b^R K_{ib} \pi_{ib} \frac{E_n^{PS} \frac{H^Y D^T}{D_r}}{U_{ib}} \tag{4.23}$$

The total battery replacements are then the sum of battery replacements from providing baseload and peak shaving energy.

4.3 Contributions from diesel engines

The specific fuel oil consumption (SFOC) of diesel engines depend on their load in %MCR as covered in 2.2. Although a constant specific SFOC is assumed, the percentage loading will be used as the decision variable, to allow for the inclusion of defining a piecewise linear function so that the model can be expanded upon. A range of different engine sizes may be considered available for usage. A total number of engines may be installed of one engine size. In order to use the %MCR as a decision variable, each engine needs to be enumerated, in a similar way as for fuel cells and batteries. A maximum number of engines that need to be available for selection therefore needs to be defined. This is done similarly as in ([66]), where the maximum power demand during the vessel's lifetime is considered. The maximum number of engines of type m needed to be available in the defined catalog of engines can be expressed as:

$$Y^m \geq \left\lceil \frac{P^{Demand}}{P^R_m} \right\rceil \tag{4.24}$$

For modeling reasons, all engines of all types will be concatenated into one large set of engines, in a one-dimensional vector, indexed by d. In that vector, each index will correspond to a specific engine with its corresponding power rating P^R_d, specific fuel oil consumption of fuel f G_{df}, as well as decision variables.

4.3.1 Contribution to operational expenditures from diesel engines

The fuel and emission costs from using diesel engines are calculated similarly as for the calculation for fuel cells and batteries. A variable for the load on diesel engine d in operational state o in time-period t can be defined. To include the possibilities of using fuels with different contents of sulfur, the variable can be defined as χ_{dfot}, the load in percentage MCR of diesel engine d using fuel f in operational state o in time-period t.

4.3.1.1 Fuel costs

The total fuel costs can be calculated in a similar manner as for fuel cells:

$$\text{Fuel costs} = \sum_{t\in T}\sum_{o\in O}\sum_{d\in D}\sum_{f\in F^{DE}} H^Y D^T R_{ot} C_{ft} G_{df} P^R_d \chi_{dfot} \tag{4.25}$$

We can define R^D_{wf} as the specific emissions to air in [g/kwh] of the emission type w using fuel f in diesel engines, and the tax on emission type w in time-period t as C^E_{wt}. Then, from the same modeling approach as for the emissions from fuel cells, the total cost of emissions can be expressed as:

$$\text{Emission costs} = \sum_{t\in T}\sum_{o\in O}\sum_{d\in D}\sum_{f\in F^{D}}\sum_{w\in W} H^Y D^T R_{ot} C^E_{wt} R^D_{wf} P^R_d \chi_{dfot} \tag{4.26}$$

4.3.2 Contribution to capital expenditures from diesel engines

In the same manner as for fuel cells and batteries, a binary variable can be defined as the decision if an engine d is bought or not, α_d. then the total investment costs can then be expressed as:

$$\text{Diesel engines investment cost} = \sum_{d\in D} C^I_d P^R_d \alpha_d \tag{4.27}$$

4.3.3 Contribution to operational expenditures from diesel engines

Operational expenditures depends on the number of maintenance intervals needed. The cost contribution is modeled as an annual maintenance cost dependent on the size of the machinery. Then the total maintenance costs can be expressed as:

$$\text{Diesel engines maintenance cost} = \sum_{d\in D}\sum_{t\in T} C^M P^R_d D^T \alpha_d \tag{4.28}$$

4.4 Constraints

The costs must be connected to operational constraints. A basic constraint is for instance that a fuel cell stack cannot have a load unless it is bought. Another example is the allowance of being used with fuel f only if tanks are provided, and auxiliary equipment is installed. The installed system must fulfill the following requirements, with the variables defined in the previous section as a basis:

4.4.1 Power demand

The total power demand must be met in each operational state in each time period:

$$\sum_{e\in E^{FC}}\sum_{i\in I_e}\sum_{f\in F^{FC}} P^R_{ie}\varphi_{iefot}\eta_e + \sum_{b\in B}\sum_{i\in I_b}\frac{K_{ib}\rho_{ibot}}{R_{ot}D^R}\eta_e + \sum_{d\in D} P^R_d x_{dfot}\eta_d + \geq P^D_{ot}, \forall t\in T, o\in O_t \tag{4.29}$$

4.4.1.1 Constraints for operation of fuel cells

Power limits:

If a fuel cell stack i of type e using fuel f in operational state o in time-period t is providing load it needs to be switched on, and the load needs to be above a lower limit. The load also needs to be lower than an upper limit. This can be expressed as:

$$\varphi_{iefot} \leq L^u_e\theta_{iefot}, \forall e\in E^{FC}, i\in I_e, f\in F^{FC}, t\in T, o\in O_t \tag{4.30}$$

$$\varphi_{iefot} \geq L^l_e\theta_{iefot}, \forall e\in E^{FC}, i\in I_e, f\in F^{FC}, t\in T, o\in O_t \tag{4.31}$$

Fuel usage:

A constraint should also be included to ensure that a fuel cell is not using more than one type of fuel at a time, this can be formulated as:

$$\sum_{e\in E^{FC}}\sum_{i\in I_e}\sum_{f\in F^{FC}}\theta_{iefot}\leq 1,\forall t\in T,o\in O_t \tag{4.32}$$

Enforced selection of fuel cells:

If a fuel cell stack i of type e is used at any time during the vessel's lifetime, it needs to be bought. This can be expressed as:

$$\sum_{t\in T}\sum_{o\in O_t}\sum_{f\in F^{FC}}\theta_{iefot}\leq \lambda_{ie}*nF^{FC}*nO*nT,\forall e\in E^{FC},i\in I_e \tag{4.33}$$

Necessary size of reformers:

If a fuel cell stack i of type e is used at any time with fuel f, an appropriate reformer system may need to be bought, depending on whether the fuel cell – fuel combination requires this. A matrix A_{ef} can be defined, where its entries are either 0 or 1 depending on if an external fuel reformer is needed using fuel f in fuel cell type e. Then the constraints controlling the size of the fuel reformer system q can be expressed as:

$$\theta_{iefot}P_{ie}A_{ef}\leq q,\forall t\in T,o\in O_t,e\in E^{FC},i\in I_e,f\in F^{FC} \tag{4.34}$$

Enough storage capacity:

The total fuel consumption of fuel in a roundtrip requiring separate tanks (hydrogen, LNG) must not exceed the installed capacity of the storage. This constraint can be defined as:

$$\sum_{o\in O_t}\sum_{e\in E^{FC}}\sum_{i\in I_e}D^R R_{ot}P^R_{ie}\varphi_{iefot}G_{fe}\leq \sum_{f\in F^{FC}}\sum_{h\in H}z_{hf},\forall t\in T,o\in O_t \tag{4.35}$$

Accelerated degradation:

As accelerated degradation happens at low and high loads, a variable δ^H_{eifot} can as mentioned be defined to indicate whether the fuel cell system is operating in this region or not. If the load is above the defined upper level, this variable should be 1, and 0 else. The expression governing this relationship can be defined as the following:

$$\varphi_{iefot}-0.8\leq\delta^U_{iefot},\forall e\in E^{FC},i\in I_e,f\in F^{FC},t\in T,o\in O_t \tag{4.36}$$

4.4.2 Batteries

Battery investment:

Enforcing that a battery stack is bought if it is providing base-load can be done similarly as for the fuel cell system. If the power supplied from a battery stack i of type e is positive at any time, it needs to be bought. This can be expressed by introducing the binary variable ζ_{ibot}, indicating if a battery stack is providing base-load:

$$\rho_{ibot}\leq\zeta_{ibot},\forall b\in B,i\in I_b,t\in T,o\in O_t \tag{4.37}$$

Then, the following enforces that the battery stack is bought:

$$\sum_{t \in T} \sum_{o \in O_t} \zeta_{ibot} \leq \pi_{ib} * \mathrm{nO} * \mathrm{nT}, \forall b \in B, i \in I_b \tag{4.38}$$

Enough battery power installed:

As the battery may be used for both providing load evening (peak shaving and load shedding) and base load, the installed battery system must be sized accordingly, to be able to provide the sum of the base power and maximum peak power if this is the case. Ω_{ot}^{PS} and Ω_{ot}^{LS} can be defined as the maximum peak shaving and load shedding energy in operational state o in time period t respectively. Then the constraints can be expressed by the following equations:

$$\sum_{i \in I_b} P_{ib}^{R} \pi_{ib} \geq \sum_{i \in I_b} \frac{\rho_{ibot} K_{ib}}{R_{ot} D^{R}} + \sum_{i \in I_b} \pi_{ib} \Omega_{ot}^{PS}, \forall b \in B, t \in T, o \in O_t \tag{4.39}$$

$$\sum_{b \in B} \sum_{i \in I_b} P_{ib} \pi_{ib} \geq \Omega_{ot}^{LS}, \forall t \in T, o \in O_t \tag{4.40}$$

Enough installed capacity for load compensation:

As peak shaving and load shedding require power as well as energy, as the power will be integrated over time, the battery system must be sized to be able to provide both maximum peak shaving energy and load shedding energy. Its capability to provide or absorb energy is dependent on how much energy is in the battery already. As the model does not control this factor, an assumption about to which level the battery is charged when it shall provide or absorb energy is made. This reference SOC is assumed to be 50%. Then, taking into account upper and lower limits of the SOC of the battery, delimited by L_b^u and L_b^l, and the maximum energy needed to be absorbed and provided in operational state o in time period t as $\Psi_{ot}^{max,d}$ and $\Psi_{ot}^{max,c}$ respectively, the constraints can be expressed as:

$$\sum_{b \in B} \sum_{i \in I_b} K_{ib} \pi_{ib} \geq \frac{\Psi_{ot}^{max,d}}{L_{bot} - L_b^{L}}, \forall t \in T, o \in O_t \tag{4.41}$$

$$\sum_{b \in B} \sum_{i \in I_b} K_{ib} \pi_{ib} \geq \frac{\Psi_{ot}^{max,c}}{L_u - L_{bot}^{R}}, \forall t \in T, o \in O_t \tag{4.42}$$

Enough battery capacity installed for a roundtrip:

In the case that a battery system is used to provide base-load, it is assumed that the energy is charged by shore. Therefore, the battery stack needs to be sized accordingly so that it, in fact, can provide the amount of energy needed in a round trip. We also assume that the energy losses from peak shaving and load shedding, defined as W_{ot} are covered by charging from shore-power, so this should be included in the equation. Also accounting for the lower and upper limits of the state of charge of the battery, defining the possible/valid region of operation, the constraint can be expressed as:

$$\sum_{o \in O_t} \sum_{b \in B} \sum_{i \in I_b} D^{R} R_{ot} \rho_{ibot} P_{ib}^{R} + \sum_{o \in O_t} W_{ot} \leq \sum_{b \in B} \sum_{i \in I_b} K_{ib} \pi_{ib} (L_e^{U} - L_e^{L}), \forall t \in T \tag{4.43}$$

Limitation on number of battery packs:

As abovementioned, the number of battery stacks must be limited to 1 for the peak shaving energy constraint to be possible. This is expressed as:

$$\sum_{b \in B} \sum_{i \in I_b} \pi_{ib} \leq 1 \tag{4.44}$$

4.4.3 Diesel engines

Indicator for diesel engine switched on:

As for fuel cells and batteries, if an engine has a load χ_{dfot}, it need to be running. This can be expressed by the variable β_{dfot}. The engine's operating region may also need to be limited. These constraints can be expressed as:

$$\chi_{dfot} \leq \beta_{dfot} L^U, \forall d \in D, f \in F^D, t \in T, o \in O_t \tag{4.45}$$

$$\chi_{dfot} \geq \beta_{dfot} L^L, \forall d \in D, f \in F^D, t \in T, o \in O_t \tag{4.46}$$

Constraint ensuring diesel engine is bought if it is switched on:

As for fuel cells and batteries, a diesel engine can only be used (with any fuel) if it is bought, or in other words - if it is ever used, it needs to be bought. This can be expressed by the following:

$$\sum_{t \in T} \sum_{o \in o_t} \sum_{f \in F^D} \beta_{dfot} \leq \alpha_{dfot} * nT * nO * \text{nFuels}, \forall d \in D \tag{4.47}$$

Maximum one fuel at a time:

Also, we need to include a constraint limiting the number of fuels an engine can use at the same time, if for instance the price is the same and there are no additional fixed costs of using the different fuels. This can be expressed as:

$$\sum_{f \in F^D} \beta_{dfot} \leq 1, \forall t \in T, o \in O_t, d \in D \tag{4.48}$$

Fuel-compliance:

As different time-periods are considered, and because the vessel might be operating in different regions with different regulations on emissions to air, a constraint ensuring that the fuel used is in compliance with regulations should be included. A parameter Γ_f can be defined to indicate whether a fuel is compliant in operational state o in time-period t with no use of exhaust after treatment. The corresponding constraint enforcing compliance can then be defined as:

$$\beta_{dfot} \leq \Gamma_{fot}, \forall d \in D, f \in F^D, t \in T, o \in O_t \tag{4.49}$$

4.5 Compact mathematical formulation of optimization model

The resulting optimization model can be presented in compact form by sets, parameters, optimization variables as well as the mathematical equations, as in the following:

4.5.1 Sets, parameters and optimization variables

Sets	
T	Time periods, indexed by t
O	Operational states, indexed by o
D	Set of diesel engines, indexed by d
E	Set of fuel cell types, indexed by e
B	Set of battery types, indexed by b
F	Set of fuels, indexed by f
F^{FC}	Subset of fuels for fuel cells, indexed by f
F^{D}	Subset of fuels for diesel engines, indexed by f
W	Set of air emissions considered, indexed by w
H	Set of fuel storage tank types, indexed by h

Parameters	
H^{Y}	Hours in a year
D^{T}	Duration of time periods in years
C^{F}_{ft}	Cost of fuel f in time period t
C^{t}_{e}	Cost of electricity in time period t
C^{I}_{e}	Investment cost for fuel cell type e [\$/kW]
C^{I}_{b}	Investment cost for battery type b [\$/kWh]
$C^{Inverter}$	Investment cost for battery power inverter, [\$/kW]
C^{I}_{d}	Investment cost for diesel engine d, [\$/kW]
C_{hf}	Investment cost for fuel tank type h for fuel f, [\$/kg]
C^{A}	Cost of auxiliary systems for fuel cells (reformer)
C^{M}_{e}	Maintenance cost of fuel cell type e, [\$/kW]
C^{M}_{b}	Maintenance cost of battery type b, [\$/kW]
C^{M}_{d}	Annual maintenance cost for diesel engines, [\$/kW]
C^{R}_{e}	Replacement cost for fuel cell type e, [\$/kW]
C^{R}_{b}	Replacement cost for battery type e, [\$/kWh]
C^{E}_{wt}	Tax on air emission type w in time period t [\$/ton]
Γ_{fot}	Fuel compatibility of fuel f with regulations in operational state o in time period t without emission gas aftertreatment, [0/1]
P^{R}_{ie}	Rated power of fuel cell stack i of type e, [kW]
P^{R}_{ib}	Rated power of battery stack i of type b, [kW]
P_{d}	Rated power of diesel engine d, [kW]
K^{R}_{ib}	Rated capacity of battery stack i of type b, [kWh]
U_{ib}	Available energy throughput for battery stack i of type b, [kWh]
V_{e}	Allowed performance drop for fuel cell type e, [V]
$\Psi^{max,d}_{ot}$	Maximum peak shaving energy needed to deliver in operational state o in time period t, [kWh]

$\Psi_{ot}^{max,c}$	Maximum load shedding energy needed to absorb in operational state o in time period t, [kWh]
$\Omega^{max,d}$	Maximum peak shaving power needed to deliver in operational state o in time period t, [kW]
$\Omega^{max,c}$	Maximum load shedding power needed to absorb in operational state o in time period t, [kW]
L_e^u	Upper load limit for diesel engine e, fuel cell type e and battery type e, [%MCR]
L_e^l	Lower load limit for diesel engine e, fuel cell type e and battery type e, [%MCR]
L_{ot}^r	Reference SOC in operational state o in time period t
I_{ot}	Initial SOC for batteries in operational state o in time period t, [%]
G_{fe}	Specific fuel consumption of fuel f by fuel cell type e, [g/kWh]
G_{fd}	Specific fuel consumption of fuel f by diesel engine d, [g/kWh]
R_{fw}^{FC}	Specific air emission factor of emission type w from fuel cells using fuel f, [g/kWh]
R_{fw}^{D}	Specific air emission factor of emission type w from diesel engines using fuel f, [g/kWh]
R_{ot}	Fraction of time in operational state o in time period t, [%]
P_{ot}^{D}	Power demand in operational state in time period t, [kW]
E_n^{PS}	Amount of energy required for peak shaving instance n in operational state o in time period t in a typical roundtrip, [kWh]
E_n^{LS}	Amount of energy required to absorb for load shedding instance n in operational state o in time period t in a typical roundtrip, [kWh]
W_{ot}	Amount of lost energy in a typical roundtrip in operational state o in time period t, [kWh]
A_{ef}	Parameter indicating if reformer is necessary when using fuel f with fuel cell type e, [0/1]
L_{bot}^{R}	Reference state of charge of battery type b in operational state o in time period t
L_e^U	Upper load limit for fuel cell type e
L_e^L	Lower load limit for fuel cell type e
L_d^U	Upper load limit for diesel engine d
L_d^L	Lower load limit for diesel engine d

