Sizing Optimization of a Hybrid Propulsion powertrain for a Crew Transfer Vessel incorporating uncertainties: towards a cost-effective, eco-friendly design

Savvas Karagiorgis

TU Delft

Sizing Optimization of a Hybrid Propulsion powertrain for a Crew Transfer Vessel incorporating uncertainties:

towards a cost-effective, eco-friendly design

by

Savvas Karagiorgis

to obtain the degree of Master of Science in Marine Technology in the specialization of
Marine Engineering
at the Delft University of Technology,
to be defended publicly on Thursday September 22, 2022 at 13:30.

Student number:	4821815	
Thesis number:	MT.21/22.050.M	
Thesis committee:	Dr. ir. H. Polinder,	TU Delft, Chair
	Dr. S. Nasiri,	TU Delft, Daily Supervisor
	Dr. X. Wang,	ZF Wind Power, Daily Supervisor
	Dr. ir. Lindert van Biert,	TU Delft

Cover image from cmb.tech

ABSTRACT

A major transition became necessary for the maritime industry to meet the IMO's targets for mitigating the carbon footprint of the sector by at least 50% by 2050. One of the promising methods to lower the emissions is the ship's hybridization. An enormous increase in pilot and demonstration projects for that purpose is being observed. This research was contacted through the involvement of TU Delft in such a project called the Implementation of Ship Hybridisation.

The design and optimization of hybrid propulsion systems is a complex and challenging task due to the different power sources involved and the dependence on the energy management and control. The physical system and the control algorithm should be designed in an integrated manner to obtain an optimal system design. This study applies a multi-objective double-layer optimization methodology to optimize the sizing and energy management of a hybrid ship propulsion system to be installed on a Crew transfer vessel. A proposed hybrid topology which combines diesel engines, batteries and fuel cells is considered. The proposed approach incorporates the development of fuels and electricity prices as well as the investment costs of the system's components as an uncertainty element. The introduction of emission reduction measures such as carbon tax was also considered in the study. Future trajectories for the relevant uncertainties were developed and incorporated in the optimization methodology to provide decision-makers with a more realistic picture of the solution space.

The analysis of the optimization results was based on the Total cost of ownership (TCO) and the emission reduction potential of the optimal designs produced by the optimization methodology. The results show that instead of choosing a hybrid propulsion system for the vessel under study, an all-electric propulsion system which is based entirely on batteries and fuel cells is the most economical and environmentally friendly option. Incorporating diesel engines has a negative impact on the operational expenditures of the system in the long term. A fully electric propulsion system would require a larger initial investment from the ship owner, but it would pay off over the course of the ship's remaining useful life.

This research can be used as a reference to base the decision of the stakeholders on choosing a new propulsive system for their vessel. The parameters of the optimization methodology can be easily changed to explore more options and expand the design solution space if this thesis' results don't satisfy the shipowner. In addition, it is suggested that a professional user interface designer be involved in the development of a real life decision support tool, incorporating the multi-objective optimization methodology.

Dedicated to my mother for her constant love and support, and the sacrifices
she made to help me achieve my goals.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

GHG	greenhouse gas	1
CO_2	Carbon dioxide	1
IMO	International Maritime Organisation	1
GDP	Gross Domestic Product	1
MEPC	Marine Environment Protection Committee	1
ISHY	Implementation of Ship Hybridisation	2
CTV	Crew Transfer Vessel	2
FC	Fuel Cells	1
ICE	Internal Combustion Engine	3
EM	electic motor	3
ESS	energy storage systems	16
Li-ion	Lithium-Ion	11
RES	Renewable Energy Sources	25
KPIs	Key performance indicators	6
TCO	Total cost of ownership	38
CAPEX	Capital expenditures	35
OPEX	Operating expenditures	35

1 INTRODUCTION

On December 12, 2015 the biggest step to greenhouse gas (GHG) emissions mitigation was taken, when parties at the United Nations Climate Change Conference - COP 21 made an agreement to combat climate change. The main goal of the agreement also known as the *Paris agreement* was to keep the global average temperature rise to well below 2°C above pre-industrial levels [United Nations, 2015]. Following the same growth as global Gross Domestic Product (GDP) over the last 40 year the maritime transport has increase by 250%. The maritime sector's emissions are accountable for around 3% of the global anthropogenic GHG emissions in 2018 [Bouman et al., 2017; Smith et al., 2015b]. If no emission abatement measures are implemented in "business-as-usual" scenarios with a tripling of world trade expected, the emissions are predicted to increase by $150-250\%$ by the year 2050 [Smith et al., 2015a; Buhaug et al., 2009]. As a result, there is growing pressure on the shipping industry to lower its emissions. In order to contribute to the targets of the Paris Agreement, in 2018, during the 72nd session of International Maritime Organisation (IMO)'s Marine Environment Protection Committee (MEPC), IMO has adopted a new climate change strategy, bringing a huge challenge to the shipping industry for the years to come [IMO, 2020]. A goal was set to reduce GHG from international shipping by at least 50% by 2050 and Carbon dioxide (CO_2) emissions by 40% before 2030, and 70% before 2050, with all goals having 2008 as a baseline year.

Despite the fact that actions are being taken, there are still many unknowns. Policies and regulations are affected by political uncertainty. New regulations will be implemented, though it is unclear how quickly and harshly. Technical and economic uncertainties exist in addition to political uncertainties. Technical uncertainties relate to how quickly emerging technologies are developing and economic uncertainties are connected to fuel and electricity prices that have an impact on investments and operational measures. Given the long lifespan of vessels, it is currently essential to take potential changes and developments into account when making decisions regarding the specifications for both newly constructed and existing vessels. A major transition became necessary for the maritime industry and is the responsibility of naval architects and marine engineers to meet the coming regulations in a way that makes sense both technical and economical.

One of the promising methods to lower CO_2 emissions is hybridization and electrification. The benefits of hybrid propulsion for de-carbonization of the shipping sector have been studied in recent years with Fuel Cells (FC) and battery systems having high potential as relatively new technologies for shipping [DNV GL, 2018]. Ferries, passenger ships, and service vessels have adopted batteries quickly in recent years. Ampere, the first battery-powered car ferry, entered service in 2015, and as of mid-2021, 522 ships with batteries were in operation or on order (including fully electric vessels and hybrids that can be chargeable and non-chargeable hybrids) [DNV-GL, 2021a]. Some of the vessels can operate full-electric, but almost all of them still use hybrid systems that rely on diesel or biofuels to increase their operating range or provide redundancy in the event of a power outage. Moreover, governments like Norway are planning to use hydrogen fuel cells in their public ferry industry as the next step in the conversion to zero-emission technologies. An increase in zero-emission pilot and demonstration projects supports this development. At the same time, the electrical revolution of the automotive industry was and would continue to be beneficial for maritime sector by adapting their experience in design and control strategies.

1.1 Implementation of Ship Hybridisation (ISHY)

The Implementation of Ship Hybridisation (ISHY) is project that aims *"at the development, testing and validation of technical tools and socio-economic models for the implementation of hybrid and hydrogen fuel cell technologies in vessels and ports, and realising the development and demonstration of the feasibility of these technologies by retrofitting different types of existing vessels, different kinds of new built vessels and new bunkering facilities in ports in order to increase the adoption likelihood of this low or zero carbon technology in a sector with high impact potential"* [Interreg 2 Seas, 2019].

The project brings together a number of partners which include a variety of fleet owners, engine builders, knowledge institutions and port authorities. TU Delft is a partner in the project with primary focus the development of a methodology to choose the powertrain components of optimum power rating and technology for a hybrid vessel in order to reduce its CO_2 emissions. This involves a comprehensive overview of components, the development of a library of component models, and the methodology to choose the optimal components [Maritime and Transport Technology, 3mE, TU Delft, 2019].

This master thesis is inspired by the TU Delft involvement in the ISHY project. A multi-objective double-layer optimization methodology that was developed by TU Delft researchers was used and further developed in order to build a strategy that can assist ship owners in deciding whether and when to retrofit their vessels as well as the optimum design for doing so at the chosen moment. GEOxyz a partner of ISHY project sees potential in hybrid propulsion for a Crew Transfer Vessel (CTV) in their fleet [GEOxyz, 2022] and they are providing the vessel's data for this study in order to receive recommendations and guidelines for the retrofitting of their vessel or the design and construction of a new similar vessel that is hybrid and to be used for the same purposes. The outcome of this study aims to benefit GEOxyz and all the stakeholders involved in the ISHY project.

1.2 Hybrid Technology

The traditional configuration that the marine energy systems have historically relied on was simple. The propulsion power was produced from the main engine or in other words the prime mover, while the electric power demands were managed from auxiliary engines. Considering the vast number of combinations of a vessel's propulsion and electric power demand, having each component dealing with a specific demand is not the most energy efficient approach. Hybrid propulsion was presented as an attractive solution to this inefficiency of conventional marine systems and having as example how popular was in the automotive industry [Guzzella et al., 2007; De Jager et al., 2013] very recently hybrid arrangements were implemented in several type of ships. Naval vessels, yachts, harbour tugs and supply vessels have already adopted hybrid propulsion systems, with Geertsma et al. [2017] addressing in detail their classification, benefits, challenges, and opportunities in a review of developments. Having both the main engine and auxiliary engines to contribute both to the electric and propulsive power demand by implementing a hybrid electric propulsion system offers flexibility to the total power production. Moreover, if energy storage systems and fuel cells are also included in such hybrid architectures the overall efficiency of the hybrid power supply system is enhanced together with many more advantages.

In short, the main advantages of a hybrid propulsion system are [De Jager et al., 2013]:

- High redundancy and reliability. Energy storage devices such as batteries can provide back-up power in case of a failure of the main engine or reduce the number of engines running at specific time, leading to reduction in maintenance cost as well as fuel consumption.

- Reduce emissions. A hybrid system allows to operate the ship either from the Internal Combustion Engine (ICE) or the electic motor (EM) which is mechanically coupled to the same shaft, thus by using batteries or fuel cells the ship has the freedom to operate even emission free if it is required.

- Transient load response. ICE ability to transient load is limited, hence energy storage devices can deal with load variation and the engines can run at optimum constant load.

- Adaptation to a variation of operating modes. Related to the previous point due to the fast system response and flexibility the operational capability of the vessel is enhanced.

- Reduction of fuel consumption. The main engines would not run inefficiently at part load, as the coupled electric motor can provide propulsion for low speeds.

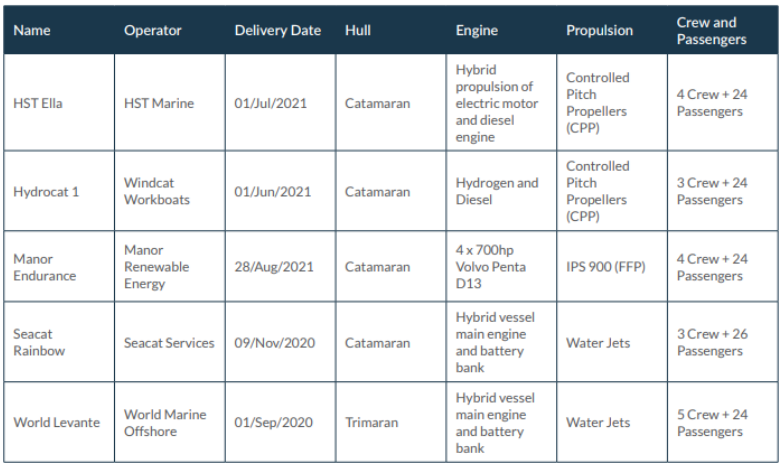
- Reduced noise and vibrations, which is important for navy, research or passenger vessels.

However, designing and optimizing hybrid propulsion systems is a challenging task. The availability of numerous power, propulsion, and energy system topologies with different energy storage and conversion technologies presents a significant challenge. The ship design problem has several objectives and includes topology, sizing, control, and energy management. These constraints necessitate a multidisciplinary, multi-objective approach.

1.3 Crew Transfer Vessels (CTVs)

The scientific community has already identified the benefits arising from the adoption of hybrid propulsion, and such systems are slowly being introduced to commercial vessels. Crew transfer vessel is a type of Offshore support vessels (OSVs) that are good candidates to be designed around a hybrid propulsion system. Jafarzadeh and Schjølberg [2018] investigated which vessels are most suited for hybrid propulsion systems, based on their operational profile in Norwegian waters and it was found that offshore and passenger ships can benefit the most from hybridization, diesel-electric propulsion or other electric concepts, such as downsizing diesel engines to enable operation at optimal points while fuel cells and/or batteries supply peak and partial loads. This is because they spend a significant fraction of their total operational time in part-load where the fuel efficiency is sub-optimal. CWIND [2021]; PIRIOU [2020]; HST Marine [2021]; Seacat [2020]; Damen [2022]; Mayflower Wind [2021]; Strategic Marine [2022] are some of the companies that have already built, ordered or having in build hybrid CTVs and some examples of the best in class CTVs in practise today are listed in Table 1.1.

Table 1.1: Some examples of the best in class CTVs in operation or construction adopted from Offshore Renewable Energy (ORE) [2021]



Name	Operator	Delivery Date	Hull	Engine	Propulsion	Crew and Passengers
HST Ella	HST Marine	01/Jul/2021	Catamaran	Hybrid propulsion of electric motor and diesel engine	Controlled Pitch Propellers (CPP)	4 Crew + 24 Passengers
Hydrocat 1	Windcat Workboats	01/Jun/2021	Catamaran	Hydrogen and Diesel	Controlled Pitch Propellers (CPP)	3 Crew + 24 Passengers
Manor Endurance	Manor Renewable Energy	28/Aug/2021	Catamaran	4 x 700hp Volvo Penta D13	IPS 900 (FFP)	4 Crew + 24 Passengers
Seacat Rainbow	Seacat Services	09/Nov/2020	Catamaran	Hybrid vessel main engine and battery bank	Water Jets	3 Crew + 26 Passengers
World Levante	World Marine Offshore	01/Sep/2020	Trimaran	Hybrid vessel main engine and battery bank	Water Jets	5 Crew + 24 Passengers

CTVs are mainly used for service and repairs of offshore wind towers and substations related to electricity transmission infrastructure. Their task is to take service crews, along with the required equipment and parts, from the port or residential unit (offshore accommodation vessels (OAV)), and transport them to the wind tower's specific location. They are able to take on a dozen or so people who, depending on the work performed, are distributed to individual wind tower.

The studied crew transfer vessel goes through several different phases during its operation. A typical operational profile of the vessel's power demand in Figure 1.1 indicates these different phases. At the port, where the maintenance personnel will be picked up the ship travels at a low speed and its power demand will be relatively low. Once the ship is out of port, it will increase its speed to transport the maintenance personnel from the port to the wind farm as quickly as possible, and the power demand of the ship will be maximum. At the wind farms, the vessel will provide a safe passage for the technicians between the CTV and the wind boat landing by pushing against the wind turbine boat landing with the vessel's bow fender. At this phase, the vessel's required power will be relatively limited. Once the maintenance in one wind tower is finished, the ship will continue to navigate quietly at a limited speed, transporting maintenance personnel from one wind turbine to another. When the personnel have to be transported back to the port, this will be done again in a minimum time, so the required power will increase once more to the maximum. At the port the power demand will be reduced again. It takes around 1.5 hours to arrive at the wind farm. The ship stays in the working area for about 7 hours with some short distance moving. It then takes 1.5 hours to return. The total travelling period of the CTV is about 12 hours, starting from the harbour.

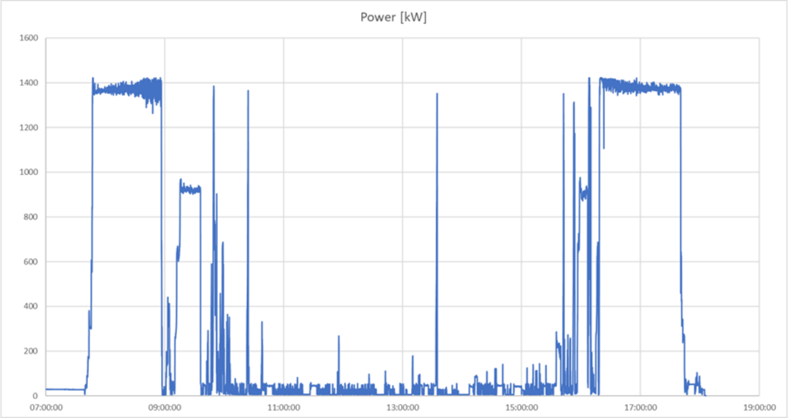


Figure 1.1: Typical operational profile of the studied CTV's power demand

1.4 Reasearch Relevance

1.4.1 Industrial relevance

More and more orders of hydrogen-fueled, hybrid or electric CTVs appear very recently in the offshore renewables sector, which indicates the relevance of this study to the industry's trends. As mentioned the construction of this master thesis was inspired from the involvement of TU Delft researchers in the ISHY project. This thesis intends to contribute to the goals of the ISHY project and increase the likelihood to adopt hybrid and hydrogen fuel cell technology in ships and ports by providing the advantages of their adoption on a vessel of GEOxzy a partner of the project.

This research can be used as reference work to base GEOxyz decision on choosing the hybrid propulsion system for their CTV. If this thesis results doesn't provide a decisive answer to their problem the optimization methodology used can be adjusted to explore more opportunities and expand their design solution space. More fleet owners within and outside of ISHY project that have vessels with similar operational profiles and are interested in their hybridization can benefit from this thesis.

1.4.2 Scientific relevance

The scientific relevance of this thesis can be found in both the multi-objective optimization methodology used as to the goal to combine different power sources and energy storage to improve the propulsion system of a CTV and make it hybrid. Only recently Bureau Veritas has classified the world's first hybrid-powered CTV [Nick Blenkey, 2021] which means that public scientific knowledge about CTV hybridization is very limited and an increase in research about their feasibility is therefore relevant.

1.4.3 Societal and environmental relevance

The main goal of the CTV's hybridization is to reduce emissions. If adopted, these low or zero emission technologies will help create a more environmentally friendly supply chain, increase access to green energy, and ultimately decarbonize the offshore wind industry, bringing us one step closer to a society with no emissions while also helping us meet the IMO and Paris Agreement targets.

1.5 Research objective and Research questions

The research objective of the master thesis is to:

Identify the most cost-effective and eco-friendly propulsion system for a Crew Transfer Vessel based on a multi-objective double-layer optimization methodology developed at TU Delft, by incorporating future uncertainty and developing scenarios for plausible futures.

The main research question that this thesis would like to answer is:

What are the power and energy ratings of the components of the hybrid propulsion powertrain that should be installed in order to have a cost-effective and eco-friendly Crew Transfer Vessel?

To provide an answer to the main research question, the following sub research questions have been formulated:

Sub question 1**:** *Which uncertainties can be identified that affect the sizing optimization problem for the CTV's hybrid propulsion system?*

Considering the aforementioned challenges and to provide decision-makers with a more realistic picture of the solution space, this thesis proposes integrating uncertainties introduced by the physical and financial environments into a multi-objective double-layer optimization methodology.

Sub question 2**:** *What are the future scenarios on exogenous factors/ uncertainties, and how will these influence the sizing of the hybrid CTV? (e.g. future prices, technology maturity)*

Based on forecasts and data provided by experts in technical reports and literature, various scenarios are developed to represent the impact on design and sizing of the uncertainties related to fuel costs, regulations, CO_2 prices, and technology advances. In each scenario, consequences of hybridization on the CTV are analysed.

Sub question 3: *How the cost-effectiveness of the optimum configuration solutions produced by the optimization methodology would be determined?*

A cost assessment method that incorporates initial investment costs and operational costs over the span of the vessel's life would be utilized.

1.6 Research Scope and Assumptions

This thesis will research the sizing optimization of a proposed hybrid propulsion system for a CTV. The following points serve as indicators of the research's scope and assumptions:

- The study is limited to optimize a chosen, proposed hybrid topology. The hybrid design configuration combining diesel engines, fuel cells, batteries would be the only focus. Only batteries and fuel cells as energy storage and conversion systems are considered on having potential on reducing emissions if are combined with diesel engines on the studied vessel. That is to prevent of resulting in endless combinations of configurations, but the model would be possible to analyze more different combinations if adjusted.

- The auxiliary loads and the sizing of the electric motors/generators will not be included in the optimization problem.

- Weight and volume limitations would not be considered in the study, thus the technical feasibility of the installation is out of scope.

- Degradation of the battery and fuel cells is not considered and would not be modeled into the optimization problem.

- Economic uncertainties, such as fuel and electricity prices and the possibility of CO_2 tax adoption will be considered.

- The technology development of the components would be translated only in changes in investment costs. Other factors that are influenced such as efficiencies, energy densities, lifecycle improvements are neglected.

- Several future scenarios/pathways would be created to investigate the impact of future uncertainties at the vessel design/sizing optimization process.

- The optimization output would be evaluated regarding the cost-effectiveness and the projected emissions reduction.

- The economic evaluation would neglect replacement costs, maintenance and depreciation of the system's components.

1.6.1 Key performance indicators (KPIs)

To compare the new, optimized layout options with one another and the vessel's conventional propulsion system, a number of evaluation criteria must be established. Defining Key performance indicators (KPIs) is a very valuable way of measuring performance and serves as a tool for making decisions. An important aspect of KPIs is that they assist in sorting and limiting the amount of relevant data by making comparisons. KPIs in shipping are often related to costs, emissions, efficiency, delivery time, profits, safety, and more. Two different KPIs will be used to evaluate the new configurations.

- Cost-effectiveness. The hybrid optimum configurations produced from the optimization will be evaluated according to the expenses (investments and operational costs) over the ship's lifespan.
- Emission reduction/mitigation. The optimal configurations with 50 and 75% lower carbon emissions than the conventional system would be identified.

1.7 Structure of the report

Chapter 2 provides background information on fuel cells, batteries, and hybrid propulsion, as well as the benefits of installing them on ships. This chapter also covers the reasons why particular battery and fuel cell types are better suited for this application as well as the production and storage of the hydrogen used in the analysis of the thesis. Additionally, an introduction is given about optimization problems and techniques relevant to the ones being utilized in this research. Chapter 3 gives an overview of the uncertainties, which are involved in the design of a hybrid propulsion system for a Crew transfer vessel as well as an insight into forecasts used for developing different scenarios for the thesis' optimization problem. The conventional propulsion system for the CTV is described in Chapter 4, as is the proposed hybrid system that will be studied and optimized. Chapter 5 describes the optimization problem and the multi-objective methodology that is used to solve it, together with the steps of the thesis's research approach. Chapter 6 determines the studied scenarios and the outcomes of the simulation experiments are then presented. In addition, the analysis of the optimized hybrid electric propulsion system layouts is discussed. Finally, conclusions are drawn by giving answers to the research questions in Chapter 7. Moreover, suggestions for further research are given, together with recommendations and guidelines to GEOxyz based on the findings of the research.

2 BACKGROUND

2.1 Propulsion Topologies

Diversity in operational profiles of ships resulted to the development of a variety of propulsion systems. Figure 2.1 illustrates some of the propulsion systems in practice today. The optimisation of the power and propulsion plant is a trade-off between efficiency and adaptability to different operating points with the goal to perform successfully on many criteria. An extensive review was employed by Geertsma et al. [2017], that classifies the propulsion topology into mechanical propulsion, electrical propulsion and hybrid propulsion. The former two topologies would not be further discussed because the focus of this study would be on hybrid propulsion.

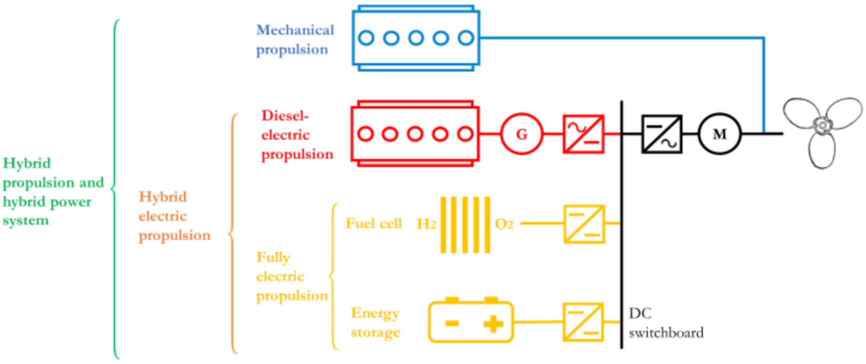


Figure 2.1: Typical propulsion systems of hybrid and electric ships in practise today [Jafarzadeh and Schjølberg, 2018]

2.1.1 *Hybrid Propulsion*

A hybrid powertrain utilises at least two powertrains to generated power compared to conventional ones that consist of only one. The development of hybrid topology was motivated by the fact that the advantages of both electrical and mechanical propulsion can be combined. This hybridization allows generating a broad spectrum of topologies, depending on the connections between the powertrains, and a wide variety of patterns regarding power delivery. The most typical layout is presented in Figure 2.2a.

A direct mechanical drive providing propulsion for high speed with high efficiency is coupled through a gearbox to the same shaft with an electric motor. The electric motor can provide the propulsion power for low load requirements to avoid operating the main engine inefficiently in part load and act as a potential power booster in high load demand or sharp accelerations. The two powertrains can operate independently from each other but also assist each other. Another use of the electric motor is as a generator, converting mechanical energy from the main engine to electricity to meet the electrical loads on the vessel's electric network or charge the battery pack in the case of hybrid propulsion with hybrid power supply (Figure 2.2b).

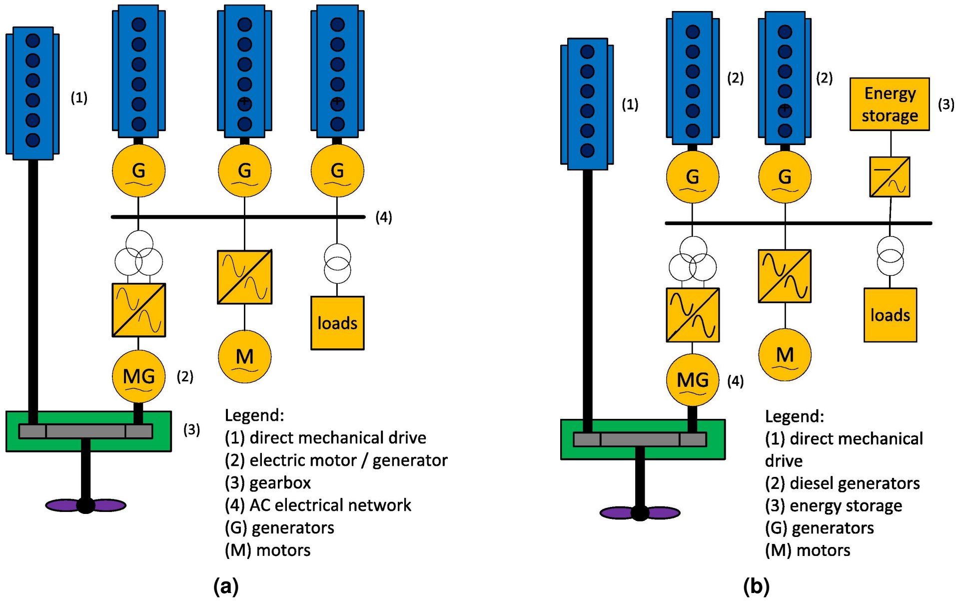


Figure 2.2: (a) Typical hybrid propulsion system (b) Typical hybrid propulsion system with hybrid power supply [Geertsma et al., 2017]

This architecture benefits from the advantages of both electrical and mechanical propulsion with an even higher degree of redundancy and efficiency in both design and part-load conditions. Hybrid propulsion can be in conjunction with hybrid power supply. In this case, the electrical power is provided by a combination of two or more power sources. The power sources can be classified in combustion power supply (diesel engines, gas turbines or steam turbines), electrochemical power supply (fuel cells) and stored power supply from energy storage systems (batteries, flywheels, or supercapacitors). With the benefits of stored energy in batteries as a part of hybrid power supply and the main advantages already discussed in Section 1.2, other advantages of this configuration include:

The use of battery can enable load levelling and peak shaving, depending on power fluctuations and power demands. As a result, the engines can maintain a more efficient operating point as their loading is constant, and their installed power can also be reduced. The lessening of the engine sizing can be beneficial for vessels with a requirement for high propulsion availability such as DP vessels. The batteries offer redundancy in electric propulsion providing back-up power in diesel generator failure and the need for running extra diesel engines as spinning reserve can be avoided. Fewer transmission losses than electrical propulsion as fewer conversion stages occur when the direct mechanical drive generates propulsive power. Moreover, the powertrain components' sizing can be optimized to deliver the total power demand most efficiently, determined the optimal 'power-split'. What is more, the fuel consumption and local emission can be reduced even further when the battery is recharged alongside, especially if renewable energy sources (i.e. wind energy) generate the grid's power.

