Zero-emission double ended ferries

A concept exploration study

W.T. Schot

August 2018

SDPO.18.018.m.

Zero-emission double ended ferries

A concept exploration study

by

W.T. Schot

in partial fulfilment of the requirements for the degree of

Master of Science
in Marine Technology

at the Delft University of Technology,
to be defended publicly on
Tuesday August 21, 2018 at 14:00 PM.

Report number:	SDPO.18.018.m.	
Student number:	4228189	
Project duration:	November 13, 2017 – August 21, 2018	
Thesis committee:	Prof. ir. J.J. Hopman	Delft University of Technology
	Dr. ir. R.G. Hekkenberg	Delft University of Technology
	Dr. ir. S. Schreier	Delft University of Technology
	Ir. R.A. Huijsman	Damen Shipyards

This thesis is confidential and cannot be made public until August 21, 2023.
Parts of this thesis that remain confidential after this date, are censored.

Abstract

Advancements in zero-emission technologies are making it increasingly possible to replace fossil fuel energy systems by zero-emission alternatives. As a result, within the maritime industry, double ended ferries using zero-emission energy systems are gaining interest and even already being built. However, it remains a long and costly process to determine which zero-emission energy system types are possible for which double ended ferries. The large amount of system types and the complexity of each type results in resource-intensive investigations when examining the full scope of possibilities. This is a hurdle for concept exploration in the early designs stage.

The goal of this thesis has been to develop a concept exploration tool for zero-emission double ended ferries, that determines the feasibility of different energy systems, creates corresponding design parameters and helps decide between zero-emission energy types.

The research goal was achieved in three steps. Firstly, knowledge was gained on double ended ferry design, double ended ferry operations, zero-emission energy systems and the early design stage. Research into zero-emission energy systems resulted in lithium-ion battery energy systems, hydrogen fuel cells energy systems and supercapacitor energy systems being identified as likely feasible energy systems for double ended ferries. In the second step, the knowledge was used to create the concept exploration model. This model consists of a set of algorithms that determines technical and economical parameters of double ended ferry concepts for each of the identified zero-emission energy types, for a provided transportation need. The model also does this for a diesel-electric energy system, that serves as a benchmark. Equal economical comparison of the concepts is aided by providing the net present value of the investment in the energy system, for each concept. In the third step, the model is transformed into the concept exploration tool, through implementation in the Python programming language. This step also includes obtaining results from the concept exploration tool.

One use of the concept exploration tool is by shipyards, in their early design process. The tool can provide naval architects with insights into which zero-emission energy systems are possible for a provided transportation need, as well as the characteristics of the corresponding concept designs.

A second use for the concept exploration tool is the analysis of large amounts of input. This can provide insights into how design input parameters influence the concept designs and the preferences for certain energy system types. This was done by performing a parameter variation study. The results of analysing the obtained data are expressed through 24 conclusions. These are divided into four sets, per party for which the conclusions are expected to be of the highest interest. These are Energy System Suppliers, Governments, Ferry Operators and Shipyards

The most important conclusion of this thesis is that zero-emission energy systems are technically feasible and can be cost competitive with diesel-electric energy systems. This to such an extent, that they should be seriously considered for every double ended ferry. Based on the net present value of the energy systems over the vessel lifetime, battery energy systems are most frequently cost-competitive with diesel-electric systems. Hydrogen energy systems are only competitive in highly specific cases and mostly too expensive to be cost competitive with diesel systems. Supercapacitor energy systems are cost competitive when upward of 30 daily trips are sailed, over short distances.

Acknowledgements

This thesis marks the end of my journey at the Technical University in Delft. The path leading me to this point has been filled with amazement and awe. Time and time again the intricacies of technological advancements have surprised me and kept me captivated. However, the passion of the people involved in developing these advancements has been the most inspirational part of my journey.

I would like to thank all the people from Damen Shipyards for their enthusiasm and help whenever I faced challenges or simply during conversations about future technological developments. The many conversations about a zero-emission future, have been a true inspiration. In particular, I would like to thank Renger Huijsman for being my daily supervisor at Damen Shipyards. Your feedback and our sparring sessions have been invaluable in writing this thesis.

Additionally, I would like to express my gratitude towards Hans Hopman, my supervisor from the TU Delft. His very constructive feedback and clear interest in the subject matter resulted in very productive, enjoyable and motivating meetings.

Next, I would like to thank my parents, my sister and my brothers for their support and encouragement. Through the high and low points of this journey I knew that I could always count on you. And last but certainly not least, I would like to thank my girlfriend. I greatly value your support and admire your attitude towards pushing boundaries.

W.T. Schot
Delft, August 2018

Nomenclature

Abbreviations

AC	Alternating Current
AEQ	Automotive Equivalent
AFC	Alkaline Fuel Cell
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditures
CFD	Computational Fluid Dynamics
CPP	Controllable Pitch Propellers
DC	Direct Current
DOD	Depth of Discharge
FEC	Full Equivalent Cycles
FESS	Flywheel Energy Storage System
FPP	Fixed Pitch Propellers
GPS	Global Positioning Satellite
GT	Gross Tonnage
GUI	Graphical User Interface
HVAC	Heating Ventilation and Air Conditioning
IMO	International Maritime Organization
KVC	Knowledge Value Chain
LAES	Liquid Air Energy Storage
LCB	Longitudinal Centre of Buoyancy
LFP	Lithium Iron Phosphate
LTO	Lithium Titanate
MCFC	Molten Carbonate Fuel Cell
MDO	Marine Diesel Oil
NiCd	Nickel Cadmium
NMC	Nickel Manganese Cobalt Oxide

NPV	Net present value
OPEX	Operating Expenses
PCU	Passenger Car Equivalent
PEM	Proton Exchange Membrane
R&D	Research and Development
SOFC	Solid Oxide Fuel Cell
SOLAS	International Convention for the Safety of Life at Sea
SSP	Siemens Schottel Propulsor

Symbols

Δ	Displacement	$[t]$
γ	True wind angle	$[rad]$
η_H	Hull efficiency	
η_r	Relative rotative efficiency	
η_O	Open water efficiency	
η_i	Ideal axial efficiency	
η_s	Shaft efficiency	
η_{gb}	Gearbox efficiency	
ρ	Water density	$[kg/m^3]$
Af	Frontal area	$[m^2]$
B	Beam of the vessel on the waterline	$[m]$
C_B	Block coefficient	
C_{TL}	Telfer Coefficient	
C_T	Thrust loading coefficient	
C_x	Aage-Brix wind-force coefficient	
D_p	Propeller diameter	$[m]$
$F_{n\Delta}$	Displacement Froude number	
g	Gravitational acceleration	$9.81[m/s^2]$
H_s	Significant wave height	$[m]$
ke	Amount of engines per shaft	
kp	Amount of propellers	

L_b	Distance of the bow to 95% of maximum beam on the waterline	$[m]$
L	Ship length	$[m]$
L_{pp}	Length between perpendiculars	$[m]$
L_{wl}	Load waterline length	$[m]$
P_b	Engine break power	$[W]$
P_e	Effective power	$[W]$
q	Dynamic pressure of the apparent wind	$[kg/ms^2]$
$R_{aw-STA1}$	Added wave resistance using STAwave-1 method	$[N]$
$R_{aw-Kreitner}$	Added wave resistance using Kreitner method	$[N]$
R_T	Total resistance	$[N]$
R_{wind}	Added wind resistance	$[N]$
t	Thrust deduction factor	
T	Draught	$[m]$
$\check{u}$	True wind speed	$[m/s]$
u_a	Apparent wind speed	$[m/s]$
V	Sailing speed	$[m/s]$
v_s	Sailing speed	$[m/s]$
v_w	Wind speed	$[m/s]$
w	Wake fraction	

Contents

1

Introduction

Double ended ferries are ferries with an identical bow and stern. This gives double ended ferries equal performance sailing forward and backward. The need to turn the vessel around when changing sailing direction is thereby removed. The resulting time savings are a large contributor to their worldwide application in transport systems; whether travelling over the IJ-river in Amsterdam for your daily commute, crossing the Amazon river in a 4x4 or exploring the Hong Kong metropolis waterways. Urban and rural areas in many countries rely on double ended ferries as an essential part of public transport.

Two examples are Norway and Canada, where the large amount of waterways and lakes challenge conventional transport by road. Both countries use large fleets of double ended ferries for providing their public transport. In 2016 people travelled via boat in public transport in Norway 11.4 million times, this is equal to more than twice the countries' population[61][60]. That same year BC-ferries, the largest operator in British Columbia, transported 8.3 million vehicles and 21.0 million people[28]. Most of the double ended ferries operated are done so over relatively short trip distances. It is there where the time savings from the use of double ended ferries have the largest impact on the total trip time.

An effect of the relatively short distances over which double ended ferries operate, is that they have a low energy consumption per trip. At present time the vast majority of operating double ended ferries fulfil this energy consumption by burning fossil fuels. This whilst the low energy consumption per trip makes the ferries suitable candidates for the use of zero-emission energy systems. There are multiple reasons for the use of such systems in favour of fossil fuel energy systems.

Firstly, the current fossil fuel driven ferries pollute the environment by discharging pollutants into their environment during operation. These pollutants contribute to climate change and negatively affect the environment the ferry operates in. Secondly, the availability of fossil fuels is limited. The operation of ferries in the current manner is not sustainable in the future, as fossil fuel reserves will be depleted. Thirdly, the price of renewable zero-emission energy is dropping within the range of fossil fuel energy prices [13], increasing the cost competitiveness of ferries using this energy. This trend is a result of price decreases of energy storage components, occurring due to increasing scale effects in production cost.

1.1. Problem statement

Current improvements in technology are making it increasingly possible to implement zero-emission energy systems in newly built and existing double ended ferries. At the same time cost decreases are making these systems increasingly financially feasible. The problem is that **there is no clear point**

from which an increasing possibility becomes a possible reality. This stems from the large amount of types of zero-emission energy system and the complexity of each type. To fully asses the feasibilities of zero-emission energy systems for double ended ferries, each type needs to be investigated for each design case. The result is a lot of work and an inefficient design process.

1.2. Research goal

The key to solving the stated problem is data driven decision making. Data is the starting point for exploration of zero-emission double ended ferry concepts. A framework that uses data to create concept designs, can provide insights into what are possible realities. Through exploring concepts based on different energy system types, case-specific and general decisions are aided. By varying parameters within the framework, insights into their influence on possible realities can be established. To achieve this the framework is needed. Therefore, the **main research goal** of this thesis is:
Develop a concept exploration tool for zero-emission double ended ferries that determines the feasibility of different energy systems and creates corresponding design parameters, which helps decide between zero-emission energy types.

The concept exploration tool can be used to analyse large amounts of data to provide insight into the parameters influencing zero-emission double ended ferries. These insights support the decision making between zero-emission energy system types and the influence of parameter variations on this choice. The concept exploration tool can also be used for single design cases, to show feasible zero-emission double ended ferry concepts.

1.3. Research structure

The development of the concept exploration tool and parameter variation analysis, was done in a structure following a section of the steps of the knowledge value chain (KVC). The section from data acquisition to intelligence application was followed.

The knowledge value chain is a model that illustrates the path from data to value. The intermittent steps determine if, how en with what efficiency an organisation can create value from its resources. This path is shown in Figure 1.1. This path is chosen as the structure for this thesis as up to the application of intelligence, the KVC describes the process of data driven decision making.

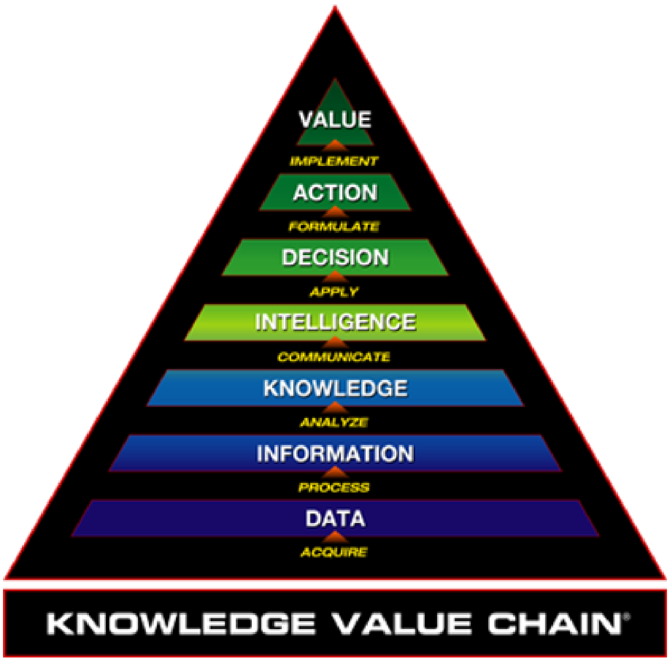


Figure 1.1: Knowledge Value Chain [54]

The structure of this thesis is split into three steps: Knowledge acquiring, Model development and Results extraction. In each part, certain sections of the path of the knowledge value chain are completed. The steps are discussed in the order in which they occur from bottom to top in the KVC. Figure 1.2 shows which sections of the KVC are completed in which steps, along with the corresponding chapters and subjects.

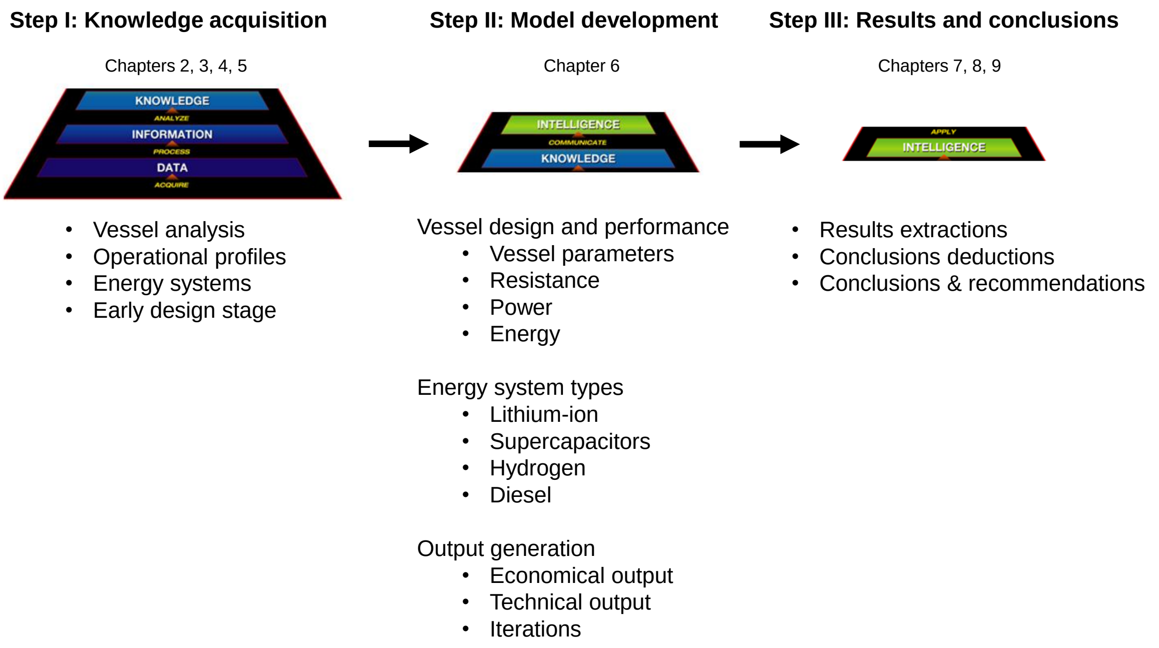


Figure 1.2: Research steps from left to right; I, II and III

This structure is set up as a certain flow of information is needed to achieve the end results. The knowledge acquired in step I forms a basis for the model development in step II. This basis consists of numerical knowledge and more general knowledge insights. Step III contains the results and conclusions. Using insights gained in step I the process of result extraction from the model is set up and explained. From these results conclusions and recommendations for zero-emission double ended ferries are finally derived.

The three steps in which the research is structured are discussed in more detail in the following subsections. For each step, a set of research questions is formulated to dictate the course of the research. The questions related to vessel design, vessel operations, energy systems, early design stage and model development are not questions that need to be or will be explicitly answered in this thesis. The questions serve to guide the path of developing the concept exploration tool. The questions related to the parameter analysis are explicitly answered by a set of conclusions discussed in chapter 8.

1.3.1. Step I: Knowledge acquisition

The first step in the development of the concept exploration tool is obtaining knowledge of the concepts that are to be explored: zero-emission double ended ferries. This knowledge is obtained through the first three parts of the knowledge value chain, as seen in most left in Figure 1.2. The knowledge required is split into four parts; vessel design, vessel operations, energy systems and the early design stage.

Vessel design
First, to explore vessel concepts and create concept designs knowledge regarding the design of double ended ferries is discussed in chapter 2.

- What are the characteristic design aspects of double ended ferries?

Operational profiles
Second, knowledge is needed on where double ended ferries are used for. When exploring and creating vessel concepts their usage has a high influence on the design and the requirements for the used energy systems. This usage can be captured in the operational profile and corresponding performance values, which are discussed in chapter 3.

- What are the operational profiles of currently operational double ended ferries?
- Are double ended ferries still relevant in the future?

Energy systems
Third, knowledge is needed on which energy systems are capable of providing the double ended ferries with zero-emission energy. In exploring zero-emission double ended ferry concepts knowledge on the technical and economical characteristics is essential for useful concept designs. By using knowledge gained on operational profiles, the most likely feasible candidates are filtered from all possible zero-emission energy system types. These candidates are described in chapter 4.

- Which zero-emission energy system types could be effectively used in double ended ferries?
- What are the technical and economical characteristics of these system types?

Early design stage
Lastly, knowledge on the early design stage is obtained. The concept exploration of zero-emission

double ended ferries takes place in the early design stage of the shipbuilding process. Which information and data are available during this stage is essential for developing and using the tool, and is explained in chapter 5.

- Which demands and variables influencing double ended ferry design are known in the early design stage?
- Which demands and variables can be used to establish concept designs for a concept exploration tool?