Variables	
φ_{iefot}	Load on fuel cell stack i of type e using fuel f in operational state o in time period t [% MCR]
ρ_{ieot}	Depth of discharge of battery stack i of type b in operational state o in time period t [% of capacity]
χ_{dfot}	Load on diesel engine d using fuel f in operational state o in time period t, [% MCR]
θ_{eot}	1 if fuel cell stack i of type e is switched on in operational state o in time period t, using fuel f, 0 otherwise
ζ_{ibot}	1 if battery stack i of type b is switched on in operational state o in time period t, 0 otherwise
β_{dfot}	1 if diesel engine d is running in operational state o in time period t, using fuel f, 0 otherwise
λ_{ie}	1 if fuel cell stack i of type e is selected, 0 otherwise
π_{ib}	1 if battery stack i of type b is selected, 0 otherwise
α_d	1 if diesel engine d is selected, 0 otherwise
δ^U_{iefot}	1 if fuel cell stack i of type e is running in high load region in operational state o in time period t using fuel f, 0 otherwise
z_{hf}	Size of storage tank system h for fuel f, [kg]
q	Size of reformer system, [kW]

4.5.2 Mathematical formulation

$$
\begin{aligned}
\min z = \ & \textbf{Fuel costs:} \\
& \sum_{t\in T}\sum_{o\in O_t}\sum_{f\in F^{FC}}\sum_{e\in E^{FC}}\sum_{i\in I^E} H^y D^T R_{ot} C^F_{ft} G_{fe} \varphi_{iefot} P^R_{ie} \\
& + \sum_{t\in T}\sum_{o\in O}\sum_{e\in E^B}\sum_{i\in I_e} C^E_t K_{ie} \rho_{ieot} \frac{H^Y D^T}{D_r} \\
& + \sum_{t\in T}\sum_{o\in O}\sum_{d\in D}\sum_{f\in F^{DE}} H^Y D^T R_{ot} C_{ft} G_{df} P^R_d \chi_{dfot} \\
& + \ \textbf{Emission costs:} \\
& = \sum_{t\in T}\sum_{o\in O_t}\sum_{w\in W}\sum_{f\in F^{FC}}\sum_{e\in E^{FC}}\sum_{i\in I^E} H^y D^T R_{ot} C^F_{wt} R_{fw} \varphi_{iefot} P^R_{ie} \\
& + \sum_{t\in T}\sum_{o\in O}\sum_{d\in D}\sum_{f\in F^D}\sum_{w\in W} H^Y D^T R_{ot} C^E_{wt} R^D_{wf} P^R_d \chi_{dfot} \\
& + \ \textbf{Investment costs:} \\
& = \sum_{e\in E^{FC}}\sum_{i\in I^E} C^I_e P^R_{ie} \lambda_{ie} + \sum_{f\in F^{FC}}\sum_{h\in H} C^I_{hf} z_{hf} + \sum_{f\in F^{FC}}\sum_{e\in E^{FC}} C^A_{ef} q_{ef} \\
& + \sum_{e\in E^B}\sum_{i\in I_e} \pi_{ie}(C^I_e K_{ie} + C^A_e P^R_{ie}) \\
& + \sum_{d\in D} C^I_d P^R_d \alpha_d \\
& + \ \textbf{Maintenance costs:} \\
& = \sum_{t\in T}\sum_{e\in E^{FC}}\sum_{i\in I^E} C^M_e P^R_{ie} \lambda_{ie} D^T + \sum_{t\in T}\sum_{b\in B}\sum_{i\in I_b} C^M_b P^R_{ib} \pi_{ib} D^T + \sum_{d\in D}\sum_{t\in T} C^M P^R_d D^T \alpha_d \\
& + \ \textbf{Replacement costs:} \\
& = \sum_{e\in E^{FC}}\sum_{i\in I_e} C^R_e P^R_{ie} \sum_{t\in T}\sum_{o\in O}\sum_{f\in F^{FC}}\sum_{e\in E^{FC}}\sum_{i\in I^E} \frac{H^Y D^T R_{ot}(J^N_e \theta_{iefot} + J^H_e \delta^H_{eifot})}{V_e} \\
& + \sum_{t\in T}\sum_{o\in O}\sum_{e\in E^B}\sum_{i\in I_e} C^R_b K_{ie} \frac{K_{ie}\rho_{ieot}\frac{H^Y D^T}{D_r}}{U_{ie}} \\
& + \sum_{t\in T}\sum_{o\in O_t}\sum_{n\in N_{ot}} C^R_b K_{ib} \pi_{ib} \frac{E^{PS}_n \frac{H^Y D^T}{D_r}}{U_{ie}}
\end{aligned} \tag{4.50}
$$

subject to

$$
\sum_{e\in E^{FC}}\sum_{i\in I_e}\sum_{f\in F^{FC}} P^R_{ie}\varphi_{iefot}\eta_e + \sum_{e\in E^B}\sum_{i\in I_e} \frac{K_{ie}\rho_{ieot}}{R_{ot}D^R}\eta_e +
$$

$$
\sum_{d\in D} P^R_d x_{dfot} \eta_d \geq P^D_{ot}, \qquad t \in T, o \in O \tag{4.51}
$$

$$
\varphi_{iefot} \leq L^u_e \theta_{iefot}, \qquad e \in E^{FC}, i \in I_e, f \in F^{FC}, t \in T, o \in O_t \tag{4.52}
$$

$$
\varphi_{iefot} \geq L^l_e \theta_{iefot}, \qquad e \in E^{FC}, i \in I_e, f \in F^{FC}, t \in T, o \in O_t \tag{4.53}
$$

$$
\sum_{e\in E^{FC}}\sum_{i\in I_e}\sum_{f\in F^{FC}} \theta_{iefot} \leq 1, \qquad t \in T, o \in O_t \tag{4.54}
$$

$$
\sum_{t\in T}\sum_{o\in O_t}\sum_{f\in F^{FC}} \theta_{iefot} \leq \lambda_{ie} * nF^{FC} * nO * nT, \qquad e \in E^{FC}, i \in I_e \tag{4.55}
$$

$$
\theta_{iefot} P_{ie} A_{ef} \leq q, \qquad t \in T, o \in O_t, e \in E^{FC}, i \in I_e, f \in F^{FC} \tag{4.56}
$$

$$
\sum_{o\in O_t}\sum_{e\in E^{FC}}\sum_{i\in I_e} D^R R_{ot} P^R_{ie} \varphi_{iefot} G_{fe} \leq \sum_{f\in F^{FC}}\sum_{h\in H} z_{hf}, \qquad t \in T, o \in O_t \tag{4.57}
$$

$$
\varphi_{iefot} - 0.8 \leq \delta^U_{iefot}, \qquad e \in E^{FC}, i \in I_e, f \in F^{FC}, t \in T, o \in O_t \tag{4.58}
$$

$$\rho_{ieot} \leq \zeta_{ieot}, \qquad e \in E^B, i \in I_e, t \in T, o \in O_t \tag{4.59}$$

$$\sum_{t \in T} \sum_{o \in O_t} \zeta_{ieot} \leq \pi_{ie} nO * nT, \qquad e \in E^B, i \in I_e \tag{4.60}$$

$$\sum_{i \in I_e} P^R_{ie} \pi_{ie} \geq \sum_{i \in I_e} \frac{D_{ieot} K_{ie}}{R_{ot} D^R} + \sum_{i \in I_e} \pi_{ie} \Omega^{PS}_{ot}, \qquad e \in E^B, t \in T, o \in O_t \tag{4.61}$$

$$\sum_{e \in E^B} \sum_{i \in I_e} P_{ie} \pi_{ie} \geq \Omega^{LS}_{ot}, \qquad t \in T, o \in O_t \tag{4.62}$$

$$\sum_{e \in E^B} \sum_{i \in I_e} K_{ie} \pi_{ie} \geq \frac{\Psi^{max,d}_{ot}}{L_{eot} - L^L_e}, \qquad t \in T, o \in O_t \tag{4.63}$$

$$\sum_{e \in E^B} \sum_{i \in I_e} K_{ie} \pi_{ie} \geq \frac{\Psi^{max,c}_{ot}}{L_u - L^R_{eot}}, \qquad t \in T, o \in O_t \tag{4.64}$$

$$\begin{aligned} &\sum_{o \in O_t} \sum_{e \in E^B} \sum_{i \in I_e} D^R R_{ot} \rho_{ieot} P^R_{ie} + \sum_{o \in O_t} W_{ot} \leq \\ &\sum_{e \in E^B} \sum_{i \in I_e} K_{ie} \pi_{ie} (L^U_e - L^L_e), \qquad t \in T \end{aligned} \tag{4.65}$$

$$\sum_{e \in E^B} \sum_{i \in I_e} \pi_{ie} \leq 1 \tag{4.66}$$

$$\chi_{dfot} \leq \beta_{dfot} L^U, \qquad d \in D, f \in F^D, t \in T, o \in O_t \tag{4.67}$$

$$\chi_{dfot} \geq \beta_{dfot} L^L, \qquad d \in D, f \in F^D, t \in T, o \in O_t \tag{4.68}$$

$$\sum_{t \in T} \sum_{o \in o_t} \sum_{f \in F^D} \beta_{dfot} \leq \alpha_{dfot} * nT * nO * \text{nFuels}, \qquad d \in D \tag{4.69}$$

$$\sum_{f \in F^D} \beta_{dfot} \leq 1, \qquad t \in T, o \in O_t, d \in D \tag{4.70}$$

$$\beta_{dfot} \leq \Gamma_{fot}, \qquad d \in D, f \in F^D, t \in T, o \in O_t \tag{4.71}$$

The objective function (4.50) minimizes the total cost of the system over the vessel's lifetime. Constraint (4.51) demand ensures that the power demand in all operational states is met. Constraints (4.52) and (4.53) ensures that if a fuel cell stack is providing load, it is switched on, and operated within its power limits. Constraint (4.54) ensures that only one fuel - fuel cell combination is providing load at a time. Constraint (4.55) ensures that a fuel cell stack is bought if it is used at any time during the lifetime of the vessel. If a fuel - fuel cell combination requiring reformers is used, the corresponding size of reformers need to be bought. This is ensured by constraint (4.56). Constraint (4.57) ensures that enough tank capacity for fuels used in fuel cells is installed, while constraint (4.58) governs the relationship between the load on fuel cells and if accelerated degradation occurs. If a battery stack is providing baseload, it needs to be switched on. This is governed by constraint (4.59). Then, if a battery stack is switched on at any time during the vessel's lifetime, it needs to be bought, governed by constraint (4.60). Constraints (4.61) to (4.64) ensures that the selected battery system is large enough to provide peak power and energy, while constraint (4.65) ensures that enough battery capacity is installed to provide the necessary energy in a roundtrip if it providing baseload. Constraint (4.66) ensures that only one battery stack is bought. If a diesel engine is providing load, it need to be switched on and operated within the allowed limits. This is governed by constraints (4.67) and (4.68). If a diesel engine is switched on at any time, it needs to be bought. This is governed by constraint (4.69). Constraint (4.70) ensures that only one fuel is used in a diesel engine at a time, while 4.71 ensures that the fuel used is compliant with regulations.

Chapter 5

Case study

This chapter aims to exemplify and validate the applicability of the optimization model developed. The model is deterministic, and two scenarios have been explored, each with their different assumptions about future fuel prices and emission tax regulations. For simplicity and consistency, the same mission profile is used for both scenarios. Both cases have an operational profile as described in table 5.1. For simplicity and consitency, the same operational profile is assumed for both scenarios. The operational profile is only made-up, in order to test the model. Due to a very long computational time, the model is scaled down in terms of power demand and duration of a roundtrip. The increase in computational time happens due to the necessary increased size of the power system. This can be explained by the increase in available fuel cell stacks and battery stacks needed, as well as diesel engines, when power demand increases. The optimization model is implemented in Matlab with a problem-based approach and *intlinprog* as the solver.

The different factors included are fuel prices, fuel compliance both inside and outside ECA's, emission taxes and requirements for electricity-only modes. As HFO is not compliant with the IMO 2020 regulative, MDO and ultra-low-sulfur-fuel-oil (ULSFO) (less than 0.1% sulfur content) are the only available fuel oils available for diesel engines.

Table 5.1: Operational parameters for both scenarios.

Parameters	**Transit low ECA**	**Transit high ECA**	**Transit low**	**Transit high**	**Operation**	**Port**
Power demand T1 [h]	600	1000	600	1000	1100	400
Power demand T2 [h]	600	1000	600	1000	1100	400
Fraction of time T1 [%]	0,03	0,02	0,4	0,05	0,45	0,05
Fraction of time T2 [%]	0,03	0,02	0,4	0,05	0,45	0,05

The load fluctuation is as mentined assumed to be known, and a test-load fluctuation pattern is created, with the basis on a repetitive pattern from environmental loads (waves, wind, current). The period is defined to be 10 seconds on average, with a peak and through at every 5 seconds each. Then the total number of peaks and throughs each minute is 6. The total number of peaks and throughs each hour is then 6 times 60 = 360, and the total number of peaks and throughs each roundtrip becomes the number of peaks and throughs each hour times the duration of roundtrips in the time-period. The power needed for peak shaving and load shedding in an operational state is for simplicity taken as a fraction of the power demand in that operational state. A simplification is also made to find the energy associated with the peak shaving and load shedding instances. As the load compensation instances will only be at their fullest in a fraction of the total duration of the peak, an equivalent duration of the full level is assumed, here 0.01 seconds.

5.1 Case 1 - No additional regulations

This scenario assumes a steady 10% growth of fuel oil prices from time-period 1 to time-period 2, while it has been assumed that electricity prices and thereby the production of hydrogen has been subject to a 10% decrease. It is also assumed that no additional fuel-compliance regulations are implemented in time-period 2. Emission tax development have been extrapolated from the average increase in tax levels from 2007 to 2019 (5). No electricity-only modes is assumed in this scenario. The scenario parameters are summarised in table 5.2

Table 5.2: Scenario paramters for scenario 1.

	Description	Parameter	T1	T2	Unit
Price development	10% increase	**MDO - <0,5%**	555,00	610,50	[$/ton]
	10% increase	**ULSFO - <0.1%**	800,00	880,00	[$/ton]
	10% decrease	**LH2**	6.160,00	5.544,00	[$/ton]
	10% decrease	**H2700bar**	5.544,00	4.989,60	[$/ton]
	10% decrease	**LNG**	450,00	495,00	[-]
	10% decrease	**Electricity**	0,06	0,06	[$/kWh]
Fuel compliance development ECA	No change	**MDO - <0,5%**	no	no	[-]
		ULSFO - <0.1%	yes	yes	[-]
Fuel compliance development non-ECA	No change	**MDO - <0,5%**	yes	yes	[-]
		ULSFO - <0.1%	yes	yes	[-]
Tax development	Avg. increase	**Nox**	2.811,02	3.484,17	[$/ton]
		$\mathbf{CO_2}$	-	-	[$/ton]
		$\mathbf{CH_4}$	-	-	[$/ton]
Electric-only requirements	None	**ECA**	no	no	[-]
		Non-ECA	no	no	[-]

5.1.1 Resulting power system

Table 5.3 shows the resulting costs of the power system for scenario 1, divided into CAPEX, VOYEX and OPEX. As seen, based on the assumed parameters, the model chooses a combination of all three power generating sources. As can be seen in table 5.4, the machinery system consists of a battery system of one battery module with a rated power and capacity of 420 kW and kWh, a LT-PEMFC fuel cell system consisting of 13 fuel cell modules of 100kW rated power each, and one diesel engine with a rated power of 1200 kW. Figure 5.1 shows the power distribution in the different operational states and time periods from the different power generating sources installed. Figure 5.3 and 5.4 shows that only LNG is used as fuel for fuel cells. The usage of batteries is limited, as seen in figure 5.1. An explanation for this may be that since a battery system is required to be installed for load-compensation purposes, and electricity is cheap, it is beneficial to utilize the stored energy. However, to utilize electricity stored in batteries to a larger extent, a larger battery system need to be installed, which is not cost-optimal due to the large investment costs, which explains that only a portion of the required power is covered by batteries, in only one operational state in each time period. It can also be observed that the batteries provide different amounts of power in the different operational states in the different time periods. This can be explained by the fact that the fraction of time in each operational state differs, so that the total energy provided in operational state 2 and 3 would be the same if the usage of batteries is limited by the available amount of energy. It should also be mentioned that the optimization problem is down-scaled, which affects the necessary size of the power system installed. As seen from figure 5.2, diesel engines are as as expected used with ULSFO in operational state 2 in time period 1. This operational mode is in an ECA where ULSFO is the only compliant fuel. In the other operational states where diesel engines are used, MDO is used. A reason for the model not choosing diesel engines to provide power in any operational state in time period 2 may be the assumed increased taxes on NOx-emissions in this time period.

Table 5.3: Resulting costs for the optimal power system for scenario 1. Values in $.

Capex		**Voyex**		**Opex**	
Fuel cells	305.500	**Electricity**	35.733	**FC: Maintenance**	1.300.000
FC: Reformer	60.606	**FC:Fuel**	5.207.371	**B: Maintenance**	176.400
FC: Tanks	37.205	**DE: Fuel**	960.972	**DE: Maintenance**	124.800
Batteries	546.000	**FC: Emissions**	266.803	**FC: Replacement**	754.683
Power inverter	16.800	**DE: Emissions**	320.376	**B: Repl. from baseload**	67.438
Diesel engines	62.400			**B: Repl. from LC**	63.873
Total capex	1.028.511	**Total voyex**	6.791.255	**Total opex**	2.487.194
System cost					10.306.960

Table 5.4: The installed power system for scenario 1.