A proper design hybrid propulsion architecture must have an effective control system. A good design control strategy must be built to achieve optimal performance in the plant's design requirements, such as reduced fuel consumption and emissions, or high availability. The control system or in other words the Energy Management Strategy has to be designed to allow the plant to benefit from the combination of the mechanical and electrical propulsion system. For example, in a hybrid power supply, the battery has to be charged and discharged at the right time. The dynamic load has to be shared the right way between the diesel engine, the battery or other power source (i.e. fuel cells) to maximize the reduction in fuel consumption, and emissions and minimize the maintenance load.

2.2 Batteries

Batteries are known energy storage systems that store electrical energy as chemical energy. Batteries through chemical reactions can also transform their chemically stored energy into electrical [DNV GL, 2016]. The conversion can be reversible for some batteries, but not for all. Batteries that can be discharged only once (disposable) are classified as primary and batteries that can recharge as secondary [Mutarraf et al., 2018]. Batteries for maritime application are secondary, and only those will be studied in this project.

2.2.1 *Types*

Batteries can be divided according to their chemical components as well. The most relevant, available, and commercial ones in the global market are:

- Lithium-Ion (Li-ion) batteries
- Nickel-Metal Hydride (Ni-MH) batteries
- Nickel-Cadmium (Ni-Cd) batteries
- Lead-Acid batteries
- Sodium-Sulphur (Na-S) batteries
- Vanadium-flow (V-flow) batteries

The terms 'specific energy' and 'energy density' are often interchanged with each other. However, the first refers to the amount of energy contained per unit of mass, while the second refers to the amount of energy contained per unit of volume. The higher the specific energy is, the lighter the battery is per energy content. A similar situation occurs regarding energy density. The higher the energy density is, the more compact the battery is per energy stored. Figure 2.3 shows the aforementioned battery types in terms of energy density and specific energy. Therefore, those located in the right top corner will be the most suitable battery type due to the limited space available and the ship's sensitivity to heavy equipment. Hence, Lithium-Ion (Li-ion) battery types should be selected as the best candidate.

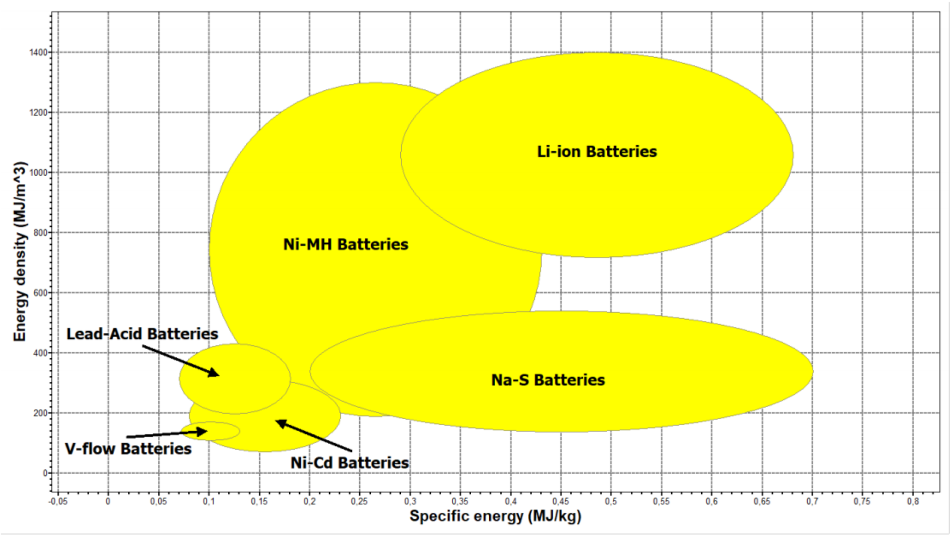


Figure 2.3: Rechargeable battery types in terms of energy density and specific energy [CES EduPack, 2019]

However, other characteristics need to be analyzed as they can counteract these excellent energy properties of Li-ion battery. These characteristics are summarized in Table 2.1 and they are: 1) Operating costs which relate the expenses for one charge-discharge cycle per unit of energy, considering maintenance cost, heating and labour. 2) Cycle life which describes the number of times a battery can be charged and discharged before is discarded, which happens when the capacity deteriorates to 80% of the initial capacity. 3) Cycle efficiency, that is the percentage between output and input energy to the battery. Furthermore, in Figure 2.4 the relation between operating costs and cycle efficiency is indicated. Looking at Table 2.1 and Figure 2.4, Li-ion batteries have no significant disadvantages compared to the other types.Their high cycle efficiency range (80 to 95%) indicates minimizing losses and being even more beneficial than the other types.

Table 2.1: Rechargeable battery properties summary [CES EduPack, 2019]

	Energy density $[MJ/m^3]$	**Specific energy** $[MJ/kg]$	**Operating cost** $[EUR/(MJ \cdot cycle)]$	**Cycle life**	**Cycle efficiency**
Lead-Acid	200 - 430	0.07 - 0.18	0.0007 - 0.0024	200 - 1500	0.70 - 0.90
Ni-Cd	72 - 310	0.08 - 0.23	0.0007 - 0.0047	800 - 1200	0.60 - 0.85
Na-S	140 - 540	0.20 - 0.70	0.0032 - 0.0033	3600 - 4700	0.75 - 0.83
V-flow	110 - 170	0.07 - 0.13	0.0032 - 0.0033	10000 - 16000	0.71 - 0.88
Ni-MH	190 - 1300	0.10 - 0.43	0.0004 - 0.0024	300 - 1000	0.65 - 0.85
Li-Ion	720 - 1400	0.29 - 0.68	0.0016 - 0.0040	300 - 2000	0.80 - 0.95

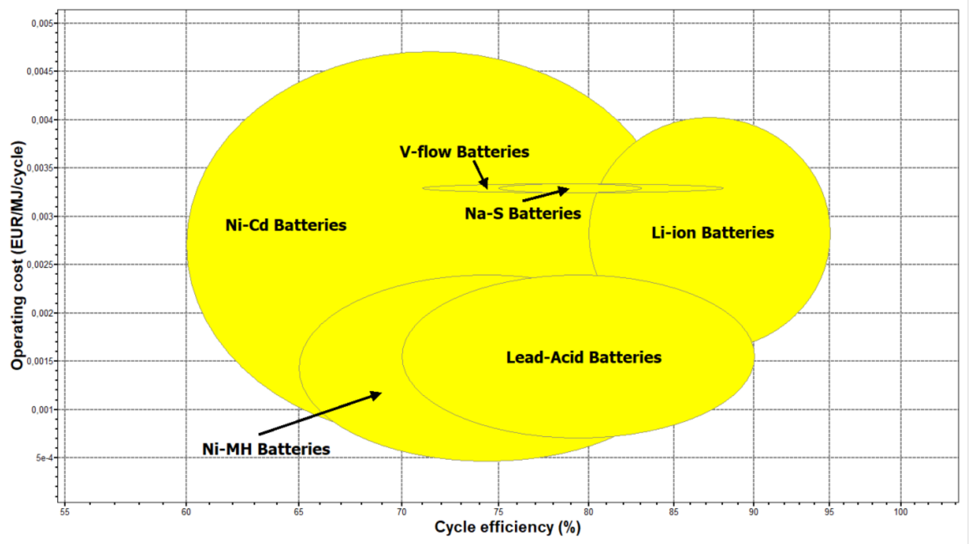


Figure 2.4: Rechargeable battery types in terms of operating cost and cycle efficiency [CES EduPack, 2019]

The use of batteries is not uncommon for automotive applications and, hence, most literature regarding battery technologies for transportation is focused on automotive applications. Electric cars like Toyota Prius, Nissan LEAF, Think city, Smart and Tesla Model S all have Li-ion batteries installed. The research done on making electric cars commercial feasible has put the Li-ion batteries in a leading position both on land and at sea, as in recent years is an attractive option for maritime applications as well. Hybrid ships and all-electric battery ships such as Viking Lady, Viking Queen, Edda Ferd and Ampere have all preferred a Li-ion type of battery due to their technological maturity.

Based on these, it is decided to focus on Li-ion cells in this study and all other battery types will not be considered in the rest of the master thesis.

2.2.2 *Batteries functionalities in hybrid systems*

Batteries can exhibit several functions to support other energy sources in hybrid propulsion architectures, enhancing the system's performance, reducing emissions, and fuel consumption.

Most of the benefits that energy storage systems provide to such architectures have already been discussed in previous sections. Thus, batteries functionalities in a hybrid configuration would be presented below shortly.

Batteries may be used as the primary source of power for propulsion in specific operation modes, like in low speed in ports or in zero-emissions areas, enabling compliance with regulations and shutting down the main engines. That means that batteries can be beneficial for blackout prevention, as an emergency source power for essential and emergency services. Batteries can be used for boosting and peak shaving. When the load demand is higher than the maximum power the main energy source can produce, the battery delivers the additional energy. Load levelling is also possible, allowing generator sets to be operated at a constant load reducing maintenance requirements and costs. Batteries are also better on handling high-frequency load fluctuations than diesel engines or fuel cells, resulting in load smoothing. During larger load steps, a battery has higher responsiveness than an ICE or a fuel cell system and ensures that the propulsion system can follow transient loads, providing 'ramp support'. Figure 2.5 presents some of the different applications of a battery in hybrid systems.

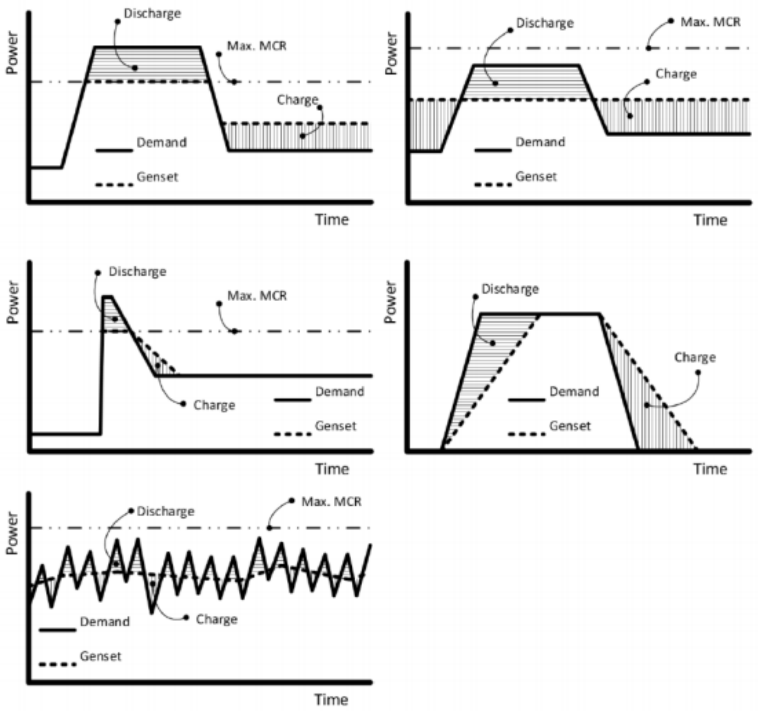


Figure 2.5: Power profiles of different battery functionalities in hybrid systems (from left to right and top to bottom: boosting, load levelling, peak shaving, ramp support and load smoothing) [Boekhout M., 2020]

2.2.3 *Commercially available marine Li-ion batteries*

GEOxyz has contacted several battery manufacturers to identify the ideal battery for the hybrid propulsion system. The information gathered from those manufactures, together with batteries' ratings are shown in Table 2.2.

2.3 Fuel cells

Fuel cells are electrochemical devices that convert the chemical energy of a fuel directly into electrical energy. Although fuel cells are not a new technology, as William Grove developed

Table 2.2: Commercially available marine Li-ion batteries based on information gathered from Geoxyz

Manufacturer	**Energy rating [kWh]**
Corvus Energy	280 140 254 269
EST-Floattech	252 136.5
Super B	148
Lithium Werks	102.4
Hymove	200

in 1842 the first fuel cell, the success and efficiency of ICE limited the commercial application of FC in the maritime environment during the 20th century. In recent years efforts have been applied for the development of fuel cells and their onboard use on ships to protect the environment and comply with the strict regulations.

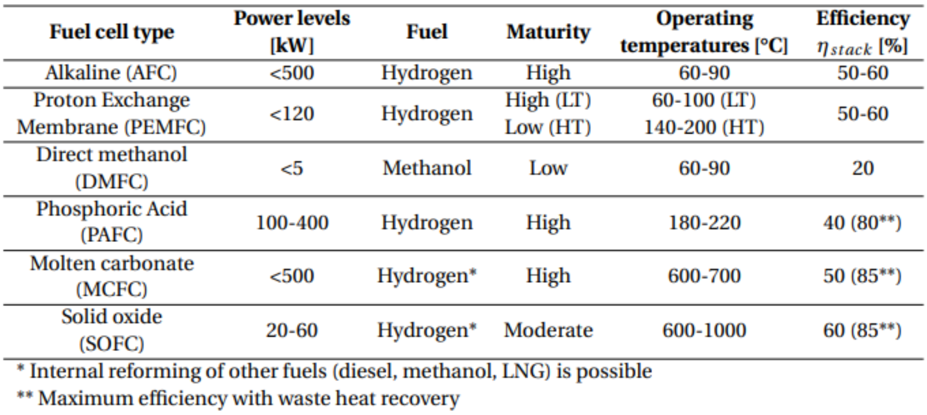
2.3.1 *Types of Fuel Cells*

Different types of fuel cells have been developed since their origin and are available in the market. Fuel cell types are classified and named based on the material of the electrolyte used in the system [Welaya et al., 2011; Markowski and Pielecha, 2019]. DNV GL distinguished seven types [DNV GL, 2017]:

- 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 such as temperature ranges, efficiencies, fuel options, transient loading capabilities, tolerance to impurities, and power levels. Table 2.3 shows some of the main characteristics of the fuel cell types listed above.

Table 2.3: Different characteristics of main types of fuel cells. Adopted from Boekhout M. [2020]



Fuel cell type	Power levels [kW]	Fuel	Maturity	Operating temperatures [°C]	Efficiency η_{stack} [%]
Alkaline (AFC)	<500	Hydrogen	High	60-90	50-60
Proton Exchange Membrane (PEMFC)	<120	Hydrogen	High (LT) Low (HT)	60-100 (LT) 140-200 (HT)	50-60
Direct methanol (DMFC)	<5	Methanol	Low	60-90	20
Phosphoric Acid (PAFC)	100-400	Hydrogen	High	180-220	40 (80**)
Molten carbonate (MCFC)	<500	Hydrogen*	High	600-700	50 (85**)
Solid oxide (SOFC)	20-60	Hydrogen*	Moderate	600-1000	60 (85**)

* Internal reforming of other fuels (diesel, methanol, LNG) is possible

** Maximum efficiency with waste heat recovery

Fuel cells are divided into low and high-temperature (LT/HT) fuel cells, and the temperature they operate plays a crucial role in their main characteristics. Low-temperature fuel cells are sensitive to impurities and require purification [Van Biert et al., 2016]. A reforming unit needs to be installed if other fuel types instead of pure hydrogen are supplied to low-temperature fuel cells. However, this reforming unit is not necessary in the same scenario for high-temperature fuel cells as their high temperature is sufficient for the reforming processes to occur automatically and internally. Fuel cells and especially high-temperature fuel cells suffer from material degradation during extended operations, which results in the reduction of the system's efficiency over time and thus increased fuel consumption.

DNV-GL has analysed the different types of fuel cells and selected the three most promising one. It is concluded that LT-PEMFC's, HT-PEMFC's and SOFC's are the most promising fuel cell technologies for marine applications [DNV GL, 2017]. More studies have a general agreement that these three types have the highest potential, though LT-PEM fuel cells have higher feasibility in the short-term [Van Biert et al., 2016; Corbo et al., 2009; Leo et al., 2010; Stambouli and Traversa, 2002; Taner, 2015; Van Nguyen and Knobbe, 2003; Welaya et al., 2011].

For these reasons, LT-PEM is the only type of fuel cell that was selected to be used in this project. Their high degree of maturity, fast start-up time and favourable power-to-weight ratio are very beneficial for maritime applications.

2.3.2 Advantages and challenges of fuel cells

Fuel cells offer better fuel efficiency than internal combustion engines, as the chemical energy is converted directly to electrical energy without going through thermal and mechanical conversion. For most fuel cell types, the stack efficiency ranges between 50% and 60%. It remains mostly the same across their operating power range in contrast with ICE and gas turbines, making them suitable for part load applications. FC cause lower air emissions as there is no combustion process and this gives low CO_2 and NOx emissions and approximately zero SOx emissions. In case pure hydrogen is used, only water and heat is released made them an emission-free power supply. In HT fuel cell or PAFC where a lot of waste heat is contained in the emission, the waste heat can be recovered and used to drive a stream turbine to create electricity. In that way, the overall system efficiency can be increased to $80-85\%$. In addition, fuel cells do not have moving parts, resulting in noise reduction and less maintenance and operation costs as they are simple to operate. Another advantage of fuel cell is their fuel flexibility. Most fuel cells effectively run on hydrogen, but FC's can also operate on hydrogen-containing logistic fuels like diesel, LNG and methanol.

On the contrary, fuel cells systems have the drawback of high initial investment costs. Hope-

Table 2.4: Commercially available PEM fuel cells based on information gathered from GEOxyz and literature

Manufacturer	Power rating [kW]
Nedstack	500 100
ZEPP Solutions	200 195 97
Proton engine	260 130 75
Ballard Power	200 100
Cummins	240 120
PowerCellution	200

fully, the recent developments and mass production and the growing of hydrogen infrastructure will solve this problem. Fuel cells have also a limited lifetime, and a periodic system replacement is required [Fletcher et al., 2016]. What is more, the time-delayed response of fuel cells requires energy storage systems (ESS) to work together with them, providing additional power during peak demands and absorb excess energy during low power demand [Garcia et al., 2009]. In case pure hydrogen is not available and other fuel types are used, a separate reforming unit is needed for LT-FC's which can affect and decrease the system's efficiency significantly ($\sim$ 15%) [U.S. Department of Energy, 2020]. A complex water management system is another challenge to low-temperature fuel cells as pure hydrogen is present in both liquid and gas phases [DNV GL, 2017; Van Biert et al., 2016].

2.3.3 *Commercially available PEM fuel cells*

GEOxyz has contacted several fuel cell manufacturers to identify the ideal fuel cell system for the hybrid CTV. The information gathered are shown in Table 2.4.

2.4 Hydrogen

LT-PEM fuel cells were selected to be considered further in this project as mentioned in the end of Section 2.3.1 and they run effectively on pure hydrogen. A fuel cell is the most efficient method to extract energy from hydrogen. Hydrogen opens up a way to full decarbonisation of the transport sector. Alternative fuels like hydrogen reduce the dependence on fossil fuels that are now the main source of energy. With the renewable energy market growing steadily towards the future, it can be expected that hydrogen reaches a competitive level with fossil fuels between 2025 and 2030 [Bloomberg, 2019; McKinlay et al., 2020].

2.4.1 *Production*

Although hydrogen is the most abundant element in the universe, it is locked up in compounds like fossil fuels, gasses and water and it requires a lot of energy to liberate those molecules so that is available to us in its purest form. Hydrogen can classify as black/brown, grey, blue and green based on the emission levels, feedstock and production technology.

Black/brown hydrogen, produced from coal gasification. For the production of grey hydrogen currently natural gas is the primary source being used and the natural gas is converted in steam methane reformers (SMR) into carbon dioxide and hydrogen. Autothermal reforming (ATR) is other method to produced grey hydrogen from natural gas but less commercially advanced than SMR. As of today almost all the hydrogen produced worldwide is produces exclusively using fossil fuels without CCS. Blue hydrogen would be produced if in any of the aforementioned production technologies, Carbon Capture Storage (CCS) is added, and blue hydrogen currently accounts for 1% of all hydrogen production. If hydrogen is produced from renewable resources like wind and solar power, it is called green hydrogen and during this production process no GHGs are emitted. Green hydrogen can be produces from water electrolysis were an electrolyzer uses electricity to split water into hydrogen and oxygen. Only green hydrogen produced by renewable energy will be used further in the analysis of this study. Black, grey and blue are not CO_2-neutral and would be considered out of scope for this thesis.

2.4.2 *Storage*

Storage of hydrogen is a point of attention. Hydrogen has the highest gravimetric density (amount of energy per mass) of any fuel [Arabul et al., 2015]. Its density though in ambient conditions (20 °C and 1 bar) is very low compare to other compounds and which results to a very low volumetric density (the amount of energy per volume) too. This causes challenges to store it in a more compact form and be applicable for use in the transportation sector. Vessels or vehicles have limited volume, and hydrogen must be processed before it can be transported efficiently. There are four different methods that have the potential for higher energy density when storing hydrogen. For this research a choice has been made that green hydrogen would be utilised, stored in liquid form, and the other methods of storing hydrogen would be left out of scope after described shortly below.

Liquefaction

By liquefying hydrogen, the volume of the fuel decreases significantly. The hydrogen is liquefied by cooling to a temperature of -253 °C, its freezing point and second lowest of all elements. Liquid hydrogen (LH_2) is classified as a cryogenic liquid as temperatures below 200 K (-73°C) are known as cryogenic temperatures. After liquefaction in ambient pressure, hydrogen's volume density is 848 times higher than hydrogen in ambient temperature. However, a large amount of energy is required to stored and liquefy hydrogen at such low temperatures.

Compression

Hydrogen is compressed typically between 350 and 700 bars. Composite pressure vessels (COPV) with capacities between those pressures' values have been developed and commercially available [Barthélémy et al., 2017]. The volumetric density of hydrogen compressed to 700 bar increase 440 times compared to hydrogen at atmospheric pressure. By either compressing or liquefying hydrogen, the fuel volume decreases significantly, but the volume is still notably higher compared to currently used fossil fuels. Large and heavy tanks are required to contain the hydrogen which is a clear drawback considering the space and weight restrictions for vessels and vehicles. Furthermore, safety risks are presented.

Cry-compression

Cry-compression is the technique of combining cooling and pressure. It is challenging and energy-intensive to liquefy hydrogen and keep it that state due to its low boiling point. At 13 bar pressure, the boiling point of LH_2 can increase to -240 °C. However, additional pressure above this point does not have any effect on the H_2 boiling point. Hydrogen is much denser in a liquid state, and when this technology of cryo-compression matures in the future, higher energy densities are expected [Barthélémy et al., 2017; Van Biert et al., 2016].

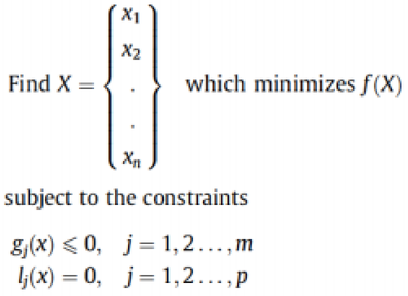
Solidification

Apart from physical-based hydrogen storage methods such as compressed or liquid hydrogen, material-based storage options exist. Hydrogen can also be stored on solids' surfaces (by adsorption) or within solids (by absorption). In this category, a promising hydrogen carrier is Sodium borohydride ($NaBH_4$) in which hydrogen is chemically stored. This technology is still under development but has massive potential for future maritime applications.

2.5 Optimization

In order to find the best solutions to challenging real-world problems that are frequently constrained by specific restrictions, it is common practise to develop mathematical models appropriate for optimization techniques. The problem to be solved is represented by an objective function, which is a function of several decision variables for which the best values must be determined. A solution must satisfy technological and operational constraints, which are expressed through different equations.

A generalized minimization problem definition is shown in Figure 2.6. Where f(X) is the objective function, X is an n-dimensional design vector, with the variables that are subject to optimization. At the same time, $g_j(x)$ and l_j (x) are inequality and equality 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

$$g_j(x) \leqslant 0, \quad j = 1, 2 \ldots, m$$
$$l_j(x) = 0, \quad j = 1, 2 \ldots, p$$

Figure 2.6: General optimization formulation [Eriksson and Gray, 2017]

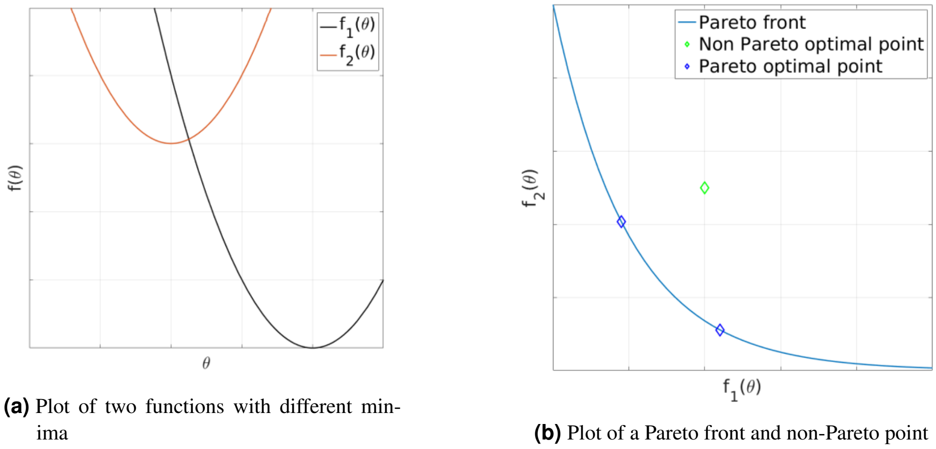
A tool in the form of an optimization model is also suited for ship design-related problems like the one in this thesis.

There are numerous methods for solving mathematical optimization problems as the field of optimization is broad. The problem can be formulated in one of several high-level programming commercial solvers, after which the software will use a suitable generalised optimization technique to solve it. It is common to distinguish between problems based on their linearity or non-linearity, as well as whether they contain only continuous decision variables, integer decision variables, or a combination of the two. The objective function and constraints for linear problems are constructed in a way that prevents the decision variables from being divided or multiplied by one another. On the other hand, in non-linear problems, it is possible to multiply and divide decision variables, but the complexity and implementation effort quickly rise, and the number of solvers that can be used in that situation is limited. [Jaurola et al., 2019]. If appropriate, piecewise linearization can be used to linearize a problem's nonlinear features. Applying artificial intelligence strategies like heuristic optimization methods is an additional choice. While heuristic algorithms often find solutions that are close to the global optimum within a certain error, they do not always find global optimum solutions like linear solutions do [Eriksson and Gray, 2017].