1.3.2. Step II: Model development

The second step is to communicate the knowledge to create intelligence. This is done by using the gathered data, information and knowledge, to provide intelligence. In the form of a set of algorithms, intelligence on the relations between design variables, fixed demands and energy system parameters is formulated. By combining these algorithms and creating the applicable linkages between them, a model for the concepts exploration of zero-emission double ended ferries is developed. This process is completed in three parts as indicated in Figure 1.2, where the subjects of the algorithms developed in each part are shown. The final step in model development, is to lower the hurdle that prevents knowledge from being used for decision making by making intelligence in the model easily accessible for application. To facilitate this, the model developed will be automated in a tool which generates the energy system parameters and corresponding vessel design parameters when given input.

Step II is described in chapter 6 and uses the research questions below as a guide.

- Which factors dictate double ended ferry designs?
- What determines the feasibility and desirability of a double ended ferry?
- How can the relations between the design input, energy system parameters and vessel design be captured in a design method or algorithm?

1.3.3. Step III: Results and conclusions

The tool makes intelligent easily accessible for single case analysis at a shipyard, and functions as an output of this thesis. Secondly, the tool is used for the analysis of the parameters influencing the design, operations, feasibility and desirability of double ended ferries. This analysis adds new insights to current intelligence and stimulates the use these insights for deciding between zero-emission energy types. The third step in the research structure, using the questions related to parameter analysis, is described in chapter 7 and chapter 8

- What is the influence of individual parameters on energy system type feasibility and desirability?
- Which individual parameters dictate the location of the tipping point of feasibility and desirability?

1.4. Scope

The scope of this thesis is firstly defined by the vessel type; double ended ferries. Only considered are double ended ferries transporting passengers and vehicles with a shuttle service sailing profile. Other vessel types will not be explored. Double ended ferries transporting only passengers are not within the scope. The applicability of this research to other vessel types will not be thoroughly investigated. **Within the design of double ended ferries, the energy system will be the focus point. This system begins with the energy type specific components at the terminal and ends with electrical power going to the electrical engine.** Aspects investigated include, but not limited to, energy storage, energy transfer and energy release. The system boundaries are chosen as such because the system that stores the energy on land and transfers this to the vessel can greatly influence the technical parameters of the energy system. The costs of this land-based system and the cost of having energy at the dock are also of importance to the study. The considered energy system ends when stored energy has been converted to electrical energy flowing to the electrical engines. This is due to the large number of options and motives that come in to play when choosing the propulsion system to transform the available energy to the water.

In this thesis the definition of zero emissions is crucial. The definition used is that only during operation must the energy system produce zero emissions. Recommendations for the production of energy supplied to the land-based facilities will be made, but is ultimately beyond the control of a shipbuilder. Financial calculations based on the energy cost for the operation of the vessel will make use of renewable energy sources. Hereby the cost is assumed to be constant over the time of day.

The concept exploration tool will depend on the details of the operational profile and known design variables/demands in the early design stage. As this thesis is written at Damen Shipyards Gorinchem, the early design stage process is assumed to be in line with the process at this shipyard.

1.5. Future double ended ferry market

Although this thesis focuses on zero-emission energy systems for double ended ferries, it is only reasonable to take one step back and question the usage of the ferries themselves. Are ferries still going to be a part of public transport in the future? The short answer is yes, but for the long answer one must consider that ferries are not the optimal solution for every scenario. Drawbacks of ferries are that they provide a discontinuous form of transport, which makes the users highly dependant on the ferry schedule. Ferries are also a relatively slow manner to cross a body of water in comparison to a bridge and they are more dependant on weather conditions than road or tunnel transport. These aspects of ferry transport might be incentives for governments to replace ferry lines by bridges or tunnels in the future. The Norwegian Public Roads Administration already (October 2017) has plans to replace seven ferry routes by other connection forms to reduce the travel time between the north and the south of Norway [5]. This example shows that governments are continuously eliminating inefficiencies from their nations public transport plan and that some of these might be ferries.

The second part of the long answer underlines that there are scenarios where ferries are a favourable choice for public transport. In urban areas, such as the IJ-river area in Amsterdam, some ferries are still favoured over other connection forms [6]. This can be due to a variety of reasons such as safety, shipping access or finances. A feasibility study performed by CH2M Hill in 2016 concerning the replacement of the ferry connecting Gabriola Island to Nanaimo in British Columbia concluded that a fixed link would have a negative net present value (NPV). According to the study "The negative Net Present Values indicates that the present value of this project" [1]. The learning is that there is a future market for ferries, but some operating routes will be discontinued.

---

[1] "Gabriola Island Fixed Link Feasibility Study",CH2M Hill, January 2016

1.6. Zero-emission energy

Double ended ferries pollute the very environment their passengers live in. The vast majority of currently operating vessels discharge pollutants into their surroundings whilst operating, due to them obtaining their energy from burning fossil fuels. The byproducts of this combustion being the pollutants. For many decades this type of energy generation has been by far the most practical, cost-effective and widely implemented method across many industries. However, this is changing. There are currently feasible alternatives to fossil fuel energy systems that store renewable and not emit any pollutants when operating. Renewable energy means that it cannot be depleted. Examples of sources are the sun, wind, rivers and thermal energy from the Earth. The implementation of systems into ferries capable of storing and using renewable sources has already begun. There are ferries currently operating on supercapacitors, hydrogen fuel cells and battery-systems which operate on energy generated using solar panels, wind turbines, hydroelectric dams and geothermal plants. In chapter 4 these energy storage systems and generators will be explained further.

An important note to zero-emission energy is that it depends on what is part of the scope. As stated in section 1.4 the zero-emission system described in this thesis only concerns the operations of the ferry. Within this scope operating with zero emissions as a result is possible. But operating any ferry will cause emissions beyond this scope. Most industrial activities that companies and people perform cause the discharge of emissions to the environment. Firstly, the production of materials used in the components of a vessel will almost certainly have emissions as a byproduct. Second, the transformation of these materials to vessel components will need energy which can come from polluting energy producers. Third, the assembly of the components of a vessel again needs energy and tools of which the production is most likely not emission free. With these three processes that potentially emit pollutants into the environment and the vast amount of components and systems in a vessel, it is practically impossible to produce a 100% zero-emission double ended ferry. The ferry will only ever be 100% emission free if services and products from all of its suppliers and their suppliers and so on, back until the basic elements and sources from the earth, are obtained free of emissions. Even though this is not impossible, it is currently improbable to a very high extent. A quote that best illustrates what to make of this current improbability is:

> “*So many of our dreams, so many dreams at first seem impossible. And then they seem improbable. And then when we summon the will, they soon become inevitable.*”
>
> Christopher Reeve, *1996*

I

Knowledge acquisition

2

Vessel Analysis

Double ended ferries are the vessels focused on in this thesis. This chapter investigates current designs and design possibilities. The definition of a double ended ferry is discussed at the beginning. Subsequently, the occurring design variations of the superstructure are discussed. The chapter ends with a brief explanation of conventionally used energy systems in double ended ferries. It should be noted that this chapter does not aim to be an encyclopedia for double ended ferry design. Rather it discusses design aspects that turned out to be relevant for the development of the concept exploration tool in step II of this thesis.

2.1. Double ended ferry definition

According to the Cambridge Dictionary, a ferry is *"a boat or ship for taking passengers and often vehicles across an area of water, especially as a regular service"*[21]. This is exactly what ferries have been since people started providing the service of transport over a body of water. Currently the word "ferry" can refer to many specific types of vessel that are used to take passengers and/or vehicles across a body of water with regular service. The types depend o.a. on what they transport, the required speed with which they transport, where they transport and how often they transport.

One of these types of ferry is the double ended ferry, sometimes also referred to as bi-directional ferry or double-ender. This type of ferry has identical fore and aft bodies. This gives the ferry identical sailing characteristics in both sailing directions, eliminating the need to turn around when changing sailing direction. The mid-ship symmetry can be clearly seen in Figure 2.1 and Figure 2.2, which shows the Damen 8117 double ended ferry.

Figure 2.1: Damen 8117 double ended ferry - artist impression - side view [56]

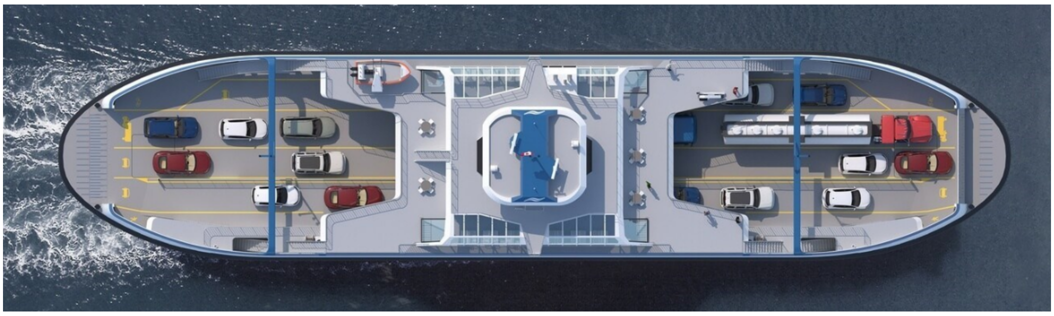


Figure 2.2: Damen 8117 double ended ferry - artist impression - top view [56]

Double ended ferries typically operate on relatively short routes, where the major demand is a short terminal time. Not needing to turn the vessel after every docking to orientate the bow in the sailing direction, contributes largely to fulfilling this demand. Another asset of double ended ferries is the absence of complicated manoeuvring when docking, as the vessel can sail straight into the terminal. Especially on busy waterways or areas with strong current, this eliminates potentially dangerous situations and reduces the stress on the captain and crew. A third benefit is that the handling of the ferry is the same at every departure or arrival, making the operations of the vessel more straightforward. Double ended ferries arrive and depart along the same route, whilst conventional ferries need to manoeuvre to re-orientate their bow. This manoeuvring time can take up a significant portion of the day depending on the amount of trips each day. Time that could be used to make more trips and increase transport capacity.

2.2. Above the waterline

Where hull shape of double ended ferries is fully symmetrical, for the superstructure and components this is not necessarily the case. For some components and design features, such as life rafts and kitchen areas, a symmetrically placed duplicate is not actually needed. This implies non-symmetry unless they are placed in the middle of the vessel. The condition within which these components and features can be non-symmetrical is that the longitudinal centre of buoyancy (LCB) must be in the middle of the vessel. Within this LCB demand however, there are many options for the design of the superstructure. As will be discussed in subsection 6.2.5, the general design of this superstructure influences the energy consumption. This means that the superstructure design also influences the concept exploration of zero-emission of double ended ferries.

2.2.1. Ro-pax design aspects

Ro-pax refers to vessels transporting passengers and vehicles. Within the ro-pax category, the types of vehicles that need to be transported influence the position of the deck-house and deck dimensions. The vast size range of cars and size trends in different parts of the world determine how many of each type fit in a certain space. Additionally, different operators use different lengths and heights for their standard car measurement. These variables all influence the design of the vessel. When an operator wants to be able to transport trucks, any superstructure above the vehicle deck needs to provide enough height clearance for the trucks to pass under it, as shown in Figure 2.3. A drawback to this is that the space above the normal cars is not used. A solution is then to add ramps at the sides of the vehicle deck, that act as double decks (Figure 2.4). The choice can also be made to place the entire superstructure next to the hull, as shown in Figure 2.5. This removes the physical height limitation and the complexity of an overspanning construction. A very small amount of vessels operating in the United States of America have the superstructure in the middle of the vessel. This is shown in Figure 2.6.

Figure 2.3: Height clearance for trucks [42]

Figure 2.4: Ferry with side ramp [42]

Figure 2.5: Ferry with open single sided superstructure [29]

Figure 2.6: Ferry with central superstructure [10]

In some cases, more vehicles need to be carried than a single deck can store on its surface area. Aside from increasing the vessel length and width, a solution to this is to add more decks. Some ferries do this by adding a second deck under the main car deck. A ramp is then placed in that deck, through which access is provided to the double bottom. An example of this can be seen in Figure 2.8. Another option is to add a second deck on top of the main deck. A picture of such a configuration can be seen in Figure 2.7.

Figure 2.7: British Columbia ferry with double deck [27]

Figure 2.8: Double bottom car deck [42]

2.2.2. Superstructure

The route that the double ended ferry is required to sail is dominant in the design. A first aspect of the route is the climate at the ferry route. This will determine the amount of shelter and comfort that the ferry needs to provide to passengers and cars. In cold climates, the superstructure must be quite advanced. It needs shelter the passengers from the weather and provide a warm place during transit. In warmer climates, too much heat can be a problem. The ferry must then provide a cool and shaded space. Therefore the design of the superstructure will change. In Figure 2.9 a ferry designed for Estonian waters and in Figure 2.10 a ferry designed for Gambian waters is shown. The superstructure of the Gambian ferry is much more open than the Estonian ferry and without heating, as the cold is not likely to cause any issues. A sun-tarp for shade and against the rain can be installed though. The Estonian ferry has a much more enclosed superstructure to shelter against the cold in the winter times. An exception can be seen in ferries travelling over very short distances. As passengers and cars are on the ferry for a very limited time, no accommodation for passengers or shelter for vehicles is provided. An example of this is shown in Figure 2.11

Figure 2.9: Cold climate ferry from Estonia [14]

Figure 2.10: Warm climate ferry from Gambia [47]

Figure 2.11: Ferry without accommodation [30]

The body of water that the ferry will sail over is a second aspect of the location. Ferries that sail in rough bodies of water must be designed to keep high waves from overflowing the car deck. Such a ferry is shown in Figure 2.12. If the ferry sails in sheltered waters, the watertight height can be much lower. The ferry shown in Figure 2.10 is an example of this. The height of the hull above the waterline is much lower than for the ferry designed for rough waters.

Figure 2.12: Ferry in rough waters [9]

2.3. Conventional energy systems

The energy systems that are currently most widely used in double ended ferries are diesel energy systems or diesel-hybrid energy systems.

2.3.1. Diesel

Conventional diesel energy systems operate solely by converting fossil fuel to mechanical energy and heat.

Energy storage and transportation The energy storage in conventional diesel energy systems only occurs in the form of liquid fossil fuel storage. The most widely used type of this storage liquid is

Marine Diesel Oil (MDO). The liquid is stored in tanks placed in the hull of the vessel. When a vessel runs out of fuel, the tanks are refilled at a fuelling station. These fuelling stations consist of large fuel tanks and pumps, which pump fuel from the large tanks to the vessels tanks.

Energy configuration Converting the energy stored in the liquid fuel is done using diesel engines. These are fed with the fuel from the tanks, which is burned in the engines to produce mechanical energy. This energy is transported to the propulsor via a rotating drive shaft. In some cases, a gearbox can be placed in between both to convert high speed and low torque rotation from the engines to low speed and high torque rotation for the propellers.

The energy configuration of diesel energy systems in double ended ferries can have multiple variations, but all double ended ferries have at least one engine room at each end of the vessel. The engines are directly or through a gearbox connected to the propulsor. A variation to this configuration is to have multiple engines connected to the gearbox in each engine room.

Auxiliary power The auxiliary power for conventional diesel-driven ferries can be provided in three ways. The first is to install separate diesel-driven generators whose sole purpose is to provide power for the auxiliary system. A second option is to add a shaft generator to provide auxiliary power when the vessel is sailing. The shaft generator is then in between the main engine and the propeller. The engine can only power the shaft generator and propellor simultaneously in this configuration. A third option is possible when a gearbox is installed on the vessel. The shaft generator can then be connected to the gearbox through a separate shaft, which enables the main engine to provide power to the shaft generator en propeller simultaneously and separately.

2.3.2. Diesel-hybrid

Diesel-hybrid energy systems use a combination of electrical and diesel engines to produce the mechanical energy going to the propulsor, but all energy is still generated by burning fossil fuel.

Energy storage and transportation Energy storage is the same as for conventional diesel systems; only in a liquid fossil fuel. The transportation of the energy occurs in both electrical and mechanical form. The electrical transportation occurs from the diesel generators to the electrical engine and the mechanical transportation occurs from the electrical and diesel engines to the propulsor.

Energy configuration Energy conversion in diesel-hybrid propulsion is done by diesel engines. The difference with conventional diesel systems is that some diesel engines are coupled to a generator unit. This generator converts the mechanical engine from the diesel engines to electrical energy. This electrical energy flows to the switchboard from where it is redirected to the auxiliary vessel systems or the electrical engine. This electrical engine is connected to the propulsor through a gearbox and converts the electrical energy it receives from the switchboard to mechanical energy going to the propulsor. Multiple diesel-generator combinations can be connected to the switchboard in this configuration. Additional to the electrical engine, a diesel engine is also connected directly to the gearbox. This allows the propulsion energy to come from the diesel generators through the electrical engine or directly from the diesel generator. Multiple configurations can be created with the hybrid system.

Auxiliary power In diesel-hybrid energy systems the auxiliary power is provided by the diesel generators.

2.3.3. Diesel-electric

Diesel-electric energy systems are systems that only use diesel generators to generate the energy needed to propel the vessel and supply auxiliary systems with energy.

Energy storage and transportation As with diesel and diesel-hybrid energy systems all energy is provided through the combustion of fossil fuels in the diesel engines. The energy is transported in electrical and mechanical form. Electrical energy from the diesel generators to the electrical engines and mechanical energy from the electrical engines, through the drive shaft, to the propulsor.

Energy configuration The energy configuration of diesel-electric energy systems differs from diesel-hybrid energy systems on the fact that only diesel generators are used to provide energy in diesel-electric systems. The are no diesel engines directly or through a gearbox, powering the propulsor. The configuration is such that multiple diesel-generators are connected to the main switchboard, through which the energy generated is distributed to one or multiple electrical engines. These drive the propulsor directly.

3

Operational profiles

In this chapter, the operational profiles of double ended ferries are analysed. This starts with an explanation of what an operational profile is. Subsequently, the operational profiles of currently operating double ended ferries are discussed. The operational profiles of future double ended ferries are then considered. These operational profiles are of interest to this thesis, as they provide knowledge into how double ended ferries are used and use dictates design.

3.1. Definition operational profile

The operational profile of a vessel describes how it is used. This description can contain the location, weather conditions, speed, sailing distance and many other factors that give information about the use of a vessel. Having accurate knowledge of the operational profile of the vessel will thus enable a design that is tailored to the use of the vessel. If this is not the case, there will be a mismatch between the use that a vessel was designed for and the actual use by the client. This is a bad situation for both parties; the client has a sub-optimal vessel for the intended use and the shipyard has not been able to provide the client with its best solution. Defining the operational profile of a vessel is thus an important part of the design process.