Power systems	**No.installed**	**Nominal kW**	**Installed kW**	**Nominal kWh**	**Installed kWh**
Batteries					
Type 1	0	300	0	300	0
Type 2	1	420	420	420	420
Fuel cells					
LT-PEMFC	13	100	1300	-	-
HT-PEMFC	0	100	0	-	-
SOFC	0	100	0	-	-
Diesel engines					
Type 2	1	1200	1200	-	-

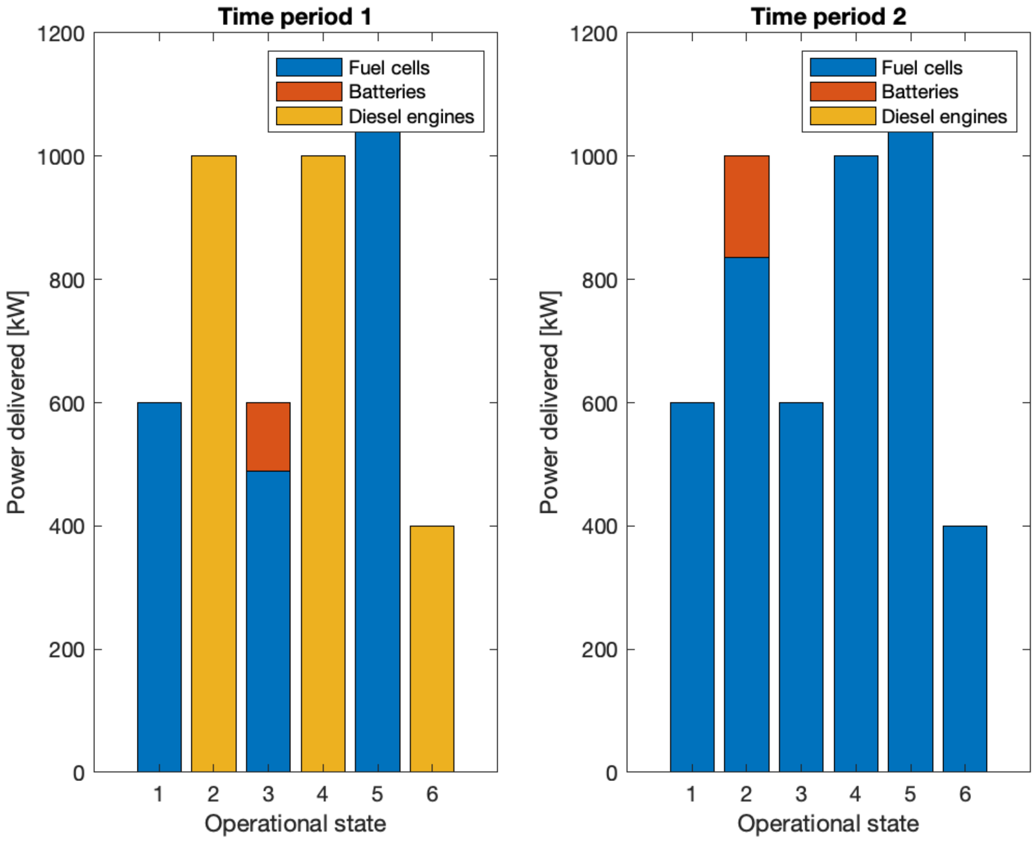


Figure 5.1: Power delivered by power sources in scenario 1.

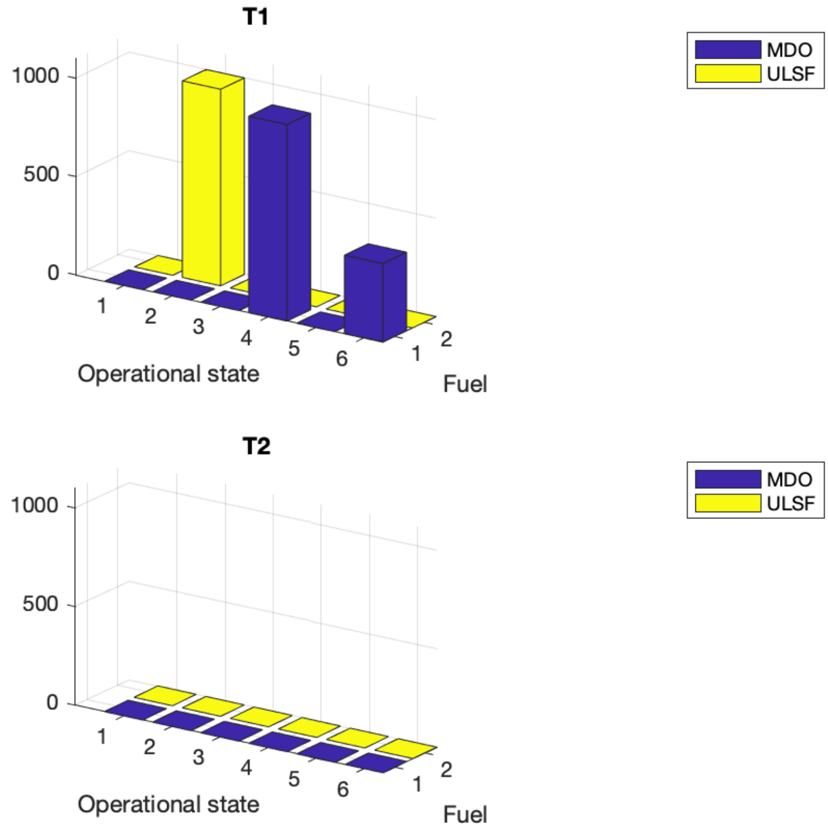


Figure 5.2: Power delivered from diesel engines in the various operational states in scenario 1, by fuel type.

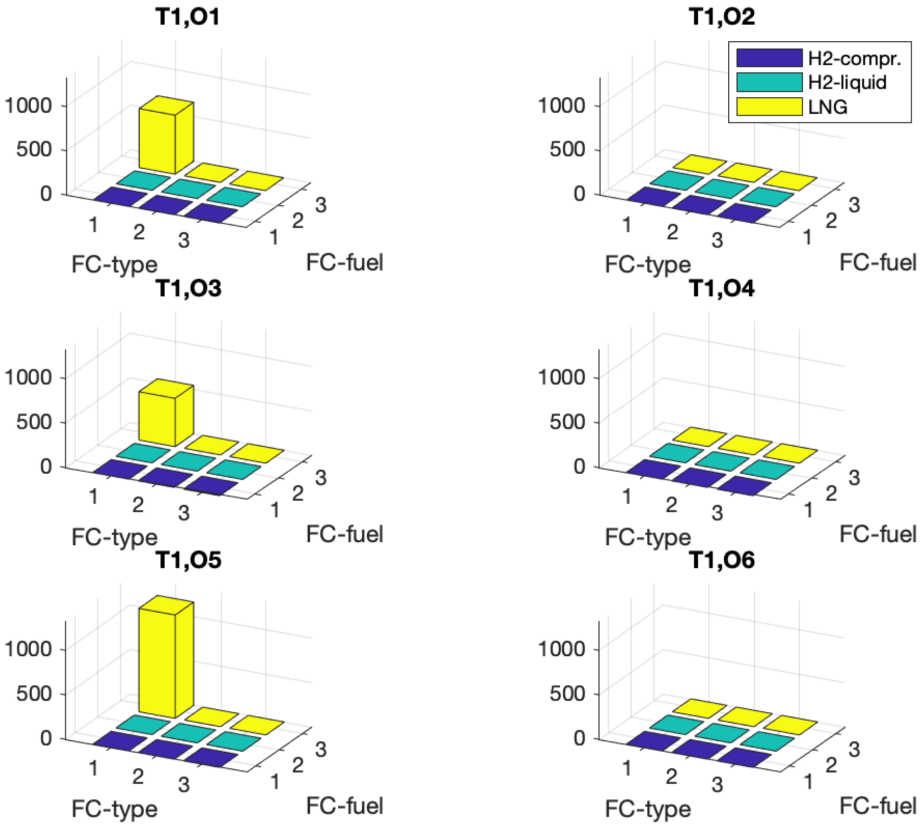


Figure 5.3: Power delivered from fuel cells in the various operational states in time period 1 in scenario 1, by fuel and fuel cell type.

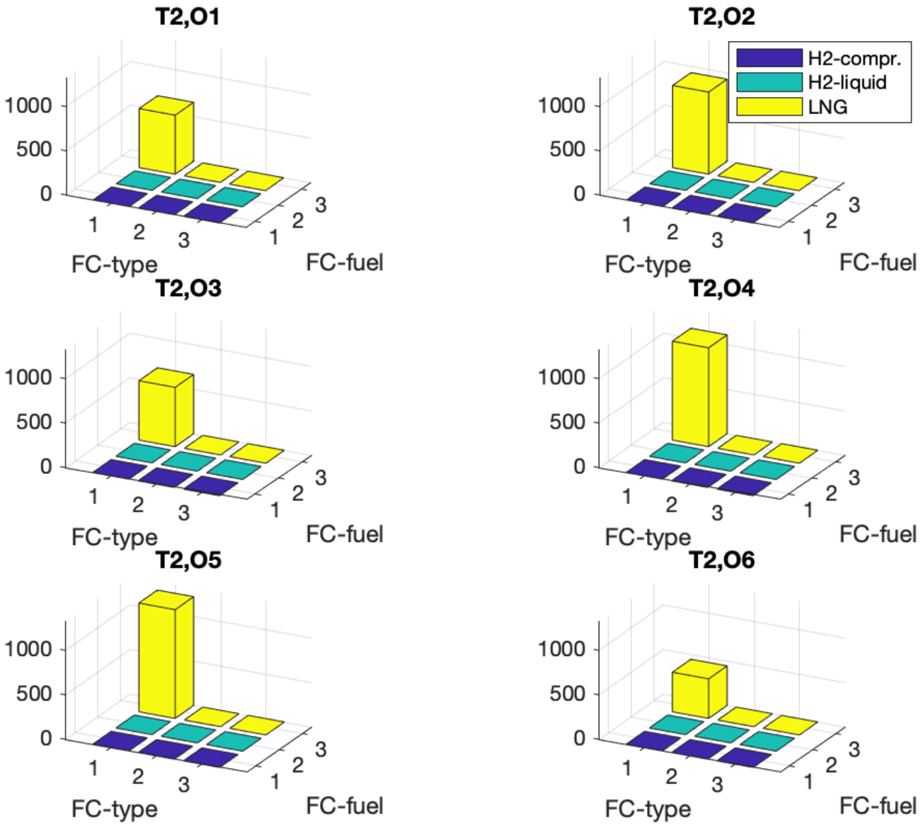


Figure 5.4: Power delivered from fuel cells in the various operational states in time period 2 in scenario 1, by fuel and fuel cell type.

5.2 Case 2 - Strict environmental regulations

The same fuel price development as for scenario 1 is expected in scenario 2, but stricter environmental regulations are assumed. In ECAs, an electricity-only mode is enforced, and a global tax on emissions of CO_2 is included. Emissions of NOx and CH_4 are converted to CO_2-equivalents to include these contributions. The scenario is summarised in table 5.5.

Table 5.5: Scenario paramters for scenario 2.

	Description	Parameter	T1	T2	Unit
Price development	10% increase	**MDO - <0,5%**	555,00	610,50	[$/ton]
	10% increase	**ULSFO - <0.1%**	800,00	880,00	[$/ton]
	10% decrease	**LH2**	6.160,00	5.544,00	[$/ton]
	10% decrease	**H2700bar**	5.544,00	4.989,60	[$/ton]
	10% decrease	**LNG**	450,00	495,00	[-]
	10% decrease	**Electricity**	0,06	0,06	[$/kWh]
Fuel compliance development ECA	None compliant	**MDO - <0,5%**	no	no	[-]
		ULSFO - <0.1%	no	no	[-]
Fuel compliance development non-ECA	No change	**MDO - <0,5%**	yes	yes	[-]
		ULSFO - <0.1%	yes	yes	[-]
Tax development	$1*NOx = 298*CO_2$	**Nox**	2.811	11.920	[$/ton]
Global tax on CO_2		**CO_2**	-	40	[$/ton]
	$1*CH_4 = 25*CO_2$	**CH_4**	-	1.000	[$/ton]
Electric-only requirements	Enforced in ECAs	**ECA**	yes	yes	[-]
		Non-ECA	no	no	[-]

5.2.1 Resulting power system

The resulting costs of the power system for scenario 2 are presented in table 5.6. The power distribution in the different operational states is presented in figure 5.5. As the power profile is the same for both scenarios, the power system is not unexpectedly the same. Diesel engines can be observed to be used to a lesser extent, at the expense of fuel cells, which also is reflected in increased investment costs of fuel tanks in scenario 2. LNG is used as the fuel for fuel cells in this scenario as well as seen in figure 5.7 and 5.8. The usage of batteries is limited in this scenario as well, as seen in figure 5.5, and can be explained by the same reasoning as for scenario 1. Diesel engines are only used in time-period 1, as for scenario 1 as seen in figure 5.6. They are only used in non-ECA operational states, however, as an electricity-only mode is enforced in these regions in this scenario. The exclusion of diesel engine power in time-period 2, as for in scenario 1, may be due to the increased taxes on emissions of NOx.

Table 5.6: Resulting costs for the optimal power system for scenario 2. Values in $.

Capex		**Voyex**		**Opex**	
Fuel cells	305.500	**Electricity**	22.012	**FC: Maintenance**	1.300.000
FC: Reformers	60.606	**FC: Fuel**	7.228.909	**B: Maintenance**	176.400
FC: Tanks	37.205	**DE: Fuel**	680.652	**DE: Maintenance**	124.800
Batteries	546.000	**FC: Emissions**	873.495	**FC: Replacements**	879.527
Power inverter	16.800	**DE: Emissions**	268.535	**B: Repl. from baseload**	41.683
Diesel engines	62.400			**B: Repl. from LC**	63.873
Total capex	1.028.511	**Total voyex**	9.073.604	**Total opex**	2.586.283
System cost					12.688.398

Table 5.7: The installed power system for scenario 2.

Power systems	**No.installed**	**Nominal kW**	**Installed kW**	**Nominal kWh**	**Installed kWh**
Batteries					
Type1	0	300	0	300	0
Type2	1	420	420	420	420
Fuel cells					
LT-PEMFC	13	100	1300	-	-
HT-PEMFC	0	100	0	-	-
SOFC	0	100	0	-	-
Diesel engines					
Type2	1	1200	1200	-	-

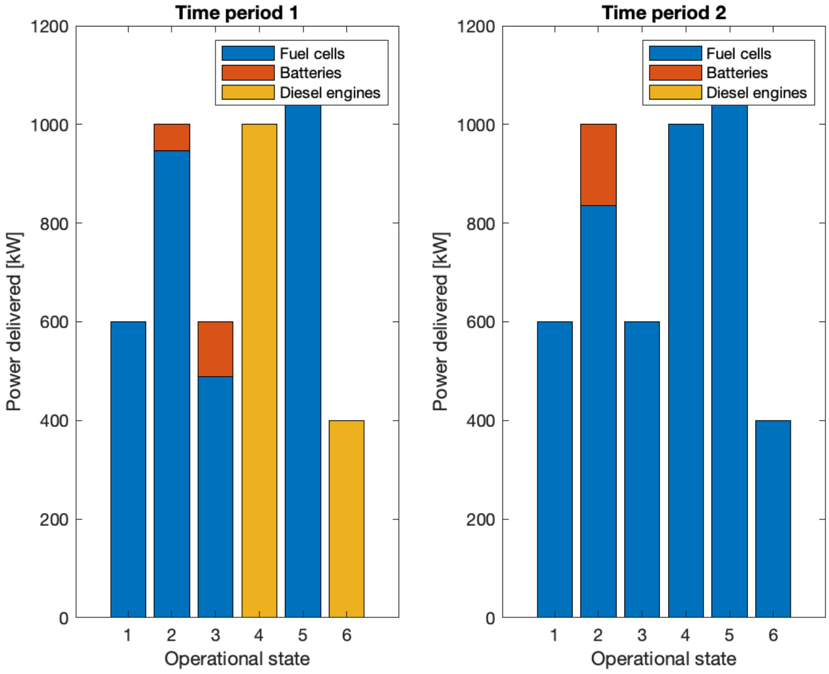


Figure 5.5: Power delivered by the different power sources in scenario 2.

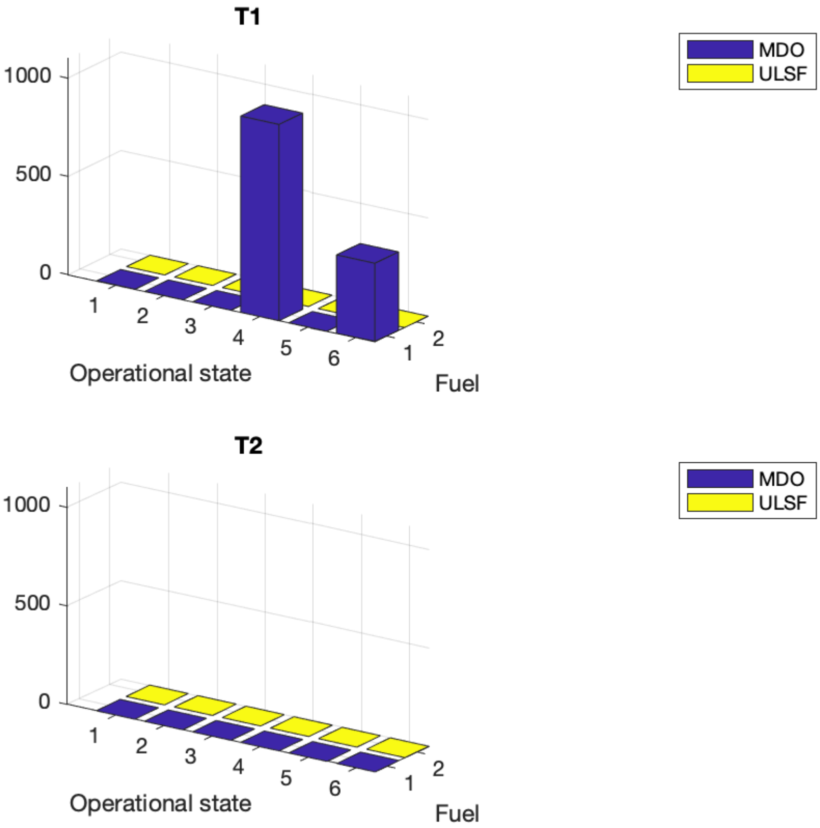


Figure 5.6: Power delivered from diesel engines in the various operational states in scenario 2, by fuel types.