2.5.1 Multi-objective optimization

Most real-world problem searches and optimization problems involves multiple objectives. If more than two objective functions have to be optimized simultaneously, a single solution that optimizes all of the objectives rarely exists. Multi-objective evolutionary algorithms (MOEAs) can solve optimization problems that involve more than one competing or conflicting objective functions. Those algorithms owe their name to the similarity to Darwin's evolution theory as by applying nature's evolutionary principles search for a set of Pareto-optimal solutions. These optimal solutions each perform differently with respect to each of the different objective functions. A Pareto optimal solution is a point in parameter space for which no objective function can be further optimized without compromising the performance of another objective.

A visual example of the need for multi-objective optimization and the typical shape of a Pareto front is shown in Figure 2.7. The example illustrates a situation in which two objective functions cannot both be optimized simultaneously because of the differences in their minima. A 2-D Pareto front can be created, where each point on the front represents the performance of a parameter set that minimizes one of the two functions without sacrificing the other, as an alternative to finding a single optimal solution. A set of non-dominated solutions forming the Pareto front (Figure 2.8) which means that no solution on the front is better than the other and they have the same fitness value based on the multiple objectives involved in the problem.



(a) Plot of two functions with different minima

(b) Plot of a Pareto front and non-Pareto point

Figure 2.7: An illustrative example of a Pareto front of two function with different minima

MOEAs have the unique ability to find multiple optimal solutions in one single run [Mishra et al., 2013], were the poorest solutions (defined as a population) are eliminated. Particle swarm optimization (PSO), ant colony optimization (ACO), and genetic algorithms (GA) were listed as some of the most popular MOEAs in the literature. One of the first of these evolutionary algorithms was the non-dominated sorting genetic algorithm (NSGA), which was proposed by Srinivas and Deb [1994]. The NSGA-II introduction by Deb et al. [2002]

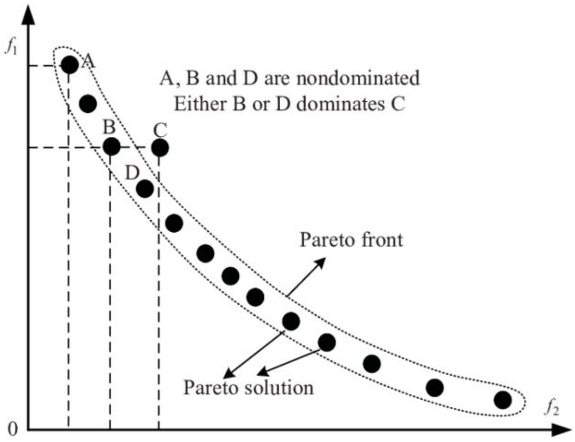


Figure 2.8: Graphical illustration of Pareto optimal solution and Pareto front [Cai et al., 2016]

revolutionised the industry and led to the development of numerous complex MOEAs. The NSGA-II is still the most widely used MOEAs today and has been extensively used to address various optimization problems in a variety of fields and applications. Its source code, which is written in a variety of programming languages, is available online for free and is also integrated into a number of popular computing and simulation tools and environments. NSGA-II will be used in the optimization problem of the current project and MATLAB was used as programming language.

2.5.2 Nested system level optimization architecture

Hybridization of a ship results in a more complicated design and optimization for the propulsion system. It can be formulated as a multi-objective optimization problem that spreads over multiple levels (topology, size and control). Due to the popularity of hybrid propulsion in the automotive industry, the system-level optimization methodologies have been thoroughly researched and applied to electric vehicle applications. Silvas et al. [2016] discusses existent methodologies used for integrating the plant and control optimization, together with the used optimization algorithms in an extensive review. Three optimization architectures are widely used in automotive industry for solving the overall system-level design problem (Figure 2.9). The control design (the inner layer) nested within the plant design is the most popular optimization architecture (the outer layer) and it is adopted in the methodology utilised in this thesis with a double-layer optimisation problem being constructed.

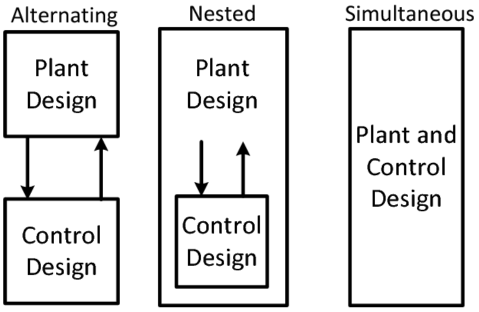


Figure 2.9: Coordination Architectures for System-Level Design in in Hybrid Electric Vehicles [Silvas et al., 2016]

The algorithms used to optimize the two layers are where most double-layer optimizations diverge. While multi-objective genetic algorithms (GAs) like NSGA-II or particle swarm optimization (PSO) are better suited to handle a very large design space (outer layer) [Gao and Mi, 2007; Donateo et al., 2008], exhaustive search is used for the plant design problem at the early stage [Hofman et al., 2008]. Dynamic programming, such as mixed integer linear programming (MILP), offers more promise than the conventional rule-based (RB) algorithm for solving the control design problem in the inner layer [Silvas et al., 2014; Gao and Mi, 2007]. Works that have examined optimization problems associated with ships' hybrid power systems employing automotive design and control knowledge can be found in Valera-García and Atutxa-Lekue [2018]; Zhu et al. [2018]; Trivyza et al. [2018]; Wang et al. [2021]; Huang et al. [2021]; Sciberras et al. [2016]; Van Vu et al. [2017]

3 UNCERTAINTY

One of the goals of this study is to propose a strategy to incorporate uncertainty in the ship design optimization to derive more robust and future-proof guidelines for the installation of a hybrid system on a CTV. Uncertainties are things that are not known, or known only imprecisely, as defined by McManus and Hastings [2006]. Uncertainty in these aspects is typically related to changes in the future operating environment. It's crucial to understand that the future will inevitably be uncertain when developing capital-intensive ocean engineering projects. It is frequently necessary to make design decisions before relevant future information is resolved.

Risk and uncertainty in terms of systems design are closely related. Risk is the objectified uncertainty regarding the possibility of an unfavourable event occurring. Stakeholders are searching for projections that can tell them what the future will look like or methods to lessen uncertainty and thus mitigate risks in order to assist them in making smart decisions.

3.1 Relevant Uncertainties

A good understanding of the involved uncertainties is crucial. In the case of the design of a hybrid propulsion system for a Crew transfer vessel the identified uncertainties are related to the following categories:

- Economic:

  A permanent and major uncertainty is the development of fuel prices. What oil prices will be tomorrow is only a matter of speculation. However, when costs and profits are crucial decision factors for stakeholders, fuel prices may have a significant impact on decision-making. Fuel and electricity prices are characterised by high volatility. This unpredictability of electricity has also an impact on the price of alternative fuels such as green hydrogen that will be used in this study.

- Technology Development:

  Many CO_2 reduction technologies are currently under development. Some of those technologies are in the final stages of development and will soon or have already been made available to stakeholders. Other promising technologies are still in the early stages of development and will require more time to reach the market. It is inevitable that current technologies will advance over time, but it is impossible to predict how quickly. The decarbonization technologies' accessibility and rate of advancement have a significant influence on ship design. Some of the technologies' properties that are directly impacted are investment costs, efficiencies, the rate of degradation-life expectancy, 'specific energy' and 'energy density' that affect installation restrictions like volume and weight. It is good to note here that in this study the technology development of the power systems used will be related only to costs.

- Regulatory:

  Even though there are CO_2 emission targets, it is unclear how they will translate into actual regulations. What are the regulations' restrictions, and when do they take effect? Is a global carbon shipping tax would be adopted? How those involved in the maritime industry need to prepare, what modifications are necessary to comply with the rules, and what would happen to the shipowner if they weren't followed? All of these concerns are a part of the uncertainty surrounding CO_2 emission regulations. Decisions on

Table 3.1: Examples of uncertainties in marine system design [Erikstad and Rehn, 2015]

Field	Example
Economic	Oil price, freight rates, interest rates and suppy/demand
Technology	Energy efficiency improvement and lifetime enhancement
Regulatory	SOx/NOx emissions and ballast water treatment
Physical	Sea ice, sea states, marine icing and extreme temperatures

the various proposals to reduce greenhouse gases, including carbon levies, are due to be taken at future MEPC meetings.

The impact of uncertainty at all stages of ship design, as well as its implications in optimization studies, have been widely investigated in the literature [Hannapel, 2012; Hannapel and Vlahopoulos, 2010; Nikolopoulos and Boulougouris, 2018, 2020; Erikstad and Rehn, 2015; Ebrahimi et al., 2020; Gaspar et al., 2012a,b; Keane et al., 2015; Priftis et al., 2020]. Uncertainty needs to be incorporated into the solution of the ship design optimization problem, as it dramatically influences ship design. Traditional optimization techniques that ignore uncertainty result in over-optimized, unrealistic designs that are not robust. The required error margin that develops during the design process can be minimized if these uncertainties and their impacts are promptly captured [Priftis et al., 2020]. Different types of uncertainty exist, some of which can be actively managed through design and others of which cannot. According to the different ways that uncertainty can be influenced, Lin et al. [2013] divide it into three categories:

- Exogenous uncertainty. Uncertainty that is outside the control of the decision maker and external. This can be for example market rates, fuel prices, or market demand for a ship.
- Endogenous uncertainty. Uncertainty that can be managed actively by decision makers. An example may be the response of the ship to waves or the maximum speed of the vessel, which can be resolved by better computational models.
- Hybrid uncertainty. Uncertainty can be partially influenced by decision making. An example is the chance for ship to win a contract which depends on the ship's capabilities.

The relevant uncertainties addressed in this thesis are mainly exogenous.

It is crucial to concentrate on value robustness when handling uncertainty in the design of ocean engineering systems. According to Ross and Rhodes [2008], this refers to a system's capacity to ”continue delivering stakeholder value in the face of changing contexts and needs”. Value in this context is not always monetary and is instead related to the preferences of the stakeholders. However, for commercial capital-intensive ocean engineering projects, it typically is, referring to costs. This is vital to the strategy for handling uncertainty.

3.2 Uncertainty in multi-objective optimization

In many cases, the information used to solve optimization problems is based on estimations, judgment-based, uncertain data, or unknown information. The uncertainties in the optimization problem's variables are frequently ignored in the literature. Numerous approaches to incorporating uncertainty into project parameters are presented in the literature. First, when a lower and upper bound are known, Monte Carlo simulation with a uniform probability may be used to provide estimates of the parameters. A known probability density function, such as the exponential probability distribution used by Engelhardt-Funke and Kolonko [2004], can sometimes be used to represent the uncertainty in parameters. In practice, usually there are no probability distributions available for the parameters with uncertainty. Shackles model, for instance, could be used when there is no information for a probability density function [Li and Sinha, 2009]. To deal with uncertainty, fuzzy parameter representations are frequently employed [Pai, 2016; Mohagheghi et al., 2015]. Multi-objective optimization can also use fuzzy objectives or fuzzy goals. In order to present the provided solutions with uncertainty, the idea of Pareto optimality appears promising.

However, incorporating uncertainty will affect the computation time of an optimization method. A good representation of reality must be balanced against the length of computation required for optimization. For that reason a straightforward approach is implemented to capture the uncertainties characterise the parameters included in this research's optimization problem. Future trajectories are constructed in this study by varying the assumptions in two different main dimensions. These dimensions were: costs and Renewable Energy Sources (RES) penetration in the power systems. Simulations were executed for future years until 2035, with for the year 2026 two variants (RES penetration have influence and no influence on electricity prices).

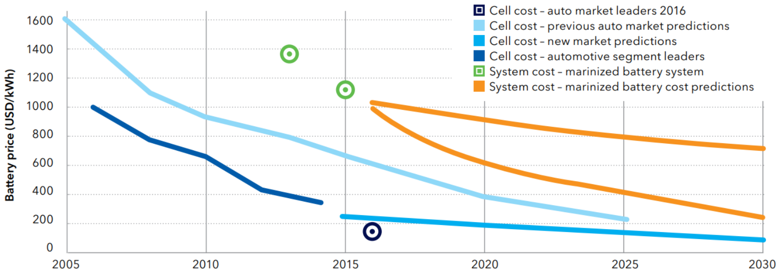
3.3 Forecasts

Making future plans is challenging for decision-makers due to the aforementioned uncertainties. This is the reason why many institutions create their own techniques or models to manage these uncertainties and produce forecasts for their clients (such as shipping firms, shipyards, etc.), who use this information to make investments or other decisions. There are many forecasts; some are made public and some are not. Governmental organisations that focus on national objectives make some forecasts [Offshore Renewable Energy (ORE), 2021], followed by intergovernmental organisations [IRENA, 2020] and commercial institutions, particularly classification societies. Forecasts/ Future projections for prices of fuels and for investment costs of components that were used for the scenario generation in the thesis analysis will be discussed shortly below.

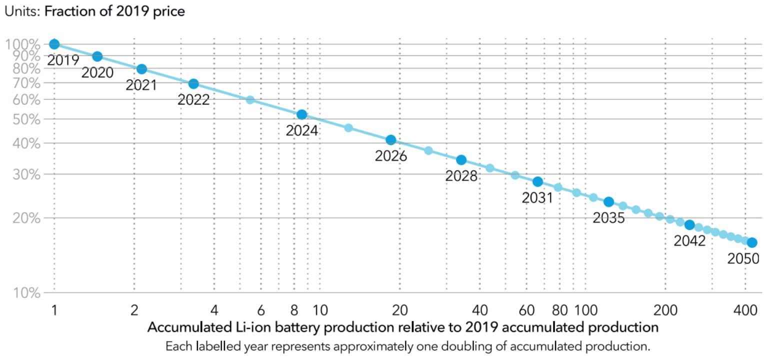
3.3.1 Batteries

Prices for batteries are falling quickly, almost too quickly for accurate characterization,while performance has significantly improved, at least in some market areas. Demand in the automotive and consumer electronics industries is the main driver of these cost reductions. Costs for battery packs for electric vehicles have decreased over the past ten years, falling from 1000 USD/kWh in 2010 to 210 USD/kWh at the end of 2017 [Man Energy Solutions, 2019], but prices continue to vary widely based on performance, technology, and application. For many years, lithium-ion batteries are likely to hold the top spot in technology. If other technologies can compete on price, they might become market-ready and replace lithium-ion technology.

Figure 3.1 indicates trends in battery cell pricing as well as potential trajectories for full maritime systems adopted from two technical reports of Det Norske Veritas - Germanischer Lloyd (DNV GL) [DNV-GL Maritime, 2019; DNV-GL, 2021b]. Fully electric ships are an advancement in power system design, but they are currently only practical for a small number of applications, like ferries and short-sea shipping. Other vessels' ability to operate entirely on electricity is typically constrained by the size or price of the necessary battery system. Naturally, many other applications of battery systems also have the same restrictions. It is urgently necessary to conduct additional research and development to significantly advance this technology.



(a) Battery prices



(b) EV battery cost learning curve

Figure 3.1: DNV-GL potential trajectories for lithium-ion batteries

3.3.2 *PEM Fuel cells*

PEM fuel cells are dramatically cheaper than other fuel cell types. The automotive industry's massive investments over the past 15 to 20 years made this technology dramatically cheaper than other fuel cell types. PEM fuel cells are still too expensive for the automobile market, but their price has come down to a point where they are appealing for ship applications, while they have reached a development capable of handling ship load changes well.

The future adoption of fuel cell technologies, according to DNV, is difficult to predict because of significant market and regulatory uncertainty as well as uncertainty regarding the anticipated decline in investment costs for installing fuel cell systems onboard vessels. The most promising marine applications in the short term are for auxiliary/harbour mode solutions and short-sea shipping, such as ferries (e.g. LT-PEMFC), where ships will benefit from lower local and GHG emissions as well as lower noise and vibration levels. Mass production, which is expected to occur beyond 2022 should allow production costs to reach a competitive level. Figure 3.2 shows the projection of fuel cells cost reduction due to the effect of mass production. It is believed that it will eventually be possible to scale up to hybrid fuel cell configurations for deep-sea shipping from the auxiliary/harbour mode solutions.

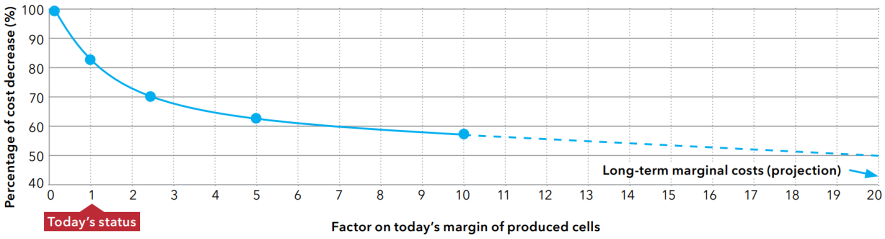


Figure 3.2: Potential scale effects of mass production of fuel cell stack costs [DNV-GL Maritime, 2019] (Today's status refers to 2019)

Table 3.2: Cost-development of renewable hydrogen in Belgium and Netherlands based on PwC projections

Year	Green Hydrogen price [$/kg]
2022	3.50 - 4.00
2023	3.25 - 3.75
2024	3.25 - 3.75
2025	3.00 - 3.50
2026	3.00 - 3.50
2027	2.75 - 3.25
2028	2.75 - 3.00
2029	2.50 - 3.00
2030	2.50 - 2.75
2031	2.50 - 2.75
2032	2.25 - 2.75
2033	2.25 - 2.75
2034	2.25 - 2.50
2035	2.00 - 2.50
2040 - 2050	1.75

3.3.3 Green Hydrogen

Recent analysis of the global market for green hydrogen by PwC [2020] revealed prospective demand growth, cost trajectories by nation, and the most promising export and import markets. The findings offer direction to industry executives and decision-makers regarding the potential future development of the green hydrogen sector. Some key results of their analysis include:

- Through niche applications, the demand for hydrogen will increase gradually and steadily until 2030. Demand will grow more quickly after 2030, especially starting in 2035.
- New alliances to develop hydrogen projects will form through cross-sector cooperation.
- Costs associated with producing hydrogen will drop by about 50% through 2030, after which they will continue to decline steadily until 2050, although at a slightly slower rate.
- In some regions of the Middle East, Africa, Russia, China, the US, and Australia, the cost of producing green hydrogen will be between €1 and €1.5/kg by 2050.
- Production costs will be around €2/kg over the same time period in areas with limited renewable resources, such a large part of Europe, Japan, or Korea, making these markets likely importers of green hydrogen from elsewhere.

3.3.4 Carbon pricing

By putting a price on carbon and/or lowering the cost of zero-emission alternatives, such as through tax breaks, R&D funds, subsidies, or a combination of these, MBMs can support the decarbonization of shipping by bridging the competitiveness gap between fossil fuels and zero-emission fuels. An average carbon price around $191 per tonne of CO_2 is needed to fully decarbonize the shipping industry by 2050, according to the analysis in Getting to Zero Coalition [2021]

The Marshall and Solomon Islands were one of the first nations to propose a carbon shipping tax, calling for a levy of $100 per tonne of carbon dioxide (CO_2) in early 2021. Very recently in May 2022, Japan proposed a global carbon tax that should start in 2025 and charge the shipping industry $56 per tonne of CO_2. The tax, if implemented, is expected to bring in more than $50 billion annually. According to the current proposal put forth by Japan, the tax would rise every five years, reaching $135 per tonne of CO_2 in 2030, $324 per tonne in 2035, and up to $637 per tonne by 2040 [Hellenic Shipping News Worldwide, 2022].

Region-specific strategies have been investigated by other authorities. For instance, the EU has also made an effort to address the carbon issue, by raising its 2030 climate ambition, committing to cutting emissions by at least 55% by 2030 [European Council, 2022]. Starting in 2023 maritime emissions will be included in the bloc's emissions trading scheme (ETS). Regardless of the flag they fly, ships will be required to buy carbon allowances when the measures in the package go into effect to cover all emissions produced during voyages within the EU and half of the emissions produced during international voyages that start or end at an EU port. Companies renting out large vessels will need to buy allowances for 20 percent of their emissions from ships that call at EU ports starting in 2023, and for 100 percent of those emissions starting in 2026. Despite not being a measure to decarbonize global shipping, according to shipping experts, it sends a signal that could stimulate global decarbonization efforts [China Dialogue, 2022]. A significant amount of money will also be raised by including maritime emissions in the ETS, which the EU can use to speed up innovation and build out infrastructure for renewable energy sources and low-carbon fuels.

4 SYSTEM DESCRIPTION

4.1 Ship conventional propulsion system and operational profile

The vessel under study is an offshore support CTV named Geosurveyor XX and is illustrated in Figure 4.1. It is mainly used for the transport of maintenance personnel from the port of Ostend to the wind farms in the North Sea. It has a length of 19.5 meters and 7.5 meters width and can accommodate three crew members and an additional of twelve passengers. The conventional propulsive system that the vessel is currently equipped is shown in Figure 4.2. The diesel fuel, which is kept in tanks, supplies all the energy required. The CTV is powered by two MTU V8 2000M72 main diesel engines, each driving a fixed pitch propeller through a ZF 3000 V gearbox. Each engine delivers a power ouput of 720 kW that results in a speed of 24 knots at full load. The main particulars of Geosurveyor XX are summarised in Table 4.1. The propulsion power is the primary load since it has major power consumption. Thus, the shipbuilder would not change/retrofit the power system for the auxiliary loads. The Capital Expenditures (CAPEX) of the mechanical propulsion system is estimated to be \$432000, with the diesel engines costing $\$300/kW$ based on Stapersma [2002]; Livanos et al. [2014]; Zhu et al. [2018]. It should be noted that in most cases, just the power sources are considered in the CAPEX calculation of the system and that would be the case in the current analysis.

Figure 4.1: GEOSURVEYOR XX

Table 4.1: Main particulars of the Geosurveyor XX [GEOxyz bvba, 2012]

Main particulars Geosurveyor XX	
Hull Type	Aluminium Catamaran
Length x Beam x Draft	19.52 x 7.46 x 1.70 m
Main engines	2x MTU V8 2000M72
Power	2x 720 kW
Maximum speed	24 knots
Accomodation for	12 passenger + 3 crew

The studied crew transfer vessel goes through several different phases during its operation.

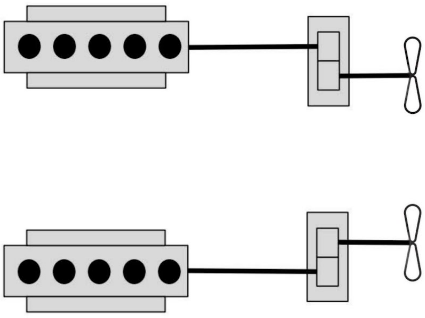
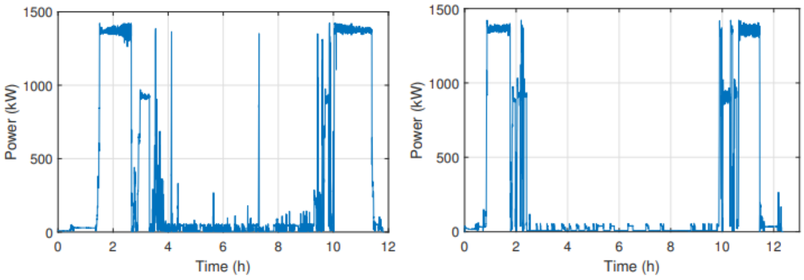


Figure 4.2: Conventional propulsion system of the Crew Transfer Vessel

Typical operational profiles of the vessel's power demand as measured from the main diesel engines on two different operations, are shown in Figure 4.3. The maximum power occurs when the ship travels to and returns from the working region and the vessel's required power is relatively limited at the wind farms. The fuel consumption for one operation is estimated to be 1.050 tons of diesel fuel [Wang et al., 2021]. Without losing generality, the following analysis does not take into account the dynamic properties on the time scale of a few seconds. The measured operational profiles are therefore condensed to the operational profile shown in Figure 4.4.



(a)

(b)

Figure 4.3: Measured operational profiles

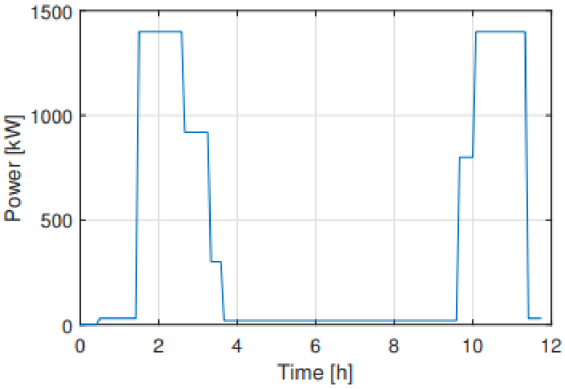


Figure 4.4: Simplified operational profile

4.2 Hybrid propulsion system

It is assumed that a new hybrid CTV would be constructed or the existing CTV would be retrofitted and its propulsion system would transformed to hybrid for reducing emissions and costs. According to the shipbuilder's experience, one powertrain topology with diesel engines, batteries, and fuel cells is initially suggested for the vessel. The scheme of the considered ship power system is shown in Figure 4.5. One set of batteries and energy storage systems, including hydrogen and diesel tanks, are included in the proposed hybrid propulsion system. Two diesel engines, two electric motors/generators, and fuel cells for energy conversion are also included. Depending on the power requirement, the diesel engines and the electric motors can drive the propellers separately or together. Based on the energy management strategy, the motors can be powered either separately or simultaneously by batteries or fuel cells. The motors can also operate as electric generators to take the excess power delivered from the engines to the propellers and convert it to electricity to meet the electrical loads on the vessel's electric network or charge the battery pack. A bi-directional DC/DC converter allows for the charging and discharging of the batteries.

Since Li-ion batteries have higher power/energy density, they are used in this configuration. Moreover, the batteries are supposed to be charged by on-shore electricity. The most thoroughly tested fuel cell technology in a maritime environment is Proton Exchange Membrane Fuel Cell (PEMFC), which is at the most advanced stages of development. Additionally, they can run at low temperatures and have the lowest cost per installed power of the FC options making them suitable for this application. According to Van Biert et al. [2016] Low Temperature PEM fuel cell (LT-PEMFC) system is suitable to provide a power dense solution for ships with mission requirements up to a dozen hours as is the case with the studied vessel. Liquid hydrogen will fuel the PEMFCs that were chosen in this study, taking into account its higher energy density. In addition it was assumed that the liquid hydrogen is produced only by renewable sources such as wind and solar energy (Green hydrogen).

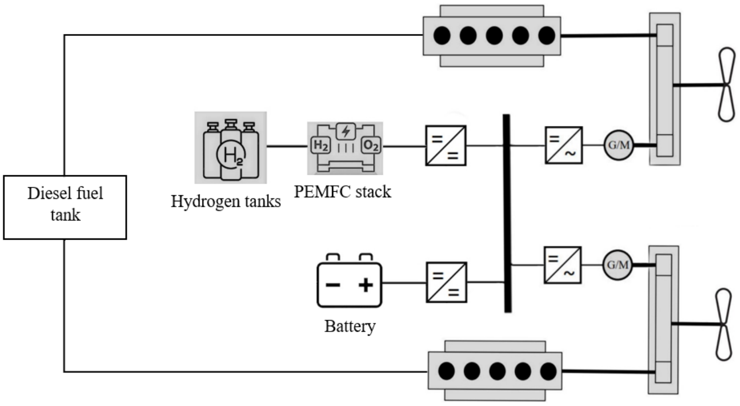


Figure 4.5: Proposed hybrid propulsion system

5 METHODOLOGY

This chapter describes the optimization problem and the multi-objective methodology that is used to solve it and produce optimal solutions. Finally, the steps of the research approach are explained.