3.2. Operational profile current ferries

To provide some insight into the actual operational profiles of double ended ferries a database of double ended ferries was created. This database consists of 112 double ended ferries currently in operation. The data was obtained from either the operator of the vessel or the yard that built the vessel. All data was publicly available on their corresponding websites. The database is comprised of vessels from 8 companies; Fiskerstrand Shipyard, Damen Shipyards, Remontowa Shipyard, Sefine Shipyard, BC Ferries, Washington State Ferries, Caledonian Macbrayne Ferries and Rosetti Marino Shipyards. Vessels from these companies operate in North America, Europe, the United Kingdom and Africa.

Three types of sailing profiles could be distinguished from the available data; a shuttle profile, a round-trip profile and a line-service profile. For 17 vessels in the database, there was no route data available or they operated on multiple routes depending on the season. Of the remaining 95 vessels, 84 have a shuttle profile, 8 have a round-trip profile and 3 have a line-service profile. Ferries with the shuttle profile only sail between two fixed ports. With a round-trip profile, ferries sail between three or more ports where they return to the first port directly after leaving the last port of the round trip. When sailing with a line-service profile, ferries again sail between three or more ports and retrace their route back to the starting port after reaching the last port of the line. In between, they visit each port that was also visited on the outward journey. As 84 of the ferries in the database have a shuttle profile, these ferries were investigated in depth.

In this thesis, the database was firstly used to gain insight into operational profiles of currently operating double ended ferries and to gain general insight into the possibility of the use of zero-emission energy systems. Secondly, the data concerning the designs was used for the prediction of the vessel parameters in the concept exploration tool. This is described in more detail in chapter 6.

3.2.1. Trip distance

One of the main goals of this database is to gain insight into the distances that shuttling double ended ferries sail, how long it takes to sail these distances and how much energy they consume. To do this data from multiple sources needed to be combined. The first step was to find double ended ferries. Using various search engines and knowledge about shipbuilding, most of the vessel data was found on the websites of the vessel operators and the shipyards who built the vessels. Pictures from both types of sources usually showed the names of the vessels. This could then be used to find the shipyard that built a certain vessel for the known vessel operator or find the operator of a vessel found to be built by the known shipyard. The result being that data about the vessel parameters was usually more elaborate on the shipbuilders' website and that operational data was mostly more elaborate on the vessel operators' website.

For the majority of the 84 vessels, the ports between which the shuttling ferries sail are mentioned on the websites. In a small number of cases, the sailing distance was also mentioned. This presented the problem that this essential piece of data was not available for most vessels. The solution was found in combining Google Maps, www.afstandmeten.nl, known sailing distances and ferry departure/arrival ports. Google Maps shows the ferry routes of many currently operating ferries. The distance of the routes can be measured with the online route creating tool of www.afstandmeten.nl. The accuracy of these distances was validated by comparing them with the route distances given by some ferry operators. In Figure 3.1, the differences between the measured and given distances (in percentage of given distance) is shown for 43 ferries of which the operators stated the sailing distance. This shows that the majority of the measured distances is within a 7% bandwidth of the given data. This is accepted to be accurate enough to provide basic insight into the operational profiles of double ended ferries. Having this system to obtain the sailing distances of ferries and knowing the arrival and destination ports the, the sailing distanced could be determined. All from publicly available sources.

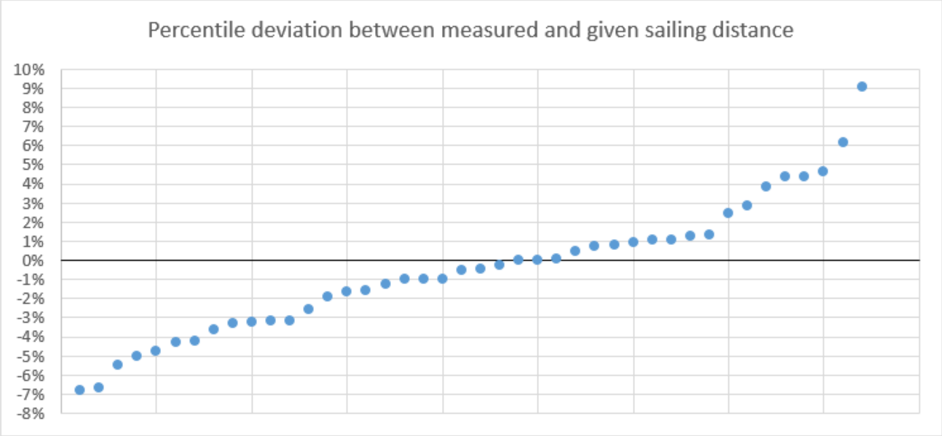


Figure 3.1: Deviation percentage between measured and given sailing distances

The described method to measure the trip distance of the ferries was used to determine the trip distance of each ferry with a shuttling profile, for which the sailing route was known. This resulted in trip distance data for 84 double ended ferries. The results are shown in the cumulative density plot shown in Figure 3.2. This figure shows that 30% of the vessels have a trip distance of 5km or lower, 64% lower or equal to 10km and 81% equal or lower to 15km. This tells us that the majority of the vessels in this database have relatively short trip distances.

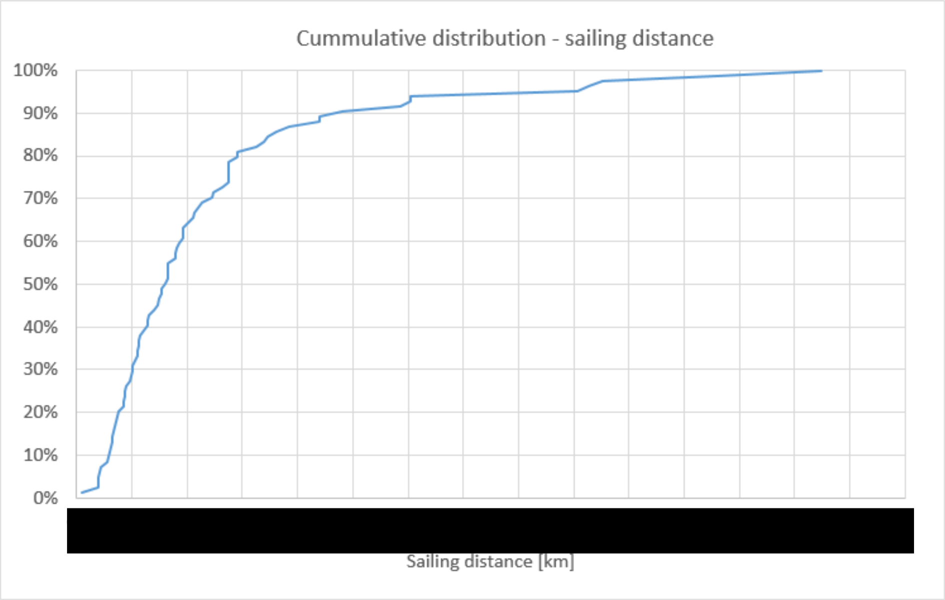


Figure 3.2: Cumulative density plot of the trip distances of double ended shuttle ferries

3.2.2. Trip time

A second aspect of the operational profile of a double ended ferry is the time it takes to complete the trip. This time is one of the factors determining the required energy capacity on board of the vessel. This sailing time was estimated for the vessels in the database by comparing corrected estimations with given data. Dividing the measured sailing distance by the known service speed gives the sailing time if the vessel always sails at full speed. To compensate for the fact that a vessel sails at lower speeds during manoeuvring, mooring, acceleration and deceleration, a correction factor is applied to this value. This value is determined by comparing the calculated sailing times with the given sailing times by some of the operators. When using a sailing time correction factor of 1.45 times or bringing the average speed back to 0.69 the service speed; the average difference between the calculated and given sailing time (in percentage of given sailing time), over the 31 vessels for which the sailing time is given, is 0% and the total sum is +4%. Overall this correction factor gives the lowest average deviation and the lowest sum of deviations. The difference for each of the given sailing times is shown in Figure 3.3. This shows that for a large part of the vessels with a sailing time below 20 minutes the estimation method underestimates the sailing time.

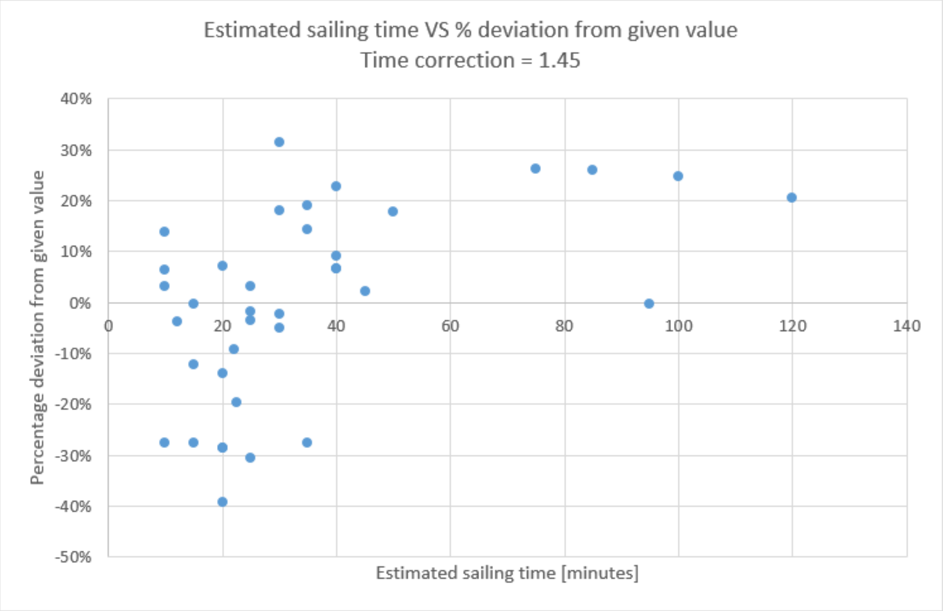


Figure 3.3: Deviations of estimated sailing times from given values for sailing time correction factor $1.45/V_{avg} = 0.69 * V_{service}$

The problem with the underestimation of the sailing times is that when they are used to calculate the needed energy capacity for a trip, this estimation will also be an underestimate with gives a false positive outlook for the application of zero-emission energy systems. This is due to the fact that a lower energy capacity per trip increases the possibility of a zero-emission energy system being feasible. A more desirable option would be to increase the correction factor to the point where none of the sailing time estimates are underestimates. That the other estimations will then become overestimates is less of a concern as one would rather sketch conservative boundaries for basic feasibility estimations than create boundaries that are overly favourable and possibly unrealistic. This results in a second correction factor of 2, which is equal to bringing the average speed back to half of the service speed. As shown in Figure 3.4 the underestimates of sailing times are almost reduced to zero.

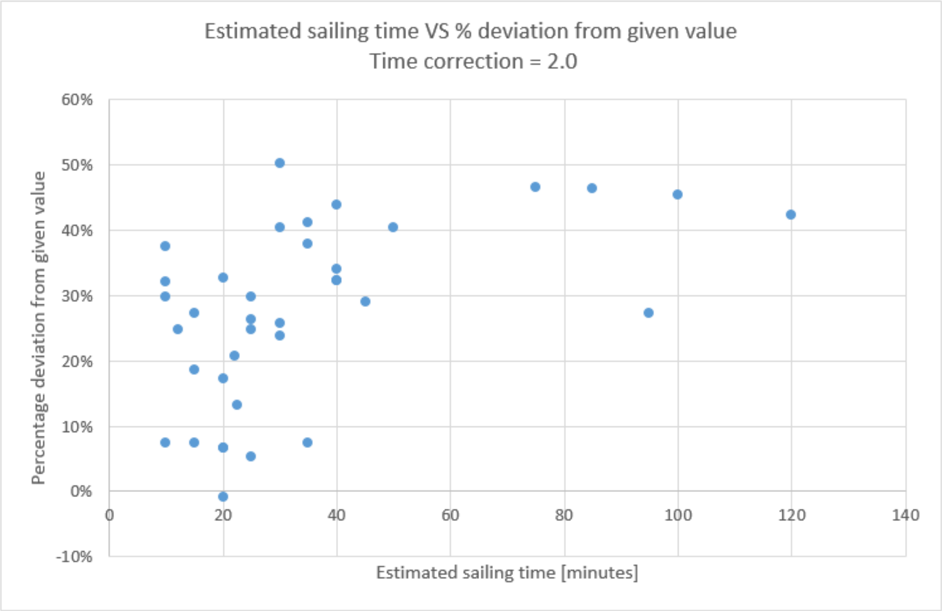
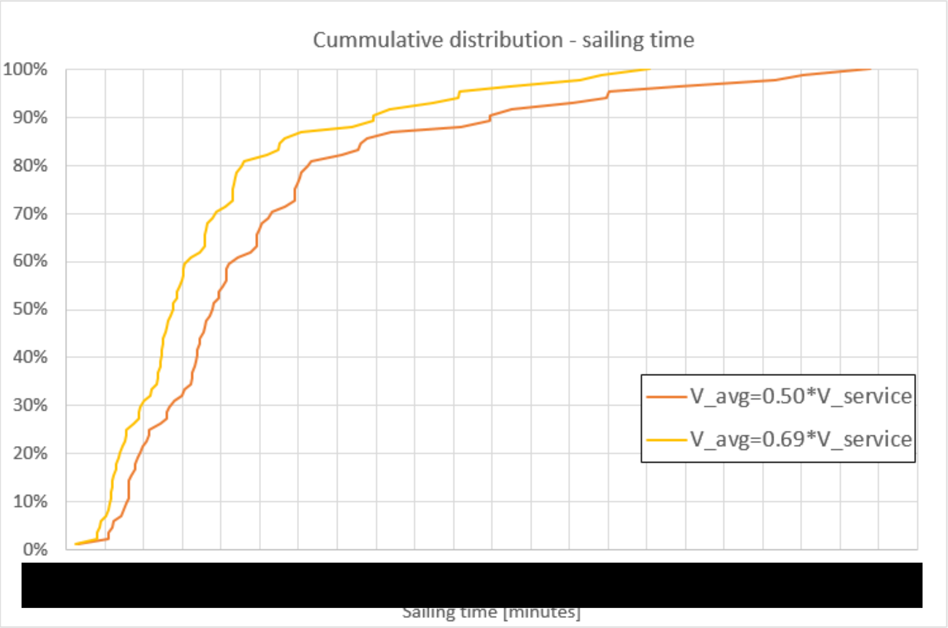


Figure 3.4: Deviations of estimated sailing times from given values for sailing time correction factor $2/V_{avg} = 0.5 * V_{service}$

It has now been established that correction factor for sailing time of 1.45 is optimistic and a factor of 2.0 more realistic and borderline pessimistic. When these are used in combination with the given service speeds of the vessels and the estimated trip distances (with a bandwidth of approximately 7% w.r.t. the given values) estimates can be made for the sailing times. The results are shown in the cumulative density plot in Figure 3.5. This plot shows that in the lower bound 32% of the vessels has a trip time lower or equal to 30 minutes and in the upper bound this value is 58%.



[redacted]

Figure 3.5: Cumulative density plot of trip time of double ended shuttle ferries

3.2.3. Trip energy consumption

An important factor in the feasibility of a zero-emission energy system for a double ended ferry is the amount of energy that the system needs to deliver during one trip. Having data on the energy consumption of currently operating double ended ferries will provide insight into the range of energy consumption of double ended ferries. This can be used to set and find general boundaries to which possible zero-emission energy systems must come close to justify further research. It is important to state that auxiliary energy consumption is not included in this estimate, due to the lack of vessel specific data.

The starting point for the energy estimation is the data in the cumulative density plot of the sailing times. The boundaries set by the lines in that plot can be transformed to energy capacities using the installed power on the vessels. Multiplying the sailing time by the amount of power installed on the vessel gives the energy consumption of the vessel if the engines run at full capacity during the whole trip. This is of course never the case. Therefore a correction factor must be applied. This correction factor is determined by the cubic relation between vessel speed and required engine power. One main assumption is that the maximum installed power is that used to achieve the service speed. This will result in a slight overestimation of the required capacity as the power consumption is always lower for the service speed. The overestimation is made as not enough data is available about the power at the service speed and it will ensure against projecting an overly optimistic low value of energy consumption. The cubic relation results in 0.125 times the maximum power being used on average if the average speed is half the service speed (sailing time correction factor of 2). For the sailing time correction factor of 1.45, the speed is 0.69 the service speed. Cubing this results in an engine correction factor of 0.328 times the maximum engine power being used on average. For both sailing time correction factors and engine correction factors, the energy consumption during one trip is shown by the lines shown in the cumulative density plot in Figure 3.6. To show what would happen to the energy consumption cumulative density lines if the needed power was to increase by 25%, two additional lines are plotted that show the respective plots.

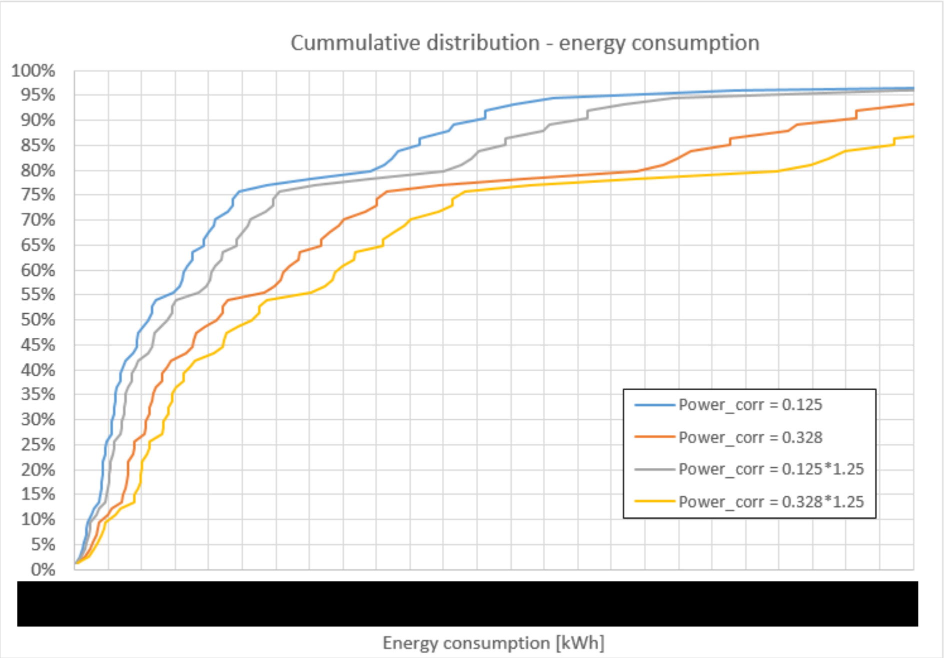


Figure 3.6: Cumulative density plot of the energy consumption of double ended shuttle ferries

3.3. Operational profile future ferries

The future of double ended ferry design is completely dependent on the future of double ended ferry use and need. The future transportation activities of the operators determine all of the design aspects of the ferries. When working on design aspects or design methods for these future ferries it is thus essential to gain knowledge about these future operational profiles. Some general expectations of future ferry operations are researched as also the data and methods with which operational profiles are determined in the early design stage.