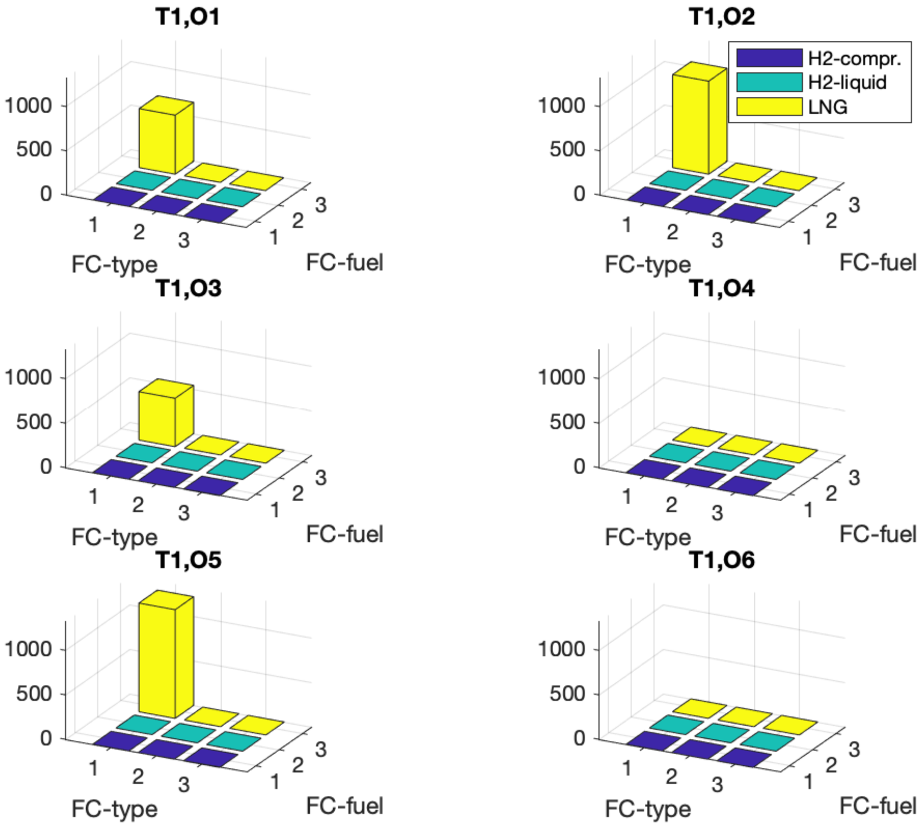


Figure 5.7: Power delivered from fuel cells in the various operational states in time period 1 in scenario 2, by fuel and fuel cell type.

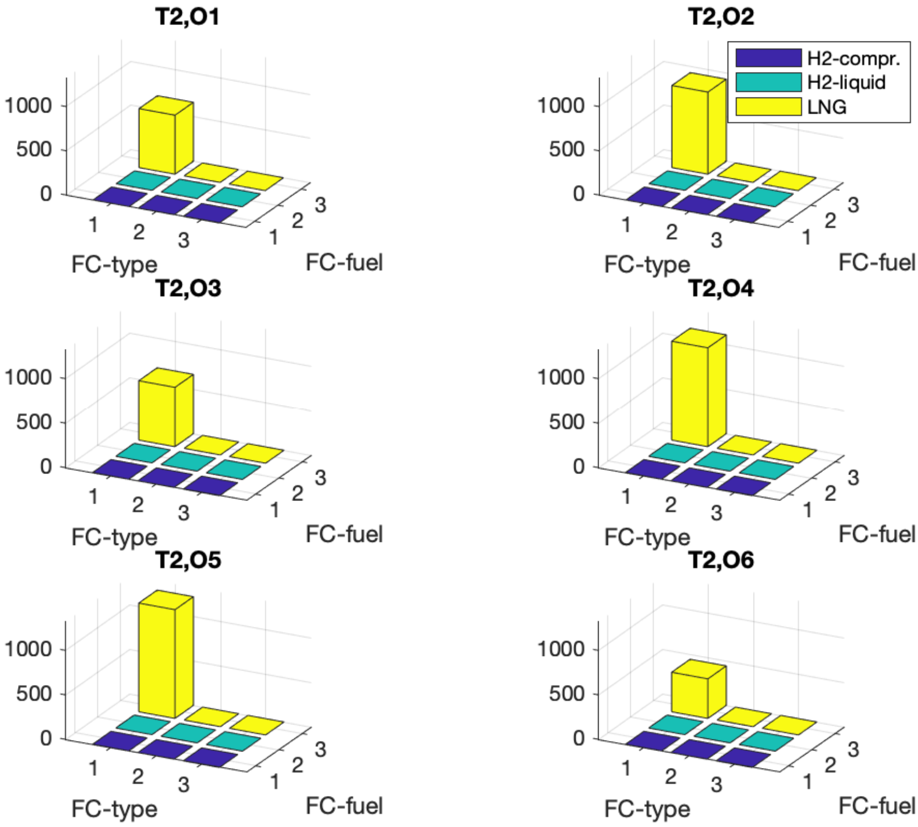


Figure 5.8: Power delivered from fuel cells in the various operational states in time period 2 in scenario 2, by fuel and fuel cell type.

Chapter 6

Discussion

The modeling approach, system assumptions and simplifications with their implications are discussed in this chapter. A model in this context is as mentioned only an approximation of the real system, and every aspect cannot be included. It should be noted that a model is only valid in the specified system scenario it is defined for, and model assumptions and simplifications therefore directly affect the results. It should also be noted that the model is by no means a complete representation of the system, and several expansions can be made with the result of enhanced precision.

6.1 Choice of modeling approach

The modeling approach chosen, is a compromise between reducing complexity and creating a solvable model that includes the most important factors when considering the machinery system in a conceptual design phase. The model needs to solve a two-fold optimization problem, concurrently deciding on the selection of the power system, and how to operate the selected power system. An approach based on the work by (66) was used, where the vessel's lifetime could be represented by different operational states and time-periods.

With the inclusion of ESS, the energy balance needs to be taken into account. As the problem is modeled in the frequency domain with different operational states and time-periods, instead of in the time domain, an approximation of the energy management strategy is done. The load profile is divided into an average base-load and a fluctuating behaviour. The main power generating system only sees the average load, and the battery provides the ability to both provide and absorb the needed power. The cyclic behavior of switching on an off the power system is left out in this modeling approach, in addition In reality, such aspects affects the performance as well as performance degradation of the power system. This factor affects the accuracy of the optimal solution to the selection of the power system found, and a question is therefore whether another approach will provide a more cost-efficient solution.

6.2 System simplifications and assumptions

6.2.1 System performance-related simplifications

6.2.1.1 Specific fuel oil consumption

As covered in 2.2, diesel engines inhibit a nonlinear relationship between fuel consumption and the load in the percentage of MCR. This aspect is as mentioned left out but could be included through a piecewise linearized approximation. Including this this nonlinear aspect would with high probability affect fuel consumption and therefore the optimal choice of diesel engines.

6.2.1.2 Efficiency loss in fuel cells

The efficiency loss from using fuel cells in combination with fuels that need reformers have been generalized to an efficiency loss independent of which fuel is used, as no information has been obtained about this factor. The inclusion of this aspect would also with high probability affect the optimal selection of the fuel cell system.

6.2.2 Specific emission constants

As for fuel consumption, specific emission factors are assumed independent of load on the diesel engines, as well as fuel cells when applicable. Emissions from diesel engines are however, as for fuel consumption, dependent on the load in % MCR. The inclusion of this factor would therefore also alter the optimal solution as it affects the emission costs.

6.2.3 C-rate

For simplification, a C-rate of 1 was assumed. The C-rate could be subject to optimization as well, as it affects battery performance. However, this more related to the dynamic aspect of a vessel's performance, and it was therefore left out to optimize the C-rate of the batteries.

6.2.4 Prices and regulations

Some of the prices of various system components, fuels as well as taxes have been challenging to obtain, and simplifications and assumptions have been made here as well in order to create scenarios to test the model in. The varying quality of these factors affects the quality of the results of the model, which needs to be taken into account when analyzing the results. Following prices and costs are subject to improved accuracy:

- Tanks - sizes and costs
- Reformers - sizes and costs
- Fuel prices
- Emission taxes

6.2.5 Performance degradation

6.2.5.1 Fuel cells

As mentioned, limited information and no concise methods applicable to the problem have been found in literature regarding performance degradation of fuel cells. Fuel cell degradation mechanisms have therefore been limited to a constant cell voltage degradation in normal load regions, with an additional accelerated degradation factor when fuel cells are operated in higher load regions. Uncertainty is connected to how much increase in degradation the fuel cells experience in higher load, as well as at which level higher load should be defined to be. In addition, due to linearity restrictions, only an approximation to this feature has been included, where the fuel cell is either operating in high load or not, meaning that there is no level in between. It is possible - and tried - to include several variables to create a semi-smooth relationship, but the inclusion of additional variables had a large impact on the solution time and was therefore left out. A reformulation of the model would possibly enable a more thorough inclusion of this aspect.

6.2.5.2 Batteries

As for fuel cells, no concise method was found that includes all effects. Linearity restrictions also limited the possible approaches to which degradation characteristics could be included, and an approach based on equivalent throughput was used. Another approach would most probably lead to another optimal solution.

6.2.6 Operational characteristics

As for the system characteristics, operational characteristics affect the optimization model's outcome. The main focus of this thesis has been to develop an optimization model that can be used in a general way and be tested in different scenarios, rather than finding an exact solution. Therefore, exact figures have not been prioritized, and assumptions and simplifications have been made where possible regarding the operational characteristics and scenarios:

- Average power demand in operational states
- Load fluctuation pattern
- Emission regulations
- Operational regulations

6.3 Model performance

Since a linear model had to be developed, several more variables had to be included to model the same system. The model also increases in size with increasing power demand. This, in turn, increases the solution time rapidly. To obtain results in a reasonable time, a max limit of time elapsed was used. This reduces the number of solutions found, and the solutions found in this thesis cannot therefore not be guaranteed to be optimal.

Chapter 7

Conclusion & further work

7.1 Conclusion

In this thesis, the problem of selecting a cost-optimal machinery system for low-emission shipping has been explored. A literature review of the relevant topics for such a problem was performed to provide as a foundation to the modelling. Topics include current emission contributions from the shipping industry, emission abatement regulations, power system topologies, fuel cell- and battery technology, hybrid shipboard power systems and sizing optimization studies. Based on this, a linear deterministic optimization model was developed and implemented in Matlab through a problem-based approach. Two scenarios were tested to explore the applicability of the model. Scenario 1 assumes no further environmental regulations beyond the IMO2020 regulative. In scenario 2, strict environmental regulations are expected to be applied in order to fulfill IMO's commitment to reduce greenhouse gases by 50% by 2050. The vessel's operational profile was assumed the same for both scenarios for simplicity, as was fuel price development. A combination of all three power generating sources was chosen as the most optimal selection for both scenarios, to some surprise as this would imply higher investment cost. The investment cost, however, is only one of three contributions. With the price- and emission tax assumptions it seems as lower fuel- and emission costs as well as lower maintenance- and replacement costs weighed up for the higher initial investment costs.

As no work to the author's knowledge has been done on a sizing optimization problem in a green-shipping context where future operations are accounted for, many assumptions and simplifications had to be made. The model developed therefore has its shortcomings and is subject to improvement, and must be seen as more a foundation and inspiration for machinery optimization for low-emission shipping.

7.2 Further work

As all factors cannot necessarily be included in the model due to complexity and limitation on time, several factors have been left out in the model, and should be included in eventual further work:

Safety regulations

Regulations concerning power system redundancy are left out in the developed optimization model. The extent to which additional capacity to deliver power is required is dependent on the operational modes of the vessel, and will therefore be coupled with the vessel type.

Area constraints

Although some flexibility regarding available machinery space exist in the early ship design phase, increasing the machinery space does not necessarily come without cost. An extension of the model should therefore include this aspect, as an initial selected optimal power system may not be feasible. Making room for additional machinery space would then increase costs, possibly alter the optimal solution.

Option to install exhaust gas after-treatment systems

Shipowners are installing exhaust gas after-treatment systems to a wide extent to comply with the stricter regulations. An interesting problem would be to explore the trade-off between switching to new, clean power systems and installing the aforementioned emission abatement measures.

Dual-fuel engines

In this thesis, LNG is considered as a possible fuel for fuel cells, but not for diesel engines. Some diesel engines may utilize both marine fuel oils as well as LNG, and this option should also be included in an extension of the model.

Fuel cells and fuels

Although hydrogen and LNG are stated to be the most promising options for fuels utilized in fuel cells, several other options exist, as well as other fuel cell types. As more research progress, further inclusion of these options would be interesting to explore.

Zero-emission shipping study

The available power generating sources in the model in an operational state are defined in the constraints, and it is possible to perform a case study on the optimal power system selection for a zero-emission case. This can be done by leaving out power generated from diesel engines in the equation governing power demand. As such a case have not been presented in this thesis, it should be interesting to explore the optimal power system selection for a zero-emission case.

Net present value calculations

This optimization model does not account for interest rate and thus the net present value of future costs. As some costs incur at different points in time, they effectively become weighted differently due to the development of the global economy. From an economic point of view, this will affect what the optimal power system selection should be, and further development of the model should focus on including this aspect.

Modelling approach

The linear model was developed as the Genetic Algorithm in Matlab were unable to find feasible solutions to the problem, and several nonlinear relationships had to be left out. These nonlinear relationships should be included either by formulating piecewise linearisations or by developing a nonlinear model that can be used by another algorithm. Other modeling approaches could also be explored. Results from a time-step-based approach being able to assess performance degradation to a more thorough extent, could for instance be compared to the approach in this thesis.

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Appendix A

Fuel cell- and battery characteristics

A.1 Fuel cell system

A.1.1 Fuel cells

Table A.1: Fuel cell types considered, with their system parameters.

Type	**Power [kW]**	**Price [$/kW]**	**Maint. cost [$/kW]**	**Expected life [hours]**	**EOL limit [% MCR]**	**Repl. cost [$/kW]**
LT-PEMFC	120	235	50	20 000	0,8	70,5
HT-PEMFC	100	492,5	50	25 000	0,8	147,75
SFOC	100	750	50	30 000	0,8	225

A.1.2 Fuel tanks

Table A.2: Fuel tanks considered for fuel cell fuels, with their parameters.

Tank type	**Tank capacity [kg]**	**Tank cost [$/kg]**
LH2	1200	300
H2-700bar	60	270
LNG	1200	240

A.1.3 Need of reformer with fuel cell - fuel combination

Table A.3: Whether the fuel - fuel cell combination requires fuel reformning or not.

Fuel cell\Fuel	H2	LNG
LT-PEMFC	No	Yes
HT-PEMFC	No	No
SOFC	No	No

A.1.4 Fuel characteristics for fuels considered

Table A.4: Fuel characteristics - efficiencies, energy content, SFC and emission factors.

	Energy characteristics				Emissions [g/kWh]			
Fuel	**Fuel efficiency [%]**	**Energy per kg [kJ/kg]**	**Energy per kg [kWh/kg]**	**SFC [g/kWh]**	**Co2**	**Ch4**	**Sox**	**Nox**
H2 (liquid and gas)	0,55	142000	39,4	25,4	0	0	0	0
LNG	0,45	52000	14,4	69,2	412	3	0,003	1,17

A.2 Battery system

A.2.1 Batteries considered

Table A.5: System parameters for Li-ion battery type 1 considered, based on ([13]).Battery type 2 is introduced in the Matlab script problemSetup.m, with differences only in capacity, price anc cycle life.