5.1 Methodology used

This section provides an overview of the double-layer optimization method along with the description of the objectives and constraints for the optimization problem. Moreover, the evaluation method for analysing the costs of hybrid propulsion system layouts over the remaining life of the CTV will be described.

5.1.1 *Definition of the optimization problem*

Refer to the system-level optimization architecture developed for EV applications, a multi-objective double-layer optimization methodology is presented in Wang et al. [2021], and the same methodology is employed in this thesis work. The whole process is a nested architecture in which the sizing of the plant is coupled with the full optimization of the control design. The control design (the inner layer) is nested within the plant design (the outer layer). The operational profile of the vessel is given as an input together with the quantity, initial suggested power/energy rating and cost of investment per kW/kWh of the components, the purchase price of fuels, and cost of on-shore electricity. Operational restrictions, such as the state-of-charge (SOC) of the battery and the fuel cell operation range, are included to form the constraints of the problem.

5.1.2 *Objectives*

The optimization problem has three objectives to minimize: 1) Capital expenditures (CAPEX), 2) Operating expenditures (OPEX), and 3) weight of diesel fuel consumed (W_{DF}) and are optimized simultaneously. Three objective functions of the outer layer are given by equations 5.1, 5.2 and 5.3. A well-known evolutionary based algorithm NSGA-II is applied for the outer layer of the optimization, where the CAPEX of the hybrid propulsion topology are estimated. The second objective function (OPEX) is related to fuel costs, linearly dependent on the fuel prices (Diesel Fuel C_{DF}, Liquid hydrogen C_{H_2}), the CO_2 price/tax per ton of diesel fuel consumed (C_{CO_2}) and the cost of on-shore electricity for charging the batteries, disregarding from the operational costs, maintenance, depreciation and other non-fuel-related costs. The third objective function which is the amount of consumed diesel fuel will be used as an indication for the emissions impact of the design.

$$OF_1^{GA} = CAPEX(P_{DE}^r, E_{Bat}^r, P_{FC}^r, N_{DE}, N_{Bat}, N_{FC}), \tag{5.1}$$

$$OF_2^{GA} = OPEX(W_{DF}, V_{H_2}, C_{CO_2}) + OPEX_{Bat} \tag{5.2}$$

$$OF_3^{GA} = W_{DF}(P_{DE}, N_{DE}, X_{DE}) \tag{5.3}$$

A CO_2 tax per ton of diesel fuel consumed (C_{CO_2}) is also added as an extra costs in the

Table 5.1: Variables of NSGA-II

		Value	
	Variables	**min**	**max**
Power rating of diesel engines [kW]	P_{DE}^r	0	2000
Energy rating of batteries [kWh]	E_{Bat}^r	0	5000
Power rating of fuel cells [kW]	P_{FC}^r	0	2000

objective function of OPEX in the outer and inner layer (Equation 5.4) with the objective to take emission reduction policies into account.

$$OF^{LP} = OPEX(W_{DF}, V_{H_2}, C_{CO_2}), \tag{5.4}$$

The CAPEX objective is a function of the power/energy rating and quantity of diesel engines, batteries and fuel cells (Table 5.1) and is formulated as:

$$CAPEX = C_{DE}N_{DE}P_{DE}^r + C_{Bat}N_{Bat}E_{Bat}^r + C_{FC}N_{FC}P_{FC}^r \tag{5.5}$$

N_{DE} is the number of diesel engines wich is 2. N_{Bat} and N_{FC} is the number of battery and fuel cell sets which is for both 1. C_{DE}, C_{Bat} and C_{FC} are the coefficients representing the investment costs per kW for DE and FC and per kWh for the batteries.

The OPEX model of the inner layer predicts the consumption of liquid hydrogen and diesel fuel. A mixed integer linear programming (MILP) algorithm is used in the inner layer of optimization to schedule the start/stop number, the running time, and the associated power of the components, or, to put it another way, to optimize the energy management strategy. MILP has a single objective which is to minimize the OPEX. The OPEX formulation are represented by 5.6 and its variables are integers.

Table 5.2 gives the variables of the inner layer optimization. They are the power and binary variables of each component associated to each time interval. For the binary variable, 1 denotes that the component turns on and 0 denotes that it turns off. The inner layer does not take into account the price of the electricity used for on-shore battery charging. This is due to the fact that the batteries always being discharged to their minimum state of charge (SOC) in order to minimize the amount of diesel and hydrogen fuel consumed by the powertrain.

$$OPEX = \sum_{t=0}^{H}\left(C_{DF}\sum_{i=1}^{N_{DE}} W_{DF}^i(t) + C_{H_2}\sum_{k=1}^{N_{FC}} V_{H_2}^k(t) + C_{CO_2}\sum_{i=1}^{N_{DE}} W_{DF}^i(t)\right), \tag{5.6}$$

where,

$$W_{DF}^i(t) = f_{DF}(P_{DE}^i(t))\Delta t \cdot X_{DE}(t), \tag{5.7}$$

$$V_{H_2}^k(t) = f_{FC}(P_{FC}^k(t))\Delta t \cdot K_{E-m}K_{m-V} \cdot X_{FC}(t) \tag{5.8}$$

$f_{DF}(P_{DE}^i(t))$ is a function of the fuel consumption rate with respect to the instantaneous power of the diesel engines and $f_{FC}(P_{FC}^k(t))$ is a function relating the output power to the total power generated by fuel cells. V_{H_2} is the volume of the consumed H_2. K_{E-m} and K_{m-V} are conversion coefficients $0.03kg/kWh$ and $24.8L/kg$ respectively, relating the power generated to the consumed hydrogen [Wang et al., 2021; Baldi et al., 2022]. Someone can refer to Wang et al. [2021] for a more detail explanation of the methodology in general and on how to arrive to the analytical representation of f_{DF} and f_{FC} using piecewise linear approximation in order to included them in the linear programming algorithm .

Table 5.2: Variables of MILP

	Variables
Diesel engines power	P^i_{DE}
Batteries power	P^j_{Bat}
Fuel cells power	P^k_{FC}
Diesel engines binary variable	X^i_{DE}
Batteries binary variable	X^j_{Bat}
Batteries binary variable	X^k_{FC}

5.1.3 Constraints

Following the formulation of the outer and inner layer functions the constrains of the optimization problem are as follow.

$$0 \leq P^i_{DE}(t) \leq P^r_{DE}, \tag{5.9}$$

which means that no diesel engine should produce more power than it is rated for. Similarly, the power constraint for the batteries is:

$$P^{r,c}_{Bat} \leq P^j_{Bat}(t) \leq P^{r,dc}_{Bat}, \tag{5.10}$$

where $P^j_{Bat}(t)$ can be either positive in discharging mode or negative in charging mode. This eliminates the need for additional binary variables to be used to stop a specific set of batteries from being charged and discharged at the same time [Banaei et al., 2020].
Additionally, it is crucial to prolong the battery life by maintaining the SOC within a reasonable range with the used of following constraint as:

$$SOC_{min} \leq SOC^j(t) \leq SOC_{max}, \tag{5.11}$$

where,

$$SOC^j(t) = SOC^j(t-1) - \frac{P^j_{Bat}(t) \cdot X^j_{Bat}(t)\Delta t}{E^r_{Bat}} \tag{5.12}$$

SOC_{min} is 0.2 and SOC_{max} is 0.8 in this case study.
The fuel cell system is predicted to function in practise at between 10% and 90% of its rated output power [Banaei et al., 2020]. As a result, the fuel cells are subject to the following limitation.

$$0.1P^r_{FC} \leq P^k_{FC}(t) \leq 0.9P^r_{FC} \tag{5.13}$$

Finally, the total power demand/consumption of the propulsion system during its operation should balance with the total power generated by the components of the configuration.

$$P_L(t) = \sum_{i=1}^{N_{DE}} P^i_{DE}(t)X^i_{DE}(t) + \sum_{j=1}^{N_{Bat}} P^j_{Bat}(t)X^j_{Bat}(t) + \sum_{k=1}^{N_{FC}} P^k_{FC}(t)X^k_{FC}(t) \tag{5.14}$$

$P_L(t)$ is the total power demand based on the measured operational profile of the main engines of the conventional configuration (Figure 4.3).
For this multi-objective problem, the non-dominated sorting genetic algorithm II (NSGA-II)

is used to find Pareto optimal solutions. The CAPEX and OPEX models produce and assess the first population of N propulsion designs while taking the energy management strategy into consideration. The optimization objectives are applied to all N propulsion designs, and the best (fittest) ones from the previous generation are used to create a new generation of N propulsion designs. The population size N and the generations are chosen as 100 and 50 for this study, respectively.

Economic evaluation-Total cost of ownership (TCO)

The Total cost of ownership (TCO) approach would be used to asses the investment and operation costs of the optimal hybrid propulsion designs under the different scenarios. This method has also been applied in other studies to evaluate the costs of different power plant solutions and fuels to reduce carbon emissions [Baldi et al., 2019; Mestemaker et al., 2019]. A mathematical formulation of the TCO is given below.

$$TCO = CAPEX + C_{OP} \cdot OPEX \cdot Y \tag{5.15}$$

In 5.15, C_{OP} is the number of days per year that the vessel operates. C_{OP} is assumed 300 days in this study. Additionally, Y is the estimated lifespan of the vessel in years once it has been modified with a new propulsion system, which is presumed 15 years.

5.1.4 Steps of the research approach

The diagram 5.1 illustrates the steps taken in this study's research approach.

The steps are described below as follows:

- Step 1: A literature review was carried out. Many different scientific and industrial publications were gathered. Some of the findings are discussed in Chapter 2, where the background of the research was discussed, and in Chapter 3, where the relevant uncertainties of the study's optimization problem are introduced.
- Step 2: Using the data gathered, different scenarios trajectories were constructed by varying the uncertain parameters characterise the optimization problem. The generated scenarios would be determined in Chapter 6.
- Step 3: The optimization algorithm was run multiple times with different parameters using the multi-objective optimization methodology described in Chapter 5 and returned system designs on Pareto fronts that are optimal representatives for the created potential futures. Given that the algorithm's population size was set to 100, each run's Pareto fronts would contain 100 optimal solutions.
- Step 4: Two evaluation methods were used to find one optimal hybrid system configuration per year (per run) from the produced Pareto fronts. The KPIs discussed in Section 1.6.1 are directly related to these evaluation methods. First, the Total Cost of Ownership was used to filter the optimal solutions and identify the one layout with the lowest costs, defined as the most cost-effective in each year of the constructed scenarios. The hybrid optimal layouts with 50% and 75% less emissions compared to the ship's traditional mechanical propulsion system were also discovered using the second evaluation method.
- Step 5: The TCO of the optimal propulsion configurations from both evaluation methods was calculated and a comparative study and analysis of the optimized system layouts was carried out (Chapter 6).
- Step 6: From the analysis the ship owner can determine whether and when to invest in new propulsion system. Furthermore, based on the most likely scenario (and commercial available components) initial design guidelines are given to the ship owner.

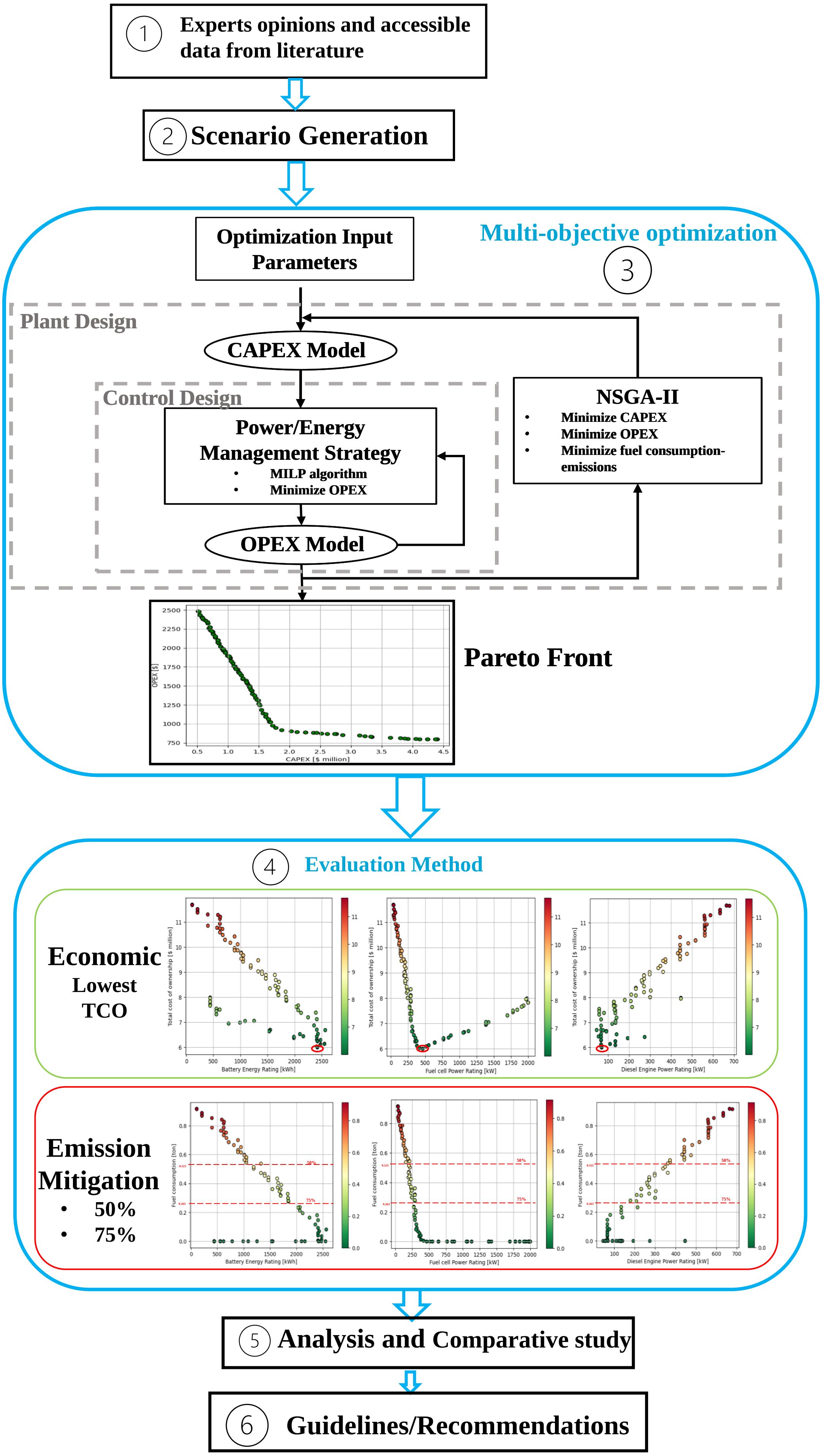


Figure 5.1: Illustration of the Research Approach

6 SIMULATIONS

The produced optimal designs from the multi-objective double-layer optimization methodology will vary with different costs of investment, different fuel and electricity prices and the introduction of new regulations such as a carbon tax. All those parameters are also required inputs of the optimization problem. Reports provided by experts like DNV-GL Maritime [2019], PwC [2020], BloombergNEF [2019], Man Energy Solutions [2019] were used in order to get different projections and information about these uncertain parameters of the optimization problem. As a consequence of this method the optimisation can be run multiple times with different parameters and return designs that are optimal representatives for all possible situations (possible futures). The different scenarios would be determined and investigated in the next sections.

6.1 Scenario Generation

Stakeholders are searching for projections that can tell them what the future will look like or methods to lessen uncertainty in order to assist them in making smart decisions. For this study the investment price per kW for diesel engines is assumed to be constant through the years due to the technological maturity of diesel engines [Stapersma, 2002; Livanos et al., 2014; Trivyza et al., 2018; Zhu et al., 2018]. In addition, price projections for marine fuel cells and lithium-ion batteries can be found in Figures 6.1 and 6.2 [DNV-GL Maritime, 2019; DNV-GL, 2021b]. Due to mass production and consumer demand, battery prices are falling significantly. The total cost of the battery system, which includes the cost of system integration, module fabrication, battery control hardware and software, power electronics, thermal management, and testing, is anticipated to be 600$\$/kWh$ in 2020 [DNV-GL Maritime, 2019]. It is 90% of the cost in 2019. Prices between 2022 and 2035 are expected to be 70%, 60%, 52%, 47%, 42%, 38%, 34%, 32%, 29%, 28%, 27%, 26%, 25%, 24%, respectively of its price in 2019 [DNV-GL Maritime, 2019].

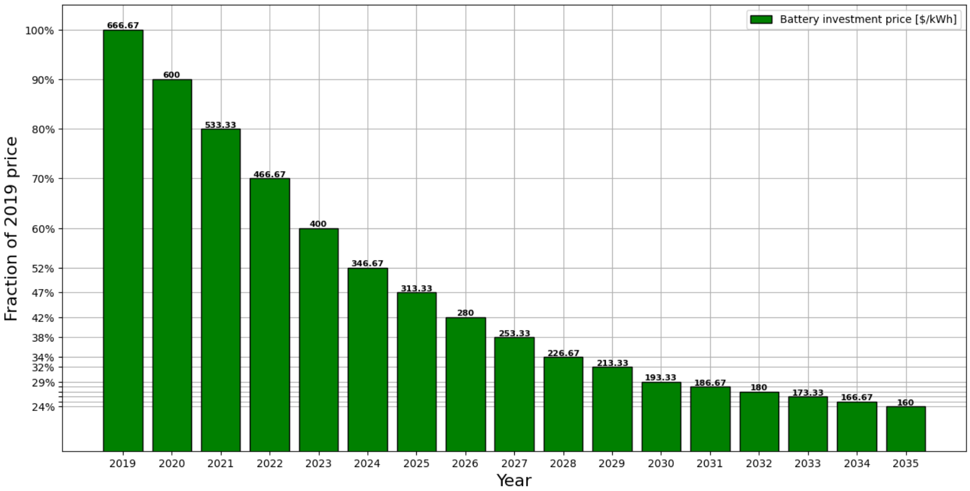


Figure 6.1: Cost development of lithium-ion batteries [$\$/kWh$] for both future trajectories

The prices for PEMFC are following projections adopted from DNV-GL as well. Adopting from Battelle Memorial Institute [2017] and TNO [2020], a total price of 2000$\$/kW$ is considered for the fuel cell system, which is 65% of 2018 price. The prices between 2023 and 2035 are anticipated to be 63%, 61%, 60%, 58.5%, 58%, 57%, 56%, 55.5%, 54.5%, 54%, 53%, 52.5%, 52% of 2018 price.

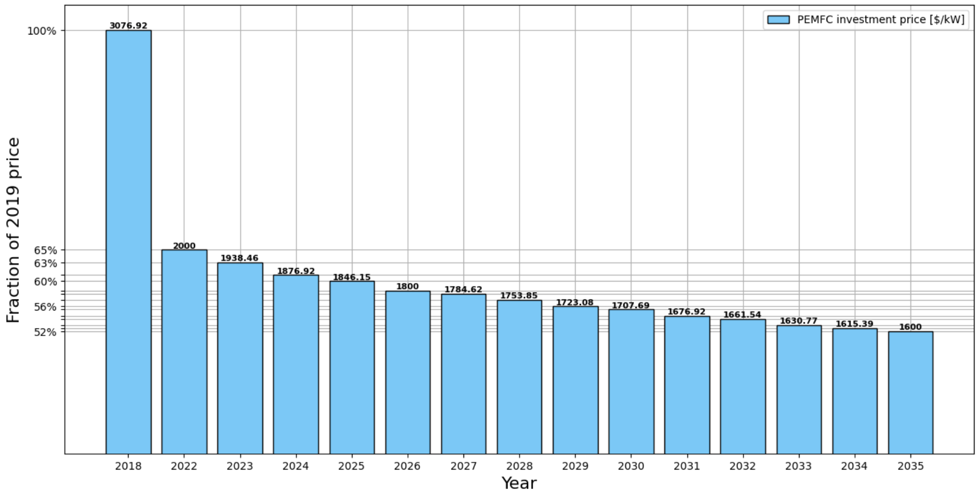


Figure 6.2: Cost development of PEMFC [$\$/kW$] for both future trajectories

According to the average of recent prices in The Netherlands, the diesel fuel price is set at $2.20 per litre, and the prices for 2023 and 2024 are modified according to Trading Economics [2022]. Due to the unpredictability of fuel prices, a constant increase of 5% has been assumed for the ensuing years as shown in Figure 6.3.

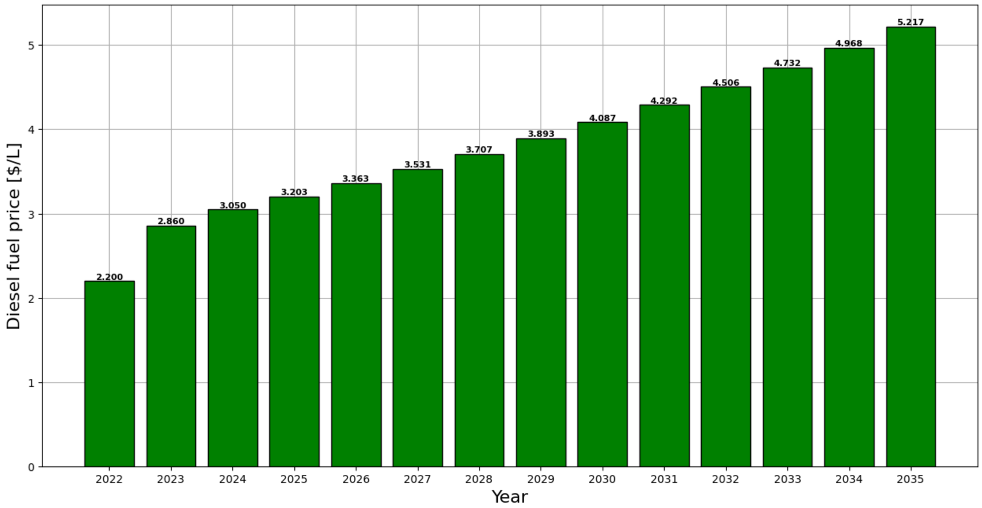


Figure 6.3: Price development of Diesel fuel [$\$/L$] for both future trajectories

Standards for a carbon tax on shipping emissions are escalating. The Marshall and Solomon Islands are one of the first nations to propose a landmark carbon shipping tax, calling for a levy of $100 per ton of CO_2 in early 2021 [Metzger, 2022]. A carbon price is added to the study after 2025 according to these costs. The carbon tax is consequently 300 per ton of diesel fuel, assuming a 3 ton CO2-eq (GWP-20 well to wake) per ton of diesel fuel. In addition, an increase of $90 per ton of diesel per year is assumed (Figure 6.4).

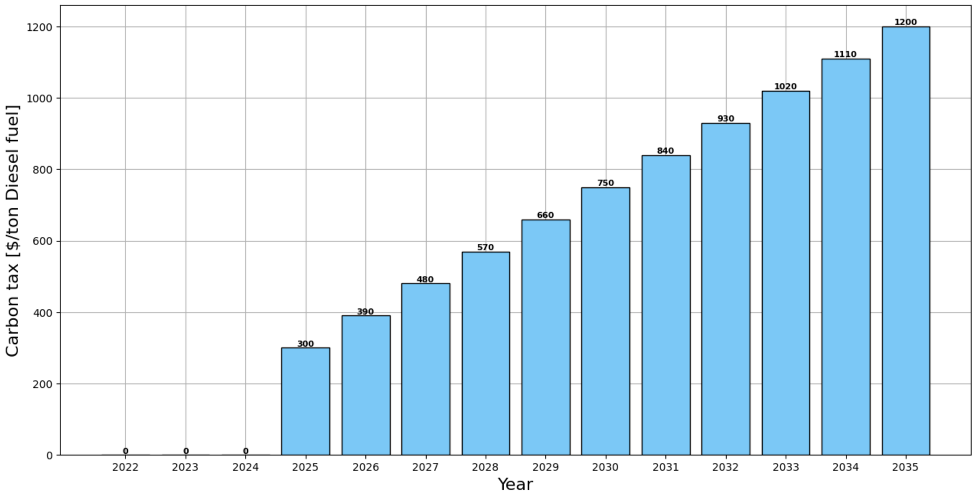
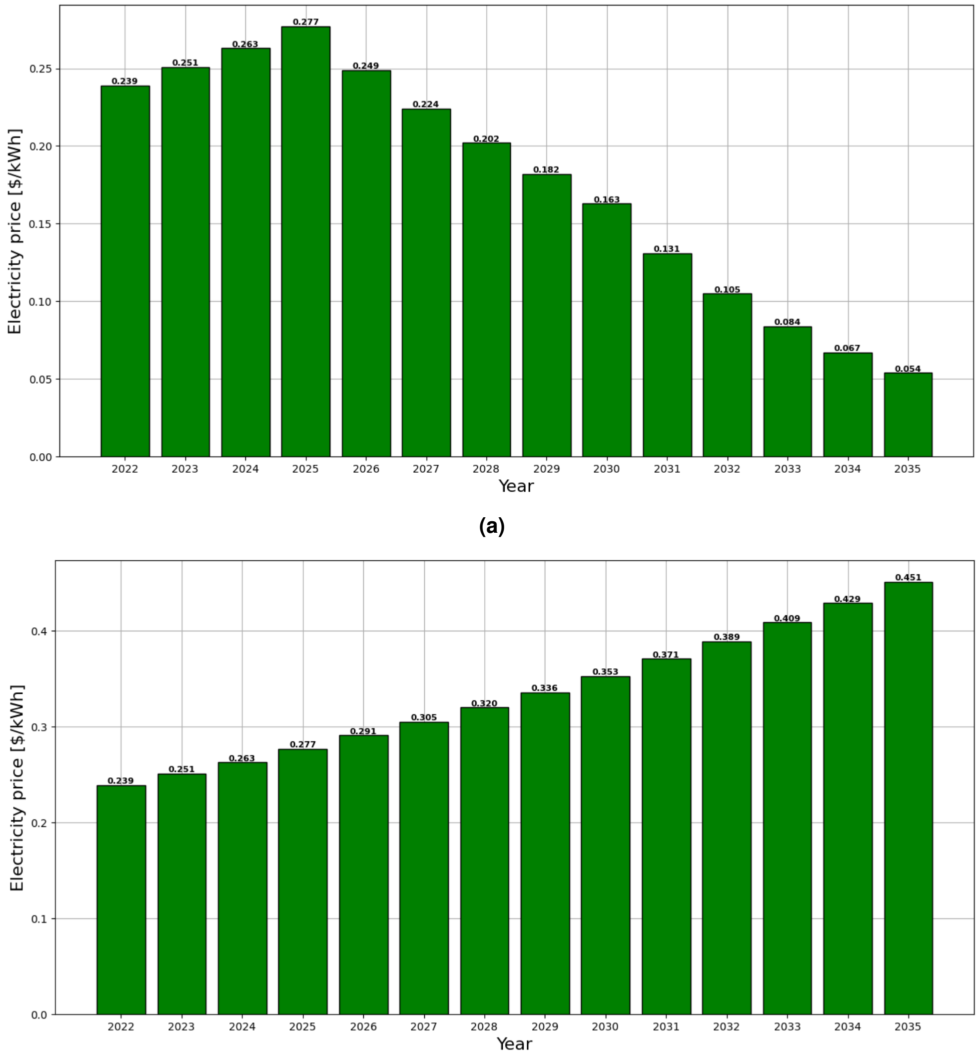


Figure 6.4: Carbon tax [$ per ton of diesel fuel] for both future trajectories

Using two alternative estimates for onshore electricity costs, two possible future trajectories are generated (Figure 6.5). The assumption of the penetration of renewable energy sources (RES) in the energy generation supply is what makes the electricity prices differ. Increased use of renewable energy sources in power systems will result in more hours of cheaper electricity. In the first future scenario, from 2026 onward, it is presumed that the penetration of renewable energy sources is sufficient to lower electricity prices. Between 2026 and 2030, a 10% decline each year is predicted, followed by a 20% decline per year between 2031 and 2035. Prior to the penetration of RES in 2026, it is estimated that the energy price rises by 5% per year, establishing the price of electricity for 2022 by recent prices for business in The Netherlands. The assumption used to create the second future path is that the penetration of RES in the power systems is insufficient to significantly impact the distribution of electricity prices. As a result, a constant increase of 5% per year for the whole future path is implemented.