3.3.1. Future need for ferries

The function of a double ended ferry is to transport people and vehicles over a body of water. This need is there because of bodies of water separating the areas where people live and work. In some cases, the water completely separates two locations and in other cases, transport over water is much faster than by land. This is true for rural areas and urban areas. The general outlook on the future is that people will keep living and working dispersed over the available land on Earth and that many of these people will be separated from places they want or need to be by bodies of water. This ensures the need for transport capacity over or under these bodies of water.

For the fulfilment of this transport capacity, ferries have competition from other transport options. The two major competitors being bridges an tunnels. Both of these options can replace the transport capacity provided by a double ended ferry. The biggest advantages of both competitors being that they provide a continuous transport capacity over the body of water and will be faster for crossing the body of water than by ferry. The second benefit of bridges and tunnels is that they are less under the influence of the weather than ferries. The financial drawbacks and benefits are highly case-specific, but generally, bridges and tunnels are much more expensive in initial cost but have lower operational expenses than ferries.

A major benefit of ferries is their flexibility. They can be deployed on several routes depending on the demand. Bridges and tunnels do not have this, which means that a high certainty of future transport demand in needed to justify the investment. Secondly, ferries have a very limited influence on the shipping traffic, whereas bridges can severely limit it. This benefit is especially the case in areas where many small ferries provide transport capacity over many routes. Replacing these with an equal amount of bridges imposes serious limitations over the shipping traffic in the area. Thirdly the space needed for tunnel entrances and bridge ramps is usually much higher than needed for the terminal of a ferry. This is an important factor in areas where land is scarce or expensive. When looking at rural areas where a low transport capacity is required over a certain route, the high investment of a bridge or tunnel is less easily justified in comparison with the cost of a small ferry.

The drawbacks and benefits of double ended ferries discussed above show some of the influencing factors when choosing for a ferry to provide transport capacity. In each specific case of transport demand, any of the factors discussed and many that were not discussed can play a role in the process of deciding how to fulfil the demand. What the discussion mainly shows is that none of the options is the sole solution for transportation over water, which means that the need for ferries in general and thus double ended ferries will not disappear in the future.

3.3.2. Future operational profiles

The operational profiles of ferries that will be built in the future, drive the research and development of double ended ferries. Ferries to be built in the future are split into two categories; new routes and replacement vessels. Predicting where future ferries will sail on new routes is difficult and uncertain, which means that it is not widely done. However, developing new solutions and concepts can be used to mould the demand for future ferries.

Currently operating double ended ferries will be replaced by a new one when they satisfy the transport demand, but have outdated systems and designs causing inefficient and/or unsafe operations. As the transport demand is clearly known, the design of these vessels can be highly specific to the demand case. General assumptions on the market development for double ended ferries can be made. [redacted] This provides a prediction of operational profiles of future double ended ferries and narrows down the field of interest for this research. As the majority of the ferries have a trip capacity toward the lower end of the spectrum, research in this area will most likely impact the most vessels.

3.4. Conclusions

To use the values for sailing distance, sailing time and energy consumption correctly for any further decisions it must be understood and summed up which assumptions and inaccuracies they are based on. The data is based on 84 shuttling double ended ferries for which the route was known. The sailing distances are measured using a method described in subsection 3.2.1. This method is validated using available data from vessel operators for the sailing distances. Of 43 vessel 92.8% are within a bandwidth of 7% of the given values by the operators. The largest deviation is 14%. The given values by the operators are assumed to be true as accurate actual GPS data of all vessels was not available. The measurement method is accepted as accurate enough to apply to the whole database for shuttling ferries. From these sailing distances, the sailing time can be estimated by using a correction factor for the service speed to determine the actual average speed over one trip. Correction factors are validated using sailing times available from vessel operators. The bandwidth for this estimation was very large with respect to 0% deviation from the given sailing time. For 1.45 or an average speed of 0.69 the service speed, the average deviation is 0%. To eliminate any underestimations w.r.t. the given times, a correction factor of 2 found, giving an average speed of 0.5 the service speed. To calculate the energy consumption, the power needed for the service speed is assumed to be the maximum and the engine power vs speed correlation is assumed to be cubic. This results in engine power correction factors that are cubic with respect to the sailing time correction factors. An important assumption for the energy consumption is that only the energy used for propulsion is accounted for due to the lack of data on auxiliary energy use.

Having stated the assumptions and inaccuracies, the information the data gives will be used for further analysis. The sailing distance distribution shows that the majority of the double ended ferries sails relatively short distances for their respective sizes. This is in line with what double ended ferries are generally designed for; short routes where removal of the need to turn at every docking reduces the trip time significantly. [redacted]

[redacted]

When looking at the feasibility of zero-emission energy systems, the energy capacity that the system needs to provide is a key factor. A higher required energy capacity increases the weight, volume and cost of the system. Therefore lower capacity requirements are positive for zero-emission energy feasibility. To provide a sober view regarding this, the focus should be on the most conservative estimate of the energy consumption of the shuttling double ended ferries in the database. [redacted]

The values that are obtained from the database serve as an indication of the operational profiles of current double ended ferries. The density plots will change if all double ended ferries currently operated in the world accounted for. However, given that this database consists of 112 double ended ferries, of which 84 in shuttling operations, operating over various types of waterways in a variety of countries and climates, there is information coming from a wide spread of areas. Thus it is deemed representative enough to make general conclusions about the operational profiles of current double ended ferries.

4

Zero-emission energy systems analysis

This chapter focuses on zero-emission energy systems. An analysis and comparison of a broad range of zero-emission energy systems were performed. This analysis provides knowledge on which types of zero-emission energy systems can be used in double ended ferries. Knowledge of how the systems work is essential for implementing them in the concept exploration tool. The characteristics of the candidates deemed likely feasible for double ended ferries are explained. The analysis of the energy systems that did not make this cut are explained in Appendix B.

4.1. Analysis structure

The energy systems explored in this thesis are defined as follows: **The energy system begins at the system specific components at the terminal and ends with the electricity going to the electrical engines on board the vessel** (section 1.4). For the "zero emissions", the definition used in this thesis is that only during operation must the energy system produce zero-emissions. The comparison and analysis of the possible systems is done by answering the following questions;

- How is energy stored? - *Energy storage*
- How is energy loaded to the storage system? - *Energy loading*
- How is stored energy converted back to usable energy? - *Energy conversion*
- How are the technical specifications determined? - *Technical specifications*
- What are the advantages? - *Advantages*
- What are the drawbacks? - *Drawbacks*
- Which support systems are needed in the terminal for the energy system? - *Terminal requirements*
- Is system used in currently operating vessels? - *Case studies*

Using the information about the different energy storage system types, some conclusions were be drawn with respect to the applicability for use in double ended ferries. This is to identify systems which can be excluded from further research due to obvious feasibility issues. The analysis of the excluded energy systems can be found in Appendix B. These are flywheels, compressed air energy storage, compressed air over water energy storage, liquid air energy storage and flow batteries. The energy systems that will be used in the further part of this thesis are described in this chapter. The performance values of the systems are given in Figure 4.6. At the end of the chapter research into electricity generation and regulations are discussed.

An important note is that the aim of this thesis is to provide knowledge and intelligence on the current application possibilities of zero-emission energy systems. There are many systems with much better performance than current systems that have future potential to function as energy storage system. But unless the specifications are of systems currently commercially available, they are not explored in this thesis. This is due to many established and new companies claiming to have found the so-called "holy grail" of energy storage. Researching the energy storage market it became obvious that there many unfounded claims of systems with extremely high performance stated on websites and in brochures. Regrettably, many of these companies fail to fulfil these promises or are still a work in progress.

4.2. Hydrogen

Energy storage, loading and conversion
The energy is stored in hydrogen. This can be stored in multiple different manners [31]:

- Compressed hydrogen - stored in high-pressure tanks
- Liquid hydrogen at -253 degrees Celsius. - stored in pressure tanks
- Bonded to a solid or liquid metal hybrid compound. - stored in tanks

- Chemically converted to ammonia or methanol - stored in tanks
- Chemically converted to synthetic natural gas - stored in high-pressure tanks
- Dissolved into liquids - stored in tanks

Energy loading of hydrogen depends on the state of the hydrogen. For converting hydrogen to usable energy, there are three methods; fuel cells, internal combustion engines and gas turbines.

Technical specifications
When looking for values for the efficiency, mass and volume of energy systems using hydrogen, the internet contains many values of varying reliability. Therefore only values from currently commercially available systems are used. In this way, the research is not based on predictions/promises of researchers and companies that have yet to prove their system parameters. Obviously, the values cannot be known to be 100% accurate, but they are deemed reliable enough for this research.

Hydrogen production and storage is essential to using a hydrogen energy system. Using electricity from renewable sources, hydrogen can be produced using electrolysis. Electrolysis is the process of using electricity to split water into hydrogen and oxygen. Multiple currently available Alkaline electrolysis systems (different sizes and companies) operate with an efficiency of 68% from input electricity to energy stored in produced hydrogen. There are also Proton Exchange Membrane (PEM) electrolysers that have an efficiency of 62% [43].

Having produced hydrogen, the next step is to store it. The most common methods as compressed, liquefied or cooled hydrogen. Hydrogen can be compressed to pressures up to 700 bar and stored in high-pressure tanks. This process has an efficiency of +/- 90% (1 kWh compression energy for each 10 kWh of hydrogen equivalent). Liquefied is obtained when hydrogen is cooled to its liquefaction temperature of -253 degrees Celsius. Liquefaction results in a large density increase. Storage is done in insulated non-pressurised tanks. Cooled hydrogen uses a combination of compression and liquefaction, as the hydrogen is cooled and compressed. The result is stored in cooled and pressurised tanks. Small-scale hydrogen liquefiers and coolers have an efficiency of +/- 65%, whilst larger efficiencies are possible at a large scale[43]. Cooled and liquefied hydrogen also need extra equipment, with respect to compressed hydrogen storage, to vaporise and heat the hydrogen before it can be used by the fuel cells. This reduces the total energy density. The impact of this reduction has the biggest relative impact on systems with a low amount of stored hydrogen. The result is that cooled and liquefied hydrogen storage are better suited for situations with a large energy demand or limited volume availability. For this reason and the large efficiency loss in comparison with compressed hydrogen, they are not further explored. Other types of hydrogen storage are excluded from this research due to technical feasibility and commercial availability reasons.

Fuel cells are electrochemical cells that convert chemical energy into electrical energy. Although there are multiple types of fuel cell types, the leading type is the proton exchange membrane fuel cell (PEM fuel cell). A fuel cell starts with bringing hydrogen into contact with the anode. This causes the hydrogen molecules to split into positively charged ions and negatively charges electrons. Next, the hydrogen protons pass through a polymer membrane (the electrolyte in PEM fuel cells) to the cathode. Whereas the electrons, which cannot pass through this membrane, flow to the cathode through an external circuit. Their flow hereby forms an electrical current. This part of the process recoups the energy used to form the hydrogen. Finally, at the cathode, the hydrogen protons and electrons combine with oxygen to produce water and heat (up to 90 degrees Celsius). This process is illustrated in Figure 4.1. Again the efficiency is determined using efficiency from presently available fuel cells made in different sizes and by different companies. The average efficiency of PEM fuel cells is 55%, from energy stored in the used hydrogen to net power output. Using an Alkaline electrolyser and under the assumption of no loss in storage, this leads to an efficiency of 37.4% from input electricity to output electricity.

Proton exchange membrane fuel cells are not the only type of fuel cell technology available. Other types differentiate themselves on the electrolyte, anode and cathode material. Some of the differences are discussed in this section. PEM fuel cells have a higher mass/power and volume/power density than the other options, whilst not being significantly outclassed in other areas such as lifetime, efficiency and cost.

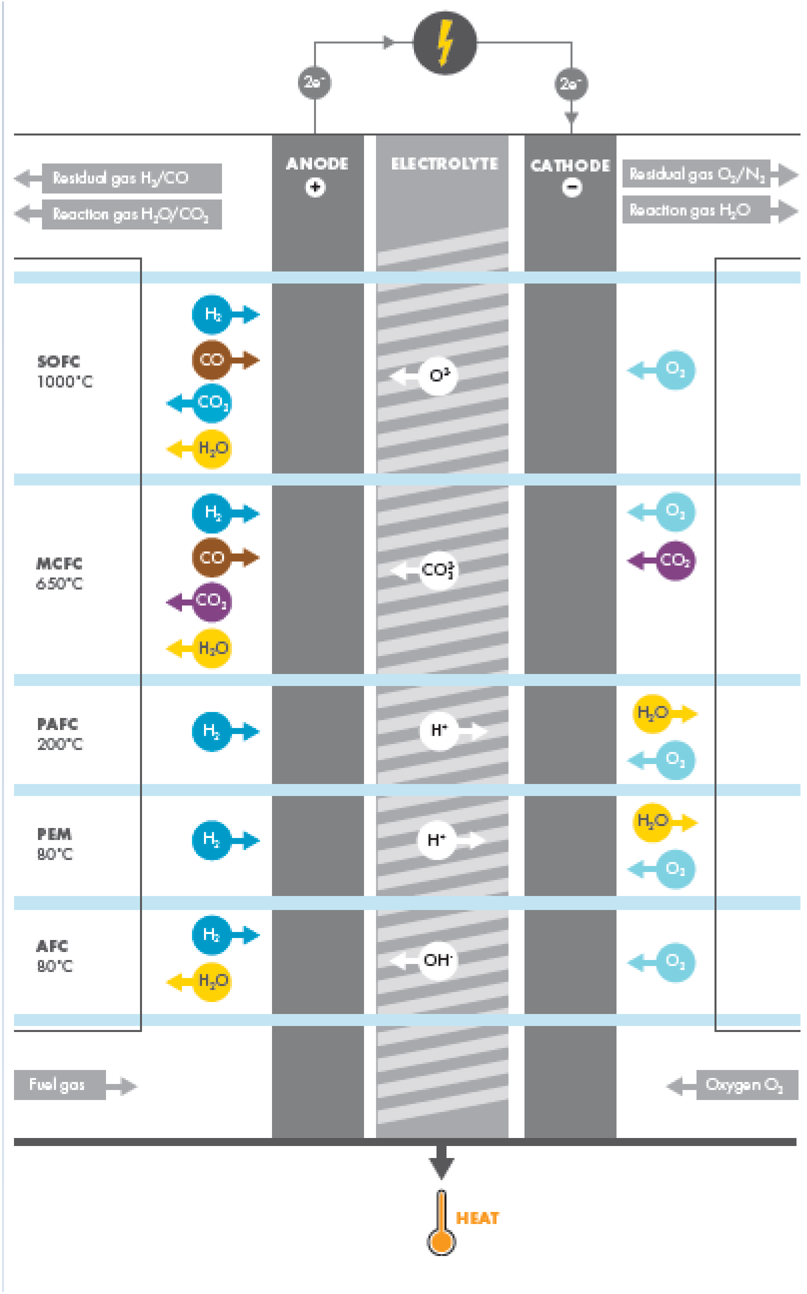


Figure 4.1: Schematic representation of the different reaction in the different types of fuel cells. [43]

A second type is the molten carbonate fuel cell (MCFC). It uses a molten carbonate salt suspended in a porous ceramic matrix as an electrolyte. This electrolyte needs a temperature of approximately 650 degrees Celsius for the fuel cell to be operable [1]. At the anode, the hydrogen reacts with carbon trioxide to form water, carbon-dioxide and free electrons. The electrons flow through an external circuit to the cathode, where they react with oxygen and carbon-dioxide to form carbon trioxide. The carbon-dioxide formed at the anode can be fed to and consumed at the anode and the carbon trioxide formed at the cathode passes back through the electrolyte to the anode. The result is that the formed carbon dioxide and -trioxide are contained and reused in the fuel cell and not discharged to the environment. A challenge for this type of fuel cell is the time needed for heating up the fuel cell which hinders quick response to changing power demand.

A third type is the solid oxide fuel cell. Solid oxide fuel cells (SOFC) have the same input and output products as PEM fuel cells. The main difference is that SOFC use a solid porous ceramic electrolyte. Hydrogen reacts at the anode to split into hydrogen ions and electrons. The electrons flow through an external circuit to the cathode, where they react with oxygen to form oxygen ions. They flow through the electrolyte to the cathode, where they form water with the hydrogen ions. The operating temperature is the highest of all types of fuel cells, with temperatures reaching up to 1000 degrees Celsius. This is needed for the oxygen ions to pass through the electrolyte. The main challenge is again the temperature regulation and response time due to this high temperature [43].

A fourth type is the alkaline fuel cell. Alkaline fuel cells (AFC) use a solution of potassium hydroxide in water as their electrolyte. The hydrogen is split into hydrogen ions and electrons at the anode. The electrons flow through an external circuit to the cathode, where they react with the oxygen and the electrolyte to form hydroxide ions. These flow back through the electrolyte to the anode to form water with the hydrogen ions. The operating temperatures range up to 90 degrees Celsius. The challenge with this type of fuel cell is the deterioration of the electrolyte when in contact with carbon dioxide. As this has a large presence in the ambient air, a system is needed to provide the fuel cell with air that contains a minimum of carbon dioxide.