Type	Capacity [Ah]	Voltage [V]	Capacity [kWh]	Power [kW]	Price [$/kWh]	Maint. cost [$/kW]	Cycle life [-]	Available throughput [kWh]	Repl. cost [$/kWh]
Li-ion	500	600	300	300	1000	21	2000	600000	27,63

Appendix B

Matlab scripts

B.1 linprob.m

This script is the main script that sets up the problem and runs the various support scripts to solve the optimization problem.

```
%Main script - sets up problem and run the various scripts
%to run the optimization model and process the results



clc
clear all

%Define variables to control dependency-parameters
reducedNumberOfStates = 0;      %Reduce computational time by setting to 1
testcase = 1;                   %Choice of scenario
baseValidation = 0;             %For validation on base scenario

switch testcase
    case 1
        sheet = 1;
        casenr = 'case1newplot';%Filename-string to save results
    case 2
        sheet = 2;
        casenr = 'case22';

end



%Import operational profile
run readOperationalParameters.m


nT = size(powerDemand,1);       %number of time periods and op.states
nO = size(powerDemand,2);

%C
linearised = 1;                 %Runs linearized model variant
batReduced = 0;                 %Consider only one battery type or not
deOnly = 0;                     %Run model for diesel engines only or not
electricityOnly = 0;            %Run model for el only or not

if deOnly ~= 1
deAllowed = 1-elOnly;

if electricityOnly == 1
```

```
    deAllowed = zeros(nT,nO);
end

end

%modify o if reducedNumberOfStates == 0
if reducedNumberOfStates == 1
    fractionOfTime(1,:) = 0.5;
    fractionOfTime(2,:) = 0.5;
    powerDemand = powerDemand*0.5
end

%For filename-generation
Str = datestr(now,'yyyy-mm-dd HH_MM_SS');
filedate = Str([1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16]);
resultsDir =
    '/Users/tormagnusmichaelsen/Dropbox/Skole/Master/Matlab/ProblemBased/new/Results/'

%Import system parameters
run problemSetup.m

%Processing of system parameters
statesTable = table(durTimePeriods,powerDemand,fractionOfTime,deAllowed);

nAirEmissions = size(fcEmissions,2);        %No. of air emission-types
fcEmissionsTable = table(fcEmissions);      %Emissions from fc-fuels
deEmissionsTable = table(deEmissions);      %Emissions from de-fuels


fcTable = table(fcPower,fcPrice,fcReplCost,fcPowerArray,...
    fcEL,fcVoltage,fcAnMaintCost,fcPercentageEOL,...
    fcAllowedDegradation,fcHourlyDegradation,...
    fcUL,fcLL,fcEff,sfc);

fcSystem = table(Aef,Cef,tankCap,tankCost);

fuelsTable = table(fuelCosts,ePrice);

bTable = table(bAh,bV,bWh,bKwh,bP,bPowerArray,bCapacityArray,...
    bPrice,socMin,socMax,bAnnualMaintCost,bReplCost,bEff,bCRate,...
    bCycleLife,availThrput,bInverterPrice)

nDE = size(deP,2);                          %No. of diesel engines
nFuelsDE = size(deFCost,2);                 %No. of de fuels
nFC = 3;                                    %No. of fc-types
nFCellPacks = nFuelCellPacks;               %No. of unique fc-stacks
nB = size(bTable,1);                        %No. of battery types
bTypes = {'Type1'; 'Type2'};                %Naming
%bTypes = bTypes(1);                        %If only considering 1 type
nBPacks = maxBatPacks;                      %No. of battery stacks
nTankTypes = size(fcSystem,1);              %No. of tankt types
nFuels = size(fuelsTable.fuelCosts,2);      %No. of fc-fuels


%Initializing problem
tic
powerSystemProblem = optimproblem;

%Create variables
display('Creating variables')
run linCreateVariables.m;

%Create costs
display('Creating costs')
run linCreateCosts.m;

%Create constraints
display('Creating constraints')
run linCreateConstraints.m;


```

```
%Convert problem to struct to use with Genetic Algorithm
prob = prob2struct(powerSystemProblem);

%Analyse time spent for problem set-up
toc

%Define options and  solve problem
options = optimoptions(powerSystemProblem,'MaxTime',600);
tic
[sol,fval] = solve(powerSystemProblem,'Options',options)
toc


%Investigate solution

fcRunning = sol.fcIofESwitchedOn
deRunning = sol.deSwitchedOn
fc = sol.lFC
b = sol.dodB
de = sol.lDE
fuelCellBought = sol.fcBought
batteryBought = sol.bBought
dieselEngineBought = sol.deBought

run postProcess.m
```

B.2 readOperationalParameters.m

This script reads the operational parameters defined in the excel input file.

```
%Read operational parameters from excel file "input.xlsx" with the
%defined ranges


%Set equal to 1 if testing model due to increased running time
%at normal problem size
if reducedNumberOfStates == 1


    powerDemand = xlsread('input.xlsx',sheet,'D2:E3');
    fractionOfTime = xlsread('input.xlsx',sheet,'D4:E5');

    %Electricity-only modes
    elOnly = xlsread('input.xlsx',sheet,'D6:E7');

    %Fuel compliance in operational states
    compl1 = xlsread('input.xlsx',sheet,'D8:E9');
    compl2 = xlsread('input.xlsx',sheet,'D10:E11');

else
    powerDemand = xlsread('input.xlsx',sheet,'B2:G3');
    fractionOfTime = xlsread('input.xlsx',sheet,'B4:G5');

    elOnly = xlsread('input.xlsx',sheet,'B6:G7');

    compl1 = xlsread('input.xlsx',sheet,'B8:G9');
    compl2 = xlsread('input.xlsx',sheet,'B10:G11');

end

deFCompliance(:,:,1) = compl1';
deFCompliance(:,:,2) = compl2';
```

B.3 problemSetup.m

This script creates all necessary system parameters for the optimization problem.

```

%Sets up problem

%Used defined input
Dr = 12;                                %Duration of roundtrip in hours
hYear = 8760;                           %Hours in a year

%Define a very large number for costs for
%components that are uncompatible
bigPowerM = 99999999999;
bigFuelM = 99999999999;

durTimePeriods = 10*ones(nT,1);         %Duration of timeperiods in years


%For matrix-consistency
powerDemand = powerDemand(:,1:nO);
fractionOfTime = fractionOfTime(:,1:nO);

bigMP = max(max(powerDemand));
smallM = 0.00001;



%================Operational================
%Fuels: h2_700barg, lh2, lng
%$/tonne
%gaseous hydrogen: https://cafcp.org/content/cost-refill

%----------------Fuel costs----------------
fcFuels = {'H2700Bar';'LH2';'LNG'};
fuelCosts(:,:,1) = [5544 6160 450];     %$/tonnes
fuelCosts(:,:,2) = 0.9*fuelCosts(:,:,1);

if baseValidation == 1                  %constant price for basevalidation
    fuelCosts(:,:,2) = fuelCosts(:,:,1);
end

%Electricity
kwhCost = 0.064;
ePrice(1,1,1) = kwhCost;
ePrice(1,1,2) = 0.9*kwhCost;

if baseValidation == 1                  %constant price, basevalidation
    ePrice(1,1,2) = kwhCost;
end


%------Generating load compensation pattern--

%assuming cyclic load variability w/period of 10 seconds (from waves etc)
%= 6 peaks + throughs per minute = 6 peaks and throughs each per minute
%multiply by 60 minutes in an hour, and 12 hours in a roundtrip
%Assuming little time at full peak power

peakTime = 0.1;                             %duration at peak
if baseValidation == 1                      %to shorten computation time
    peakTime = 0.00001;
end

peakTimeTest = 6;                           %test only
peaksAndThroughsPerMinute = 60/10;
pph = peaksAndThroughsPerMinute*60;         %peaks and throughs/hour
pprt = pph*Dr;                              %peaks and throughs/roundtrip
pprt1 = pprt;
```

```
lcRatioOfPDemand = 0.1/100;
peakShavingP = ...
    lcRatioOfPDemand*mean(mean(powerDemand))*rand(pprt1,nO,nT);
loadSheddingP = ...
    lcRatioOfPDemand*mean(mean(powerDemand))*rand(pprt1,nO,nT);


%-----Calculating battery sizing basis-----
maxPeakShavingP = lcRatioOfPDemand.*powerDemand;
maxLoadSheddingP = maxPeakShavingP;

maxPeakShavingE = lcRatioOfPDemand.*powerDemand*peakTime;
maxLoadSheddingE = maxPeakShavingE;

hoursInOPerRoundTripEachT = Dr*fractionOfTime;
numberOfPeaksInEachOPerRoundTripEachT = ...
    hoursInOPerRoundTripEachT*pph;

peakShavingEnergyinEachOPerRoundtripEachT = ...
    numberOfPeaksInEachOPerRoundTripEachT*...
    lcRatioOfPDemand.*powerDemand*peakTime;

peakShavingEnergyPerRoundtripEachT = ...
    sum(peakShavingEnergyinEachOPerRoundtripEachT,2);

nRoundTripsEachT = (hYear/Dr)*durTimePeriods;

peakShavingEnergyInEachT = ...
    peakShavingEnergyPerRoundtripEachT.*nRoundTripsEachT



%================Diesel engines======================

%rated power, sfoc, rpm
run readDieselEngines.m

%Calculating number of diesel engines to be available of each model
Ym = createMaxEnginesNumber(engines,powerDemand);

%Create engines vector
[deP, gBase] = createEnginesVector(engines,Ym);

%Diesel engines relevant parameters


deEfficiency = 0.95;

%Upper and lower limit
deUL = 1;
deLL = 0.05;
deFuelTypes = {'MDO';'ULSFO'};
deFCost(1,:,1) = [555 800];                 %mdo - ulsfo, $/tonnes
deFCost(1,:,2) = 1.1*(deFCost(1,:,1));      %increase from t1 to t2

if baseValidation == 1                      %for basevalidation,
    deFCost(1,:,2) = (deFCost(1,:,1));
end

deInvCost = 52;                             %From Bassam
deAnnualMaintCost = 0.1*deInvCost;

%================Fuel cells and fuels================

%Fuel cells: LT-PEMFC, HT-PEMFC, SOFC
fcTypes = {'LT-PEMFC'; 'HT-PEMFC';'SOFC'};
fcPower = [100 100 100]';
fcNominalPrice = [235 492.5 750]';          %$/kW
fcPrice = fcNominalPrice.*fcPower;
fcAccDegrFactor = 0.3;                      %30% increased degradation
```

```

fcReplCost = 0.3.*fcNominalPrice;           %$/kw
fcEL = [20000 25000 30000]';                %Expected life, hours
fcVoltage = [630 700 700]';                 %Rated voltage
fcAnMaintCost = [50 50 50]';                %Annual maintenance cost
fcPercentageEOL = [80 80 80]';              %Performance at EOL

%Calculate allowed degradation
fcAllowedDegradation = ...
    (1/100)*(100.-fcPercentageEOL).*fcVoltage;

%Calculate hourly degradation in use, v/h
fcHourlyDegradation = ...
    fcAllowedDegradation./fcEL;
fcUL = [0.95 0.95 0.95]';
fcLL = [0.1 0.1 0.1]';

%Efficiency of fuel cells using different fuels
%fuels column-wise, fuel cell types row-wise

%EDITED: this is general fuel efficiencies, the same fuel
%efficiency in all fuel cell types, only related to
%specific fuel consumption. Efficiency loss is covered
%by nfe in power demand equation
%h2_700barg, lh2, lng
fcEff = [
    0.55 0.55 0.45;
    0.55 0.55 0.45;
    0.55 0.55 0.45];

%Fuel cell effifiency when used with reformer,
%assuming 10% loss in
fcFuelEff = [
    1 1 0.9;
    1 1 0.9;
    1 1 0.9];

%Energy content in fuels, kJ/kg: h2_700barg, lh2, lng
energyPerKg = [142000 142000 52000];
kwhPerKg = energyPerKg./3600;

%Specific fuel consumption
%converting to g/kwh
fuelConsumption = (1*1000)./kwhPerKg;

%Resulting specific fuel consumption
sfc = fuelConsumption./fcEff;


%----Air emissions - co2, ch4, sox, nox-----
%from gilbert et al/nerem, g/kwh
%assessment of full life-cycle air emissions of alternative shipping fuels
emissions.h2 = [0 0 0 0];
emissions.lng = [412 3 0.003 1.17];
emissions.hfo = [541 0.01 3.23 15.8];
emissions.mdo = [524 0.01 0.32 14.8];
emissions.lsfo = [320 0.01 0.15 10];


fcEmissions = [emissions.h2; emissions.h2; emissions.lng];
%Extending array in case of different g/kwh for different fuel cells

fcEmissions =  ones(3,4,size(fcPower,1)).*fcEmissions

deEmissions = [emissions.mdo; emissions.lsfo];
%co2, ch4, sox, nox

%Emission taxes: %$/ton, from 22,27kr/kg (skatteetaten)
%Case 2: ch4, sox, nox converted to equivalent co2
switch testcase
    case 1
```

```
        %Time period 1
        emissionTaxes(:,:,1) = [0 0 0 2811];
        %Time period 2
        emissionTaxes(:,:,2) = [0 0 0 3484];
    case 2
        %Time period 1
        emissionTaxes(:,:,1) = [0 0 0 2811];
        %Time period 2
        emissionTaxes(:,:,2) = [40 1000 0 11920];
end

%Modify for base validation case
if baseValidation == 1
    emissionTaxes(:,:,2) = [0 0 0 2811];
end


%---------Auxiliary systems---------
%Auxiliary system needed for fuel cell type e (rows)
%if used with fuel f (columns)
Aef = [
    0 0 1;
    0 0 0;
    0 0 0];

%Cost of auxiliary system/reformer for fuel cells
%assuming same cost for all $/kW
lngAuxLT = 46.62;                                %LT-PEMFC
lngAuxHT = 46.62;                                %HT-PEMFC
lngAuxSOFC = 46.62;                              %SOFC
methanolAuxLT = 46.62;
methanolAuxHT = 46.62;
methanolAuxSOFC = 46.62;

Cef = [bigFuelM bigFuelM lngAuxLT;
       bigFuelM bigFuelM lngAuxHT;
       bigFuelM bigFuelM lngAuxSOFC];


%---------Fuel storage---------------
%Tank compatibility - using capacity per module of type h
%for fuel f, setting capacity to zero if incompatible
%tank-type row-wise, fuel column-wise


%EDITED: using size of fuel storage directly in constraints instead
%of capacities per tank
h2LiquidTankCap = 1200;
lngTankCap = 1200;
h2_700TankCap = 800;


%storage cost: $/ton
%333 for light-duty per kg, assuming economy of scale-->10 times less, also 10% less
%for gas and lng
h2LiquidTankCost = 30000; %300 vs 50     300 per kg = 300000 per ton, assuming 10 times less, then 30000
h2_700TankCost = 27000;
lngTankCost = 24000;

tankTypes = {'Cryo';'Gas';'Hull'};

tankCap = [0 h2LiquidTankCap lngTankCap;
           h2_700TankCap 0 0;
           0 0 0];

tankCost = [bigFuelM h2LiquidTankCost lngTankCost ;
            h2_700TankCost bigFuelM bigFuelM ;
            bigFuelM bigFuelM bigFuelM ]; %per ton


```

```

%================Batteries================

%Check model variant
if batReduced == 1
bAh = [500]; % 700]';                          %Ampere-hours
bV = [600]; % 600]';                           %Voltage
bPrice = [1000];% 150]';                       %Nominal price
bInverterPrice = [40];
socMin = [0.3];% 0.3]';                        %Lower limit
socMax = [0.8];% 0.8]';                        %Upper limit
socRef = 0.6;                                  %Reference soc
bAnnualMaintCost = [21];% 21]';                %$/kWh
bReplCost = [27.63]; % 20]';                   %$/kWh
bEff = [0.95];% 0.95]';                        %Efficiency
bCRate = [1]; % 1]';                           %C-rate
bCycleLife = [2000];% 2500]';                  %no. of cycles guaranteed

bWh = bAh.*bV;                                 %Capacity in Wh
bKwh = bWh./1000;                              %kWh
bP = bKwh;                                     %Power, kW
availThrput = bCycleLife.*bKwh;                %Available kwh per module


else
    bAh = [500 700]';
bV = [600 600]';
bPrice = [1000 1300]';
bInverterPrice = [40 40]';
socMin = [0.3 0.3]';
socMax = [0.8 0.8]';
socRef = 0.6;
bAnnualMaintCost = [21 21]';
bReplCost = [27.63 27.63]';
bEff = [0.95 0.95]';
bCRate = [1 1]';
bCycleLife = [2000 2300]';

bWh = bAh.*bV;
bKwh = bWh./1000;
bP = bKwh;
availThrput = bCycleLife.*bKwh;

end



%======Defining fuel cell- and battery stacks=============

%--------Fuel cell calculations--------------------------
%Calculate largest number of fc packs necessary, from smallest type
%Assuming that the power rated from manufacturer is with efficiency
%taken into account
nFuelCellPacks = ceil(1.5*max(max(powerDemand))/min(fcPower))



%----Battery calculations------------------------------
%Calculate min number of battery combinations for each battery type
%(from load compensation) - to use as starting point for the lowest
%rated power and capacity from each battery type
lcEnergyMax = max(max(max(maxPeakShavingE,maxLoadSheddingE)));
lcPowerMax = max(max(max(maxPeakShavingP,maxLoadSheddingP)));

minBatPacksE = ceil(lcEnergyMax./bKwh);
minBatPacksP = ceil(lcPowerMax./bP);
minBatPakcsArray = [minBatPacksE minBatPacksP]

%Calculate the minimum number of battery packs of each type
%to supply enough power or energy in load compensation:
%Outputs a vector with minimum number of battery modules
```

```matlab
%from each type, the first entry in power vector and
%capacity vector corresponds to n*nominal power and capacity

minBatPacks = max(minBatPakcsArray,[],2)


%Calculate lost energy

lostEnergyPSEachRoundtripEachT = (1-bEff(1,1))*...
    sum(peakShavingEnergyinEachOPerRoundtripEachT,2);
lostEnergyLSEachRoundtripEachT = lostEnergyPSEachRoundtripEachT;

lostEnergyChargedAtShore = ...
    (lostEnergyPSEachRoundtripEachT...
    + lostEnergyLSEachRoundtripEachT);

%reshape for correct dimensions for summation below
lostEnergyChargedAtShore = reshape(lostEnergyChargedAtShore,2,1);

%Calculate largest number of bat packs necessary, from smallest type,
%from energy demand in a round trip + max energy
baseEnergyDemandRoundTrip = sum((Dr*fractionOfTime.*powerDemand),2);

energyDemandRoundTrip = ...
    baseEnergyDemandRoundTrip + ...
    lostEnergyChargedAtShore;

maxEnergyDemandRoundTrip = max(sum(energyDemandRoundTrip,2))
maxBatPacksArray = ceil((maxEnergyDemandRoundTrip+lcEnergyMax)./bKwh)
maxBatPacks = ceil(1.5*max(maxBatPacksArray))


%Need to create arrays with power rating for each type of fuel cell
%and power and capacity rating for eacy type of battery to
%represent the stacks

%Batteries
bPowerArray = zeros(size(maxBatPacksArray,1),maxBatPacks);
bCapacityArray = zeros(size(maxBatPacksArray,1),maxBatPacks);
for e = 1:size(bPowerArray,1)
    for i = 1:maxBatPacks
        bPowerArray(e,i) = bP(e)*i;
        bCapacityArray(e,i) = bKwh(e)*i;
        availThrputArray(e,i) = availThrput(e)*i;
    end
end

%Fuel cells
fcPowerArray = zeros(size(fcPower,1),nFuelCellPacks);
for e = 1:size(fcPowerArray,1)
    for i = 1:nFuelCellPacks
        fcPowerArray(e,i) = fcPower(e)*i;
    end
end
```