As mentioned in Section 4.2 liquid hydrogen produced only by renewable sources would be considered in this study. As a result, the electricity price has a direct impact on the hydrogen price. In the first scenario, the price of electricity rises steadily until 2025 and then drops. The price of hydrogen follows the same trends. The price for 2022 was determined by adopting the average production cost price per litre of green hydrogen in the Netherlands as of today from CFA Society Netherlands [2022] which is $\$0.202/L$ (or $\$5/kg$). The price of hydrogen will rise until 2025 and then is decreasing until 2035 based on PwC study for the Netherlands' cost-development of renewable hydrogen [PwC, 2020] (Figure 6.6a). The second scenario assumes that the hydrogen price will continue to rise over the course of the future by $\$0.5/kg$ per year to be consisted with the presumed rise of electricity prices (Figure 6.6b).

The input parameters for the two pricing scenarios represent plausible futures paths, as well as the variance in the parameters determining electricity and hydrogen price development, are shown in Tables 6.1 and 6.2.



(a)

(b)

Figure 6.5: (a) Electricity price development for the First Scenario (b) Electricity price development for the Second Scenario

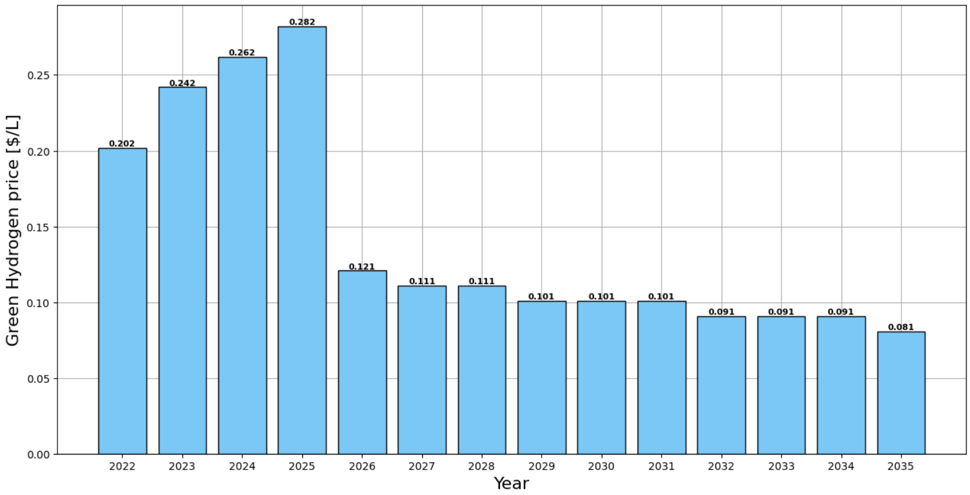
Table 6.1: The optimization problem's input parameters in the first scenario

	2022	2023	2024	2025 [a]	2026 [b]	2027	2028	Source
Diesel engine C_{DE} [$/kW]	300	300	300	300	300	300	300	[Stapersma, 2002; Livanos et al., 2014; Zhu et al., 2018]
Batteries C_{Bat} [$/kWh]	466.67	400	346.67	313.33	280	253.33	226.67	[DNV-GL, 2021b]
Fuel cells C_{FC} [$/kW]	2000	1938.46	1876.92	1846.15	1800	1784.62	1753.85	[DNV-GL Maritime, 2019]
Diesel Fuel price C_{DF} [$/L]	2.2	2.86	3.05	3.20	3.36	3.53	3.71	[Trading Economics, 2022]+Assumed based on accessible data
Hydrogen price C_{DF} [$/L]	0.202	0.242	0.262	0.282	0.121	0.111	0.111	[PwC, 2020]
Onshore Electricity price C_e [$/kWh]	0.239	0.251	0.263	0.277	0.249	0.224	0.202	Assumed based on accessible data
CO_2 price C_{CO_2} [$/$ton_{DF}$]	0	0	0	300	390	480	570	Assumed based on available data

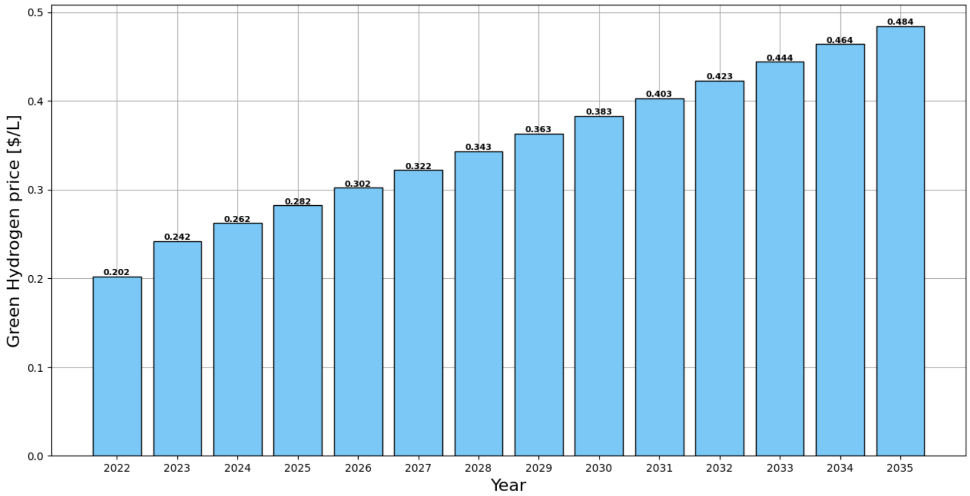
	2029	2030	2031	2032	2033	2034	2035	Source
Diesel engine C_{DE} [$/kW]	300	300	300	300	300	300	300	[Stapersma, 2002; Livanos et al., 2014; Zhu et al., 2018]
Batteries C_{Bat} [$/kWh]	213.33	193.33	186.67	180	173.33	166.67	160	[DNV-GL, 2021b]
Fuel cells C_{FC} [$/kW]	1723.08	1707.69	1676.92	1661.54	1630.77	1615.39	1600	[DNV-GL Maritime, 2019]
Diesel Fuel price C_{DF} [$/L]	3.89	4.09	4.29	4.51	4.73	4.97	5.22	[Trading Economics, 2022]+Assumed based on accessible data
Hydrogen price C_{DF} [$/L]	0.101	0.101	0.101	0.091	0.091	0.091	0.081	[PwC, 2020]
Onshore Electricity price C_e [$/kWh]	0.182	0.163	0.131	0.105	0.084	0.067	0.054	Assumed based on accessible data
CO_2 price C_{CO_2} [$/$ton_{DF}$]	660	750	840	930	1020	1110	1200	Assumed based on available data

---

[a] Carbon tax implementation
[b] Implementing RES penetration



(a)



(b)

Figure 6.6: (a) Green hydrogen price development for the First Scenario [PwC, 2020] (b) Green hydrogen price development for the Second Scenario

Table 6.2: The optimization problem's input parameters in the second scenario

	2022	2023	2024	2025 [a]	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	Source
Diesel engine C_{DE} [$/kW]	300	300	300	300	300	300	300	300	300	300	300	300	300	300	[Stapersma, 2002; Livanos et al., 2014; Zhu et al., 2018]
Batteries C_{Bat} [$/kWh]	466.67	400	346.67	313.33	280	253.33	226.67	213.33	193.33	186.67	180	173.33	166.67	160	[DNV-GL, 2021b]
Fuel cells C_{FC} [$/kW]	2000	1938.46	1876.92	1846.15	1800	1784.62	1753.85	1723.08	1707.69	1676.92	1661.54	1630.77	1615.39	1600	[DNV-GL Maritime, 2019]
Diesel Fuel price C_{DF} [$/L]	2.20	2.86	3.05	3.20	3.36	3.53	3.71	3.89	4.09	4.29	4.51	4.73	4.97	5.22	[Trading Economics, 2022]+Assumed based on accessible data
Hydrogen price C_{DF} [$/L]	0.202	0.242	0.262	0.282	0.302	0.322	0.343	0.363	0.383	0.403	0.423	0.444	0.464	0.484	[PwC, 2020]
Onshore Electricity price C_e [$/kWh]	0.239	0.251	0.263	0.277	0.291	0.305	0.320	0.336	0.353	0.371	0.389	0.409	0.429	0.451	Assumed based on accessible data
CO_2 price C_{CO_2} [$/ton_{DF}$]	0	0	0	300	390	480	570	660	750	840	930	1020	1110	1200	Assumed based on available data

---

a Carbon tax implementation

6.2 Results

The optimization is executed multiple times with various inputs based on the parameters of the two projected future trajectories. The optimization algorithm returns several optimal hybrid designs on the Pareto front in its last generation, according to the three objectives set. The two evaluation methods (TCO approach and emissions mitigation) are then used to identify the optimum hybrid system structure. It is important to note that, additional input parameter projections up to the year 2050 were required in order to use the Total cost of ownership approach for the analysis of the optimal solutions. The changing prices of the input parameters over time are taken into consideration when calculating the operational costs over the course of the ship's 15-year lifespan. The Appendix contains the additional projections for the period from 2035 to 2050.

6.2.1 First scenario

Optimal power and energy ratings:

The power/energy ratings of the optimal designs for the first future path after applying the TCO approach are given in Figure 6.7. According to the results, the designs with the lowest TCO are not incorporating the diesel engines in the solution. An all-electric system based entirely on batteries and fuel cells results in a long-term cost-effective design for all the solutions in the trajectory.

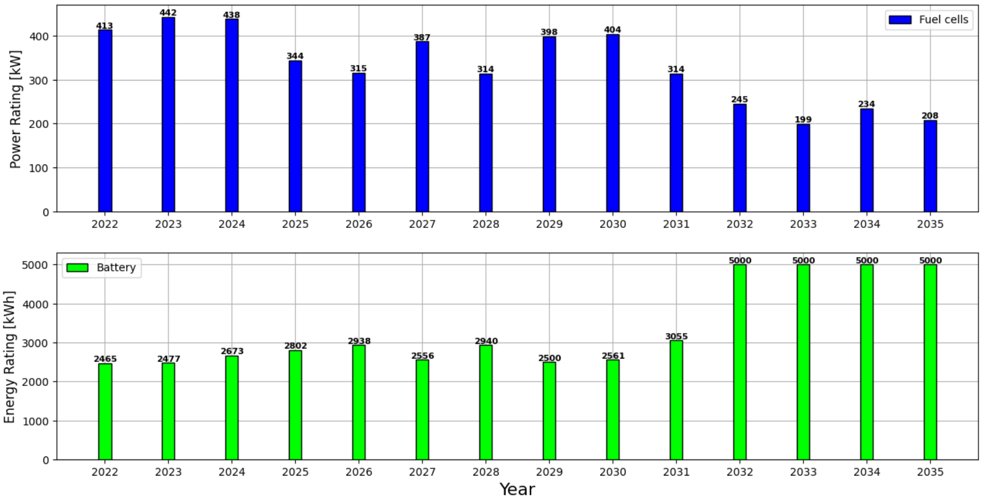


Figure 6.7: Optimal power/energy ratings considering the lowest TCO in the first scenario

The results of the optimal ratings of the components are less subject to changes between 2022 and 2031. It is depicted that the optimal battery rating is within the range of approximately 2460 and 3060 kWh until 2031 and that fuel cells are between 310 and 445 kW. Therefore, choosing a battery and fuel cell rating within these ranges is recommended if retrofitting or building a new CTV is intended to be completed before 2031. After 2032, the size of batteries and fuel cells is impacted by the sharp decline in electricity (Figure 6.5a). The outcomes of the optimization are closer to the maximum value specified for the battery energy rating variable due to the low cost of electricity. The fuel cell optimal power rating values are lower from 2032 to 2035 as the power demand is covered by the larger batteries and if replacement is required due to the batteries and fuel cells deterioration, these rating ranges can be installed as the new batteries and fuel cells.

The scenario was also looked into based on the second evaluation method, the emission mitigation. In this assessment, the design among the Pareto optimal solutions that gives a 50%

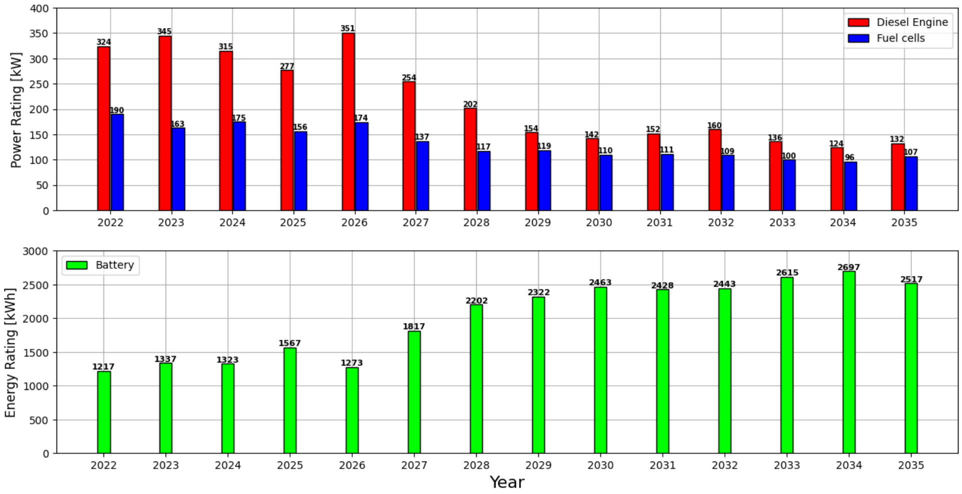


Figure 6.8: Optimal power/energy ratings based on 50% emission reduction in the first scenario

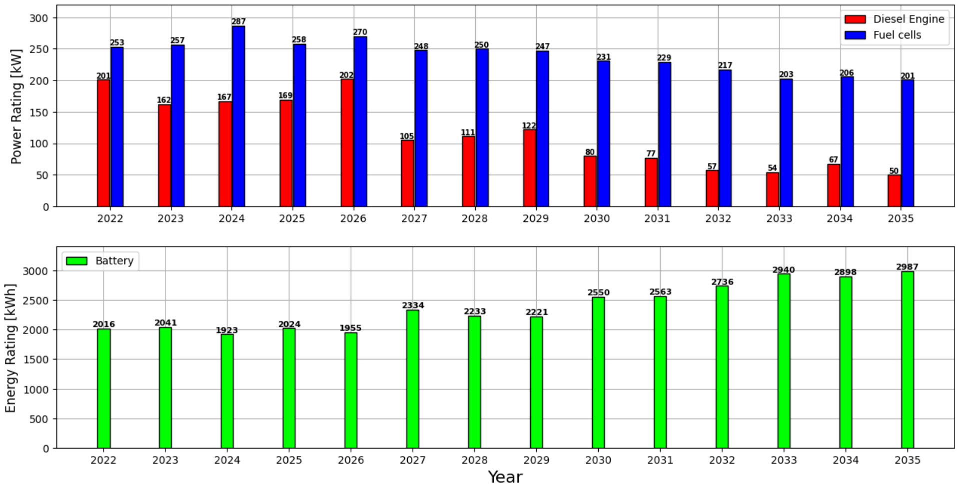


Figure 6.9: Optimal power/energy ratings based on 75% emission reduction in the first scenario

and 75% emission reduction is adopted, as the criterion to find one optimal hybrid system layout per year. The optimal power/energy ratings of this analysis for the first future path are shown in Figure 6.8 for 50% emission reduction and in Figure 6.9 for 75% emission reduction. It can be seen that diesel engines are included in the solution of the optimal hybrid configurations this time for both cases. The sizes of the diesel engines in the 75% emission mitigation case are much smaller, something which is expected and the power demand is cover by larger batteries and fuel cell ratings.

The results are less subject to changes between two periods for the optimal solutions that mitigate the emissions in half, between the years 2022 to 2027 and 2028 to 2035. The optimal ratings for the batteries are within the range approximately 1210 and 1820 kWh between 2022 and 2027, and 2200 and 2700 kWh from 2028 to 2035. For this two periods the fuel cells ratings range between 135 to 190 kW, and 95 to 120 kW and the diesel engines are within the range 250 to 350 kW and 120 to 200 kW each. If the construction or the retrofit is intended to occur before 2027 the optimal size of the components should be according to the solution of the first time period (2022 to 2027) and the size ranges between 2028 and 2035 can be used for a potential replacement of the components.

For mitigating the emissions by 75%, the power and energy ratings of the components are less subject to change until 2029, but after this year, the power demand is met by larger batteries and the power ratings of the fuel cells and the diesel engines are declining annually. This pattern that was met in the solutions for the 50% emission mitigation case too, can be explained again, by the predicted decline in electricity price over the years (Figure 6.5a). If the CTV is to be retrofitted or built before 2029 the battery size should be between 1920 to 2340 kWh, the fuel cells rating between 245 to 290 kW and the diesel engines between 100 to 200 kW. The power/energy ratings range from the later years of the future path, can be used as a reference for the future replacement of the battery and fuel cell systems due to degradation. As the diesel engine ratings are decreasing in the later years for both emission mitigation cases, if two small diesel engines are installed for the hybrid propulsion configuration, one of them can be removed or kept offline for redundancy purposes.

Total cost of ownership (TCO):

The TCO approach considers both the capital expenditures (CAPEX) and operating expenditures (OPEX) of the propulsion system over the course of the ship's remaining service life. As was already mentioned, the operational costs are based on forecasted changes in the input parameter prices over the course of the ship's useful lifespan (Section 6.1, and Appendix A). The optimal all-electric designs' total cost of ownership for each year of the future trajectory is shown in Figure 6.10.

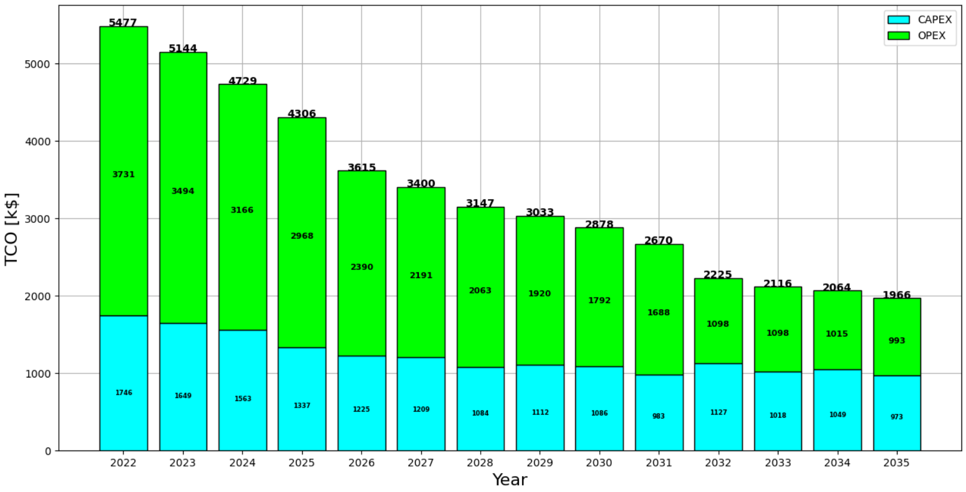


Figure 6.10: Total cost of ownership of optimal all-electric solutions in the first scenario

In Figures 6.11 and 6.12 the total cost of ownership for the designs that reduced emissions by 50% and 75% respectively is depicted. The TCO of the optimal all-electric propulsive layouts is very different and much lower from the TCO of the optimal systems that reduced emissions by 50% and 75%. When the diesel engines and their emissions are a part of the solution, the implementation of the carbon tax and the steady annual increase in the price of diesel fuel in the scenario influence operational costs over time.

Figures 6.13, 6.14 and 6.15 provide a breakdown of OPEX for the optimal designs for each of these three cases (all electric, 50%, 75% emission reduction), making it easier to understand how the inclusion of diesel engines in the design affects long-term costs. As can be seen in Figures 6.14 and 6.15, the costs of diesel fuel together with the carbon tax account for the greater part of the operational costs for the optimal solutions that reduced emissions by 50% and 75%. These two costs have been rising over time which is consistent with the predictions of the future path (Figures 6.3, A.3, 6.4, A.4). On the other hand, based on the adopted hydrogen and electricity price trends over the first future trajectory (Figures 6.5a, A.5a, 6.6a, A.6a), the operational costs of purchasing hydrogen and charging the batteries are significantly lower and tend to decrease over time in all three cases. As more diesel fuel is consumed and larger diesel engines are part of the solutions, the operational costs over time,

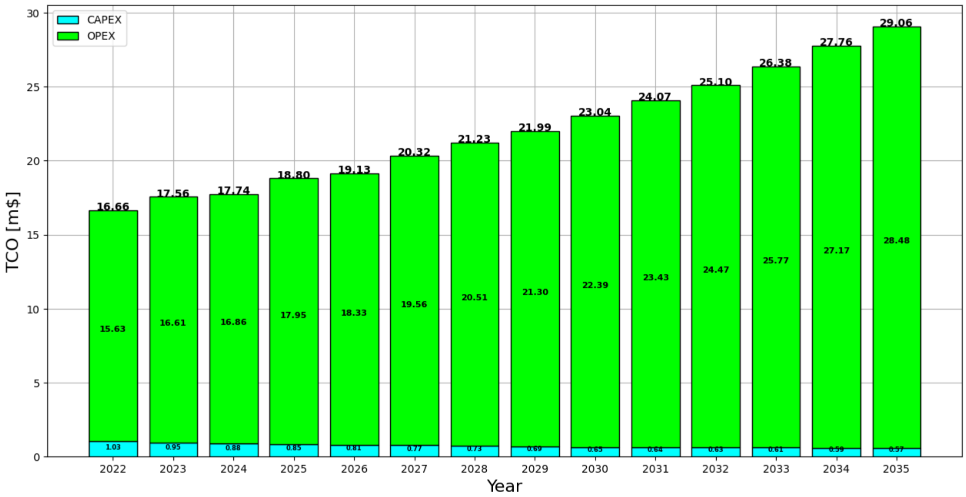


Figure 6.11: Total cost of ownership of optimal solutions based on 50% emission reduction in the first scenario

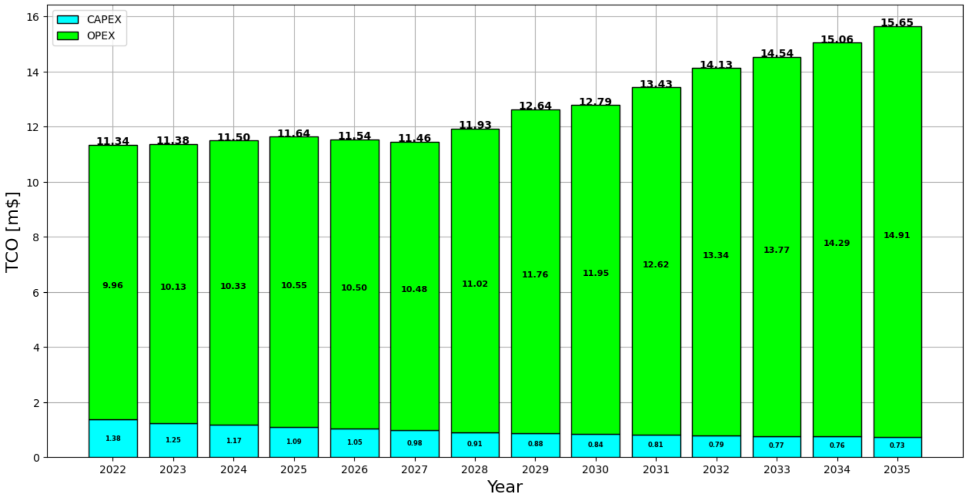


Figure 6.12: Total cost of ownership of optimal solutions based on 75% emission reduction in the first scenario

and thus, the TCO of the optimal designs that reduce emissions by 50% are higher than the case of emission mitigation of 75%. Based on the analysis, it is evident that an all-electric system with zero-emissions is the most economical option to select given the impact that adding diesel engines to the propulsive system has on the long-term costs of the vessel.

To assess which solution is the most cost-effective in a more accurate manner, the Total cost of ownership approach was crucial. The cost-effectiveness would be determined by the CAPEX, the investment costs for the propulsive system components, if the operational costs over the ship's remaining life were not calculated. The less expensive and more practical option in this situation would be to select a hybrid configuration based on the produced optimal power/energy ratings that cut emissions by 50% in comparison to the conventional propulsion system.

The CAPEX breakdown of the optimal solutions is shown in Figures 6.16, 6.17 and 6.18 to support this observation. The initial investment costs for the 50% emission reduction case are shown to be less than those for a hybrid system that reduces emissions by 75% and significantly less than those for an all-electric propulsion system.