Internal combustion engines and gas turbines are the second and third option to convert the stored chemical energy into usable energy. The burning of hydrogen is done in an internal combustion engine or gas turbine, to directly obtain mechanical energy. This is very similar to conventional fossil fuel burning. The different characteristics of hydrogen do demand a different engine design. Drawbacks of burning hydrogen using internal combustion engines and gas turbines are the trace amounts of nitrogen oxides that are produced. As this thesis focuses on zero emissions during operation, hydrogen internal combustion engines and gas turbines will not be considered further.

To asses the performance of electrolysis, storage and conversion, commercially available systems and scientific papers regarding their performance were investigated. This provided a general view of the performance range. To continue this research with realistic performance data and not taking the best performance value in each category, the performance of one electrolyser, one storage tank and one fuel cell are used in the further research. The resulting values can be found in Figure 4.6.

Advantages

- No chemical hazards
- Observable state of charge
- Zero-emission operation
- Limited capacity decay
- Low maintenance due to few moving components
- Low noise and vibration from fuel cell
- Quick charging at terminal

Drawbacks

- High capital costs
- Low power to weight ratio
- Limited amount of centralised hydrogen suppliers
- Highly flammable
- Strict storage regulations
- Low well to wheel efficiency
- Low energy density w.r.t. fossil fuel
- Relatively new in marine energy storage

Terminal requirements
The terminal requirements for hydrogen energy storage depend on how the hydrogen is supplied. There are four options to do this. Firstly, hydrogen can come from an external plant by tanker truck. The terminal then only needs the facilities to store the hydrogen and pump it to the tanks on the vessel. This option most likely has a low cost as the hydrogen can be produced at a large production plant, with lower costs due to scale effects. The second option is to fuel the ferry directly from the tanker trucks. This further decreases the investment costs for the terminal but can become expensive if frequent refuelling is necessary. In the same category, the ferry can sail to an external party for refuelling outside of the ferry schedule. The third option is to connect the terminal to a large hydrogen production plant through a distribution pipeline. This option is highly location dependent for feasibility and cost. The fourth option is to place an electrolyser unit at the terminal. Only water and electricity are then needed for the hydrogen production. This likely to be less cost-effective than obtaining the hydrogen from a centralised production plant. The benefit however, is that there is no dependency on such a plant for the hydrogen and a steady supply of hydrogen from a third party is not needed.

When operating a conventional ferry, fossil fuel is bunkered on an interval longer than a day. This is due to the fact that it is more time efficient to load a large quantity at once than many times over a shorter interval. Large storage tanks on board the vessel are possible due to the high volume and mass energy density of fossil fuels. Hydrogen has a much lower volume and mass energy density, a factor 3 mass-wise and factor 10 volume-wise. However, this not low enough to dismiss the possibility of carrying hydrogen for multiple trips. It might be feasible to install larger tanks on board the vessel to increase the fuelling intervals. This might be necessary if very short loading/unloading times are required.

Case studies
Vessels that use hydrogen as their sole energy source are feasible. Currently, these are mostly small vessels. Examples using fuel cells are the Hydrogenesis from Bristol Hydrogen Boats, the Nemo H2 canal boat and the FCS Alsterwasser from project Zemships. Examples using the combustion of hydrogen are Cheetah Marine that uses hydrogen combustion in outboard engines and the Hydroville from CMB that uses hydrogen injection in a diesel engine. Other projects including cargo vessels and submarines have used some type of hydrogen energy storage as a part of their energy system, but not as their sole energy source.

4.3. Classic batteries

There are generally two types of batteries; classic batteries and flow batteries. The latter being discussed in Appendix B. The super-ordinate characteristic of classic batteries is that the chemical reactions, on which the energy storage is based, occur at electrodes. The electrodes, an anode and a cathode, have a solid or molten state.

Energy storage, loading and conversion

The energy storage type is electrochemical. This means that the battery is composed of one or more electrochemical cells. These are devices that generate electrical energy from chemical reactions and facilitate the opposite of these reactions when electrical energy is introduced during charging. This is the principal with which all classical batteries work. The specific chemical reactions are not discussed in this thesis as only the resulting characteristics are relevant for the research. Loading or charging is done the same way as all common batteries, by connecting a source. Discharging is done by connecting a load.

Technical specifications and costs

A battery generally consists of two electrodes (an anode and a cathode), an electrolyte solution and a separator. The anode and cathode are placed in the electrolyte solution with the separator somewhere in between them. The anode and cathode can be connected outside of the solution to form an external circuit. When charging the external circuit is completed by the source. The voltage that this source provides causes ions to separate from their electrons at the cathode and flow through the separator to the anode. Their electrons flow to the anode through the external circuit as the separator blocks them from moving through the electrolyte. The battery is now charged. The ions are attracted to move to the cathode, but are limited by the fact that their corresponding electrons cannot flow through the interrupted external circuit and meet them at the cathode. The flow of electrons is possible when a load completes the external circuit. This flow of electrons is what provides the energy.

Many types of classic batteries exist. Three types of that are mostly used for energy storage are lead-acid, nickel-metal hybrid and lithium-ion. To asses their performance values, commercially available batteries and scientific papers regarding their performance were investigated. This provided a general view of the performance range of the different types of batteries. To continue this research with realistic performance data, one specific battery system was chosen to represent each battery type in the further research. The resulting values can be found in Figure 4.6.

The chosen battery system is lithium-ion. This type has lower maintenance costs than other battery types, as well as having a low self-discharge rate and longer life time. Lithium-ion batteries also have fast charge rates, an essential characteristic for the use in double ended ferries. Within lithium-ion batteries a distinction is made between batteries of different specific chemical composition. The general mechanism of the battery is the same for all sub-types, but changes is the composition alter the specific characteristics of each type. The chemical compositions used in the analysis in this thesis are Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Titanate (LTO) and Lithium Iron Phosphate (LFP).

Advantages

- Zero-emission operation
- High battery efficiency
- High well to wheel efficiency
- Silent operation
- High energy density for zero-emission energy storage
- Developed technology

Drawbacks

- High capital costs
- Uncertain battery ageing
- Fast battery ageing when high depth of discharge (DOD)
- Long charging times
- Battery recycling relatively underdeveloped
- Low energy density w.r.t. fossil fuel

Terminal requirements

When using batteries for energy storage on double ended ferries, the operator needs to be able to charge them. Depending on the ferry schedule, this also needs to be done within a certain time. The charging and discharging speed of a battery is described by the C-rate. A C-rate of 1, means that it takes 1 hour to charge or discharge the battery. With a C-rate of 2, it takes 0.5 hours to charge or discharge the battery, needing or providing twice the power to do so. The consequence is that charging and discharging the battery with higher C-rates increases the losses in the battery and decreases the efficiency. For ferries it is often the case that the sailing time for one trip is longer than the loading/unloading time in the terminal. This means that a C-rate higher than 1 is needed and that the grid at the terminal needs to be able to provide the power to charge with this C-rate. However, it depends on the charging strategy what the terminal requirements need to be exactly.

When a ferry sails at regular intervals over the whole 24 hours in a day, the battery can only be charged during the loading/unloading time and during the additional time that the ferry waits at the terminal. The batteries then need to be charged at every birthing. This can be done in three ways. The first is to charge the batteries directly from the local grid. The second is to use additional batteries at the terminal which are charged at lower C-rates continuously during the whole day and charge the batteries on the vessel with higher C-rates during the short birthing times. The third option is to use extra batteries that are charged at the terminal and that are swapped with the empty batteries on the vessel when birthed. Introducing extra batteries is obviously less desirable from a financial standpoint, but can be necessary if the local grid cannot support the required power for direct charging and improving the local grid is too expensive.

When a ferry does not sail over the whole 24 hours, the battery can also be charged overnight. The first option is to fully charge the battery overnight. This will require a large battery, as it needs to carry all of the energy that the ferry needs during the day. The second option is to fully charge the battery overnight and also charge the batteries during the loading and unloading of the vessel. In this way the total charge of the battery slowly decreases over the day, but with a limited speed due to the intermittent charging. This strategy allows for smaller batteries, due to the fact that they do not need to carry the energy for the whole day. The fact that less energy is charged at every birthing decreases the strain on the local grid.

When a ferry has a longer loading/unloading time with respect to the sailing time, the charging becomes much less of a challenge. A lower possible C-rate will lower the stress on the local grid. Only charging the batteries when the ferry is at the terminal in between trips becomes much more feasible.

Case studies

Whilst there are many vessels operating in a hybrid configuration, only a few use solely batteries as their primary energy source. An example is the MF Ampere [24]. This 80 meter catamaran double ended ferry was launched in Norway in 2016. It uses a 1040 kWh lithium-ion battery pack that powers two 450 kW electrical engines. It uses this to transport a maximum of 120 passenger cars and 360 passengers over a 5.7 km trip 34 times per day. The ferry uses 150 kWh per 20 minute trip to accomplish this. To recharge, two 410 kWh batteries slowly charge from the local grid and rapidly charge the ferry during the loading and unloading.

Figure 4.2: MF Ampere, full electric ferry [40]

A much lesser known vessel was launched by the China State Shipbuilding Corporation subsidiary Guangzhou Shipyard International. The 71m vessel is built to transport coal over a maximum distance of 80 km. It uses a 2400 kWh battery pack as energy source, which can be recharged in 2 hours and is also equipped with supercapacitors (details unknown) [58].

Figure 4.3: Launch of the first ever full electric cargo vessel [49]

4.4. Supercapacitors

Energy storage, loading and conversion

The energy storage type is electrical. This means that the energy storage is based on electrostatic charge, and not chemical reactions as with batteries. Loading or charging is done the same way as all common batteries, by connecting a source. Discharging is done by connecting a load.

Technical specifications

A supercapacitor is also known as an ultracapacitor or an electric double layer capacitor. It consists of two highly porous carbon electrodes in an electrolyte solution, separated by an ion-permeable membrane. This membrane allows ions to pass through and blocks the larger electrons, which prevents the movement of charge across the electrolyte. The electrodes can be connected through an external circuit. When charging, a voltage potential is applied over the electrodes by a source connecting the external circuit. Through the flow of electrons from one electrode to the other, one becomes positive and the other negative. This causes the positive electrode to attract the negative ions in the solution and the negative electrode to attract the positive ions. The ions do not chemically react with the electrode, but only adsorb on its surface. This is shown in Figure 4.4. With a larger surface area for adsorption to occur, more charge can be stored. This is the reason that the electrodes are made from a material that has a very high surface area per mass and volume. When discharging, a load completes the external circuit. This enables electrons to flow from the negative electrode to the positive electrode. This flow of electrons provides energy to the load. In this process, the electrodes lose their charge and release the adsorbed ions.

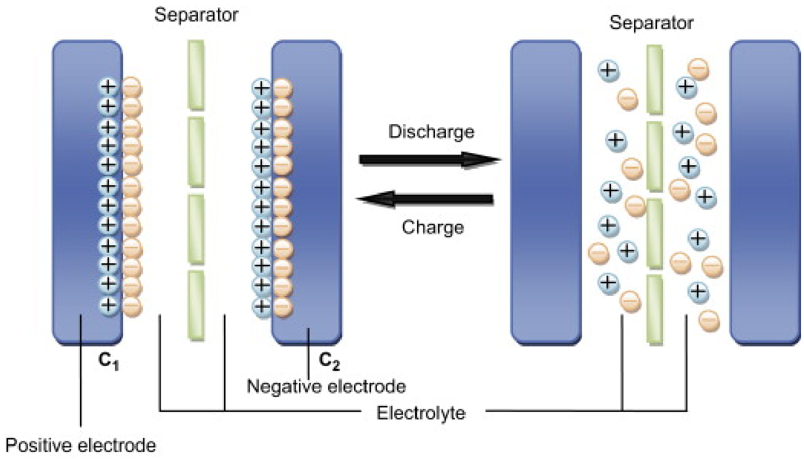


Figure 4.4: Diagram showing supercapacitor workings [22]

Advantages

- No chemical hazards
- Observable state of charge
- Zero-emission operation
- Low-temperature performance
- Fast charging
- Full discharge capacity
- High cycle life
- High power density

Drawbacks

- High capital costs
- High self-discharge rates
- Low volumetric energy density
- Low mass energy density
- Linear discharge curve

Terminal requirements

The fast charging speed of supercapacitors makes that the only logical way to employ them is by charging when unloading/loading the vessel. The result is a large power demand from the local grid during charging. To use supercapacitors for the energy storage in the vessel, the local grid must be able to handle the high power demands. Systems with land-based energy storage systems that slowly charge from the local grid, and provide the fast charging to the ferry when birthing, are not a logical choice. These will mostly add to the already relatively high costs of supercapacitors.

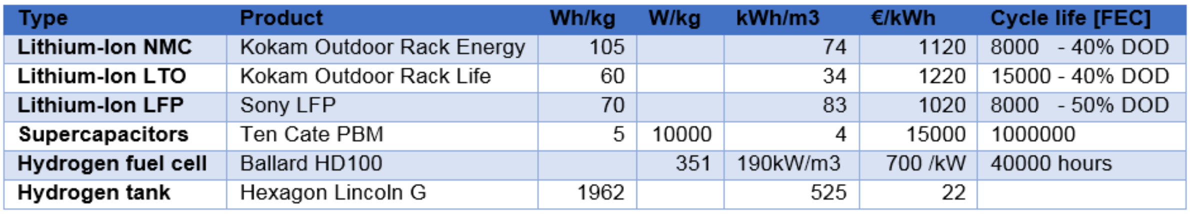
Case studies

In France there is a ferry sailing with solely supercapacitors as energy storage. Ar Vag Tredan is a 22.1 meter catamaran ferry built by STX Shipyard. The ferry is designed to transport 113 passengers and 10 bikes during a 7 minute trip with a maximum speed of 10 knots. It completes this trip 28 times a day and only needs 4 minutes to charge after each trip. The vessel is equipped with 128 supercapacitor modules weighing a total of 6 tons. The propulsion of the vessel is done by two 70kW azimuth thrusters. The operational profile of this vessel shows where the main potential of supercapacitors lies; high cycle capacity in combination with fast charging. The Ar Vag Tredan will charge and discharge its batteries 10220 times per year. With conventional battery packs, this means replacing the battery pack almost on a yearly basis or installing a very large capacity to limit the DOD. Supercapacitors, on the contrary, have a cycle life up to 1 million cycles with a DOD ranging from 80% to 100%.

Figure 4.5: Ar Vag Tredan: supercapacitor powered ferry [20]

4.5. Performance characteristics table

In this section, the performance characteristics of the energy systems are shown. A database of energy system components was created and the components from different manufacturers were compared. The technical performance from specific components, which are high performing amongst the available options available on the market, is used in this research [45][53][66][36][8][39]. For the cost parameters of the energy system components, average values from the data in the scientific papers is used[15][37][41]. Data from manufacturers regarding the price of their products is very difficult to obtain as most do not wish to disclose this information, even after a specific request for this research. Product and technology specifications from many sources were compared define the values in Figure 4.6.



Type	Product	Wh/kg	W/kg	kWh/m3	€/kWh	Cycle life [FEC]
Lithium-Ion NMC	Kokam Outdoor Rack Energy	105		74	1120	8000 - 40% DOD
Lithium-Ion LTO	Kokam Outdoor Rack Life	60		34	1220	15000 - 40% DOD
Lithium-Ion LFP	Sony LFP	70		83	1020	8000 - 50% DOD
Supercapacitors	Ten Cate PBM	5	10000	4	15000	1000000
Hydrogen fuel cell	Ballard HD100		351	190kW/m3	700 /kW	40000 hours
Hydrogen tank	Hexagon Lincoln G	1962		525	22	

Figure 4.6: Table with energy component data used in this thesis

The price of zero-emission renewable electricity and hydrogen varies greatly depending on location, contract agreements, energy demand and much more factor. Instead of giving a global estimate that in generally applicable it is much more accurate for a user to provide the cost parameter as input.

4.6. Electricity generation

Zero-emissions, as defined in this thesis, regards only the operations of the ferry, as the source of the energy is beyond the control of the shipbuilder. This does not mean that it is recommended to not think beyond this scope as a shipbuilder and ferry operator. Some recommendations, considerations and a case study are discussed in this section to not leave this topic completely untouched and to underline its relevance.

Generating renewable energy is the future. This is acknowledged and acted upon by many governmental institutions and companies ranging from small to large. Gigantic solar farms are arising in India, China and the Middle East. Onshore wind farms are arising in China and the United States whilst Northern Europe is focusing on the off-shore versions. Other renewable power plants focusing on geothermal energy and hydro-electricity are commonplace around the world. The focus is also on the storage aspect of this energy. The rise of battery storage is shown in the ever-growing amount of electrical vehicles driving the streets and excess renewable energy being stored in worlds largest battery, a 129 MWh system in the south of Australia [7]. Hydrogen production using electrolysis and renewable electricity is attracting energy giants such as Shell, committing to a project producing 1300 tonnes or 43290 MWh worth of hydrogen per year from renewable electricity in the west of Germany [18].

The primary source of energy for all energy storage types discussed in this chapter is electricity. It can spark reactions in the storage medium (batteries) and it can create the storage medium (hydrogen). The total power usage of ferries can be without emissions when this electricity comes from zero-emission renewable energy sources. Examples are generation from the sun using photo-voltaic technology (solar panels), from the wind using wind turbines, from tides using tidal generators and from rivers using hydroelectric power stations. These all produce electricity from renewable sources without emission during the power generation. An important side-note is that the production of the generation mechanism is likely not without producing emissions. This is, however, an initial amount of emission that allows the generator to produce clean energy for a lifetime ranging from 20-100 years, depending on the type. One must also not forget that for fossil fuel production similar initial emissions are discharged in addition to the emissions produced during usage. This equates to vastly more emissions than resulting from renewable energy production.

Generating electrical energy from renewable energy sources has the added benefit of possible stand-alone systems. When the location of your desired ferry route has access to sunlight, wind and/or tides (which is practically every place on the surface of the earth), it is possible to generate renewable energy at the terminal. This means that after initially building the energy generation facilities, the terminal and ferry can operate as a stand-alone system. They then do not depend on any connections or services from external parties for their energy. The benefit of this possibility is allowing ferries to operate in remote or disconnected locations without the need to connect the location to the energy grid or supply it periodically with energy mediums. This lowers the hurdle to provide ferry services is remote locations and thereby making these locations more accessible. The obvious side-note is that for building, repairs and maintenance a third partly can be necessary.