B.4 readDieselEngines.m

This script is run inside problemSetup.m and reads the diesel engine information in the excel input file.

```
%Read diesel engines information

deRange = 'C4:G10';
engines = xlsread('input.xlsx','Diesel engines',deRange);
```

B.5 linCreateVariables.m

This script defines and creates the necessary optimization variables to be optimized.

```matlab
%=================Variables==================

%------------Power-------------------------
%Fraction of load from fuel cell pack i of type e,
%using fuel f in o in t
lFC = optimvar('lFC',...
    nFC,nFCellPacks,nO,nT,nFuels,...
    'Type','continuous',...
    'LowerBound',0,...
    'UpperBound',1);


%Depth of discharge of battery pack i of type e,
%in o in t from providing base load
dodB = optimvar('dodB',...
    nB,nBPacks,nO,nT,...
    'Type','continuous',...
    'LowerBound',0,...
    'UpperBound',1);


%Fraction of load in MCR from diesel engine j
%using fuel f in o in t
lDE = optimvar('lDE',...
    nDE,nO,nT,nFuelsDE,...
    'Type','continuous',...
    'LowerBound',0,...
    'UpperBound',1);

%------------Power sources switched on--------
%Binary variable, if fuel cell pack i of type e is switched on,
%using fuel f in o in t
fcIofESwitchedOn = optimvar('fcIofESwitchedOn',...
    nFC,nFCellPacks,nO,nT,nFuels,...
    'Type','integer',...
    'LowerBound',0,...
    'UpperBound',1);

%Binary variable, if battery pack i of type e is switched on
%in o in t
bSwitchedOn = optimvar('bSwitchedOn',...
    nB,nBPacks,nO,nT,...
    'Type','integer',...
    'LowerBound',0,...
    'UpperBound',1);

%Binary variable, if diesel engine j is swithced on in o in t,
%using fuel f

deSwitchedOn = optimvar('deSwitchedOn',...
    nDE,nO,nT,nFuelsDE,...
    'Type','integer',...
    'LowerBound',0,...
    'UpperBound',1);

%------------Power sources bought------------
%Binary variable, if a fuel cell pack i of type e is bought or not
fcBought = optimvar('fcBought',...
    nFC,nFCellPacks,...
    'Type','integer',...
    'LowerBound',0,...
    'UpperBound',1);

%Binary variable, if a battery pack i of type e is bought or not
bBought = optimvar('bBought',...
```

```
    nB,nBPacks,...
    'Type','integer',...
    'LowerBound',0,...
    'UpperBound',1);

%Binary variable, if diesel engine j is bought or not
deBought = optimvar('deBought',...
    nDE,...
    'Type','integer',...
    'LowerBound',0,...
    'UpperBound',1);

%Size fuel tanks of type h for fc fuel f in tonnes
sTanks = optimvar('sTanks',...
    nTankTypes,nFuels,...
    'Type','continuous',...
    'LowerBound',0);

%Size of auxiliary system for fuel cell type e used with
%fuel f
fcAux = optimvar('fcAux',...
    nFC,nFuels,...
    'Type','continuous',...
    'LowerBound',0);

%Binary variables, if % loading of fc type e is above thresholds
fcLoadUpper = optimvar('fcLoadUpper',...
    nFC,nFCellPacks,nO,nT,nFuels,...
    'Type','integer',...
    'LowerBound',0,...
    'UpperBound',1);
```

B.6 linCreateCosts.m

This script creates the necessary cost expressions for the optimization problem.

```
%===================Fuel costs==========================

%Define fuel consumption array
fcFuelConsumptionArray = zeros(nFC,nFCellPacks,nO,nT,nFuels);

%Define fuel cost optimization expression
fcFuelCostArray = optimexpr(nFuels,nT);

%Define electricity cost arrays
elConsumptionArray = zeros(nB,nO,nT);
elCostArray = zeros(nB,nO,nT);
elCosts = 0;
deFuelCosts = 0;

%-------------------Fuel cells-------------------
%Define optimization expressione
powerDeliveredFromFuels = optimexpr(nFuels,nT,nO);
fcEnergyDeliveredFromFuels = optimexpr(nFuels,nT,nO);
fcFuelConsumptionOfFuelsInOandTinTonnes = optimexpr(nFuels,nT,nO);

%Need to expand matrices for matrix multiplication
timeMatrix1 = hYear*statesTable.durTimePeriods(1)*...
    reshape(fractionOfTime',1,nT,nO)
timeMatrix = timeMatrix1.*ones(nFuels,nT,nO)

%Calculate power delivered-->energy delivered-->fuel consumption
for t = 1:nT
    for o = 1:nO
        for f = 1:nFuels
            %power delivered from fuel f in o in t:
            powerDeliveredFromFuels(f,t,o) = ...
                sum(sum(lFC(:,:,o,t,f).*fcPowerArray));
            fcEnergyDeliveredFromFuels(f,t,o) = ...
                powerDeliveredFromFuels(f,t,o)*timeMatrix(f,t,o);
            fcFuelConsumptionOfFuelsInOandTinTonnes(f,t,o) = ...
                (1e-6)*fcEnergyDeliveredFromFuels(f,t,o)*fcTable.sfc(1,f);
        end
    end
end

fcFuelConsumptionOfFuelsInTimePeriodsInTonnes = ...
    sum(fcFuelConsumptionOfFuelsInOandTinTonnes,3);

%calculate total fuel cost
for f = 1:nFuels
    for t = 1:nT
        fcFuelCostArray(f,t) = ...
            fcFuelConsumptionOfFuelsInTimePeriodsInTonnes(f,t)*...
            fuelCosts(1,f,t);
    end
end

fcFuelCosts = sum(sum(fcFuelCostArray));


%--------------------Batteries--------------------
%Define optimization expressions
totalEnergyFromBatteries = optimexpr(nT,nO);
elCosts = optimexpr(nT,nO);

%Expand matrix for matrix multiplication
bCapacityReshaped = bCapacityArray.*ones(nB,nBPacks,nO,nT);

%Calculate energy delivered-->electricity cost
for t = 1:nT
```

```
     kwhCost = fuelsTable.ePrice(1,1,t);
    for o = 1:nO
        totalEnergyFromBatteries(t,o) = sum(sum(sum(dodB(:,:,o,t).*...
            bCapacityReshaped(:,:,o,t))))*(hYear/Dr);
        %Need to multiply with number of roundtrips (=number
        ...of times in that op.state) in that
        %time period = hoursinYear/durationOfRoundTrip
        elCosts(t,o) = totalEnergyFromBatteries(t,o)*kwhCost;
    end
end

totalElcosts = sum(sum(elCosts));


%---------------Diesel engines - fuel and emission costs---------------
%Define optimization expression
dePowernDExnOxnTxnFuels = optimexpr(nDE,nO,nT,nFuelsDE);

%Reshape and expand matrices for matrix multiplication
deFracTimeMatrix1 = reshape(fractionOfTime',1,nO,nT);
deFracTimeMatrix = deFracTimeMatrix1.*ones(nDE,nO,nT,nFuelsDE);
deSfocMat = gBase'.*ones(nDE,nO,nT,nFuelsDE);

roundTripsEachYear = hYear/Dr;
durationOfTimePeriodsMat = ...
    reshape(durTimePeriods,1,1,nT).*ones(nDE,nO,nT,nFuelsDE);
roundTripsEachTPeriodMat = ...
    roundTripsEachYear*durationOfTimePeriodsMat;

%Calculate power delivered
dePowerMatrix = deP'.*ones(nDE,nO,nT,nFuelsDE);
dePowernDExnOxnTxnFuels = lDE.*dePowerMatrix;
deEnergyDeliveredEachRoundtripMat = ...
    Dr*dePowernDExnOxnTxnFuels.*deFracTimeMatrix;

%Calculate energy delivered
deEnergyTotalMat = ...
    deEnergyDeliveredEachRoundtripMat.*...
    roundTripsEachTPeriodMat;

%Calculate fuel consumption
deFuelConsumptionInTonnesMat = (1e-6)*deEnergyTotalMat.*deSfocMat;


deFuelPricesReshaped = reshape(deFCost,1,1,nT,nFuelsDE);
deFuelPricesPermuted = permute(deFuelPricesReshaped,[1,2,4,3]);
deFuelPricesMat = deFuelPricesPermuted.*ones(nDE,nO,nT,nFuelsDE);

%Calculate fuel costs
deFuelCostsMat = deFuelConsumptionInTonnesMat.*deFuelPricesMat;

%Total fuel costs
deFuelCosts = sum(sum(sum(sum(deFuelCostsMat))));


%Emissions
%Define optimization expressions
deEmissionsArray = optimexpr(nFuelsDE,nT,nAirEmissions);
deEmissionsCostArray = optimexpr(nFuelsDE,nT,nAirEmissions)

%Calculate energy delivered
deEnergySummedOverEnginesByTimePeriodsAndFuels = sum(deEnergyTotalMat,1);
deEnergySummedOverOpStatesByTimePeriods = ...
    sum(deEnergySummedOverEnginesByTimePeriodsAndFuels,2);

deEnergyByFuelsInTimePeriodsReshaped = ...
    reshape(deEnergySummedOverOpStatesByTimePeriods,nT,nFuelsDE)';

%Calculate costs of emissions
for w = 1:nAirEmissions
    for f = 1:nFuelsDE
```

```
        for t = 1:nT
            deEmissionsArray(f,t,w) = ...
                deEnergyByFuelsInTimePeriodsReshaped(f,t)*...
                deEmissionsTable.deEmissions(f,w);
            deEmissionsCostArray(f,t,w) = ...
                (1e-6)*deEmissionsArray(f,t,w)*emissionTaxes(1,w,t);
        end
    end
end

deEmissionsCost = sum(sum(sum(deEmissionsCostArray)));


%===================Emission costs(fuel cells)========
%Emission-table: co2 - ch4 - sox - nox
%Define optimization expressions
fcEmissionsArray = optimexpr(nFuels,nT,nAirEmissions);
fcEmissionsCostArray = optimexpr(nFuels,nT,nAirEmissions);

%fuel cell energy delivered
fcEnergyDeliveredFromFuelsByTimePeriods = ...
    sum(fcEnergyDeliveredFromFuels,3); %defined under fuel costs

%Calculate cost from emissions from fuel cells
for w = 1:nAirEmissions
    for f = 1:nFuels
        for t = 1:nT
            fcEmissionsArray(f,t,w) = ...
                fcEnergyDeliveredFromFuelsByTimePeriods(f,t)*...
                fcEmissionsTable.fcEmissions(f,w,1);
            fcEmissionsCostArray(f,t,w) = ...
                (1e-6)*fcEmissionsArray(f,t,w)*emissionTaxes(1,w,t);
        end
    end
end
fcEmissionCost = sum(sum(sum(fcEmissionsCostArray)));

voyex = totalElcosts +...
    fcFuelCosts +...
    deFuelCosts +...
    fcEmissionCost +...
    deEmissionsCost;

%===================Investment costs===================

%fuel cell stacks
fcModulesInvCosts = 0;
for e = 1:nFC
    for i = 1:nFCellPacks
        fcModulesInvCosts =...
            fcModulesInvCosts + ...
            fcBought(e,i)*fcPowerArray(e,i)*fcNominalPrice(e);
    end
end

%Reformers
fcAuxInvCosts = 0;
for f = 1:nFuels
    for e = 1:nFC
        fcAuxInvCosts = fcAuxInvCosts + Cef(e,f)*fcAux(e,f);
    end
end

%fuel cell tanks
fcFuelTankCosts = 0;
for t = 1:nTankTypes
    for f = 1:nFuels
        fcFuelTankCosts = fcFuelTankCosts +...
            sTanks(t,f)*tankCost(t,f);
    end
end
```

```matlab


%Battery stacks
bModulesInvCosts = 0;
bPowerInverterCosts = 0;
bInverterCost = bInverterPrice;
for e = 1:nB
    for i = 1:nBPacks
    bModulesInvCosts = bModulesInvCosts +...
        bBought(e,i)*bCapacityArray(e,i)*bPrice(e);
    bPowerInverterCosts = bPowerInverterCosts +...
        bInverterCost(e)*(bBought(e,i)*bPowerArray(e,i));
    end
end

%diesel engines
deInvestmentCosts = 0;
for j = 1:nDE
    deInvestmentCosts = deInvestmentCosts +...
        deBought(j)*deInvCost*deP(j);
end

capex = ...
    fcModulesInvCosts +...
    fcAuxInvCosts +...
    fcFuelTankCosts +...
    bModulesInvCosts +...
    bPowerInverterCosts +...
    deInvestmentCosts;

%==================Maintenance costs==================


fcMaintenanceCosts = 0;

%Define optimization expression
bMaintenanceCostsArray = optimexpr(nB,1);
deMaintenanceCosts = 0;
for t = 1:nT
    for e = 1:nFC
        for i = 1:nFCellPacks
            fcMaintenanceCosts = ...
                fcMaintenanceCosts +...
                fcAnMaintCost(e)*...
                fcPowerArray(e,i)*...
                fcBought(e,i)*...
                durTimePeriods(1,1);
        end
    end

    for j = 1:nDE
        deMaintenanceCosts = ...
            deMaintenanceCosts +...
            deAnnualMaintCost*...
            deP(j)*...
            deBought(j)*...
            durTimePeriods(1,1);
    end
end

bMaintenanceCostsArray = ...
    sum(durTimePeriods,3)*...
    sum(sum(bPowerArray.*bBought)).*bAnnualMaintCost;

bMaintenanceCosts = sum(bMaintenanceCostsArray);

maintenanceCosts = ...
    fcMaintenanceCosts +...
    bMaintenanceCosts +...
    deMaintenanceCosts;

```

```
%==================Replacement costs==================

%Fuel cells
%Define optimization expressions
fcReplacementCosts = optimexpr(nFC,nFCellPacks);
fcDegradation = optimexpr(nFC,nFCellPacks);
fcNReplacements = optimexpr(nFC,nFCellPacks);
for e = 1:nFC
    for i = 1:nFCellPacks
        for t = 1:nT
            for o = 1:nO
                for f = 1:nFuels
                    time = hYear*fractionOfTime(t,o)*durTimePeriods(t);
%                         if basevalidation == 1
%                             fcDegradation(e,i) = fcDegradation(e,i) +...
%                         fcHourlyDegradation(e)*...
%                         time*...
%                         (fcIofESwitchedOn(e,i,o,t,f));
%                         else
                        fcDegradation(e,i) = fcDegradation(e,i) +...
                        fcHourlyDegradation(e)*...
                        time*...
                        (fcIofESwitchedOn(e,i,o,t,f) +...
                        fcLoadUpper(e,i,o,t,f)*fcAccDegrFactor);
%                        end
                end
            end
        end
        fcNReplacements(e,i) = fcDegradation(e,i)/...
            (fcAllowedDegradation(e));
        fcReplacementCosts(e,i) =...
            fcNReplacements(e,i)*fcPowerArray(e,i)*fcReplCost(e);
    end
end

totalFCReplCost = sum(sum(fcReplacementCosts));



%Batteries
%Define optimization expressions
lcBatReplCosts = optimexpr(nB,nBPacks);
nReplacementsFromLC = optimexpr(nB,nBPacks);

lcEnergyThroughput = sum(peakShavingEnergyInEachT);
for e = 1:nB
    for i = 1:nBPacks
        nReplacementsFromLC(e,i) =...
            bBought(e,i)*lcEnergyThroughput/(availThrput(e)*i);
        lcBatReplCosts(e,i) =...
           bTable.bReplCost(e)*bCapacityArray(e,i)*nReplacementsFromLC(e,i);
    end
end

totalLCBatReplCost = sum(sum(lcBatReplCosts));


bBaseEnergyThroughput = optimexpr(nB,nBPacks);
%Calculate total energy throughput for battery stacks
%Need to multiply with number of roundtrips
...(=number of times in that op.state) in that
%time period = hoursinYear/durationOfRoundTrip
for e = 1:nB
    for i = 1:nBPacks
        for t = 1:nT
            for o = 1:nO
                bBaseEnergyThroughput(e,i) = ...
                bBaseEnergyThroughput(e,i) +...
                    dodB(e,i,o,t)*...
                    (hYear/Dr)*durTimePeriods(t)*...
                    bTable.bCapacityArray(e,i);
```

```
                end
            end
        end
end

%Calculate number of replacements based on energy throughput available
%and energy delivered
numberOfReplacementsOfEachBatteryStackAndTypeFromBaseLoad = ...
    bBaseEnergyThroughput./availThrputArray;

bNominalReplCostArray = bReplCost.*ones(nB,nBPacks);
%Calculate cost of replacement of all battery stacks
costOfReplacementOfEachBatteryStackAndTypeFromBaseLoad = ...
    numberOfReplacementsOfEachBatteryStackAndTypeFromBaseLoad.*...
    bCapacityArray.*...
    bNominalReplCostArray;

%Calculate total cost of replacement of batteries from providing base load
totalBBasePowerReplCost = ...
    sum(sum(costOfReplacementOfEachBatteryStackAndTypeFromBaseLoad,2));


replCost = ...
    totalFCReplCost +...
    totalBBasePowerReplCost +...
    totalLCBatReplCost;

opex = replCost + maintenanceCosts;
costs = voyex + capex + opex;

powerSystemProblem.Objective = costs;
```