The shipowner would save money at the beginning of the investment by choosing an opti-

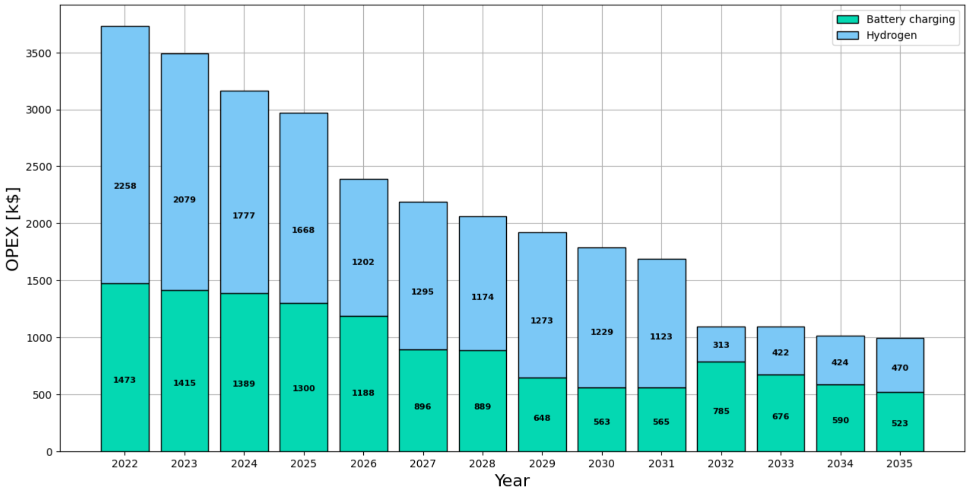
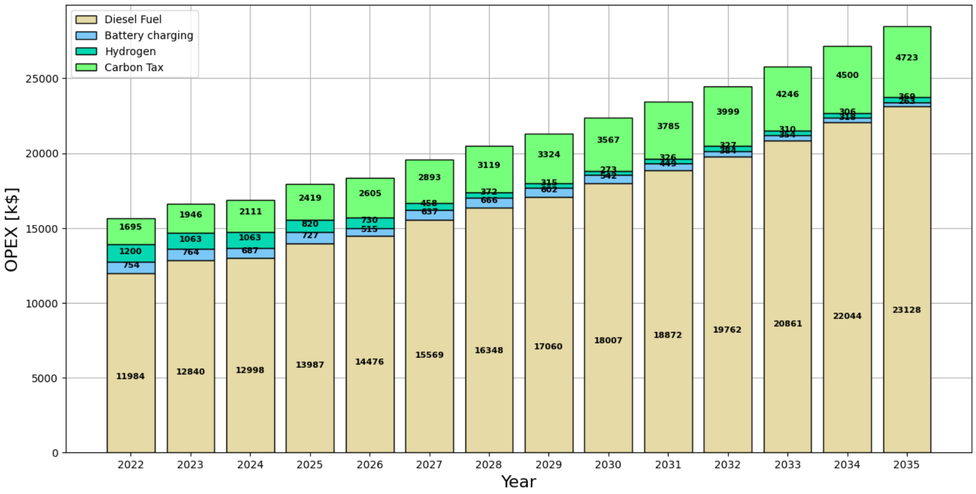
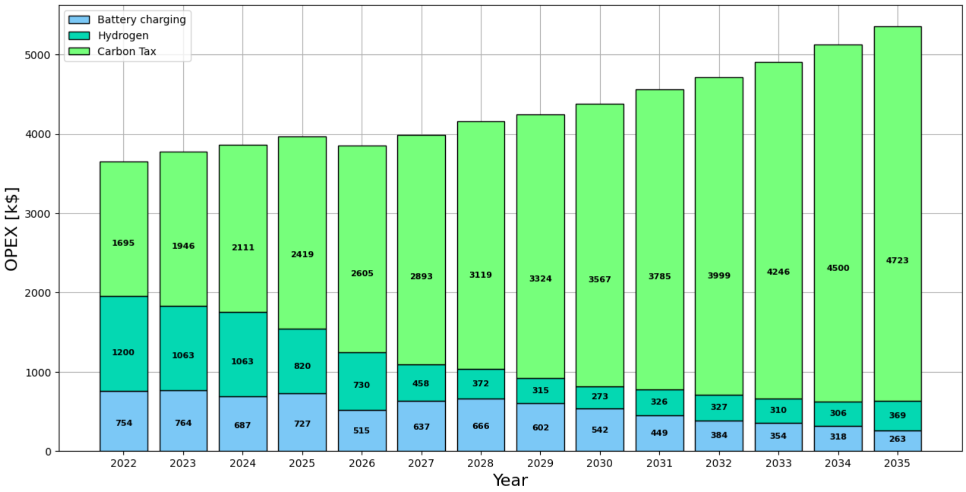


Figure 6.13: Operational expenses breakdown for all-electric optimal solutions in the first scenario

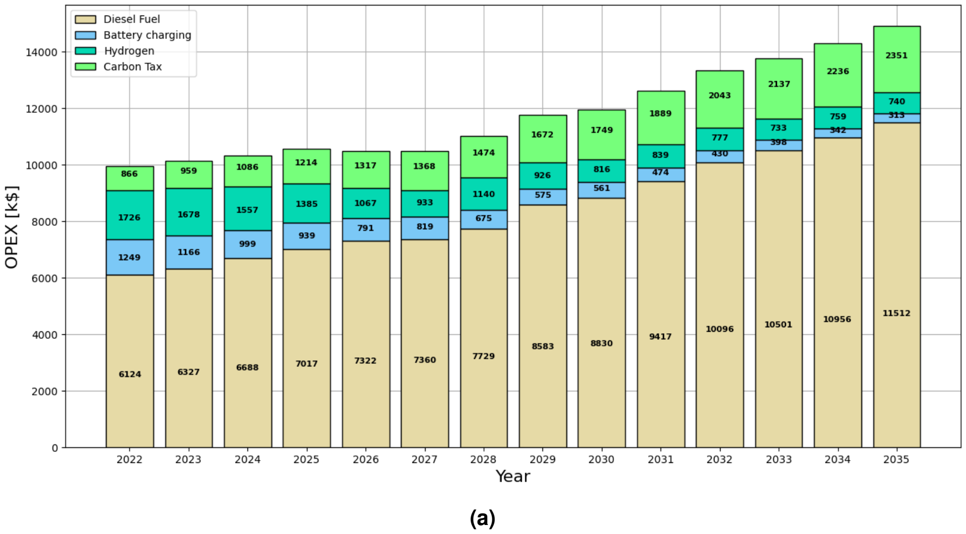


(a)



(b)

Figure 6.14: (a) Operational expenses breakdown for optimal solutions based on 50% emission reduction in the first scenario (b) A closer look on the upper section of the graph



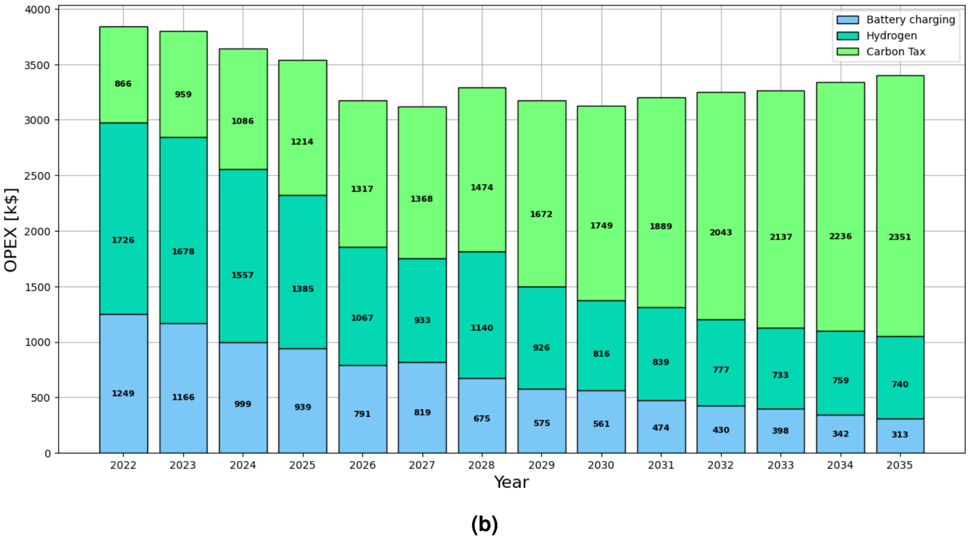


Figure 6.15: (a) Operational expenses breakdown for optimal solutions based on 75% emission reduction in the first scenario (b) A closer look on the upper section of the graph

mal configuration only taking into account the lower initial costs, but the costs in the long run would be much higher based on the projected future prices in the market, as was determined in the previous sections.

This conclusion is one of the study's main contributions as the researchers previously used the optimization methodology without analysing and considering the potential propulsion system's long-term costs. More reliable and future-proof guidelines for the sizing of the propulsion powertrain system can be provided to the stakeholders by developing scenarios and future projections and using the Total cost of ownership approach.

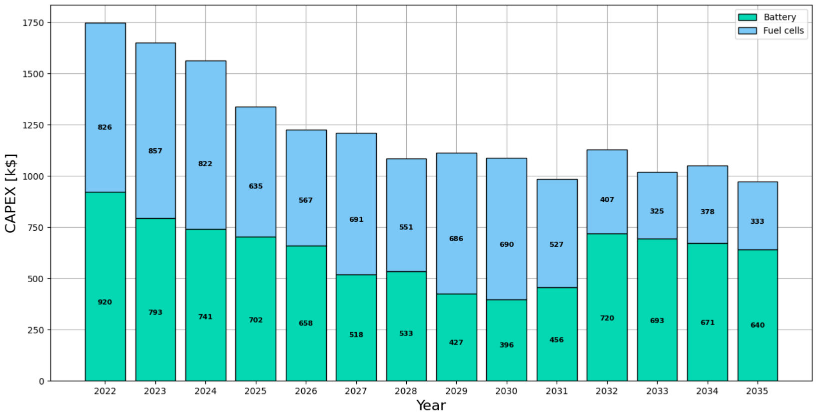


Figure 6.16: Capital expenditures breakdown for all-electric optimal solutions in the first scenario

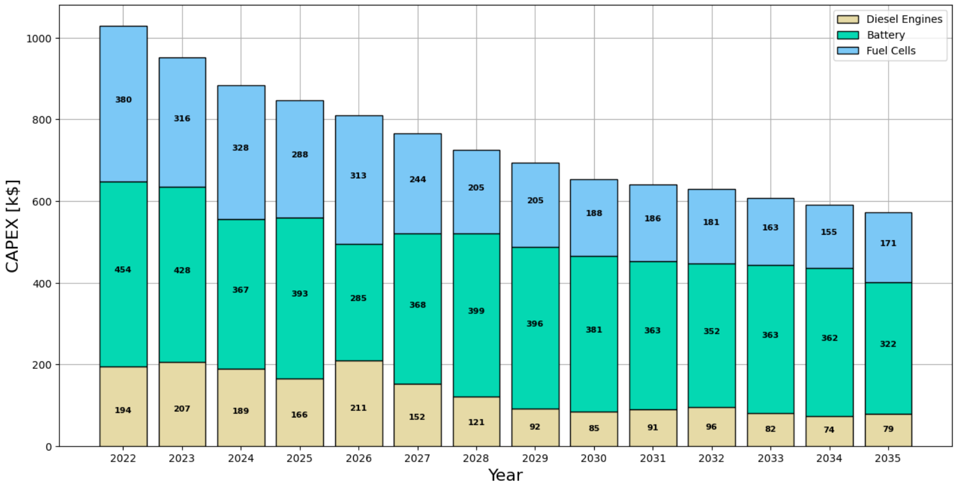


Figure 6.17: Capital expenditures breakdown for optimal solutions based on 50% emission reduction in the first scenario

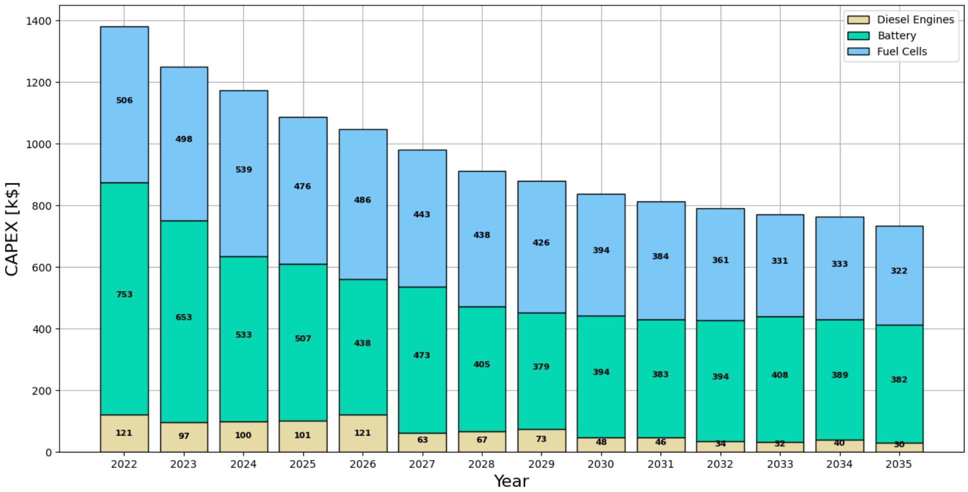


Figure 6.18: Capital expenditures breakdown for optimal solutions based on 75% emission reduction in the first scenario

6.2.2 *Second scenario*

Optimal power and energy ratings:

The power/energy ratings of the optimal designs for the second future path after applying the TCO approach are given in Figure 6.19. The same conclusions regarding the cost-effectiveness of a propulsion system using solely batteries and fuel cells can be drawn as the optimal designs with the lowest TCO have zero fuel consumption (zero emissions) and no diesel engines. An fully electric propulsion system is the most economical choice over time.

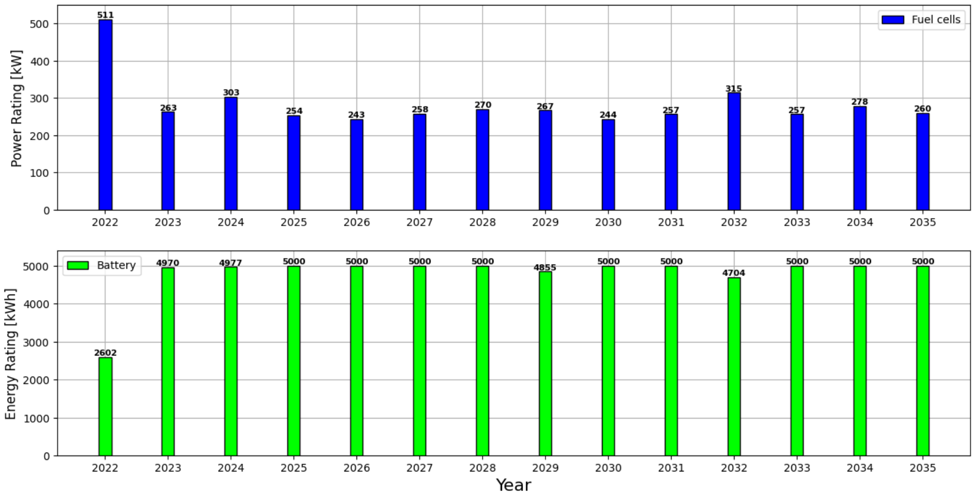


Figure 6.19: Optimal power/energy ratings based on the lowest TCO for the second scenario

Despite the fact that electricity prices are continually rising in the second scenario, the predicted decrease in battery cost investments and the increase in hydrogen price have a more considerable impact on the optimization problem. The optimal battery ratings are closer to the maximum value specified for the battery energy rating variable (5000 kWh) through the whole trajectory except in 2022 and the produced fuel cell ratings are smaller in average than the first scenario optimal solutions that have the lowest TCO as the hydrogen price is predicted to be increasing over the years.

The optimal hybrid system's ratings among the Pareto optimal solutions that reduces emissions by 50% and 75% are shown in Figure 6.20 and Figure 6.21 respectively, for the second trajectory. Similar conclusions can be drawn as with the cases of emission mitigation of the first future path analysis. The diesel engines are also included in the solution and their sizes are larger for the optimal solutions that cut the emissions in half compared to the optimal designs that reduce emissions by 75%.

In contrast to expectations, the optimal battery size tends to increase through the years, especially after 2028 for the 50% emission mitigation case and after 2033 for the 75% emission reduction case. This highlights again that the optimization problem is more significantly impacted by the anticipated decline in battery cost investment rather than the price increase of the electricity.

The power/energy ratings of the components should be first within the ranges of the produced solutions, between 2022 and 2028 for 50% emission mitigation. A battery size within the range 1215 and 1805 kWh, fuel cells size between 135 and 190 kW and diesel engine sizes between 240 to 345 kW are recommended if the CTV is to be retrofitted or built before 2028. A larger battery should be installed as a replacement according to the solutions after 2028 (2325 to 2960 kWh), and a smaller fuel cell between 75 and 120 kW.

The optimal hybrid solutions among the Pareto optimal are not subject to significant changes throughout the whole trajectory of the 75% emission mitigation evaluation case. The battery size is within the range 1920 and 2900 kWh, fuel cell ratings are between 205 and 290 kW until 2033 and those should be the sizes for the initial installation. The diesel engine rating is between 66 and 205 kW until 2029 and after has an average value around 60 kW. If two small diesel engines are installed for the configuration for both emission mitigation cases, one of them can be removed or kept offline for redundancy purposes if a larger battery would be installed later in the system's life due to degradation.

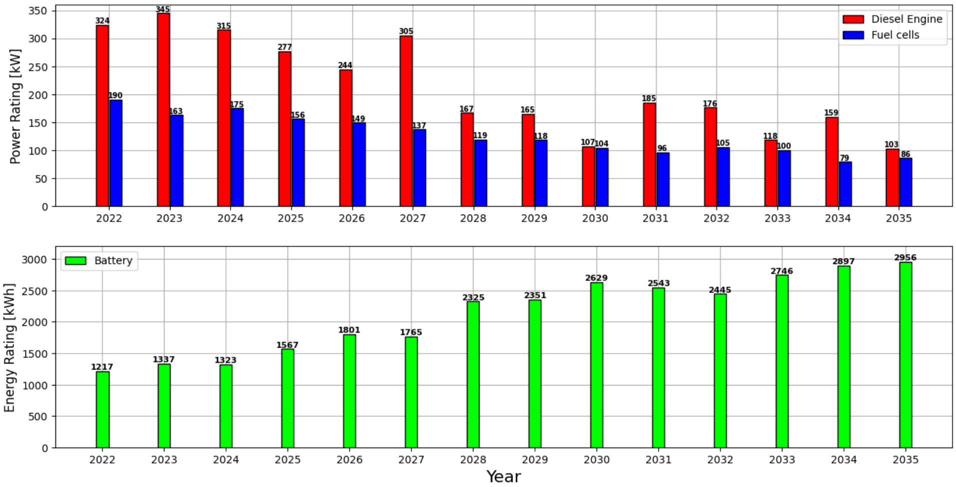


Figure 6.20: Optimal power/energy ratings based on 50% emission reduction in the second scenario

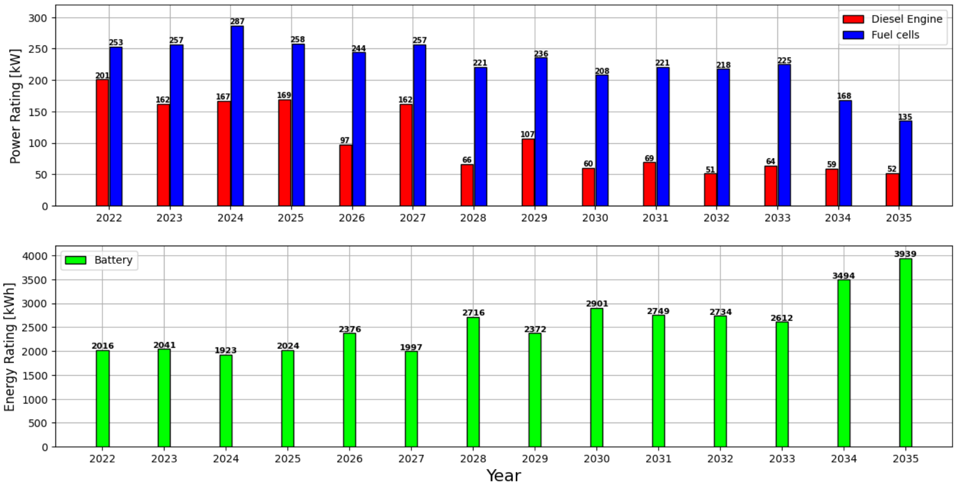


Figure 6.21: Optimal power/energy ratings based on 75% emission reduction in the second scenario

Total cost of ownership (TCO):

The Total Cost of Ownership of the optimal all-electric designs for the second scenario is shown in Figure 6.22. The TCO is now increasing through the years in comparison with the analysis in the first scenario. The steady increase of electricity prices and the increase in hydrogen price through the trajectory substantially influence the operating expenses in the long term (Figure B.1). The total cost of ownership for the designs that reduced emissions by 50% and 75% are shown in Figure 6.23 and Figure 6.24 respectively. Even though the TCO of the optimal all-electric designs is increasing through the years, is much lower than the other two cases as was realised in the first scenario. The inclusion of diesel engines in the design significantly impacts the long-term costs in this scenario as well. A breakdown of OPEX for the optimal designs for each of these three cases is given in Appendix B.1. The diesel fuel costs account for the greater part of the OPEX, but now the battery charging costs and the purchasing costs of hydrogen have a significant share in the long term operational expenses due to the scenario's projections. For the same reason the TCO (and operational expenses over the ship's remaining service life) are significant higher than the first future path in all three cases.

The analysis of this second future trajectory once again demonstrates how essential it is to implement the total cost of ownership approach in order to choose the most cost-effective design out of all generated optimal solutions. The most cost-effective design, if only CAPEX were taken into account, would once again be a hybrid propulsion system that cuts emissions in half. Long-term, the shipowner would incur excessive operational costs as a result of that choice. Therefore, it is essential that the long-term operating costs to be considered in the analysis for a more reliable selection of an optimal system, in order to identify what is actually advantageous for the shipowner more precisely.

The CAPEX breakdown of the optimal solutions can be found in Appendix B.2 to support this conclusion. The most economical options are the produced solutions that reduced emissions by 50% as their CAPEX are lower than the other optimal designs (Figures B.5, B.6, B.4). Furthermore, for all three cases it can be observed that the CAPEX of the optimal solutions are decreasing through the years despite the fact that the battery sizes are larger in the later years of the trajectory. This can be explained by the adopted battery and fuel cell investment costs trends in the scenarios (Figures 6.1, 6.2, A.1, A.2).

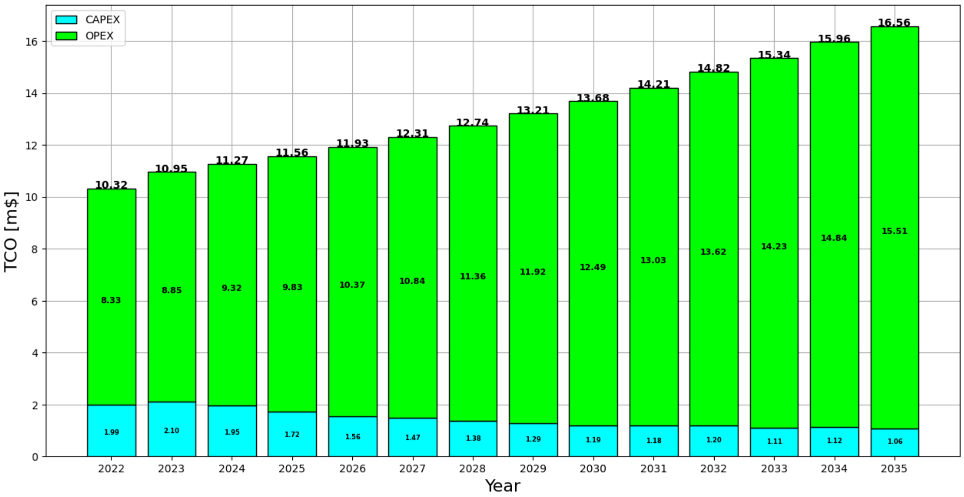


Figure 6.22: Total cost of ownership of optimal all-electric solutions in the second scenario

It should be noted that the first future trajectory is the more likely to occur and that out of the two alternative future trajectories, Renewable energy sources (RES) will most likely penetrate the energy supply and impact the prices of electricity.

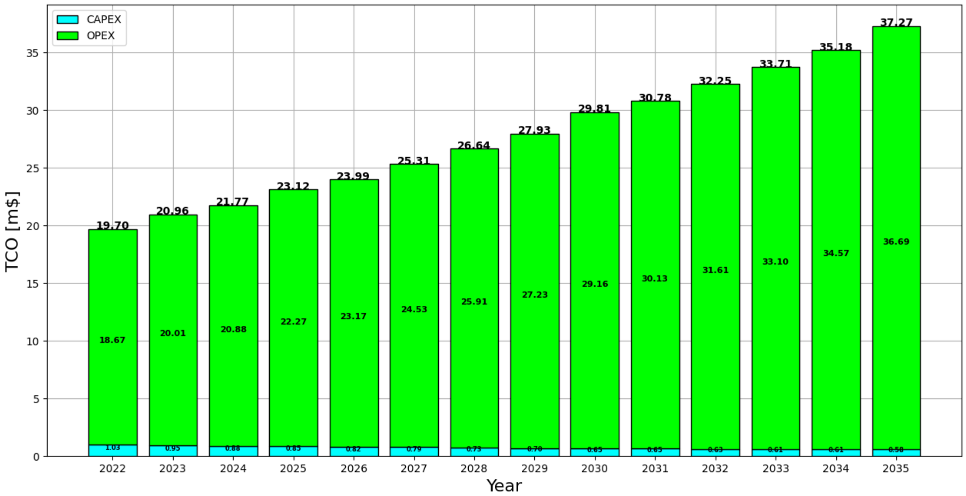


Figure 6.23: Total cost of ownership of optimal solutions based on 50% emission reduction in the second scenario

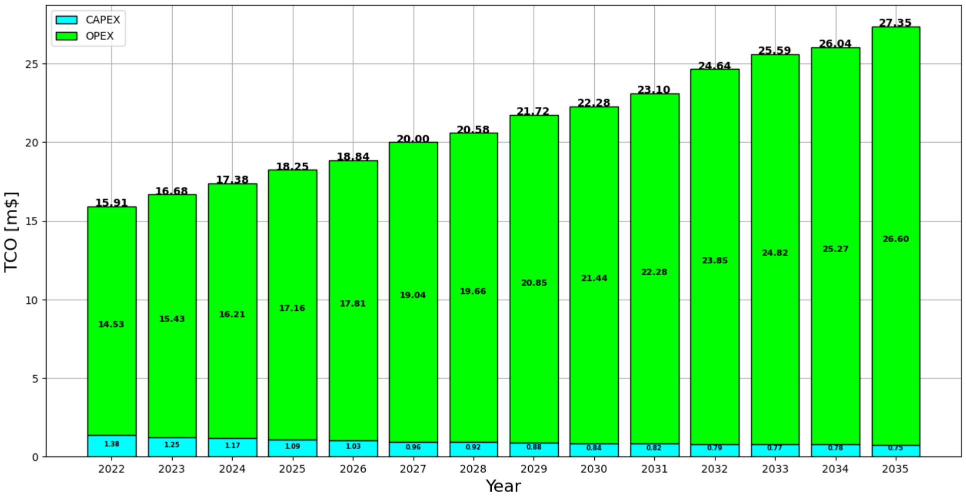


Figure 6.24: Total cost of ownership of optimal solutions based on 75% emission reduction in the second scenario

7 CONCLUSIONS AND RECOMMENDATIONS

In this chapter, the conclusions of the report are explained and discussed. These are based on the results of the previous chapters. The conclusions will give an answer to the main and sub research questions. After the conclusions, suggestions for future work are given, followed by the recommendations for the ship owner GEOxyz.

7.1 Answers to Research questions

This thesis was conducted to find the most suitable hybrid propulsion system to install for crew transfer vessel with a specific operational profile. This can be phrased in the following research question: ***What are the power and energy ratings of the components of the hybrid propulsion powertrain that should be installed in order to have a cost-effective and eco-friendly Crew Transfer Vessel?***

To assist answering this question, 3 sub-questions were formulated. These shall be answered first. Answers to the research questions are formulated according to the findings and results of this thesis.

Sub question 1**:** *Which uncertainties can be identified that affect the sizing optimization problem for the CTV's hybrid propulsion system?*

Chapter 3 provided an answer to this question. The uncertainties involved in the ship design optimization problem are exogenous and related to three categories: economic, technology development, regulatory. The precise changes in fuel and electricity prices would always be uncertain and difficult to predict but as they have a huge impact on profits and expenses of vessels they are really important for the decision making process. The rate of how technologies advancing is another unknown. It's unclear when decarbonization technologies, like fuel cells and batteries, will experience technological breakthroughs. Policies enforcing emission mitigation such as carbon taxes are being discussed, but when and how they will implemented it is unclear. All these relevant uncertainties have been translated as costs parameters in the development of the optimization problem and they have been incorporated in the capital or operational expenses models, having a significant influence on the optimal design solutions.

Sub question 2**:** *What are the future scenarios on exogenous factors/ uncertainties, and how will these influence the sizing of the hybrid CTV? (e.g. future prices, technology maturity)*

Section 6.1 determines the future scenarios. By gathering information from various scientific and industrial publications about the uncertain parameters of the optimization problem different possible futures were developed. Battery and fuel cell investment costs, different fuel and electricity prices, and the introduction of a potential carbon tax were included in these future scenarios. The assumption of the penetration of renewable energy sources (RES) in the energy generation supply is what makes the created future trajectories differ. The produced optimal designs from the multi-objective double-layer optimization methodology vary as a result of the different scenarios, and therefore, multiple designs were produced that are optimal representatives for all potential futures.