4.6.1. Case study

To illustrate the potential zero-emission renewable energy, an example case is used. The MF Ampere is the first ever ferry that uses only batteries for energy storage. It makes 34 trips each day, consuming 150 kWh per trip [57]. This equals 1862000 kWh per year. The ferry operates between Lavik and Oppedal in Norway. In this area, a solar panel with 15% efficiency generates 92 kWh/m2/year [26]. It would thus require 20239 m2 to generate the energy needed to operate the ferry. This is equal to 2.85 European football/soccer fields. At the fjord that the ferry crosses the average wind speed is 5.2 m/s on a yearly basis [26]. In these conditions, one 80 m diameter wind turbine can easily generate the needed energy for the operation of the ferry [25]. These values show that with current technologies the operation of zero-emission ferries using locally sourced renewable energy is within realistic possibilities.

If solar power and wind power are generated in places where there is more sun and more wind than in western Norway, the power generated by the systems only increases further. There are places in the world where the described solar and wind power systems generate more than double the amount of energy. An important point is that the sun and wind are not year-round constant factors, especially in Norway. The described system produces enough energy for the ferry on a yearly basis. This time factor of generation is only important if it is for stand-alone operation. When connected to a central grid, excess generated electricity is fed into the grid when it exceeds the need and electricity is drawn then the generation is lower than the need. Thereby renewable energy can be distributed between regions depending on how much renewable energy is available.

4.7. Regulations

In this section, the influence of currently enforced regulations regarding the use of zero-emission energy systems are discussed. This is done to determine if these regulations will influence the design in a concept exploration phase.

4.7.1. Hydrogen

The use of hydrogen as main energy storage medium is a recent development for the shipping industry. Hence regulations for the storage and use of hydrogen and fuel cells on board vessels are mostly work in progress. In September of 2017 a sub-committee of the International Maritime Organisation (IMO), on Carriage of Cargo and Containers, discussed the safety provisions for vessels using fuel cells [52]. Noted is that a new part E of the IGF code is a work in progress. This part would cover "installation, fire safety and other relevant matters".

Research into some rules and regulations from Det Norske Veritas, Bureau Veritas and Lloyd's Register shows that most regulations concern the more detailed aspects of the design and components [2][52][65][33][34][64][35][3]. This includes topics such as fire safety systems, ventilation of storage and usage areas and piping requirements. These are not of influence on the outcome of this thesis. It is important to note that none of these are specific to hydrogen and thus needs extra consideration before usable for classification.

The current lack of clear regulations for hydrogen powered vessels is the major challenge for building hydrogen powered vessels. IMO and SOLAS regulations only apply in certain cases, based on sailing area, capacity and vessel parameters. Otherwise, regulations from these organisations do not apply. If they do need to comply, the lack of regulations makes that a specific design and risk study needs to be performed to be considered for an exception. This is a time consuming, costly task that involves approval from many different bodies and organisations. Certification by a classification society follows a similar path, although being less time consuming, costly and bureaucratic.

4.7.2. Batteries

Det Norske Veritas states that for vessels where "the battery is used as an additional source of power and has an aggregate rated capacity exceeding 50 kWh (excluding lead-acid and NiCd batteries)" a mandatory Battery(Safety) class notation is needed [65]. For this class notation, the applicable regulations mostly focus on fire safety, system control and testing of the equipment before classification and on a regular basis thereafter. The requirements are details of the design and do not influence the outcome of this thesis. The main general requirement is that if batteries are used as a main source of power, the batteries need to be stored in two independent systems at two separate locations. This is also a requirement from the American Bureau of Shipping [51].

4.7.3. Supercapacitors

The regulations for using supercapacitors as the main source of energy on board a vessel are very slim. The American Bureau of Shipping has some regulations, which are applicable for general supercapacitor usage [50]. These regulations specify details of the safety systems within the electrical systems and fire safety. They will not influence the outcome of this thesis.

4.8. Conclusion

The main conclusion of this chapter is that lithium-ion battery energy systems, hydrogen energy systems using fuel cells and supercapacitor energy systems are likely candidates for zero-emission double ended ferries. Current state characteristics of commercially available components for these systems are shown in Figure 4.6. Additionally, a brief investigation into the possibilities of zero-emission energy generation for double ended ferries was performed. The case examined hints towards this being a realistic option for supplying the zero-emission energy systems with energy. Thirdly, the possible influence of regulations on the concept designs was investigated. The result is that this influence is negligible due to the majority of regulations focusing on design details.

5

Early design stage

In this chapter, the early design stage of double ended ferries is investigated. The variables known and demands needing to be met are discussed. How budget and terminal costs influence the possibility of zero-emission double ended ferries is elaborated upon in the last two sections. Understanding of this process is needed for the model development process, as the input requested by the model needs to match with the available information during the early design stage.

5.1. Early design stage double ended ferries

The early design stage is the part of the design process for which the concept exploration tool is to be developed. It is thus essential to understand this process and which data is available during it. This starts with the input that the client gives, concerning what the vessel will be used for and how it will be used. This leads to a set of values that describe the clients' wishes numerically. These numerical wishes are useful for exploring concepts that fulfil these wishes.

The required average speed and maximum speed dictate how fast the vessel needs to move and the vessel parameters dictate what needs to be moved. When the latter is known the resistance can be calculated. This will provide the relationship between sailing speed and needed power. Combining this with the operational profile gives information on how much energy storage is needed for the operation of the vessel. As carrying and converting this energy on board of the vessel indicates the volume and mass of the corresponding systems, the energy capacity influences the volume and mass of the vessel.

As the thesis is written at Damen Shipyards Gorinchem much of the information about the early design process and which data is available during this process, can be specific to this shipyard. Specifics on the process at other shipyards are not investigated.

5.1.1. Client demands

Clients buying double ended ferries have a transportation problem or the need for a certain transport capacity. Prior to contacting the shipyard this need for transport is defined by the client at a certain location. This can be numerically stated by the following input demands shown below. [redacted]

[redacted]

The demands are contractual and thus fixed. Obviously, these are not the only demands that a client has. Many choices need to be made in collaboration with the client during the design process, to create a vessel that fulfils the clients' wishes. However, the majority of these choices do not have to be made in the early design stage and can be made in a later design stadium.

- Amount of passengers per crossing
- Amount and type of vehicles per crossing
- Sailing route
- Maximum speed
- Sailing schedule

The amount of passengers that a ferry needs to transport per crossing is a quite self-explanatory demand. A sub-demand can relate to the amount of seats on board the vessel.

The amount and type of vehicles that the vessel can accommodate on a crossing, can vary greatly per client. To define the amount of vehicles that a ferry can carry, the Automotive Equivalent (AEQ) is used. This value states the car carrying capacity in units equal to 1 passenger car equivalent (PCU). This is the length used by one standard vehicle. Other vehicles, such as trucks, can be expressed in a certain amount of PCU. By converting all vehicles desired to be transported to PCU and adding, the total desired AEQ of a double ended ferry is determined. In this thesis, any input regarding desired car carrying capacity is assumed to be in AEQ. As described in chapter 6, this unit is sufficient for the use in this thesis.

The sailing route is the route that the vessel is assumed to sail its entire lifetime. The main parameters of this route are length, depth and sea-state. The length is the distance between the ports that the vessel will sail between. The depth can be an important restriction when sailing in shallow waters and the sea-state gives an indication of the wave and water conditions that the vessel will encounter during its lifetime. The vessel width and height can also have constraints due to small canals and bridges, but in most cases these are no limitations from the route.

The maximum speed is a general requirement in the contract of most new-built vessels. The amount of installed power needs to be sufficient to reach this speed under certain sailing conditions.

The sailing schedule is the schedule with which the operator wishes to provide transport over the sailing route. This schedule gives information about the period the vessel needs to operate each day, how much time is available for sailing the route and how much time is available for each loading and unloading. From these values, the required average speed of the vessel over the route can be determined. This is important to know when designing the energy system of the vessel.

When further specified the basic input/demands can be expanded to a more detailed level;

- Automotive Equivalent
- Passenger Car Equivalent
- Lane width
- Lane height

- Route distance
- Route depth limitation
- Shore facilities
- Daily operational period
- Available crossing time
- Available unloading/Loading time

5.2. Uncontrollable variables influencing feasibility

The feasibility of a zero-emission energy system is dependant on many variables. Many of these are external and cannot be influenced or only partly be influenced by parties involved in ferry build and operation. They are mostly related to the location of the ferry route. A list of the "uncontrollable" variables is shown below. This list contains many, but most likely not every single external variable. In this thesis, the aim is to incorporate these variables where possible and practical.

- Electricity price
- Local regulations
- Global regulations
- Availability of renewable electricity
- Availability of renewable hydrogen
- Local infrastructure
- Government support

5.3. Budget

The budget is the price that the buyer is willing to pay for the vessel or for which the shipyard is willing to build a vessel. Multiple shipyards are usually tendered for a new-built vessel and can choose to offer the buyer the vessel with certain specifications at a certain price. It is not always disclosed what the budget of the buyer is, as this can vary with what is offered for a certain price. For the buyer, the buying price of the vessel is not the only cost they will have, as the operational expenses will sum up to a large amount during the lifetime of the vessel. It is thus a balance between the Capital Expenditures (CAPEX) when buying the vessel and the Operating Expenses (OPEX) when using the vessel. A vessel that is expensive to buy and cheap to operate can then be the most desired solution or vice verse. Whether this is the case depends on many factors, including the financial status and prospectus of the buyer.

Other factors are the values that the buyer wants to convey or the opinions that they have. This can (partly) determine their choice for a vessel that might not be the most financially attractive but have less impact on the environment. The uncontrollable variables discussed previously are also at play. Availability of certain infrastructure might not be needed for certain energy systems or essential government funding might only apply to certain energy system types. These are all examples to show that financial feasibility is not only defined by the price of the vessel (including or excluding terminal modification). This means that it does not make sense to use a budget as an input variable to determine the system design. The aim is to provide the capital expenses and operational expenses for each option. The client can then use these in their decision for a certain energy system.

5.4. Terminal costs

Operating a double ended ferry with a zero-emission energy system will cause the need for modifications to the ferry terminal. The costs for the modifications of the terminal do not need to be fully attributed to the ferry. The installation of facilities that store and transfer renewable energy are useful far beyond the ferry. A hydrogen fuelling station can easily be configured to also provide a fuelling service to hydrogen cars for example. A second example is the use of a battery charging system that can be used by more vessels than the ferry. Both of these examples show that the added infrastructure can spark the use of zero-emission energy systems region where the ferry operated. In this case, third parties or a government are likely to share in the costs for the added infrastructure.

A second aspect influencing the decisions to modify the infrastructure is the length of the contracts on which the ferries operate. Some news reports share Norwegian ferry contracts with a 10 year duration [24]. The multi-year contracts give the kind of assurance of income and use that helps justify expensive modifications to the infrastructure.

In this thesis, the costs of installing hydrogen and battery charging stations at the terminal are fully attributed to the ferry. This accounts for the worst case, where the facilities are not used by other parties and the costs can thus not be shared. Costs to local infrastructure beyond the terminal are not taken into account.

5.5. Conclusion

In this chapter numerical expressions for clients' wishes have been established. Additionally, it has been identified that some variables influencing the feasibility of zero-emission double ended ferries can not or only partly be influenced by parties involved in ferry building and operation. For a portion of these variables, it is not possible or practical to be numerically expressed. The result is that whilst they are are not incorporated in the concept exploration tool, they are still of influence on the feasibility of zero-emission double ended ferries and should be considered by the users of the tool.

From the discussion of budgets for double ended ferries, it is concluded that the concepts to be created by the concept exploration tool will not be budget bound. Rather the tool will provide the user with economical parameters of the concepts, that aid data driven decision making for the users.

For terminal costs, it is determined that in this thesis, the full costs of terminal components for zero-emission energy systems are attributed to the ferry concepts. Whilst there are cases where the costs can be shared by multiple befitting parties, this is not necessarily so.

II

Model development

6

Model Development

This chapter describes the concept exploration model and its development. The logic and reasoning that lead to the algorithms that are combined to form the concept exploration model are explained. For this, the knowledge gained in the previous four chapters is combined. The chapter starts with a generic description of the model, starting with the desired end result. Working from this point to the starting point of the model, the steps needing completion in between are explained. Having defined the steps needing completion, the actual actions that were completed are then explained in detail. Subsequently, the assumptions that the model is based on are discussed, as are the implications these have for the application of the tool. At the end of the chapter, the verification and validation of the model are discussed.

By implementing the model described in this chapter in the Python programming language, the transformation from concept exploration model to concept exploration tool is achieved. As this consists purely of coding, it is not discussed in this thesis. Scripts of the code will not be provided in this thesis.

6.1. Model description

The goal of the model is to determine the feasibility of different zero-emission energy systems for double ended ferries and calculate corresponding design parameters. Understanding how feasibility is defined and the correlation with desirability is the key to identifying output for the concept exploration tool. According to the Cambridge dictionary, the definition of feasibility is: "able to be made, done, or achieved". This is exactly the definition used in this thesis. If it is certainly not possible, the is no point in trying and wasting resources doing so. With the subject of zero-emission energy systems for double ended ferries, this definition is applicable to two areas: technical and financial. A zero-emission energy system needs to be technically possible. Factors including (but definitely not limited to) available shore power and energy density, can attribute to it not technically possible being possible to use a certain zero-emission energy system in a certain case. From a financial point of view, someone or some entity needs to pay for the purchase, maintenance and operation of the system. The money available is always limited to a certain extent, be it for various reasons. When the expected or known amount needed is not available, the zero-emission energy system is not economically feasible.

6.1.1. Output generation

What does the concept exploration model need to provide as output? When setting up the model from end to beginning, this is the first question that needs to be answered. From the thesis goal, output concerning zero-emission double ended ferry concepts needs to be a result of the model. Using the conclusions from chapter 4, it is determined that output is wanted for double ended ferry concepts using lithium-ion battery energy systems, hydrogen energy systems using fuel cells and supercapacitor energy systems. Additionally, the output is desired for a diesel-electric benchmark. This is to asses the output of the zero-emission concepts with respect to current common practice.

The concept exploration tool does not provide all feasible energy systems for the given input. This due to factors influencing the desirability of an energy system. Generally, for the energy system of double ended ferries it is desirable to have a system that has a low mass, a low volume and low costs. What cannot be generally identified is how much each of these factors influences the desirability. Therefore multiple feasible concepts will be given by the tool, where it is up to the user to judge the desirability and make the final decision. However, it can be said that a system of the same chemical characteristics, but with a higher mass, volume and cost is per definition less desirable than one where all factors are lower. The choice between two such feasible systems can be made based on desirability, where the less desirable system is not given as an output by the tool.

To evaluate the concepts for which output is given, the model needs to provide both technical and economical parameters of each vessel. The technical parameters are: vessel length, vessel width, displacement, energy system mass, energy system volume, installed power and energy consumption per trip. It is important to state that the transportation capability is defined as an input and thus equal for each concept. This is because with double ended ferries the transportation requirement is defined by the needs of the client and it being equal for each vessel results in a fair comparison between them.

Since double ended ferries are assets with which companies aim to make money or governments aim to provide a service at low cost, the economical aspect greatly influences the choice for a certain energy system option. To aid this choice the initial CAPEX, total CAPEX, daily OPEX and Net Present Value of each vessel option is desired as output.

- The CAPEX is limited to cost directly related to the energy system
- The costs directly related to the energy system are for the batteries, supercapacitors, fuel cells, electrolysers, diesel engines, hydrogen tanks and diesel tanks on board the vessel and installed at the terminal
- The change in length of the vessel is assumed to have a negligible effect on the CAPEX
- The OPEX is limited to maintenance costs, electricity costs, hydrogen costs and diesel costs
- The OPEX does not include any personnel costs, as the assumption is that these do not differ per energy system

Energy efficiency

Next to the technical and economical outputs, a third output type is needed: energy efficiency. All of the options (except the benchmark) investigated are zero-emission, meaning that they do not discharge any emissions to the environment whilst operating. This does raise the question if there is an indicator that can distinguish the ships based on how sustainable or 'green' they are? In current shipping performance the Energy Efficiency Design Index is used. This gives the amount of CO2 emitted to transport one tonne of cargo over one nautical mile as an indicator of how harmful a certain vessel is to the environment. When dealing with zero-emission energy systems, energy consumption replaces CO2 emissions as the desirable to minimise. All considered zero-emission energy systems start at some point with electrical energy measured in kilowatt-hours. Defining the amount of energy needed to transport one car over one km gives an index for the transport energy efficiency of double ended ferries. A lower value for this index indicates a more efficient way to fulfil the transport need, from an operational energy usage perspective. As a result of the scope of this thesis (section 1.6), the index does not account for energy needed for the production of the energy systems. The formula for the transport energy efficiency is shown in Equation 6.1. The energy usage per trip is the amount that is needed for one fully loaded trip, taking into account the efficiencies of the storage mechanisms in the energy system. To illustrate, for batteries this is the amount of energy that is needed to charge the batteries/supercapacitors for one trip, for hydrogen the amount of energy needed to produce the hydrogen needed for one trip and for a Marine Diesel Oil the amount of energy stored in the diesel used for one trip.

$$\text{Transport Energy Efficiency Index} = \frac{\text{Total energy need per trip in basic energy unit}}{\text{car capacity} \cdot \text{trip distance}} = \frac{kWh}{car \cdot km} \tag{6.1}$$

6.1.2. Energy system types

What is needed to obtain the desired output of the concept exploration model? Having established what the output of the model needs to be, this is the second question that guides development. In short, the output of the model flows from the creation vessel concepts for each explored energy system type. This creation follows from algorithms for each energy system type. Based on the analysis of zero-emission energy system types in chapter 4, batteries, hydrogen and supercapacitors were identified as likely future solutions for double ended ferries. The earlier described output needs to be determined for each type of system. These systems will not only be compared to each other, but also to a benchmark consisting of a diesel-electric energy system. This benchmark is discussed in more detail in subsection 6.3.4.