B.7 linCreateConstraints.m

This script creates the necessary constraint expressions for the optimization problem.

```
%===============    Constraints    ====================

%------Power supplied from power sources must match the power demand------

%Necessary matrix manupliation
fcFuelRefReshaped = reshape(fcFuelEff(1:nFC,:),...
    size(fcFuelEff(1:nFC,:),1),1,1,1,size(fcFuelEff,2));
fcFuelRefReshaped1 = fcFuelRefReshaped.*...
    ones(nFC,nFCellPacks,nO,nT,nFuels);
fcPowerReshaped = fcPowerArray(1:nFC,:).*...
    ones(nFC,nFCellPacks,nO,nT,nFuels).*fcFuelRefReshaped1;
bPowerReshaped = bPowerArray.*ones(nB,nBPacks,nO,nT);
bCapacityReshaped = bCapacityArray.*ones(nB,nBPacks,nO,nT);
dePowerReshaped = deP'.*ones(nDE,nO,nT,nFuelsDE);
%assumed that diesel engine power specicifed by manufacturer is with
%efficiency accounted for

%Defining optimization constraint
powerSuppliedCon = optimconstr(nT,nO);

%create constraints if not running for diesel engines only
if deOnly == 0

for t = 1:nT
    for o = 1:nO
        pfc = sum(sum(sum(lFC(:,:,o,t,:).*fcPowerReshaped(:,:,o,t,:))));
        pb = 0.95*sum(sum(sum(dodB(:,:,o,t).*...
            bCapacityReshaped(:,:,o,t)/...
            (fractionOfTime(t,o)*Dr))));
        pde = deEfficiency*sum(sum(lDE(:,o,t,:).*...
            dePowerReshaped(:,o,t,:)));
        %if electricity-mode or not
        if statesTable.deAllowed(t,o) == 1
            powerSuppliedCon(t,o) = pde + pfc + pb == powerDemand(t,o);
            % pde + pb + pfc
        else
            powerSuppliedCon(t,o) = pfc + pb == powerDemand(t,o);
        end
    end
end

else %deOnly == 1, testing diesel engines only

for t = 1:nT
    for o = 1:nO
        pde = deEfficiency*sum(sum(lDE(:,o,t,:).*...
            dePowerReshaped(:,o,t,:)));
        powerSuppliedCon(t,o) = ...
            pde == powerDemand(t,o) + maxPeakShavingP(1,o,t);
    end
end
end

powerSystemProblem.Constraints.powerSupplied = powerSuppliedCon;

%Skip constraints if only testing for diesel engines
if deOnly == 0
%-----------Power from fuel cells must be within its limits -----------
%Below upper limit
fcLoadUpperCon = optimconstr(nFC,nFCellPacks,nFuels,nT,nO);

for e = 1:nFC
   for i = 1:nFCellPacks
       for f = 1:nFuels
           for t = 1:nT
```

```
                for o = 1:nO
                    fcLoadUpperCon(e,i,f,t,o) = ...
                        lFC(e,i,o,t,f) <= fcTable.fcUL(e)*...
                        fcIofESwitchedOn(e,i,o,t,f);
                end
            end
        end
    end
end

powerSystemProblem.Constraints.fcloadUpper = fcLoadUpperCon;

%Above lower limit
fcLoadLowerCon = optimconstr(nFC,nFCellPacks,nFuels,nT,nO);

for e = 1:nFC
    for i = 1:nFCellPacks
        for f = 1:nFuels
            for t = 1:nT
                for o = 1:nO
                    fcLoadLowerCon(e,i,f,t,o) =...
                        lFC(e,i,o,t,f) >= fcTable.fcLL(e)*...
                        fcIofESwitchedOn(e,i,o,t,f);
                end
            end
        end
    end
end

powerSystemProblem.Constraints.fcloadLower = fcLoadLowerCon;
%-----------Ensuring that fuel cells are switched on if used-------------
%using fuel f
fcRunningCon = optimconstr(nFC,nFCellPacks,nFuels,nT,nO);

for e = 1:nFC
    for i = 1:nFCellPacks
        for f = 1:nFuels
            for t = 1:nT
                for o = 1:nO
                    fcRunningCon(e,i,f,t,o) = ...
                        lFC(e,i,o,t,f) <= fcIofESwitchedOn(e,i,o,t,f);
                end
            end
        end
    end
end

powerSystemProblem.Constraints.fcRunning = fcRunningCon;
%-------Restriction on max number of fuel cells in use at a time-----
%in combination with fuel f
fcMaxNumberInUseCon = optimconstr(nT,nO);

for t = 1:nT
    for o = 1:nO
        fcMaxNumberInUseCon(t,o) = ...
            sum(sum(sum(fcIofESwitchedOn(:,:,o,t,:)))) <= 1;
    end
end

powerSystemProblem.Constraints.fcMaxNumberInUse = fcMaxNumberInUseCon;
%-----------Restricion on use of fuel cells, it must be bought-----------
fcBoughtCon = optimconstr(nFC,nFCellPacks);

for e = 1:nFC
    for i = 1:nFCellPacks
            fcBoughtCon(e,i) = ...
                sum(sum(sum(fcIofESwitchedOn(e,i,:,:,:)))) <= ...
                fcBought(e,i)*nFuels*nO*nT;
    end
end

```

```
powerSystemProblem.Constraints.fcBought = fcBoughtCon;
%------------Only one fuel cell combination i of type e--------------------
fcMaxOneIofECon = optimconstr(nFC,1);

for e = 1:nFC
    fcMaxOneIofECon(e) = sum(fcBought(e,:)) <= 1;
end

powerSystemProblem.Constraints.fcMaxOneIofE = fcMaxOneIofECon;
%------------Auxiliary system for fc-pack w/fuel f must be large enough---
fcAuxCon = optimconstr(nT,nO,nFC,nFCellPacks,nFuels);

for t = 1:nT
    for o = 1:nO
        for e = 1:nFC
            for i = 1:nFCellPacks
                for f = 1:nFuels
                    fcAuxCon(t,o,e,i,f) = ...
                        fcIofESwitchedOn(e,i,o,t,f)*...
                        fcPowerArray(e,i)*...
                        Aef(e,f) <= fcAux(e,f);
                end
            end
        end
    end
end

powerSystemProblem.Constraints.fcAux = fcAuxCon;
%------------Enough battery power installed---------------------------------
%Peak shaving
bPowerPSPCon = optimconstr(nB,nT,nO);

for e = 1:nB
    for t = 1:nT
        for o = 1:nO
            bPowerPSPCon(e,t,o) = ...
                sum((bPowerArray(e,:).*bBought(e,:))) >= ...
                sum(sum((bCapacityArray(e,:).*dodB(e,:,o,t))./...
                (fractionOfTime(t,o)*Dr))) +...
                sum(bBought(e,:)*maxPeakShavingP(t,o));
        end
    end
end

powerSystemProblem.Constraints.bPower = bPowerPSPCon;

%Load shedding
bPowerLSPCon = optimconstr(nB,nT,nO);

for e = 1:nB
    for t = 1:nT
        for o = 1:nO
            bPowerLSPCon(e,t,o) = ...
                sum((bPowerArray(e,:).*bBought(e,:))) >= ...
                sum(bBought(e,:)*maxLoadSheddingP(t,o));
        end
    end
end

powerSystemProblem.Constraints.bPowerLS = bPowerLSPCon;
%------------Enough battery capacity installed------------------------------
%Peak shaving
bCapacityPSCon = optimconstr(nT,nO);

for t = 1:nT
    for o = 1:nO
        bCapacityPSCon(t,o) = ...
            ((bCapacityArray(e,:).*bBought(e,:))) >= ...
            maxPeakShavingE(t,o)/(socRef-socMin(e));
    end
end
```

```matlab

powerSystemProblem.Constraints.bCapacityPS = bCapacityPSCon;

%Load shedding
bCapacityLSCon = optimconstr(nT,nO);

for t = 1:nT
    for o = 1:nO
        bCapacityLSCon(t,o) = ...
            sum((bCapacityArray(e,:).*bBought(e,:))) >= ...
            maxLoadSheddingE(t,o)/(socRef-socMin(e));
    end
end

powerSystemProblem.Constraints.bCapacityLS = bCapacityLSCon;
%----------If a battery has power, it must be running-----------------
bRunningCon = optimconstr(nB,nBPacks,nT,nO);

for e = 1:nB
    for i = 1:nBPacks
        for t = 1:nT
            for o = 1:nO
                bRunningCon(e,i,t,o) = ...
                    dodB(e,i,o,t) <= bSwitchedOn(e,i,o,t);
            end
        end
    end
end

powerSystemProblem.Constraints.bRunning = bRunningCon;
%----------If a battery is running, it must be bought/selected----------
bBoughtCon = optimconstr(nB,nBPacks);

for e = 1:nB
    for i = 1:nBPacks
        bBoughtCon(e,i) = ...
            sum(sum(bSwitchedOn(e,i,:,:))) <= bBought(e,i)*nO*nT;
    end
end

powerSystemProblem.Constraints.bBought = bBoughtCon;
%----------Max one battery pack i and type e---------------------------
%Needed in order for load-evening to work
bMaxOneInstalledCon = optimconstr(1,1);

bMaxOneInstalledCon(1,1) = sum(sum(bBought(:,:))) <= 1;

powerSystemProblem.Constraints.bMaxOneInstalled = bMaxOneInstalledCon;


end %end deOnly

%----------If a DE has load, it must be switched on + within limit------
%Upper limit
deRunningUpperCon = optimconstr(nDE,nT,nO,nFuelsDE);

for j = 1:nDE
    for t = 1:nT
        for o = 1:nO
            for f = 1:nFuelsDE
                deRunningUpperCon(j,t,o,f) =...
                    lDE(j,o,t,f) <= deSwitchedOn(j,o,t,f)*deUL;
            end
        end
    end
end

powerSystemProblem.Constraints.deRunningUpper = deRunningUpperCon;

%Lower limit
deRunningLowerCon = optimconstr(nDE,nT,nO,nFuelsDE);
```

```matlab

for j = 1:nDE
    for t = 1:nT
        for o = 1:nO
            for f = 1:nFuelsDE
                deRunningLowerCon(j,t,o,f) = ...
                    lDE(j,o,t,f) >= deSwitchedOn(j,o,t,f)*deLL;
            end
        end
    end
end

powerSystemProblem.Constraints.deRunningLower = deRunningLowerCon;
%----------Diesel engine j must be bought if it is ever used-----------
deBoughtCon = optimconstr(nDE);

for j = 1:nDE
    deBoughtCon(j) = sum(sum(sum(deSwitchedOn(j,:,:,:)))) ...
        <= deBought(j)*nO*nT*nFuelsDE;
end

powerSystemProblem.Constraints.deBought = deBoughtCon;
%----------A diesel engine can only use one fuel at a time-------------
%Should be covered by model

deFuelUsageCon = optimconstr(nT,nO,nDE);

for t = 1:nT
    for o = 1:nO
        for j = 1:nDE
            deFuelUsageCon(t,o,j) = sum(deSwitchedOn(j,o,t,:)) <= 1;
        end
    end
end

powerSystemProblem.Constraints.deFuelUsage = deFuelUsageCon;
%----------Diesel engine fuel compliance-------------------------------
%A fuel for diesel engines can only be used if it is compliant in the
%operational state

deFuelComplianceCon = optimconstr(nDE,nFuelsDE,nO,nT);

for d = 1:nDE
    for f = 1:nFuelsDE
        for o = 1:nO
            for t = 1:nT
                deFuelComplianceCon(d,f,o,t) = ...
                    deSwitchedOn(d,o,t,f) <= deFCompliance(o,f,t);
            end
        end
    end
end

powerSystemProblem.Constraints.deFuelCompliance = deFuelComplianceCon;
%create constraints if not running for diesel engines only
if deOnly == 0
%----------Indicator variables for fc-degradation----------------------
%Upper
fcDegrUpperCon = optimconstr(nFC,nFCellPacks,nO,nT,nFuels);

for e = 1:nFC
    for i = 1:nFCellPacks
        for o = 1:nO
            for t = 1:nT
                for f = 1:nFuels
                    fcDegrUpperCon(e,i,o,t,f) = ...
                        lFC(e,i,o,t,f) - 0.8 <= fcLoadUpper(e,i,o,t,f);
                end
            end
        end
    end
```

```
end

powerSystemProblem.Constraints.fcDegrLoadUpper = fcDegrUpperCon;
%-----------Enough energy capacity in batteries for roundtrip------------
bEnoughCapacityCon = optimconstr(nT);

capacityArray1 = bCapacityArray.*ones(nB,nBPacks,nO,nT);
bCapConTime = reshape(fractionOfTime',1,1,nO,nT);
bCapConTime1 = bCapConTime.*ones(nB,nBPacks,nO,nT);
socMax = socMax.*ones(nB,nBPacks);
socMin = socMin.*ones(nB,nBPacks);
for t = 1:nT
    baseEnergyDeliveredInOpstatesInRoundtrip = ...
        dodB(:,:,:,t).*...
        capacityArray1(:,:,:,t)./...
        (bCapConTime1(:,:,:,t)*Dr);
    sumBaseEnergyDelivered = ...
        sum(sum(sum(baseEnergyDeliveredInOpstatesInRoundtrip)));
    %total base energy delivered in a roundtrip in time period t


    bEnoughCapacityCon(t) = ...
        sumBaseEnergyDelivered + lostEnergyChargedAtShore(t) <=...
        sum(sum(bCapacityArray(:,:).*...
        bBought(:,:).*(socMax(:,:)-socMin(:,:))));

end

powerSystemProblem.Constraints.bEnoughCapacity = bEnoughCapacityCon;
%-----------Enough fuel storage for hydrogen------------------------------
fcFuelStorageCon = optimconstr(nT,nFuels);

t1 = reshape(fractionOfTime',1,1,nO,nT);
t2 = t1.*ones(nFC,nFCellPacks,nO,nT,nFuels);
powers = fcPowerReshaped;

%nFCx1x1x1xnFuels
fcSFCArray1 = reshape(fcTable.sfc(1:nFC,:),nFC,1,1,1,nFuels);
fcSFCArray2 = fcSFCArray1.*ones(nFC,nFCellPacks,nO,nT,nFuels);



for t = 1:nT
    for f = 1:nFuels
        fuelConsumptionArr = Dr.*t2.*powers.*fcSFCArray2.*lFC;
        fcBaseFuelConsumptionInTons = (...
            1e-6)*sum(sum(sum(fuelConsumptionArr(:,:,:,t,f))));

        %storage capacity in tons
        storageCapacityInTons = sum(sum(sTanks(:,f)));
        %changed ntanks from number of tanks
        %to installed capacity, size of tanks

        fcFuelStorageCon(t,f) = ...
            fcBaseFuelConsumptionInTons  <= storageCapacityInTons;
    end
end

powerSystemProblem.Constraints.fcFuelStorage = fcFuelStorageCon;

end     %end deOnly
```