Sub question 3**:** *How the cost-effectiveness of the optimum configuration solutions produced by the optimisation methodology would be determined?*

In this thesis research, a cost-effective hybrid propulsion system was chosen from the Pareto front of optimal solutions generated per year (or per run) by the multi-objective optimization algorithm using the Total Cost of Ownership approach as an evaluation method. The hybrid propulsion system's capital expenditures (CAPEX) and operating expenditures (OPEX) over the course of the ship's remaining service life are both included in the TCO. As there are two options for GEOxyz: 1) to retrofit the existing vessel or 2) to build a completely new hybrid CTV for the same purpose and missions, the remaining useful life of the CTV was assumed to be 15 years in this study. As a result, the optimal designs that were produced and had the lowest TCO per run were identified and considered to be the most cost effective ones. The TCO of those cost-effective optimal designs were compared with the designs that discovered with the second evaluation method. It was demonstrated that if the cost-effectiveness of the designs was evaluated based only on CAPEX without taking into account the long-term operational costs over the vessel's remaining life the selected design would be different and this decision would be disadvantageous for the shipowner in the long run.

The answers to the sub-questions lead the way to the answer for the main research questions.

What are the power and energy ratings of the components of the hybrid propulsion powertrain that should be installed in order to have a cost-effective and eco-friendly Crew Transfer Vessel?

The most economical and environmentally friendly power and energy ratings of the components were identified by implementing the TCO economic evaluation approach on the generated solutions from the optimization. It was discovered that, the optimum solutions with the lowest TCO are based entirely on batteries and fuel cells and produce zero emissions. Therefore, an all-electric propulsion system is the most cost-effective and eco-friendly option to be installed on the Crew Transfer Vessel, not a hybrid one.

The first future pathway is the more likely scenario to occur and that out of the two alternative future trajectories, Renewable energy sources (RES) will most likely penetrate the energy supply and impact the prices of electricity. According to this assumption, the recommendations for the power and energy ratings of the components of the fully electric propulsion system would be based on the first scenario's solutions. The proposed power and energy ratings are:

- For batteries:

  2460 - 3060 kWh if retrofitting or building a new CTV is intended to be completed before 2031. 5000 kWh if replacement after 2031 is needed due to the battery's degradation.

- For fuel cells:

  310 - 445 kW if retrofitting or building a new CTV is intended to be completed before 2031. 200 - 245 kW if replacement after 2031 is needed due to the fuel cell's degradation.

- For diesel engines:

  No diesel engines should be installed.

It would be good to mention that the exact solutions with the specific recommended ratings might be difficult to install on the existing CTV under study, especially the batteries.

7.2 Discussion and further research

The potential for conducting additional research in this area is discussed here, along with some issues that could use some more attention.

Scenario generation method

At the start of this study, Epoch-era analysis (EEA) was taken into consideration as a technique to incorporate into the optimization model, to produce future scenarios, and to handle uncertainty. Due to the fact that the algorithm was already complex enough, it was challenging to include a model of Epoch-era analysis in the algorithm's code and thus a more straightforward approach was implemented. Even though that the future trajectories were developed in a more simpler way it is shown that the proposed method's design recommendations can be beneficial for the stakeholders. Robust decision making (RDM) and Markov decision process (MDP) are two examples of additional techniques that can be used like EEA and have already been used in ship design optimization studies. An interesting future research can be to combine one of this methods to a similar ship design and sizing optimization problem.

Computation time

Due to the complexity of the optimization problem, approximately 180 to 200 minutes were needed on a high-end laptop for each run of the optimization algorithm to arrive in valid optimal results (convergence of Pareto front solutions). A method should be investigated to reduce the computation time or the optimization algorithm should be run on a supercomputer. This would make possible the development of far more future trajectories to be compared and analysed.

Optimization method

In the current methodology various assumptions and simplifications have been made to make the problem at hand more manageable. As a result, the optimization process can be enhanced in the following ways:

- The accuracy of the results would be increased by including depreciation, maintenance, and component replacement costs in the OPEX and TCO economic models.

- The optimization methodology currently generates a new optimum hybrid system for each year (every run). Modifications can be made to the algorithm in order to further optimize an already designed system.

- When constructing the optimization problem, the weight and volume restrictions can be taken into account in order to examine the technical feasibility of the produced optimal system layout.

- A sensitivity study for the input parameters can be performed to investigate the exact impact of each parameter in the optimization problem. Additionally, the sensitivity of the outcomes to different operational profiles can be examined.

- Currently, the optimization methodology optimizes only the size of the vessel's propulsion system. The scope of the optimization can be expanded to include the ship's entire power system if data regarding the electric power demand together with the propulsion power demand can be made available.

- Additional research in different power sources with decarbonization potential can be examined for the CTV. The modelling of dual fuel engines, fueled by hydrogen and diesel, might be an interesting addition to the optimization methodology.

Alternative optimization approach

The potential for charging the system's batteries at stations located at wind farms can be examined and the sizing of the system's components can be optimized based on a path-route scheduling optimization.

7.3 Recommendations for GEOxyz

GEOxyz can use this research findings to support their decision on choosing the propulsion system for their CTV. An effort was put for a good representation of reality in the optimization problem by developing scenarios that result in cost-effective and low and zero emission solutions.

It is evident from the information GEOxyz has gathered about commercial batteries (Table 2.2) that no battery size can satisfy the suggested battery sizes from the optimization methodology. Fortunately, suppliers who have already been contacted, like Corvus Energy, have answers for larger battery needs. A brand-new, comprehensive energy storage system with bigger installations was created by Corvus energy. Large zero-emission vessels, such as cargo ships, cruise ships, and large roll-on, roll-off passenger (RoPax) and RoRo ferries, are the target market for the Corvus Blue Whale ESS design [Corvus Energy, 2019]. On their website, system specifications range from 301 to 4816 kWh, with some example packs having energy ratings as high as 14448 kWh. Due to weight and space restrictions, it may be challenging to retrofit an existing vessel with such a large battery system. However, if GEOxyz decides to build a new CTV in its place, the components arrangement can be optimized, and a technical feasibility study can demonstrate that this battery size range is suitable for the new-built.

The fuel cell proposed sizes are available commercially. It is possible to compare fuel cells of comparable sizes to determine which has the best specific power, power density, and efficiency. Whether to place the system below-deck or on the open deck of the ship is a key consideration in this decision. Ballard 200 kW fuel cell has the highest specific power from the commercial available PEM fuel cells (Table 2.4) and should be used if the weight is the more critical factor. The PowerCellution 200 kW, on the other hand, has the highest power density and ought to be used when volume restrictions are more crucial. Nedstack modules appear to be good options if the module is to be installed on the ship's open deck. Although Nedstack modules don't perform as well as modules from other manufacturers in terms of specific power and power density, they are built as a 20-foot ISO container, are incredibly durable, and are designed to be used on open decks.

The parameters of the optimization methodology can be easily changed to explore more options and expand the design solution space if this thesis' results don't satisfy GEOxyz. In addition, it is suggested that a professional user interface designer be involved in the development of a real life decision support tool, incorporating the multi-objective optimization methodology. More fleet owners within and outside of the ISHY project that have vessels with similar operational profiles and are interested in their hybridization can benefit from this.

BIBLIOGRAPHY

Arabul, F.K., Senol, I., Arabul, A.Y., Boynuegri, A.R., 2015. Providing energy management of a fuel cell-battery hybrid electric vehicle. World Academy of Science, Engineering and Technology, International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering 9, 920–924.

Baldi, F., Brynolf, S., Maréchal, F., 2019. The cost of innovative and sustainable future ship energy systems, in: Proceedings of the 32nd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Wrocław, Poland, pp. 23–28.

Baldi, F., Coraddu, A., Kalikatzarakis, M., Jeleňová, D., Collu, M., Race, J., Maréchal, F., 2022. Optimisation-based system designs for deep offshore wind farms including power to gas technologies. Applied Energy 310, 118540.

Banaei, M., Rafiei, M., Boudjadar, J., Khooban, M.H., 2020. A comparative analysis of optimal operation scenarios in hybrid emission-free ferry ships. IEEE Transactions on Transportation Electrification 6, 318–333.

Barthélémy, H., Weber, M., Barbier, F., 2017. Hydrogen storage: recent improvements and industrial perspectives. International Journal of Hydrogen Energy 42, 7254–7262.

Battelle Memorial Institute, 2017. Manufacturing cost analysis of 100 and 250 kw fuel cell systems for primary power and combined heat and power applications. . URL: https://www.energy.gov/sites/default/files/2018/02/f49/fcto_battelle_mfg_cost_analysis_100_250kw_pp_chp_fc_systems_jan2017.pdf.

Bloomberg, 2019. Orsted bets hydrogen is key to climate goals. . URL: https://gcaptain.com/orsted-bets-hydrogen-is-key-to-climate-goals/. office of Energy Efficiency Renewable Energy.

BloombergNEF, 2019. A behind the scenes take on lithium-ion battery prices. .

Boekhout M., 2020. Hydrogen powered ship propulsion for high-speed craft: The implementation of fuel cell battery propulsion systems. . URL: http://resolver.tudelft.nl/uuid:d06f091c-a970-48e1-8a66-3d791b91f18a. master Thesis, TU Delft Repository.

Bouman, E.A., Lindstad, E., Rialland, A.I., Strømman, A.H., 2017. State-of-the-art technologies, measures, and potential for reducing ghg emissions from shipping–a review. Transportation Research Part D: Transport and Environment 52, 408–421.

Buhaug, Ø., Corbett, J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D.S., Lee, D., Lindstad, H., Markowska, A.Z., et al., 2009. Second imo ghg study 2009 .

Cai, Q., Ma, L., Gong, M., Tian, D., 2016. A survey on network community detection based on evolutionary computation. International Journal of Bio-Inspired Computation 8, 84–98.

CES EduPack, 2019. . URL: https://www.ansys.com/products/materials/granta-edupack/data. database. Granta Design, ANSYS Inc.

CFA Society Netherlands, 2022. Green hydrogen as an investment opportunity. . URL: https://cfavba.nl/nl/publicaties/green-hydrogen-as-an-investment-opportunity/1f7d912e-c3e8-11ec-9d27-005056b303d3.

China Dialogue, 2022. Eu carbon tax puts a price on shipping emissions. . URL: https://chinadialogue.net/en/transport/eu-carbon-tax-puts-a-price-on-shipping-emissions/.

Corbo, P., Migliardini, F., Veneri, O., 2009. Dynamic behaviour of hydrogen fuel cells for automotive application. Renewable Energy 34, 1955–1961.

Corvus Energy, 2019. Corvus blue whale. . URL: https://corvusenergy.com/products/energy-storage-solutions/corvus-blue-whale/.

CWIND, 2021. Next generation ctvs arrive to help combat emissions. . URL: https://cwind.global/next-generation-ctvs-arrive-to-help-combat-emissions/?utm_content=186260864&utm_medium=social&utm_source=facebook&hss_channel=fbp-480933401970794.

Damen, 2022. Damen builds three hybrid fast crew supply vessels on stock. . URL: https://www.damen.com/insights-center/news/damen-builds-three-hybrid-fast-crew-supply-vessels-on-stock.

De Jager, B., Van Keulen, T., Kessels, J., 2013. Optimal control of hybrid vehicles. Springer.

Deb, K., Pratap, A., Agarwal, S., Meyarivan, T., 2002. A fast and elitist multiobjective genetic algorithm: Nsga-ii. IEEE transactions on evolutionary computation 6, 182–197.

DNV GL, 2016. Dnv gl handbook for maritime and offshore battery systems. DNV GL: Oslo, Norway .

DNV GL, 2017. Study on the use of fuel cells in shipping. European Maritime Safety Agency (EMSA), Report .

DNV GL, 2018. Assessment of selected alternative fuels and technologies. . URL: https://hydrogeneurope.eu/sites/default/files/2018-04/DNV_GL_Complete-Alt-Fuels_guidance_paper_2018-04_web.pdf.

DNV-GL, 2021a. Maritime forecast to 2050. . URL: https://www.dnv.com/maritime/publications/maritime-forecast-to-2050-download.html. eNERGY TRANSITION OUTLOOK 2021.

DNV-GL, 2021b. Technology progress report a guide to 10 key energy transition technologies. . URL: https://www.dnv.com/energy-transition/technology-progress-report-2021.html.

DNV-GL Maritime, 2019. Assessment of selected alternative fuels and technologies in shipping. . URL: https://hydrogeneurope.eu/sites/default/files/2018-04/DNV_GL_Complete-Alt-Fuels_guidance_paper_2018-04_web.pdf.

Donateo, T., Serrao, L., Rizzoni, G., 2008. A two-step optimisation method for the preliminary design of a hybrid electric vehicle. International Journal of Electric and Hybrid Vehicles 1, 142–165.

Ebrahimi, A., Brett, P.O., Erikstad, S.O., Asbjørnslett, B.E., Garcia Agis, J.J., 2020. Ship design complexity, sources, drivers, and factors: A literature review. International Shipbuilding Progress 67, 221–252.

Engelhardt-Funke, O., Kolonko, M., 2004. Analysing stability and investments in railway networks using advanced evolutionary algorithms. International Transactions in Operational Research 11, 381–394.

Eriksson, E., Gray, E.M., 2017. Optimization and integration of hybrid renewable energy hydrogen fuel cell energy systems–a critical review. Applied energy 202, 348–364.

Erikstad, S.O., Rehn, C.F., 2015. Handling uncertainty in marine systems design-state-of-the-art and need for research, in: 12th International Marine Design Conference 2015 Proceedings, pp. 324–342.

European Council, 2022. Fit for 55. . URL: `https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/`.

Fletcher, T., Thring, R., Watkinson, M., 2016. An energy management strategy to concurrently optimise fuel consumption & pem fuel cell lifetime in a hybrid vehicle. international journal of hydrogen energy 41, 21503–21515.

Gao, W., Mi, C., 2007. Hybrid vehicle design using global optimisation algorithms. International Journal of Electric and Hybrid Vehicles 1, 57–70.

Garcia, P., Fernandez, L.M., Garcia, C.A., Jurado, F., 2009. Fuel cell-battery hybrid system for transport applications, in: 2009 International Conference on Electrical Machines and Systems, IEEE. pp. 1–5.

Gaspar, H.M., Erikstad, S.O., Ross, A.M., 2012a. Handling temporal complexity in the design of non-transport ships using epoch-era analysis. Transactions of the Royal Institution of Naval Architects Part A: International Journal of Maritime Engineering 154, 109–120.

Gaspar, H.M., Ross, A.M., Rhodes, D.H., Erikstad, S.O., 2012b. Handling complexity aspects in conceptual ship design, in: Glasgow, UK: Prosiding International Maritime Design Conference.

Geertsma, R., Negenborn, R., Visser, K., Hopman, J., 2017. Design and control of hybrid power and propulsion systems for smart ships: A review of developments. Applied Energy 194, 30–54.

GEOxyz, 2022. Geoxyz is developing a hydrogen powered ctv. . URL: `https://www.geoxyz.eu/en/news/geoxyz-is-developing-a-hydrogen-powered-ctv`.

GEOxyz bvba, 2012. Geosurveyor xx. . URL: `https://www.geoxyz.eu/data/documents/vessels/geosurveyor20.pdf`.

Getting to Zero Coalition, 2021. Policy options for closing the competitiveness gap between fossil and zero-emission fuels in shipping. . URL: `https://www.globalmaritimeforum.org/content/2021/11/INSIGH1.pdf`. insight brief.

Guzzella, L., Sciarretta, A., et al., 2007. Vehicle propulsion systems. volume 1. Springer.

Hannapel, S., Vlahopoulos, N., 2010. Robust and reliable multidiscipline ship design, in: 13th AIAA/ISSMO Multidisciplinary Analysis Optimization Conference, p. 9394.

Hannapel, S.E., 2012. Development of Multidisciplinary Design Optimization Algorithms for Ship Design Under Uncertainty. Ph.D. thesis.

Hellenic Shipping News Worldwide, 2022. Carbon taxes in the shipping industry—assessing japan's proposal. . URL: `https://www.hellenicshippingnews.com/carbon-taxes-in-the-shipping-industry-assessing-japans-proposal/amp/?fbclid=IwAR0mEqXdDY0vqw74SAAh9egwBpWHnBUOLq6HgF4rzYsxB33WgxT4VTNJbs0`.

Hofman, T., Steinbuch, M., van Druten, R., Serrarens, A.F., 2008. Design of cvt-based hybrid passenger cars. IEEE Transactions on Vehicular Technology 58, 572–587.

HST Marine, 2021. World's first hybrid chartwell 24 crew transfer vessel handed over to hst marine. . URL: https://www.marineinsight.com/shipping-news/worlds-first-hybrid-chartwell-24-crew-transfer-vessel-\handed-over-to-hst-marine/.

Huang, M., He, W., Incecik, A., Cichon, A., Królczyk, G., Li, Z., 2021. Renewable energy storage and sustainable design of hybrid energy powered ships: A case study. Journal of Energy Storage 43, 103266.

IMO, 2020. Imo working group agrees further measures to cut ship emissions. . URL: https://imo.org/en/MediaCentre/PressBriefings/pages/36-ISWG-GHG-7.aspx.

Interreg 2 Seas, 2019. Implementation of ship hybridisation - ishy. . URL: https://www.interreg2seas.eu/en/ISHY.

IRENA, 2020. Green hydrogen cost reduction. . URL: https://www.globalmaritimeforum.org/content/2021/11/INSIGH1.pdf. sCALING UP ELECTROLYSERS TO MEET THE 1.5°C CLIMATE GOAL.

Jafarzadeh, S., Schjølberg, I., 2018. Operational profiles of ships in norwegian waters: An activity-based approach to assess the benefits of hybrid and electric propulsion. Transportation Research Part D: Transport and Environment 65, 500–523.

Jaurola, M., Hedin, A., Tikkanen, S., Huhtala, K., 2019. Optimising design and power management in energy-efficient marine vessel power systems: a literature review. Journal of Marine Engineering & Technology 18, 92–101.

Keane, A., Gaspar, H.M., Brett, P.O., 2015. Epoch era analysis in the design of the next generation offshore subsea construction vessels, in: 2015 10th System of Systems Engineering Conference (SoSE), IEEE. pp. 322–327.

Leo, T., Durango, J., Navarro, E., 2010. Exergy analysis of pem fuel cells for marine applications. Energy 35, 1164–1171.

Li, Z., Sinha, K.C., 2009. Application of shackle's model and system optimization for highway investment decision making under uncertainty. Journal of Transportation Engineering 135, 129–139.

Lin, J., de Weck, O., de Neufville, R., Yue, H.K., 2013. Enhancing the value of offshore developments with flexible subsea tiebacks. Journal of Petroleum Science and Engineering 102, 73–83.

Livanos, G.A., Theotokatos, G., Pagonis, D.N., 2014. Techno-economic investigation of alternative propulsion plants for ferries and roro ships. Energy Conversion and Management 79, 640–651.

Man Energy Solutions, 2019. Batteries on board ocean-going vessels. . URL: https://static1.squarespace.com/static/5f0d42f16639a745affd633e/t/5ffac248fb26793593c04d70/1610269269784/batteries-on-board-ocean-going-vessels.pdf.

Maritime and Transport Technology, 3mE, TU Delft, 2019. Implementation of ship hybridisation - ishy. . URL: https://www.tudelft.nl/en/3me/about/departments/maritime-and-transport-technology/research/transport-engineering-and-logistics/theme-3-real-time-coordination-for-operational-logistics/the-implementation-of-ship-hybridization-ishy/.

Markowski, J., Pielecha, I., 2019. The potential of fuel cells as a drive source of maritime transport, in: IOP Conference Series: Earth and Environmental Science, IOP Publishing. p. 012019.

Mayflower Wind, 2021. Mayflower wind signs agreement with gladding-hearn for design/build of industry-leading hybrid electric offshore wind crew transfer vessel. . URL: https://mayflowerwind.com/mayflower-wind-signs-agreement-with-gladding-hearn-for-design-build-of-industry-leading-hybrid-electric-offshore-wind-crew-transfer-vessel/.

McKinlay, C.J., Turnock, S., Hudson, D., 2020. A comparison of hydrogen and ammonia for future long distance shipping fuels .

McManus, H., Hastings, D., 2006. A framework for understanding uncertainty and its mitigation and exploitation in complex systems. IEEE Engineering Management Review 34, 81–81. doi:10.1109/EMR.2006.261384.

Mestemaker, B., Castro, M.G., Van Der Blom, E., Cornege, H., Visser, K., 2019. Zero emission vessels from a shipbuilders perspective, in: 2nd International Conference on Smart & Green Technology for the Future of Marine Industries (SMATECH 2019)–Conference Proceedings, pp. 11–12.

Metzger, D., 2022. Market-based measures and their impact on green shipping technologies. WMU Journal of Maritime Affairs 21, 3–23.

Mishra, E.A.K., Mohapatra, E.Y., Mishra, E.A.K., 2013. Multi-objective genetic algorithm: A comprehensive survey. International Journal of Emerging Technology and Advanced Engineering 3, 81–90.

Mohagheghi, V., Mousavi, S.M., Siadat, A., 2015. A new approach in considering vagueness and lack of knowledge for selecting sustainable portfolio of production projects, in: 2015 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), IEEE. pp. 1732–1736.

Mutarraf, M.U., Terriche, Y., Niazi, K.A.K., Vasquez, J.C., Guerrero, J.M., 2018. Energy storage systems for shipboard microgrids—a review. Energies 11, 3492.

Nick Blenkey, 2021. Bv classes world's first hybrid ses crew transfer vessel. . URL: https://www.marinelog.com/offshore/offshore-wind/bv-classes-worlds-first-hybrid-ses-crew-transfer-vessel/.

Nikolopoulos, L., Boulougouris, E., 2018. A methodology for the holistic, simulation driven ship design optimization under uncertainty, in: Marine Design XIII. CRC Press, pp. 227–244.

Nikolopoulos, L., Boulougouris, E., 2020. A novel method for the holistic, simulation driven ship design optimization under uncertainty in the big data era. Ocean Engineering 218, 107634.

Offshore Renewable Energy (ORE), 2021. Decarbonising maritime operations in north sea offshore wind om. . URL: https://www.gov.uk/government/publications/decarbonising-offshore-wind-operations-and-maintenance-roadmap. innovation Roadmap produced for the UK Government DfT and FCDO.

Pai, G.V., 2016. Fuzzy decision theory based metaheuristic portfolio optimization and active rebalancing using interval type-2 fuzzy sets. IEEE Transactions on Fuzzy Systems 25, 377–391.

PIRIOU, 2020. Piriou develops crew transfer vessel (ctv) with hydrogen hybrid propulsion. . URL: https://www.marineinsight.com/shipping-news/piriou-develops-crew-transfer-vessel-ctv-with-hydrogen-hybrid-propulsion/.

Priftis, A., Boulougouris, E., Turan, O., Atzampos, G., 2020. Multi-objective robust early stage ship design optimisation under uncertainty utilising surrogate models. Ocean Engineering 197, 106850.

PwC, 2020. The green hydrogen economy - predicting the decarbonisation agenda of tomorrow. . URL: https://www.pwc.com/gx/en/industries/energy-utilities-resources/future-energy/green-hydrogen-cost.html.

Ross, A.M., Rhodes, D.H., 2008. Architecting systems for value robustness: Research motivations and progress, in: 2008 2nd Annual IEEE Systems Conference, IEEE. pp. 1–8.

Sciberras, E.A., Zahawi, B., Atkinson, D.J., Breijs, A., van Vugt, J.H., 2016. Managing shipboard energy: A stochastic approach special issue on marine systems electrification. IEEE Transactions on Transportation Electrification 2, 538–546.

Seacat, 2020. Seacat services order 'greenest ctv'. . URL: https://www.bartechnologies.uk/insights/seacat-services-order-greenest-ctv/.

Silvas, E., Bergshoeff, E., Hofman, T., Steinbuch, M., 2014. Comparison of bi-level optimization frameworks for sizing and control of a hybrid electric vehicle, in: 2014 IEEE Vehicle Power and Propulsion Conference (VPPC), IEEE. pp. 1–6.

Silvas, E., Hofman, T., Murgovski, N., Etman, L.P., Steinbuch, M., 2016. Review of optimization strategies for system-level design in hybrid electric vehicles. IEEE Transactions on Vehicular Technology 66, 57–70.

Smith, T., Jalkanen, J., Anderson, B., Corbett, J., Faber, J., Hanayama, S., O'Keeffe, E., Parker, S., Johansson, L., Aldous, L., Raucci, C., Traut, M., Ettinger, S., Nelissen, D., Lee, D., Ng, S., Agrawal, A., Winebrake, J., Hoen, M., Chesworth, S., Pandey, A., 2015a. Third IMO Greenhouse Gas Study 2014. International Maritime Organization, United Kingdom.

Smith, T.W., Jalkanen, J., Anderson, B., Corbett, J., Faber, J., Hanayama, S., O'keeffe, E., Parker, S., Johanasson, L., Aldous, L., et al., 2015b. Third imo ghg study .

Srinivas, N., Deb, K., 1994. Muiltiobjective optimization using nondominated sorting in genetic algorithms. Evolutionary computation 2, 221–248.

Stambouli, A.B., Traversa, E., 2002. Fuel cells, an alternative to standard sources of energy. Renewable and sustainable energy reviews 6, 295–304.

Stapersma, D., 2002. Diesel engines, volume 1: Performance analysis. Royal Netherlands Naval College .

Strategic Marine, 2022. New milestone for strategic marine via collaboration with sea forrest power solutions and danfoss power solutions to deliver asia's first parallel hybrid crew transfer vessel. . URL: https://www.strategicmarine.com/new-milestone-for-strategic-marine-via-collaboration-with-sea-forrest-power-solutions-and-danfoss-power-solutions-to-deliver-asias-first-parallel-hybrid-crew-transfer-vessel/.

Taner, T., 2015. Alternative energy of the future: a technical note of pem fuel cell water management. Journal of Fundamentals of Renewable Energy and Applications 5, 1–4.

TNO, 2020. Power-2-fuel cost analysis. . URL: https://smartport.nl/wp-content/uploads/2020/09/Cost-Analysis-Power-2-Fuel_def_2020.pdf.

Trading Economics, 2022. Netherlands gasoline prices. . URL: https://tradingeconomics.com/netherlands/gasoline-prices.

Trivyza, N.L., Rentizelas, A., Theotokatos, G., 2018. A novel multi-objective decision support method for ship energy systems synthesis to enhance sustainability. Energy Conversion and Management 168, 128–149.

United Nations, 2015. Paris agreement. . URL: http://unfccc.int/paris_agreement/items/9485.php.

U.S. Department of Energy, 2020. Hydrogen production: Electrolysis. . URL: `https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis`. office of Energy Efficiency Renewable Energy.

Valera-García, J.J., Atutxa-Lekue, I., 2018. On the optimal design of hybrid-electric power systems for offshore vessels. IEEE Transactions on Transportation Electrification 5, 324–334.

Van Biert, L., Godjevac, M., Visser, K., Aravind, P., 2016. A review of fuel cell systems for maritime applications. Journal of Power Sources 327, 345–364.

Van Nguyen, T., Knobbe, M.W., 2003. A liquid water management strategy for pem fuel cell stacks. Journal of Power Sources 114, 70–79.

Van Vu, T., Gonsoulin, D., Diaz, F., Edrington, C.S., El-Mezyani, T., 2017. Predictive control for energy management in ship power systems under high-power ramp rate loads. IEEE Transactions on Energy Conversion 32, 788–797.