The input for the calculations of each energy system consists of general variables, system variables and energy system constants. General variables are variables that influence each energy system type. The most important are the energy consumption per trip, the required installed power to meet the desired maximum speed, the daily amount of trips, the required car carrying capacity and the (un)loading time. System variables are variables specifically influencing the outcome of one or two (but not all) energy system types. Examples of these are shore power, hydrogen refuelling interval and diesel refuelling interval. They are defined by the user. The energy system constants are values such as fuel costs, energy system efficiencies, energy system energy densities and energy system unit costs. They are dependant on energy system suppliers, state of the economy of physical maximums. The efficiencies and characteristics of energy system types are discussed in chapter 4. The other values are derived from research described in subsection 7.2.3. The system constants can be altered by the user of the exploration tool if desired. Currently the values are set to a default shown in Figure 7.1 and Figure 7.2.

When considering battery systems a specific sub-algorithm is defined to determine the charging strategy. This is explained in detail in subsection 6.3.1. For the hydrogen energy system, there is a sub-algorithm that determines if it is cheaper to produce hydrogen at the ferry terminal or get it delivered by truck. This algorithm is explained in detail in subsection 6.3.3. The supercapacitor and diesel-electric energy system calculations do not include any sub-algorithms as is shown in Figure 6.1.

The starting point for the creation of vessel concepts is obtaining the needed input. System variables, energy system constants and some general variables are given as default by the model or provided by the user. However, for two highly influential general variables this is not the case. The energy consumption per trip and the required installed power need to be calculated in a prior step. Due to the vessel parameters of the concepts being determined through an iterative design exploration within the model, these cannot be provided by the user or set as a default. This process is described in more detail in]subsection 6.4.3

6.1.3. Vessel design and performance

What is needed to determine the energy consumption and installed power of vessel concepts? This is the question that dictates the first part of the model. To calculate them the resistance characteristics need to be determined and combined with the operational profile of the vessel. The operational profile is a given input based on how the user intends to use the vessel. The resistance characteristics of the vessel require a basic concept design that is based on the transportation need that the vessel is intended to fulfil. The transportation need input for this calculation includes the amount of cars that need to be carried, the maximum sailing speed and the weather conditions of the location the vessel will sail - all provided by the user. The operational profile is a given input based on how the user intends to use the vessel. This is the starting point of the model.

6.1.4. Basic model diagram

Combining the descriptions of the model and arranging them in order, the general flow diagram is shown in Figure 6.1 is created. This shows the general flow of information from the various types of input, through calculation/algorithm blocks, to the final desired output. The blue box represents the vessel calculations, from transportation need to energy consumption. The orange, purple and yellow blocks represent the collection of algorithms for each zero-emission energy system type. The light blue box contains the calculations of the diesel-electric benchmark. The first concept is based on data from vessels containing such systems.

In the diagram, the red lines create the iterations of the concept designs. The part of the research goal, "To calculate corresponding design parameters", consciously implies that the design parameters of a double ended ferry will change depending on the installed energy system. This change is the result of a varying system mass and volume that different types of energy systems have when supplying the same power and energy. This change in volume and mass needed for the energy system will change the total volume and mass of a vessel. Large and heavier energy systems require a larger vessel to contain it and will make the vessel heavier, where the same is true for smaller and lighter energy systems in making a vessel smaller and lighter. This, in turn, influences the resistance of the vessel, the energy the energy system needs to provide and again the size of this energy system. This process ultimately iterated to a vessel that is custom for each energy system.

Using the volume and mass of the resulting energy systems and comparing these with the volume and mass of the benchmark energy system, the delta mass and volume is calculated. These values are used to adjust the initial vessel design in the blue block, resulting in a new resistance and energy consumption, leading to new demands for the zero-emission energy systems, a corresponding new volume and mass. It is this iteration that results in 'custom' vessel concept designs for each energy system. After a certain amount of iterations, the output economical and technical parameters are given for each energy system type and the benchmark.

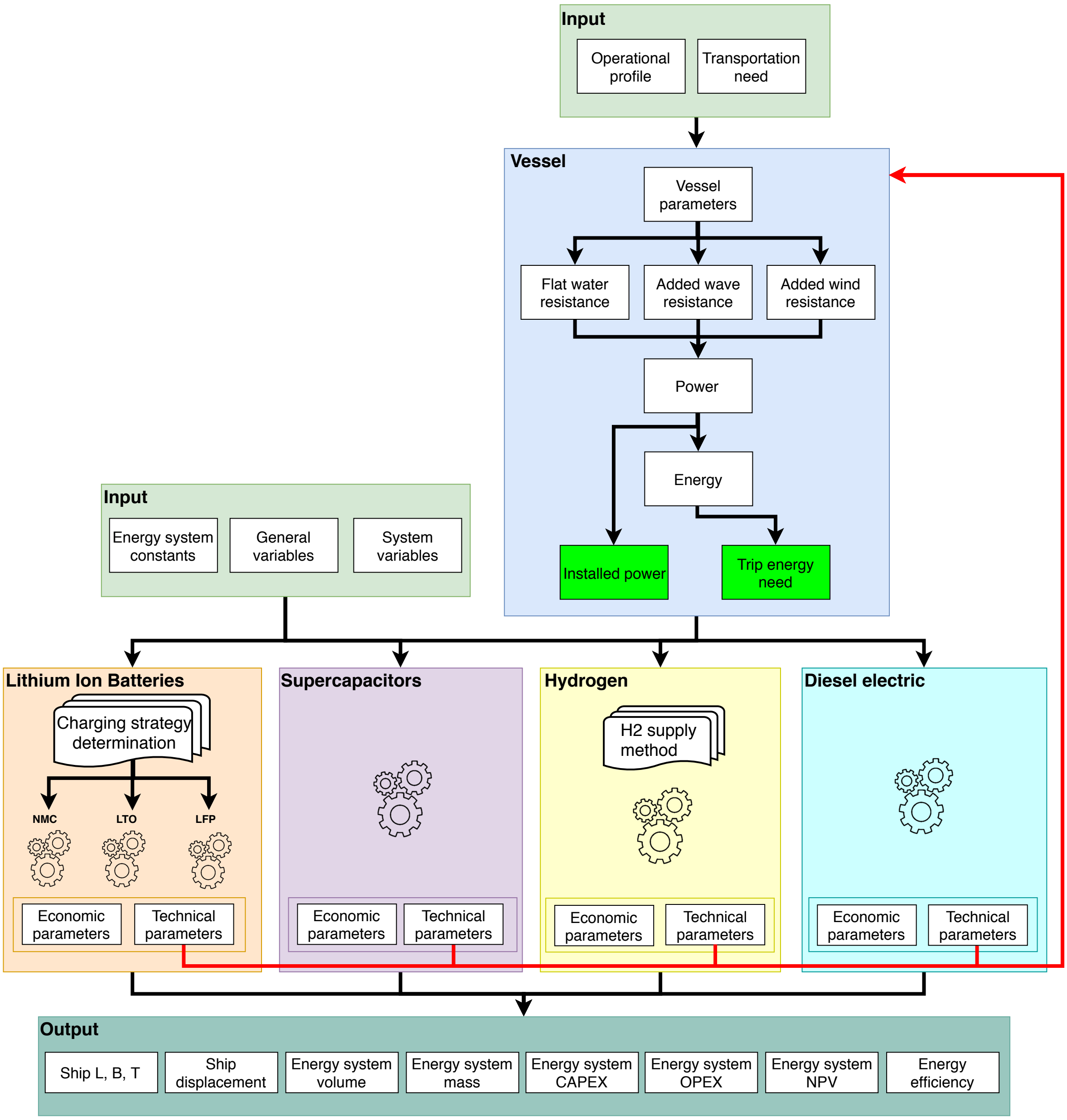


Figure 6.1: Basic model diagram

In the next section, the calculations and algorithms in each block of the flow diagram will be explained in detail. The detailed model diagram can be found in Appendix C

6.2. Vessel design and performance

The part of the model diagram described in this section is shown in Figure 6.2. Knowledge of vessel design (chapter 2), operational profiles (chapter 3), the early design stage (chapter 5) are combined to develop the vessel, resistance and energy consumption prediction algorithms.

From the functional specifications of the vessel, a concept design is created. For every design, the flat water resistance, added wave resistance and added wind resistance are derived as a function of speed. This is captured in an algorithm. Using the drivetrain characteristics these algorithms are used in another algorithm, which calculates the required power as a function of speed. Inserting the operational profile yields the energy that the propulsion system consumes during one trip and the power needed to sail at maximum speed. For the auxiliary power, an algorithm was created that uses the vessel parameters and superstructure design type to predict the power. Adding the operational profile to this yields the auxiliary energy consumption. Combining the auxuliary and propulsion energy consumption for one trip, the total energy consumption of the double ended ferry during one trip can be determined.

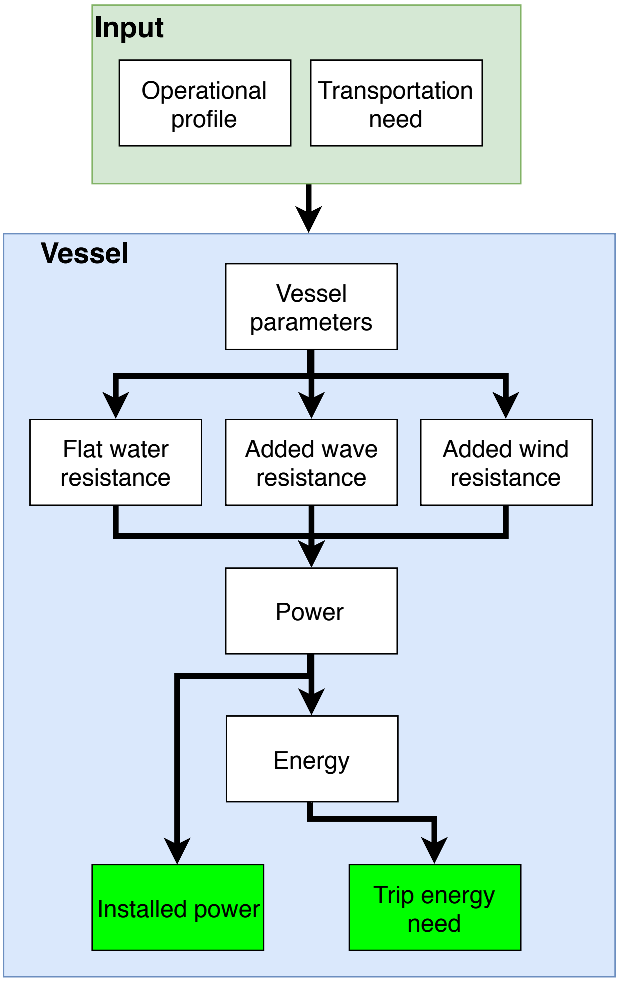


Figure 6.2: Model diagram - partial 1

6.2.1. Main vessel parameters

The main parameters of the vessel used in this model are the draught, length, width, block coefficient and volume. In some areas where double ended ferries operate and in key areas where Damen Shipyards has clients buying double ended ferries, the water depth is a major restriction for vessel draught. Therefore it is chosen to set the draught as an input value. The length and width follow from the required car carrying capacity of the vessel. The database set up during this thesis (section 3.2) showed a very strong correlation between the deck area and the car carrying capacity of double ended ferries. This is logically explained by the fact that this deck is the place where the cars are stored during transit. As the deck area is determined by the vessel length and width, both of these parameters can be determined from the required car carrying capacity using a trendline derived from the database. The graphs containing the data and corresponding trendlines are shown in figures Figure 6.3 and Figure 6.4. The car carrying capacity used in the graphs is in AEQ.

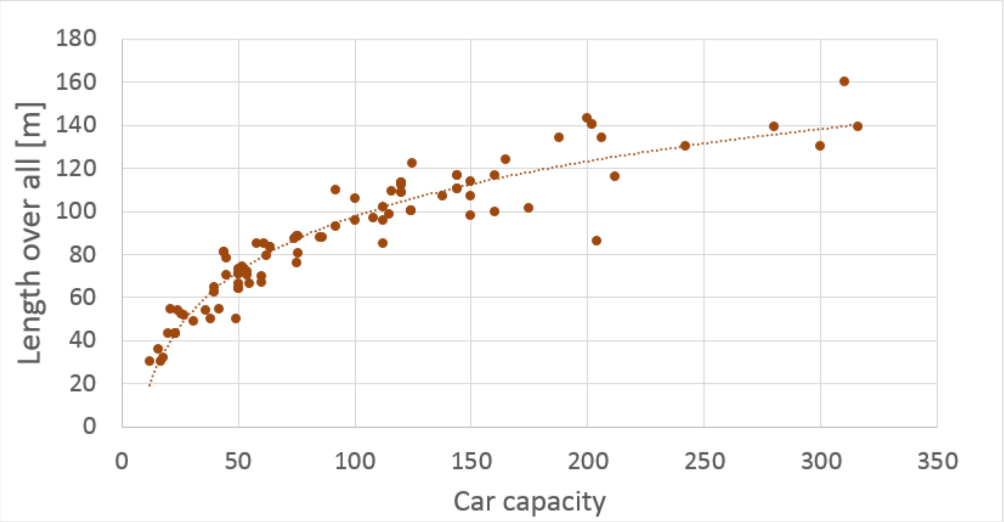


Figure 6.3: Car capacity plotted against length over all, including the trendline

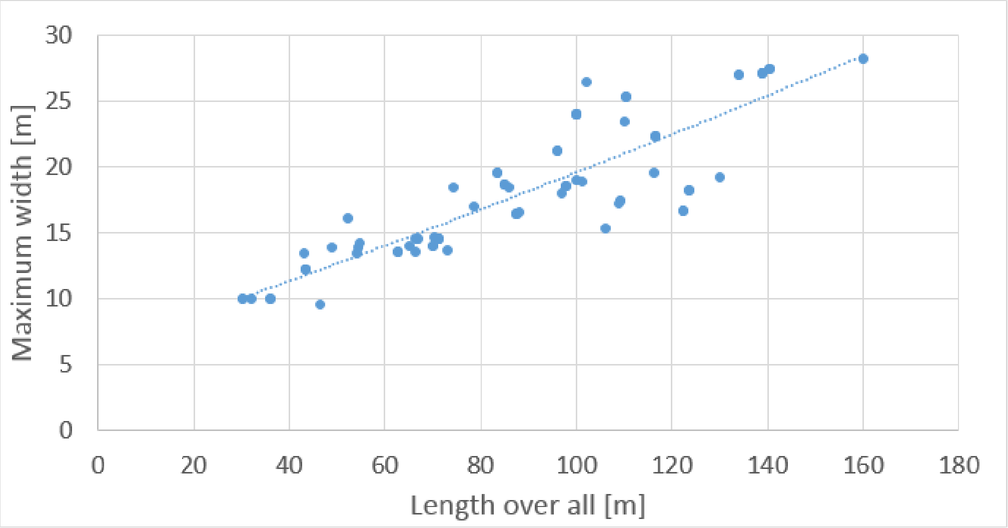


Figure 6.4: Length over all plotted against maximum width, including the trendline

Block coefficient

The block coefficient of double ended ferries diverges from conventional naval architecture principles as the vessels have do not have one specifically designed bow or stern. Both ends of the vessel are designed to perform either function. Due to this, conventional block coefficient estimation methods provide too high values for double ended ferries. The author could not find a prediction method that gives sufficiently accurate block coefficients for double ended ferries. Examining currently operating double ended ferries and empirically approximating their block coefficients, values between 0.35 and 0.5 were found. In the results analysis of this thesis (chapter 8), the assumption is made that the block coefficients is 0.38. In the created concept exploration tool however, the block coefficient is an input that can be altered by the user. Having the vessel draught, length, width and block coefficient, the volume of the vessel can be calculated.

6.2.2. Flat water resistance

The energy that a double ended ferry consumes for propulsion is a result of overcoming resistance. This resistance can be predicted as a function of vessel parameters, sailing speed and conditional parameters. This section describes the method used to determine the flat water resistance; the Telfer method. Using model-test data from multiple double ended ferries, various resistance estimation methods were compared, from which the Telfer method was eventually chosen. The main reason for this is the accurate prediction of the resistance of the double ended ferries in the available data-set. A second reason is that the input parameters in the prediction are vessel length and displacement. These can be practically correlated with a change in the mass and volume of the concepts related to the installed energy system. The full analysis and comparison, including explanation of the process, reasoning and data sets can be found in Appendix D.

The Telfer method uses the Telfer resistance coefficient. This is a non-dimensional coefficient determined using total resistance, length at the waterline, displacement and velocity. The formula for the Telfer coefficient is shown in Equation 6.2

$$C_{TL} = \frac{R_T \cdot L_{wl}}{\Delta \cdot V^2} \tag{6.2}$$

The value of the coefficient is determined using data from a set of vessels geometrically similar to the vessel for which the resistance is to be calculated. This is a strict boundary for the use of the Telfer-method. The Telfer method should not be used to calculate the resistance of vessels not geometrically similar those in the original data set. Another strict boundary is that the resistance input data comes from model-tests or full-scale measurements, and not other resistance prediction methods. For each vessel the Telfer coefficient is determined at each speed for which resistance data is available. Plotting against a speed dependant variable, curves for the coefficient are obtained. From these curves the applicable Telfer coefficient as a function of speed can be determined. How this is done depends on the results of the curves and comparison of the curves for different vessels. An example is using the average trendline. When the Telfer coefficient is known, only the length at the waterline, the displacement and the speed need to be known to calculate the total resistance.

For this thesis, the Telfer coefficient curves were plotted against the displacement-Froude number. The resulting plot with all of the Telfer curves plotted against this value is shown in Figure 6.5.