B.8 postProcess.m

This script performs a postprocess of the optimization problem to present the obtained results, in forms of plots and excel files which are saved in the directory specified in linprob.m.

```
%==================Capex===========

%Fuel cells
%Types - number installed -
%rated power - total power - inv.cost - tot inv.cost
nFuelCells = round(sum(sol.fcBought.*fcTable.fcPowerArray(1:nFC,:)./...
    fcTable.fcPower(1:nFC),2),5);
fcInstalledPower = nFuelCells.*fcTable.fcPower(1:nFC,:);
fcNonimalPower = fcTable.fcPower(1:nFC,:);
fcInstalledCosts = fcInstalledPower.*fcNominalPrice;

%Creating table
fcInstalledTable = table(fcTypes,nFuelCells,fcNonimalPower,...
    fcInstalledPower,fcNominalPrice,fcInstalledCosts);

%filename = 'fcInstalled.xlsx';
%Only need to declare filename once if writing to the same worksheet
filename = 'results.xlsx';
filename = [resultsDir sprintf('%s_%s',casenr,filename)];

writetable(fcInstalledTable,filename,'Sheet','fcInstalled');

%Batteries
%Types - n.installed - rated cap -
%rated power - total cap - total p -inv.costs - tot inv.costs
nBatteries = sum(batteryBought.*bTable.bPowerArray./bTable.bP,2);
bInstalledCapacity = nBatteries.*bKwh;
bInstalledP = nBatteries.*bTable.bP;
bNominalP = bTable.bP;
batteryCost = nBatteries.*bKwh.*bPrice;

%Creating table
bInstalledCostTable = table(bTypes,nBatteries,bKwh,bP,...
    bInstalledCapacity,bInstalledP,bPrice,batteryCost);

% filename = 'bInstalled.xlsx';
% filename = [resultsDir sprintf('%s_%s',casenr,filename)];
writetable(bInstalledCostTable,filename,'Sheet','bInstalled');



%Diesel engines
%Types - n installed - rated p - total p - nominal inv.costs - total inv.cost
deVectorCounter = 1;
enginesByTypes = zeros(length(Ym),1);
for m = 1:length(Ym)
    for n = 1:Ym(m)
        enginesByTypes(m) = ...
            enginesByTypes(m) + sol.deBought(deVectorCounter);
        deVectorCounter = deVectorCounter + 1;
    end
end

deTypes = find(enginesByTypes)';
if (sum(deTypes) <= 0) == 0
for i = 1:length(deTypes)
    engineType = deTypes(i);          %type
    engineArray(i,1) = engineType;
    engineArray(i,2) = enginesByTypes(engineType); %no. installed of type
    engineArray(i,3) = engines(engineType,1);
    engineArray(i,4) = deInvCost;
    engineArray(i,5) = ...
        engineArray(i,2)*...
```

```
        engineArray(i,3)*...
        engineArray(i,4);
end
engineTypes = engineArray(:,1);
numberOfTypes = engineArray(:,2);
deNominalPower = engineArray(:,3);
deNominalCost = engineArray(:,4);
deTotalCost = engineArray(:,5);
deInstalledPower = deNominalPower.*numberOfTypes;
else

engineTypes = 0;
numberOfTypes = 0;
deNominalPower = 0;
deNominalCost = 0;
deTotalCost = 0;
deInstalledPower = deNominalPower.*numberOfTypes;

end
deInstalledTable = ...
    table(engineTypes,numberOfTypes,deNominalPower,deInstalledPower,...
    deNominalCost,deTotalCost);
% filename = 'deInstalled.xlsx';
% filename = [resultsDir sprintf('%s_%s',casenr,filename)];
writetable(deInstalledTable,filename,'Sheet','deInstalled');

%Sum de inv.cost
deSumInvestmentCosts = sum(deTotalCost);
deSumInvCostsTable = table(deSumInvestmentCosts);
% filename = 'deSumInvCosts.xlsx';
% filename = [resultsDir sprintf('%s_%s',casenr,filename)];
writetable(deSumInvCostsTable,filename,'Sheet','deInvCost');

%tanks, reformers and power inverter
%Tanks
%type - size of system - nominal cost - total cost
totalTanksCost = sol.sTanks.*tankCost;
tanksTable = table(tankTypes,sol.sTanks,tankCost,totalTanksCost);
% filename = 'fcFuelTanks.xlsx';
% filename = [resultsDir sprintf('%s_%s',casenr,filename)];
writetable(tanksTable,filename,'Sheet','tanks');

%reformers
%size - nominal cost - total cost
reformerCost = sol.fcAux.*Cef;
reformerTable = table(fcTypes,sol.fcAux,Cef,reformerCost);
%size of reformer system
% filename = 'fcReformerSystem.xlsx';
% filename = [resultsDir sprintf('%s_%s',casenr,filename)];
writetable(reformerTable,filename,'Sheet','reformers');


%power inverter
%size - nominal cost - total cost
%power inverter
powerInverterCost = bInstalledP.*bInverterPrice;
powerInverterCostTable = ...
    table(bInstalledP,bInverterPrice,powerInverterCost);
% filename = 'powerInverterCost.xlsx';
% filename = [resultsDir sprintf('%s_%s',casenr,filename)];
writetable(powerInverterCostTable,filename,'Sheet','pInverters');


%==================Opex======================
%Fuel cells
%-----------------Maintenance costs--------
fcTotalMaintCost = fcInstalledPower.*fcAnMaintCost*20;
fcTotalMaintCostTable = ...
    table(fcTypes,nFuelCells,fcPower,...
    fcInstalledPower,fcAnMaintCost,fcTotalMaintCost);
% filename = 'fcMaintenanceCost.xlsx';
```

```
% filename = [resultsDir sprintf('%s_%s',casenr,filename)];
writetable(fcTotalMaintCostTable,filename,'Sheet','fcMaintCost');


%-----------------Replacement costs--------
hoursInOperation = 8760*20*ones(nFC,1);
fcNumberOfReplacements = ...
    (hoursInOperation.*fcHourlyDegradation)./...
    fcAllowedDegradation;
fcTotalReplCost = ...
    fcNumberOfReplacements.*fcInstalledPower.*fcReplCost;
fcReplacementsTable = ...
    table(fcTypes,fcHourlyDegradation,hoursInOperation,...
    fcAllowedDegradation,fcNumberOfReplacements,...
    fcReplCost,fcTotalReplCost);
% filename = 'fcReplacementCost.xlsx';
% filename = [resultsDir sprintf('%s_%s',casenr,filename)];
writetable(fcReplacementsTable,filename,'Sheet','fcReplCost');

%Batteries
%-----------------Replacement costs--------
bInstalledCapacity = nBatteries.*bKwh;
totalAvailThroughput = availThrput.*nBatteries;
nReplacementsFromBasePower = ...
    evaluate(sum(...
    numberOfReplacementsOfEachBatteryStackAndTypeFromBaseLoad,2),sol);

numberOfReplacementsFromLC = ...
    sum(peakShavingEnergyInEachT).*sum(sol.bBought,2)./...
    totalAvailThroughput;

totalLCReplacementCost = ...
    numberOfReplacementsFromLC.*...
    bReplCost.*...
    bInstalledCapacity;

totalBaseReplacementCost = ...
    nReplacementsFromBasePower.*...
    bReplCost.*...
    bInstalledCapacity;

batteryReplacementCostTable = ...
    table(bTypes,totalAvailThroughput,nReplacementsFromBasePower,...
    numberOfReplacementsFromLC,bReplCost,bInstalledCapacity,...
    totalLCReplacementCost,totalBaseReplacementCost);

% filename = 'batReplacementCost.xlsx';
% filename = [resultsDir sprintf('%s_%s',casenr,filename)];
writetable(batteryReplacementCostTable,filename,'Sheet','batRepl');

%-----------------Maintenance costs--------
bTotalMaintenanceCost = 20*bAnnualMaintCost.*bInstalledCapacity;
batteryMaintenanceCostTable = ...
    table(bTypes,bInstalledCapacity,...
    bAnnualMaintCost,bTotalMaintenanceCost);
% filename = 'batMaintenanceCost.xlsx';
% filename = [resultsDir sprintf('%s_%s',casenr,filename)];
writetable(batteryMaintenanceCostTable,filename,'Sheet','batMaint');

%Diesel engines
%-----------------Maintenance costs--------
deTotalInstalled = sum(sol.deBought.*deP');
deTotalMaintenanceCost = deAnnualMaintCost*deTotalInstalled*20;
deTotalMaintenanceCostTable = ...
    table(deTotalInstalled,deAnnualMaintCost,...
    deTotalMaintenanceCost);
% filename = 'deMaintenanceCost.xlsx'
% filename = [resultsDir sprintf('%s_%s',casenr,filename)];
writetable(deTotalMaintenanceCostTable,filename,'Sheet','deMaint');

%=================Voyex=================================================
```

```

%----------------Fuel costs----------------------
%Fuel cells - fuel costs
%fuels - cost t1 - consumption t1 -
...total cost t1- cost t2 - consumption t2 - total cost t2
fcFuelPricesT1 = fuelCosts(:,:,1)';
fcFuelPricesT2 = fuelCosts(:,:,2)';
fcFuelConsumptionT1 = evaluate(...
    fcFuelConsumptionOfFuelsInTimePeriodsInTonnes(:,1),sol);
fcFuelConsumptionT2 = evaluate(...
    fcFuelConsumptionOfFuelsInTimePeriodsInTonnes(:,2),sol);
fcFuelCostsT1 = evaluate(fcFuelCostArray(:,1),sol);
fcFuelCostsT2 = evaluate(fcFuelCostArray(:,2),sol);

fcFuelCostsTable = table(fcFuels,fcFuelPricesT1,...
    fcFuelConsumptionT1,fcFuelCostsT1,...
    fcFuelPricesT2,fcFuelConsumptionT2,fcFuelCostsT2);

% filename = 'fcFuelCosts.xlsx';
% filename = [resultsDir sprintf('%s_%s',casenr,filename)];
writetable(fcFuelCostsTable,filename,'Sheet','fcFuelCost');

%Fuel cells - emission costs
%emission costs by fXw in t1 - emission costs by fXw in t2

fcEmissionCosts = evaluate(fcEmissionsCostArray,sol);
fcEmissionCostsT1 = reshape(fcEmissionCosts(:,1,:),nFuels,nAirEmissions);
fcEmissionCostsT2 = reshape(fcEmissionCosts(:,2,:),nFuels,nAirEmissions);

fcEmissionCostsTable = table(fcEmissionCostsT1, fcEmissionCostsT2);

% filename = 'fcEmissionCosts.xlsx';
% filename = [resultsDir sprintf('%s_%s',casenr,filename)];
writetable(fcEmissionCostsTable,filename,'Sheet','fcEmissions');

%Batteries
%cost t1 - consumption t1 - tot cost t1-
...cost t2 - consumption t2 - tot cost t2
elPricesT1 = ePrice(1,1,1);
elPricesT2 = ePrice(1,1,2);
elConsumption = evaluate(totalEnergyFromBatteries,sol);
elConsumptionT1 = sum(elConsumption(1,:));
elConsumptionT2 = sum(elConsumption(2,:));
elCostsT1 = evaluate(sum(elCosts(1,:)),sol);
elCostsT2 = evaluate(sum(elCosts(2,:)),sol);

elCostsTable = table(elPricesT1,elConsumptionT1,elCostsT1,...
    elPricesT2,elConsumptionT2,elCostsT2);

% filename = 'elCosts.xlsx';
% filename = [resultsDir sprintf('%s_%s',casenr,filename)];
writetable(elCostsTable,filename,'Sheet','elCosts');

%Diesel engines - fuel costs
%fuels - cost t1 - consumption t1 -
...tot cost t1 - cost t2 - consumption t2 - tot cost t2
deFuelPricesT1 = deFCost(:,:,1)';
deFuelPricesT2 = deFCost(:,:,2)';
deFuelConsumption = evaluate(...
    deFuelConsumptionInTonnesMat,sol); %nDE,nO,nT,nFuelsDE


deFuelConsumptionSummed = sum(deFuelConsumption,[1 2]);
deFuelConsumptionReshaped = ...
    (reshape(deFuelConsumptionSummed,nFuelsDE,nT))';

deFuelConsumptionT1 = deFuelConsumptionReshaped(:,1);
deFuelConsumptionT2 = deFuelConsumptionReshaped(:,2);

deFuelCostsT1 = deFuelConsumptionT1.*deFuelPricesT1;
deFuelCostsT2 = deFuelConsumptionT2.*deFuelPricesT2;
```

```

deFuelCostsTable = table(deFuelTypes,deFuelPricesT1,...
    deFuelConsumptionT1,deFuelCostsT1,...
    deFuelPricesT2,deFuelConsumptionT2,deFuelCostsT2);

% filename = 'deFuelCosts.xlsx';
% filename = [resultsDir sprintf('%s_%s',casenr,filename)];
writetable(deFuelCostsTable,filename,'Sheet','deFuelCosts');

%Diesel engines - emission costs
%emission costs by fXw in t1 - emission costs by fXw in t2


deEmissionCosts = evaluate(deEmissionsCostArray,sol);
deEmissionCostsT1 = ...
    reshape(deEmissionCosts(:,1,:),nFuelsDE,nAirEmissions);
deEmissionCostsT2 = ...
    reshape(deEmissionCosts(:,2,:),nFuelsDE,nAirEmissions);

deEmissionCostsTable = table(deEmissionCostsT1, deEmissionCostsT2);

% filename = 'deEmissionCosts.xlsx';
% filename = [resultsDir sprintf('%s_%s',casenr,filename)];
writetable(deEmissionCostsTable,filename,'Sheet','deEmissions');


%-----------------System cost-----------------------
systemCost.voyex.basePowerElectricityCost = evaluate(totalElcosts,sol);
systemCost.voyex.fcFuelCosts = evaluate(fcFuelCosts,sol);
systemCost.voyex.deFuelCosts = evaluate(deFuelCosts,sol);
systemCost.voyex.fcEmissionsCosts = evaluate(fcEmissionCost,sol);
systemCost.voyex.deEmissionsCosts = evaluate(deEmissionsCost,sol);
systemCost.voyex.totalVoyex = ...
    systemCost.voyex.basePowerElectricityCost +...
    systemCost.voyex.fcFuelCosts +...
    systemCost.voyex.deFuelCosts +...
    systemCost.voyex.fcEmissionsCosts +...
    systemCost.voyex.deEmissionsCosts;

systemCost.capex.FuelCells = evaluate(fcModulesInvCosts,sol);
systemCost.capex.FCreformer = evaluate(fcAuxInvCosts,sol);
systemCost.capex.FCtanks = evaluate(fcFuelTankCosts,sol);
systemCost.capex.Batteries = evaluate(bModulesInvCosts,sol);
systemCost.capex.PowerInverter = evaluate(bPowerInverterCosts,sol);
systemCost.capex.DieselEngines = evaluate(deInvestmentCosts,sol);
systemCost.capex.totalCapex = ...
    systemCost.capex.FuelCells +...
    systemCost.capex.FCreformer +...
    systemCost.capex.FCtanks +...
    systemCost.capex.Batteries +...
    systemCost.capex.PowerInverter +...
    systemCost.capex.DieselEngines;

systemCost.opex.fcMaintenanceCosts = evaluate(fcMaintenanceCosts,sol);
systemCost.opex.bMaintenanceCosts = evaluate(bMaintenanceCosts,sol);
systemCost.opex.deMaintenanceCosts = evaluate(deMaintenanceCosts,sol);
systemCost.opex.fcReplacementCosts = evaluate(totalFCReplCost,sol);
systemCost.opex.bBaseReplacementCosts = ...
    evaluate(totalBBasePowerReplCost,sol);
systemCost.opex.bLCReplacementCosts = evaluate(totalLCBatReplCost,sol);
systemCost.opex.totalOpex = ...
    systemCost.opex.fcMaintenanceCosts +...
    systemCost.opex.bMaintenanceCosts +...
    systemCost.opex.deMaintenanceCosts +...
    systemCost.opex.fcReplacementCosts +...
    systemCost.opex.bBaseReplacementCosts +...
    systemCost.opex.bLCReplacementCosts;

systemCost.capex.sumCosts = ...
    systemCost.opex.totalOpex +...
    systemCost.capex.totalCapex +...
```

```
    systemCost.voyex.totalVoyex;

systemCost.capex.totalCost = fval;

filename = 'systemCost.xlsx';
filename = [resultsDir sprintf('%s_%s',casenr,filename)];

opexTable = struct2table(systemCost.opex);
opexTable = table(opexTable{:,:}.',...
    'RowNames',opexTable.Properties.VariableNames)
%filename = 'opex.xlsx';
%filename = [resultsDir sprintf('%s_%s',casenr,filename)];
writetable(opexTable,filename,'WriteRowNames',true,'Sheet','Opex');

voyexTable = struct2table(systemCost.voyex);
voyexTable = table(voyexTable{:,:}.',...
    'RowNames',voyexTable.Properties.VariableNames)
%filename = 'voyex.xlsx';
%filename = [resultsDir sprintf('%s_%s',casenr,filename)];
writetable(voyexTable,filename,'WriteRowNames',true,'Sheet','Voyex');

capexTable = struct2table(systemCost.capex);
capexTable = table(capexTable{:,:}.',...
    'RowNames',capexTable.Properties.VariableNames)
%filename = 'capex.xlsx';
%filename = [resultsDir sprintf('%s_%s',casenr,filename)];
writetable(capexTable,filename,'WriteRowNames',true,'Sheet','Capex');


for t = 1:nT
    for o = 1:nO
        pfc1(t,o) = sum(sum(sum(...
            sol.lFC(:,:,o,t,:).*fcPowerReshaped(:,:,o,t,:))));
        pb1(t,o) = 0.95*sum(sum(sum(sol.dodB(:,:,o,t).*...
            bCapacityReshaped(:,:,o,t)/...
            (fractionOfTime(t,o)*Dr))));
        pde1(t,o) = deEfficiency*sum(sum(...
            sol.lDE(:,o,t,:).*dePowerReshaped(:,o,t,:)));
    end
end

powerInOandT = pfc1 + pb1 + pde1;
power3d(:,:,1) = pfc1;
power3d(:,:,2) = pb1;
power3d(:,:,3) = pde1;

figureName = 'PowerDistributionInOperationalStates';
figure1 = figure('Name',figureName);
for t = 1:nT
    subplot(1,nT,t);
    powers = power3d(t,:,:);
    for j = 1:size(powers,3)
        powersReshaped(j,:) = powers(:,:,j);
    end
    bar(powersReshaped','stacked')
    xlabel('Operational state')
    ylabel('Power delivered [kW]')
    title(["Time period " + t])
    legend('Fuel cells','Batteries',...
        'Diesel engines','location','northwest')
end

  filename = [figureName + ".png"];
    filename = [resultsDir sprintf('%s_%s',casenr,filename)];
    saveas(figure1,filename);




%----------------Plot--------------------
dePowerInOpstates = deEfficiency*sol.lDE.*dePowerReshaped;
```

```
dePowerInOpstatesByFuels = sum(dePowerInOpstates,1);
for f = 1:nFuelsDE
    dePowerInOpstatesReshaped(f,:,:) = ...
        dePowerInOpstatesByFuels(1,:,:,f);
end
dePowerInOpstatesReshaped

figureName = 'dePowerPlot';
figure('Name',figureName);
for t = 1:nT
    subplot(nT,1,t);
    bar3(dePowerInOpstatesReshaped(:,:,t)');
    view(-56,19);
    legend('MDO','ULSF');
    title(["T" + t]);
    xlabel('Fuel');
    ylabel('Operational state')
    zlim([0 max(max(powerDemand))]);
end
    filename = [figureName + ".png"];
    filename = [resultsDir sprintf('%s_%s',casenr,filename)];
    saveas(gcf,filename);


%Base power from fuel cells
%bar3(newmat)
powerFromFC = fc.*fcTable.fcPowerArray(1:nFC,:);
fcPowerRounded = round(powerFromFC,5);
for t = 1:nT
    figureName = ["fcPowerPlot" + "T" + t]
    figure('Name',figureName);
    plotindex = 1;
    for o = 1:nO

        subplot(nO/2,2,plotindex,'align');
        fcPowers = sum(fcPowerRounded(:,:,o,t,:),2);
        newmat = reshape(fcPowers,nFC,nFuels);

        bar3(newmat)
        view(-63,21);
        title(["T"+ t + "," + "O" + o])
        %set(gca,'YDir','normal') % reverse the y-axis
        xlabel('FC-fuel')
        ylabel('FC-type')
        zlim([0 1.2*max(max(powerDemand))]);
        if plotindex == 2
            legend('H2-compr.','H2-liquid','LNG','location','northeast');
        end
        plotindex = plotindex + 1;
    end
    filename = [figureName + '.png'];
    filename = [resultsDir sprintf('%s_%s',casenr,filename)];
    saveas(gcf,filename);
end
```

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