Wang, X., Shipurkar, U., Haseltalab, A., Polinder, H., Claeys, F., Negenborn, R.R., 2021. Sizing and control of a hybrid ship propulsion system using multi-objective double-layer optimization. IEEE Access 9, 72587–72601.

Welaya, Y.M., El Gohary, M.M., Ammar, N.R., 2011. A comparison between fuel cells and other alternatives for marine electric power generation. International Journal of Naval Architecture and Ocean Engineering 3, 141–149.

Zhu, J., Chen, L., Wang, B., Xia, L., 2018. Optimal design of a hybrid electric propulsive system for an anchor handling tug supply vessel. Applied energy 226, 423–436.

A

COST DEVELOPMENTS OF THE INPUTS PARAMETERS FROM 2036 TO 2050

The prices for lithium-ion batteries and PEMFCs from 2036 to 2050 are following the same projections that adopted for the years between 2022 and 2035 [DNV-GL Maritime, 2019; DNV-GL, 2021b]. The lithium battery prices between 2036 and 2050 are expected to be 23%, 22%, 21%, 20.5%, 19.5%, 19%, 18.5%, 18.25%, 18%, 17.75%, 17.5%, 17.25%, 17%, 16.75%, 16.5% respectively of its price in 2019. The prices of PEMFCs are anticipated to be 51.5%, 51%, 50.5%, 50%, 49.5%, 49%, 48.5%, 48%, 47.5%, 47%, 46.5%, 46%, 45.5%, 45%, 44.5% of 2018 price.

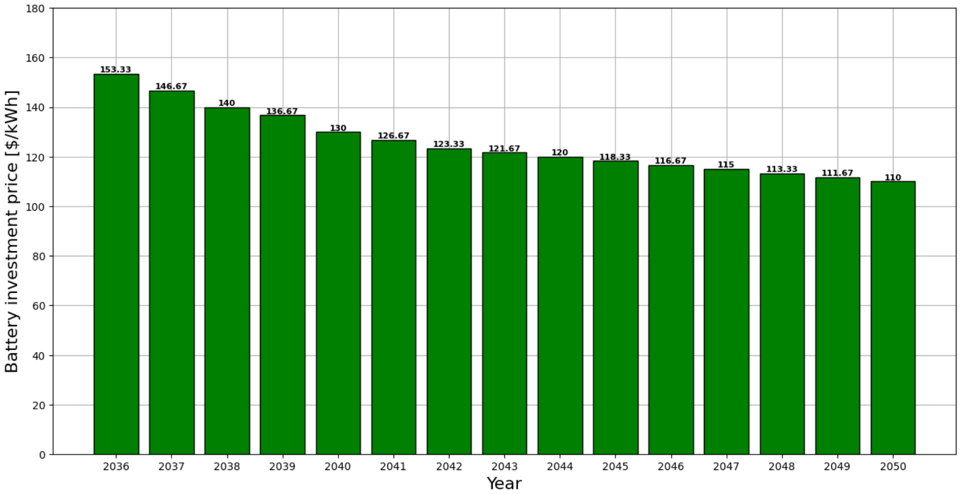


Figure A.1: Cost development of lithium-ion batteries [$\$/kWh$] for both future trajectories from 2036 to 2050

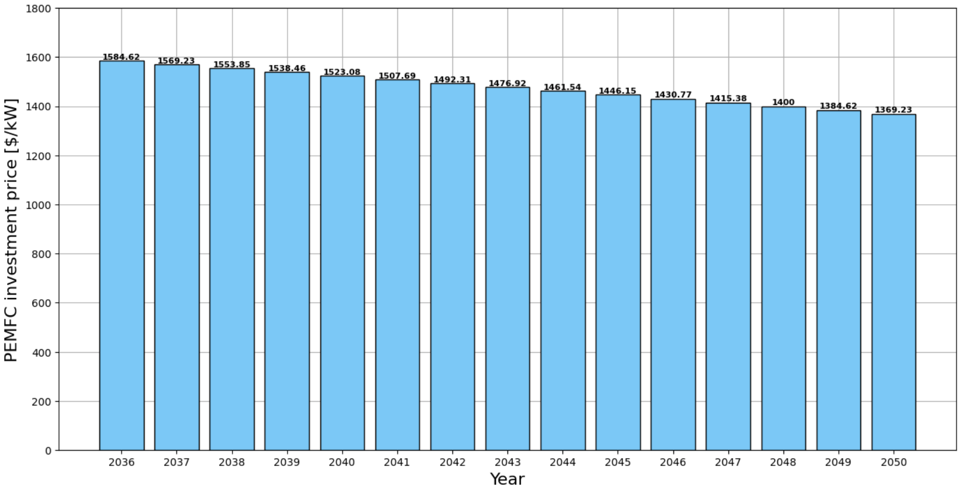


Figure A.2: Cost development of PEMFC [$\$/kW$] for both future trajectories from 2036 to 2050

A constant annual increase of 5% has been assumed through the years until 2050 for the diesel fuel price.

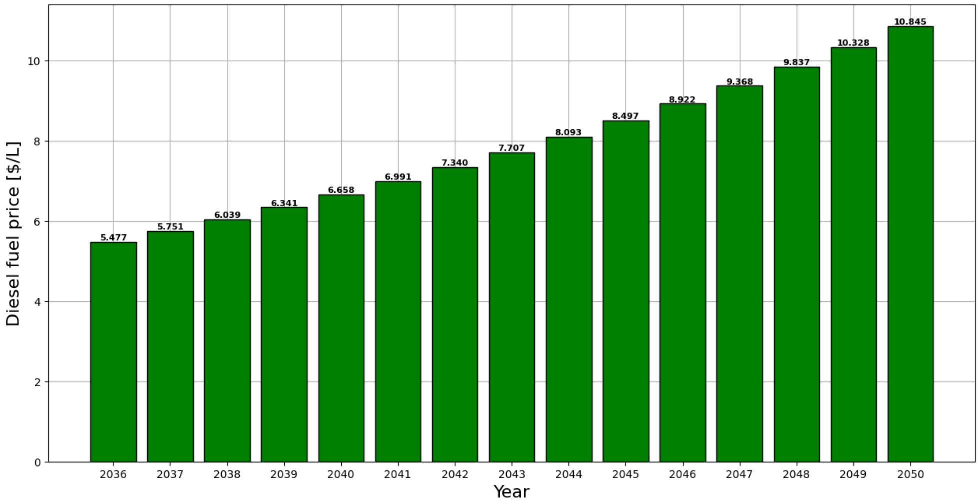


Figure A.3: Price development of Diesel fuel [$\$/L$] for both future trajectories from 2036 to 2050

An annual increase of $90 per ton of diesel per year was assumed for the following years until 2050 for the carbon tax.

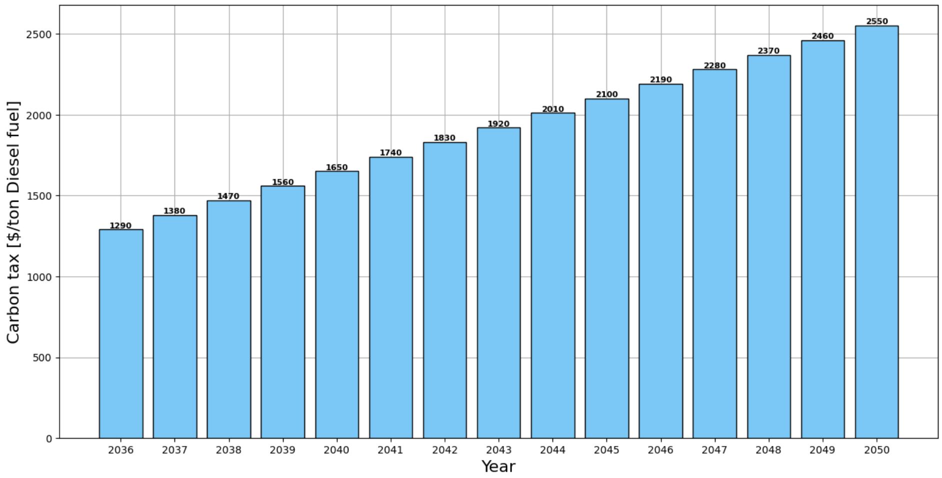


Figure A.4: Carbon tax [$ per ton of diesel fuel] for both future trajectories from 2036 to 2050

For the first scenario, a 10% decline each year is predicted for the price of electricity for the years after 2035 until 2050. A constant increase of 5% per year until 2050 is implemented for the second scenario. The cost development for the hydrogen was based again on PwC study. It was projected that the price of renewable hydrogen would not be lower than $\$1.75/kg$ or $\$0.071/L$ until 2050 and that is why it was kept constant from 2026 to 2050. The second scenario assumes that the hydrogen price will continue to rise over the course of the future by $\$0.25/kg$ per year from 2035 to 2050.

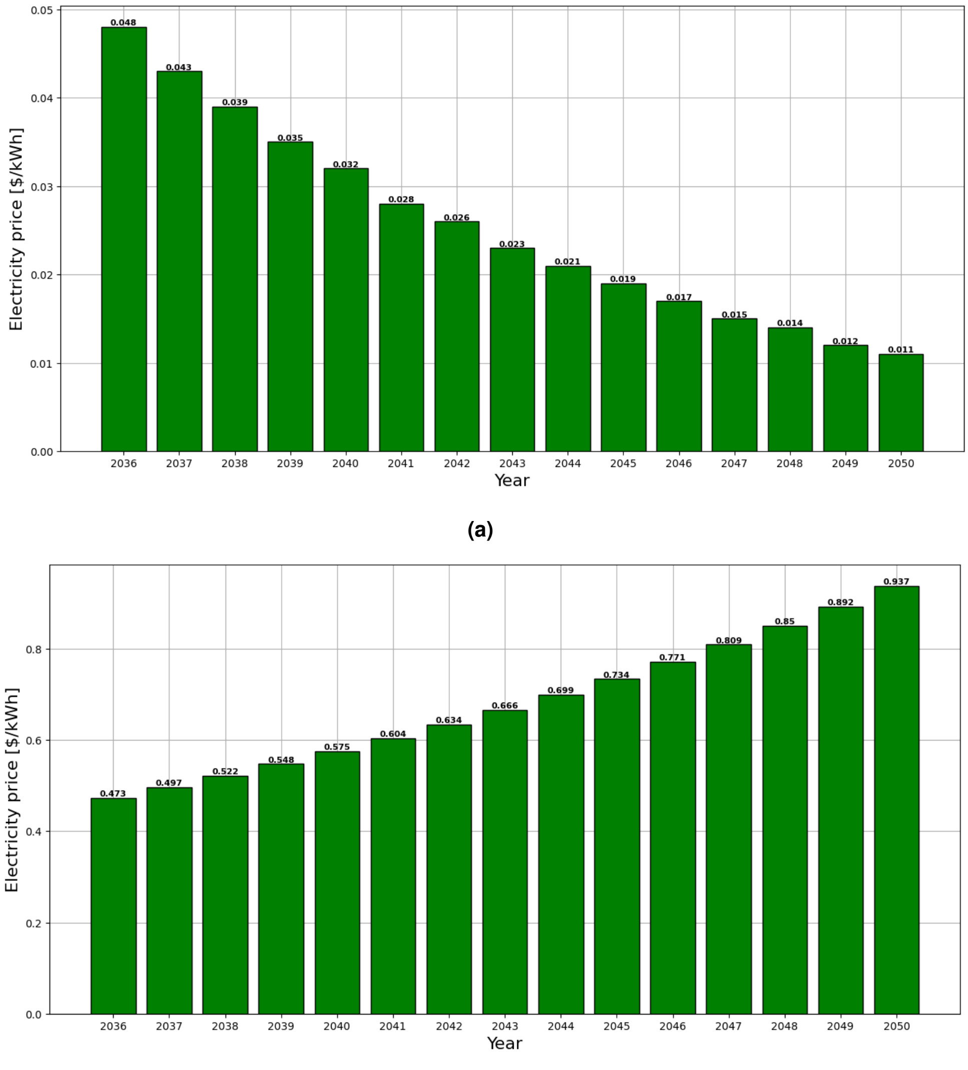
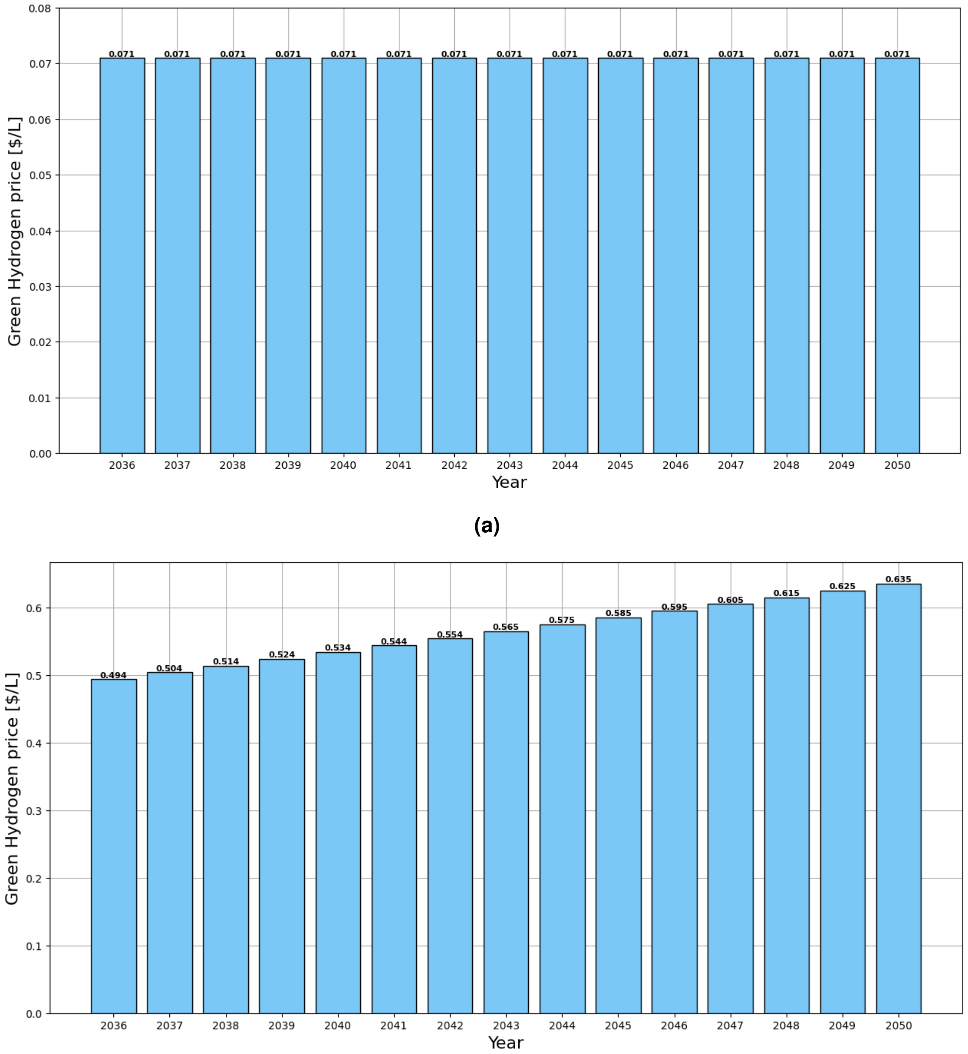


Figure A.5: (a) Electricity price development for the First Scenario from 2036 to 2050 (b) Electricity price development for the Second Scenario from 2036 to 2050



(a)

(b)

Figure A.6: (a) Green hydrogen price development for the First Scenario from 2036 to 2050 [PwC, 2020] (b) Green hydrogen price development for the Second Scenario from 2036 to 2050

B OPEX AND CAPEX BREAKDOWN FOR THE SECOND SCENARIO

B.1 OPEX breakdown

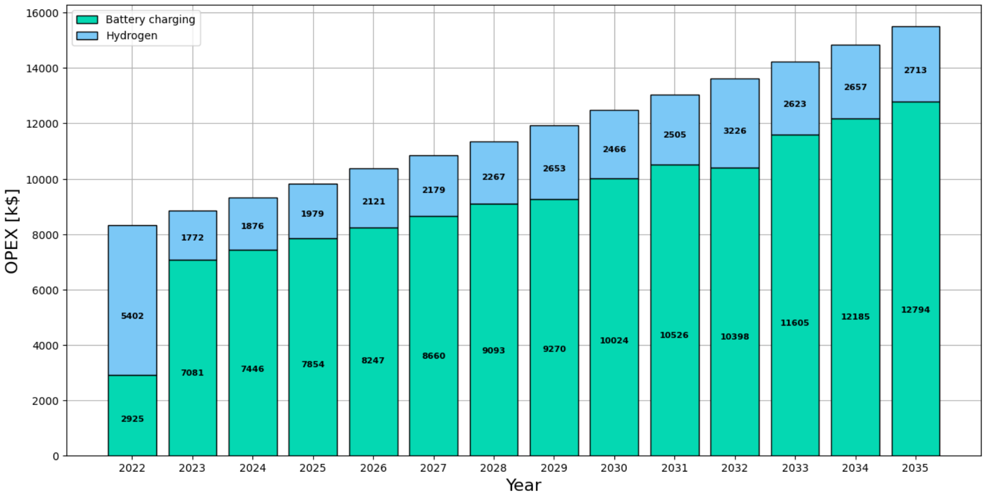
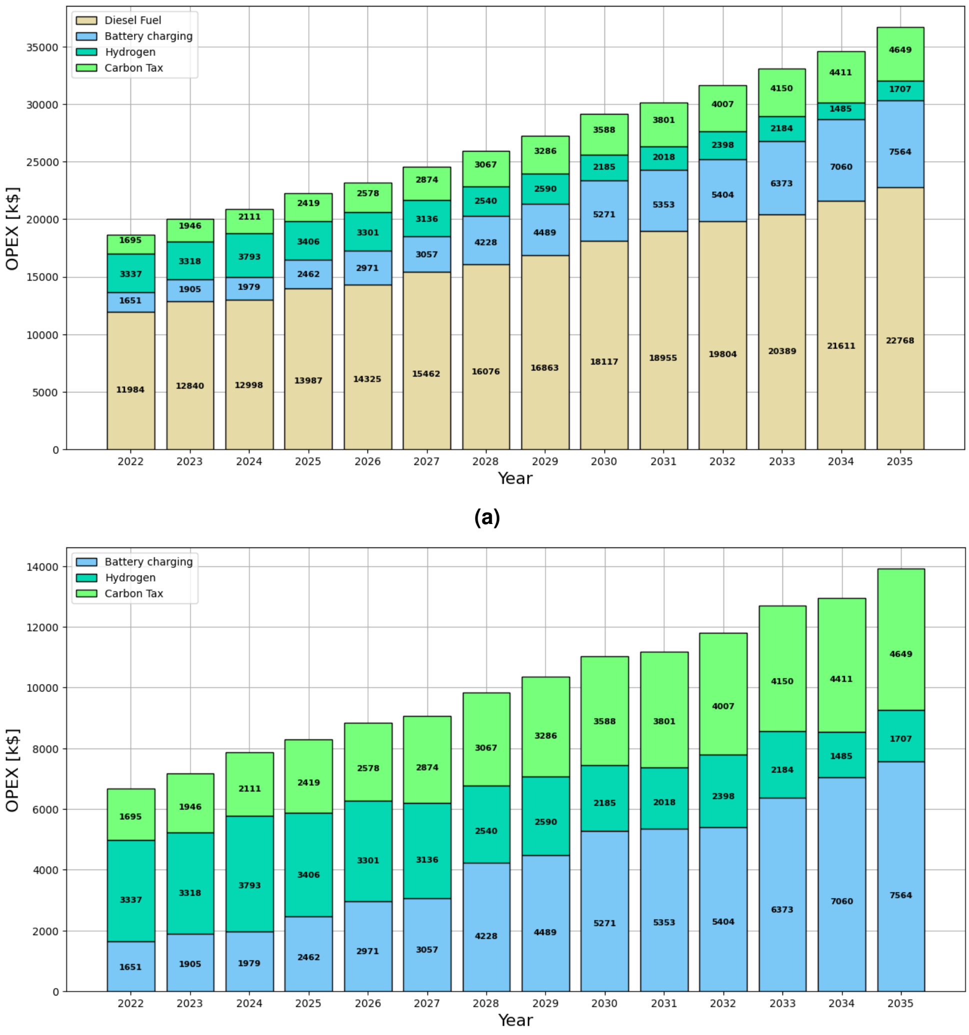


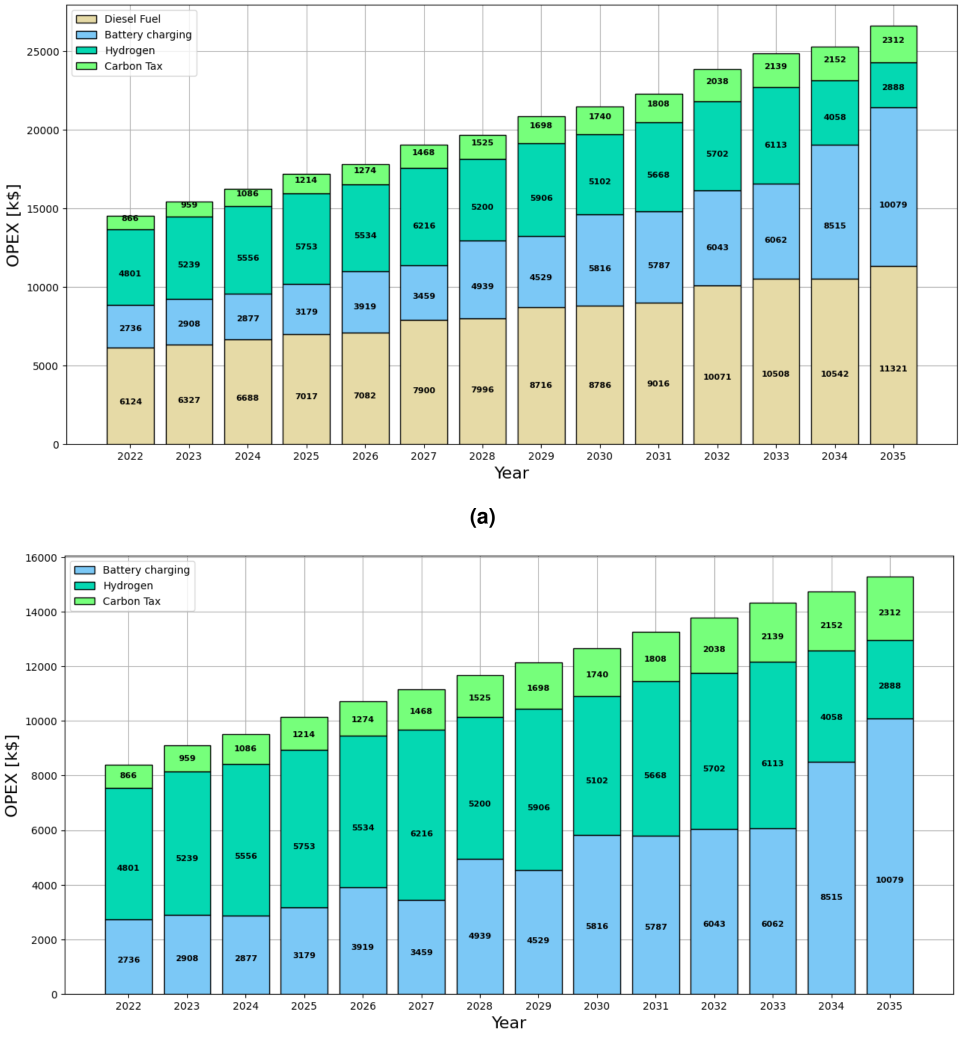
Figure B.1: Operational expenses breakdown for all-electric optimal solutions in the second scenario



(a)

(b)

Figure B.2: (a) Operational expenses breakdown for optimal solutions based on 50% emission reduction in the second scenario (b) A closer look on the upper section of the graph



(a)

(b)

Figure B.3: (a) Operational expenses breakdown for optimal solutions based on 75% emission reduction in the second scenario (b) A closer look on the upper section of the graph

B.2 CAPEX breakdown

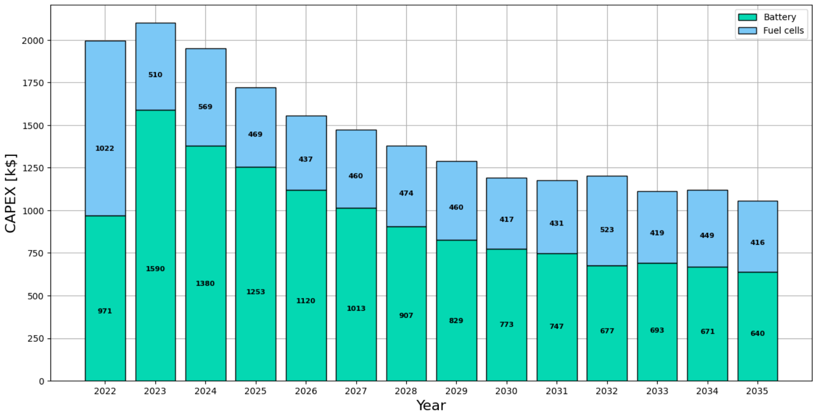


Figure B.4: Capital expenditures breakdown for all-electric optimal solutions in the second scenario

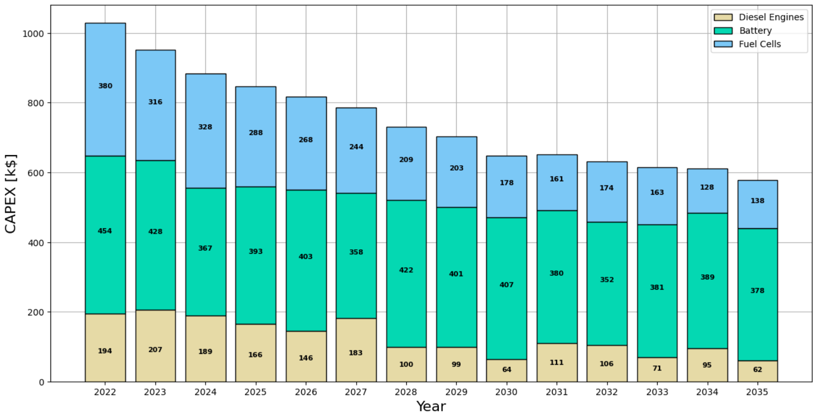


Figure B.5: Capital expenditures breakdown for optimal solutions based on 50% emission reduction in the second scenario

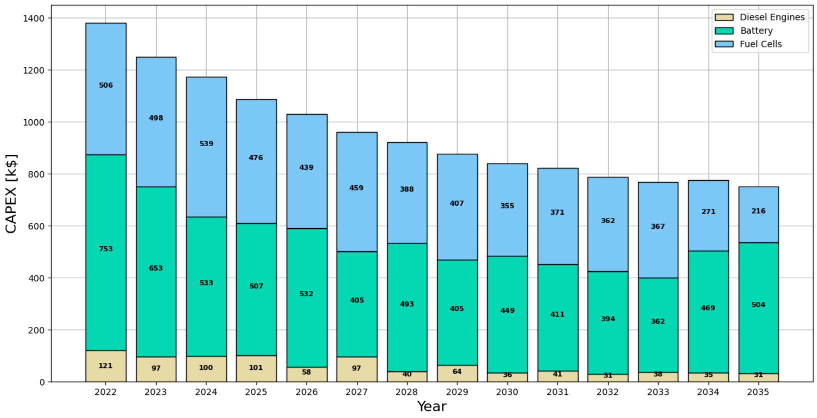


Figure B.6: Capital expenditures breakdown for optimal solutions based on 75% emission reduction in the second scenario


TUDelft