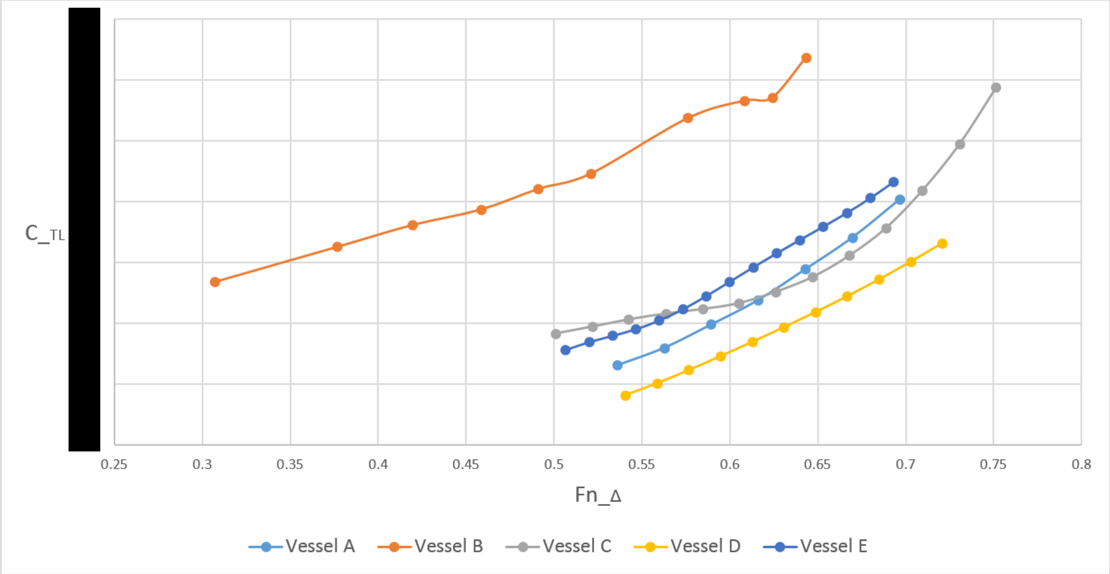


Figure 6.5: Telfer coefficient plotted against displacement-Froude

This graph shows that the Telfer coefficients generally follow a similar trend. With exception of vessel B. The model test data of this vessel, also showed discrepancies in the expected resistance curve. Both factors added to this data being of questionable quality. Therefore the data of this vessel was excluded from further research. The data for the other vessels was not obtained from the same source. Therefore any error has not influenced the rest of the data set. In this thesis, the average trendline of the curves was used to determine the Telfer coefficients for further usage. The resulting formula is shown in Equation 6.3.

$$C_{TL} = \boxed{A} \cdot F_{n\Delta}^2 - \boxed{B} \cdot F_{n\Delta} + \boxed{C} \tag{6.3}$$

6.2.3. Wave and wind resistance

The environment in which a double ended ferry operates in has an influence on the resistance of the vessel. Wave and wind forces can increase or decrease the resistance. This results in a higher or lower energy consumption and thus influences the performance requirement of the installed energy system. In this section the methods used to determine the added resistance due to waves and wind are explained.

STAwave-1 added wave resistance

The STAwave-1 added wave resistance prediction method is for short waves, in the range lower than 25% of the L_{pp}. With waves in this range the added resistance results from the reflection of waves on the hull. The dominating component in the added resistance of this reflection is a second order wave force. The influence of this force on the geometry of the vessel is calculated by a simplified expression of the integration of the force over the geometry [38], shown in equation Equation 6.4. This formula is validated for a significant wave height of $H_s \leq 2.25\sqrt{L_{pp}/100}$. Other assumptions are that heave and pitch are small, and that the vessel encounters head waves[17].

$$R_{aw-STA1} = \frac{1}{16}\rho g H_s^2 B \sqrt{\frac{B}{L_b}} \quad [N] \tag{6.4}$$

Kreinter added wave resistance

The Kreitner added wave resistance prediction method was developed by J. Kreitner in 1934, that uses basic vessel parameters determine the added resistance in waves. The method is valid for waves up to 1.5-2 meters [16]. As shown in Equation 6.5, the formula uses the relation between block coefficient, width and length for its prediction.

$$R_{aw-Kreitner} = 0.64 H_s^2 B^2 C_B \rho \frac{1}{L_{wl}} \quad [N] \tag{6.5}$$

In the model both the STAwave-1 wave resistance and the Kreitner added wave resistance are calculated, if both are applicable. Which of the two resulting values is the larger is then determined and used for the added wave resistance component of the total resistance.

Aage-Brix added wind resistance

The method used to predict the added wind resistance is one based on Aage-Brix wind-force coefficients (Cx). These coefficients were published in 1993 for a large variety of vessel types [11], but the values for nine of the vessel types were originally determined using model test by C. Aage and published in [4]. In this thesis the Aage-Brix coefficients for a car ferry are used, as these were determined for a double ended ro-pax ferry. The coefficients can be found in Appendix E. These are the drag coefficients for the wind force along the longitudinal of the vessel. When multiplied by the frontal surface area of a vessel and the dynamic pressure of the apparent wind, the wind-force coefficient along longitudinal direction yields the added resistance of the vessel (Equation 6.6). The equation for calculating the dynamic pressure of the apparent wind, q, is shown in Equation 6.7. In this equation, u_a, is the apparent wind speed. This is calculated as a function of true wind speed, apparent wind speed, vessel speed, air density and angle of the true wind, as is shown in Equation 6.8.

$$R_{wind} = q \cdot Af \cdot Cx \quad [N] \tag{6.6}$$

$$q = \frac{\rho}{2} \cdot u_a^2 \quad \left[\frac{kg}{m \cdot s^2}\right] \tag{6.7}$$

$$u_a = \sqrt{\breve{u}^2 + v_s^2 + 2 \cdot \breve{u} \cdot v_s \cdot cos\gamma} \quad \left[\frac{m}{s}\right] \tag{6.8}$$

Where:
$\breve{u}$ = True wind - velocity
v_s = Vessel speed
γ = True wind - angle

The resulting wind resistance is dependant on the sailing speed and direction of the vessel. For the model the Aage-Brix added wind resistance prediction was modelled into a function that uses frontal surface area, true wind velocity, true wind heading, vessel speed, downwind sailing heading and upwind sailing heading. When sailing downwind the vessel experiences force in the sailing direction and when sailing upwind against the sailing direction. Creates a difference between the energy required to complete an upwind trip and a downwind trip. For further energy consumption calculation the average wind resistance is used. A similar situation holds for the required power to achieve the maximum speed. However, for this only the upwind trip is taken into account, as the vessel will need more power to achieve its maximum speed when sailing against the wind.

6.2.4. Propulsion power

The characteristics of the drivetrain are decisive in determining the amount of propulsion power needed to overcome the resistance of the vessel. The aim of the exploration tool is to only define the general parameters of the hull and not the specifics of the hull design. However, some of the efficiencies influencing the drivetrain characteristics are related to the specifics of the hull. Simplified prediction methods are used for these, as designing specific hulls for each concept using a concept exploration tool is very time consuming and very complex.

The effective power needed to overcome the resistance is the resultant of the multiplication of the resistance and vessel speed, as shown in Equation 6.9.

$$P_e = R_T \cdot v_s \tag{6.9}$$

The propeller power is determined from the resulting value using the amount of propellers, hull efficiency, relative rotative efficiency and open water efficiency, as shown in Equation 6.10. The hull efficiency is calculated using Equation 6.11, with the description of the calculation method used to determine the thrust deduction factor and wake fraction directly below. For the relative rotative efficiency, a value of 100% is assumed.

$$P_p = \frac{P_e}{kp \cdot \eta_H \cdot \eta_r \cdot \eta_O} \tag{6.10}$$

$$\eta_H = \frac{1-t}{1-w} \tag{6.11}$$

Thrust deduction factor

The value for the thrust deduction was determined using a method published by Harvald in 1983 [46]. The vessel length, vessel width and block coefficient are inputs for several calculations with the final output being the thrust deduction factor. The method starts by calculating three sub-variables as shown in Equation 6.12, Equation 6.13 and Equation 6.14. The thrust reduction then results from Equation 6.15, Equation 6.16, Equation 6.17 and Equation 6.18. In comparing the resulting values with model tests, Harvald added a correction method to make the results match better. The equations for this correction is shown in Equation 6.19 and uses the length displacement ratio. The fact that this method is based on the length, width, block coefficient, displacement and propeller diameter makes it suitable for this thesis as the varying vessel parameters for the concept designs are length and displacement. The varying parameters are expanded upon in chapter 7

$$e = \frac{0.625 \cdot B}{L} + 0.08 \tag{6.12}$$

$$f = 0.165 - \frac{0.25 \cdot B}{L} \tag{6.13}$$

$$d = 525 - \frac{8060 \cdot}{L} + 20300 \cdot (\frac{B}{L})^2 \tag{6.14}$$

$$t_1 = d + \frac{e}{f \cdot (0.98 - C_B)^3 + 1} \tag{6.15}$$

$$t_2 = -0.01 \cdot F_a \tag{6.16}$$

F_a a is a factor determined by the hull shape of the vessel. A U-shape hull gives an Fa of -2, a V-shaped hull +2 and 0 for an N-shaped hull form.

$$t_3 = 2 \cdot (\frac{D_{prop}}{L} - 0.04) \tag{6.17}$$

$$t_{Harvald} = t_1 + t_2 + t_3 \tag{6.18}$$

$$t_{Corrected} = t_{Harvald} - 0.26 + 0.04 \cdot \frac{L}{\Delta} \tag{6.19}$$

Wake fraction

The method used to predict the wake fraction is again published by Harvald in 1983 and obtained from the same document [46]. The input for the calculation are length, width, block coefficient, displacement and propeller diameter. The calculation method follows a similar process as the thrust deduction, with the first step being the calculation of a set of sub variables shown in Equation 6.20, Equation 6.21 and Equation 6.22. These variables are then used in Equation 6.23, Equation 6.24, Equation 6.25 and Equation 6.26 to determine the wake fraction, which is corrected using Equation 6.27

$$a = \frac{0.1 \cdot B}{L} + 0.149 \tag{6.20}$$

$$b = \frac{0.05 \cdot B}{L} + 0.449 \tag{6.21}$$

$$c = 585 - \frac{5027 \cdot}{L} + 11700 \cdot (\frac{B}{L})^2 \tag{6.22}$$

$$w_1 = a + \frac{b}{c \cdot (0.98 - C_B)^3 + 1} \tag{6.23}$$

$$w_2 = \frac{0.025 \cdot F_a}{100 \cdot (C_B - 0.7)^2 + 1} \tag{6.24}$$

F_a a is a factor determined by the hull shape of the vessel. A U=shape hull gives a n Fa of -2, a V-shaped hull +2 and 0 for an N-shaped hull form.

$$w_3 = -0.18 + \frac{}{\frac{D_{prop}}{L} + 0.002} \tag{6.25}$$

Where $w_3 = 0.1$ if the calculated w_3 is larger than 0.1.

$$w_{Harvald} = w_1 + w_2 + w_3 \tag{6.26}$$

$$w_{Corrected} = 0.7 \cdot w_{Harvald} - 0.45 + 0.08 \cdot \frac{L}{\delta} \tag{6.27}$$

Open water efficiency

The open water efficiency of the propeller is approximated by calculating the efficiency of the propeller using the actuator disk theory and then applying a correction factor. In short the actuator disk theory assumes a disk with an infinite amount of blades, exerting a force on a flow. The perfect in-compressible flow passing through the disk is assumed not to be subjected to drag by the disk and the axial velocity is uniform and smooth over the disk. Also, other viscous effects are not taken into account. The result is the ideal axial efficiency of a propellor of the specified diameter and inflow speed. The calculation starts with the thrust loading coefficient. The formula for this is shown in Equation 6.28. The advance velocity, propeller diameter and required thrust are the inputs for this formula. Using the formula shown in Equation 6.29 the thrust loading coefficient is used to determine the ideal axial efficiency.

$$C_T = \frac{T}{\frac{1}{2}\rho v_A^2 \frac{\pi}{4} D_p^2} \tag{6.28}$$

$$\eta_i = \frac{2}{1 + \sqrt{1 + C_T}} \tag{6.29}$$

When operating in the real world the assumptions of the actuator disk theory obviously do not hold. Propellers do not have an infinite amount of blades and viscous effects can be very important for the performance of the propeller. Axial loss, rotational losses and viscous losses result in a lower efficiency than ideal. Using approximated curves for η_o of conventional Wageningen B-series propellors (prepared by Breslin and Andersen) an equation for a correction factor was developed by Kristensen and Lützen [46]. This correction factor is equal to $0.81 - 0.14 \cdot C_T$ or 0.65, which ever is the larger number.

The engine break power is calculated using Equation 6.30. The gearbox efficiency is assumed to be 94% and the shaft efficiency 99.25%. The amount of engines per shaft differs per case.

$$P_b = \frac{P_e}{\eta_s \cdot \eta_{gb} \cdot ke} \tag{6.30}$$

6.2.5. Auxiliary power

The auxiliary energy consumption of a double ended ferry can have a significant impact on the energy system. Continuously transporting passengers and cars creates an energy demand for much more than only propulsion. To gain quantitative insight into the actual impact, a prediction method for the auxiliary power of double ended ferries was investigated. The starting point being the definition of what the auxiliary power is used for in double ended ferries. The double ended design eliminated the need for bow thrusters or extra propulsion for manoeuvring other than the main propulsion system. Other systems on board consuming power are the systems for navigation and control of the vessel, leisure systems such as kitchen or entertainment and the heating, ventilation and air conditioning (HVAC). Based on the knowledge that the HVAC systems form a large part of the power consumption of vessels transporting passengers, the assumption was that this was the main power consuming system.

The main drivers of the power consumption of HVAC systems are the volume of the space needed to be heated, ventilated or cooled and the temperature difference that needs to be overcome for this space. A measure for this overall internal volume of a vessel is the gross tonnage (GT). Data on this Gross Tonnage was available for the majority of the vessels in the double ended ferry database set up for this thesis. This gross tonnage is a factor of the type of superstructure of the vessel, the length, width and depth. The first three of these are available for the vessels in the database. Looking into the correlation between the gross tonnage and length multiplied by width, the graph in Figure 6.6 was obtained.

At first sight, there is no clear trend or correlation. This is because this data includes vessels with various types of superstructures. Building in the knowledge gained in chapter 2, three types of superstructure were identified; open, semi and closed. Examples of each type of vessel are shown in Figure 6.7, Figure 6.8 and Figure 6.9. The open superstructure has a large open deck space with little internal volume as a result. The closed superstructure will have much more internal volume per deck area due to the deck being fully enclosed. The semi is a combination of both, having open deck space at both ends but a significantly larger superstructure than the open superstructure. When the data from Figure 6.6 is categorised per superstructure type, clear correlations arise. This is presented in Figure 6.10. When deck area increases, the gross tonnage of the open superstructure ferry increases less dramatically than that of the semi and closed. The gross tonnage of the semi, in turn, increases less steep than that of the closed superstructure ferry.

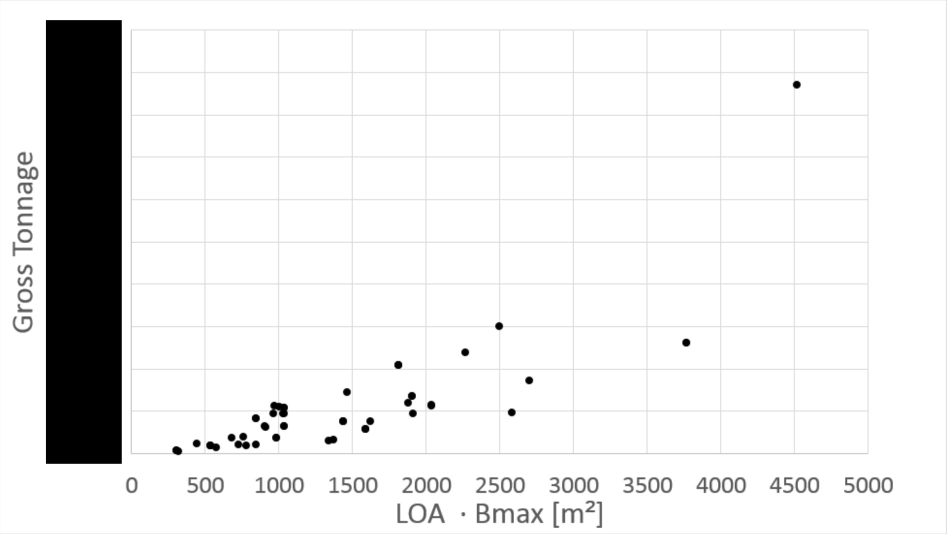


Figure 6.6: Gross tonnage vs Length over all multiplied by maximum width

Figure 6.7: Ferry with an open superstructure

Figure 6.8: Ferry with a semi-open superstructure

Figure 6.9: Ferry with a closed superstructure

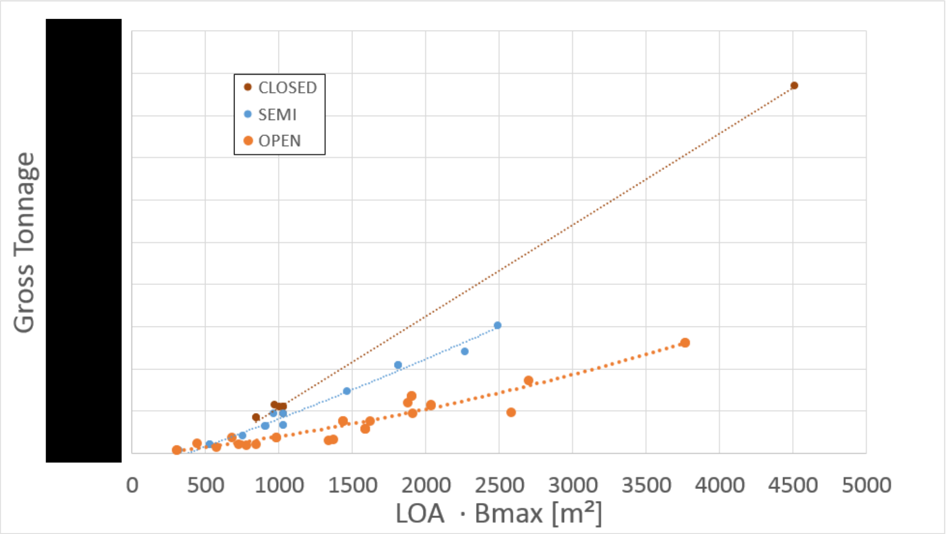


Figure 6.10: Categorised gross tonnage vs Length over all multiplied by maximum width

The trendlines for prediction of the GT used in the design tool are:
Open: $GT = \boxed{A}(LB)^2 + \boxed{B}LB - \boxed{C}$
Semi: $GT = \boxed{A}(LB)^2 + \boxed{B}LB - \boxed{C}$
Closed: $GT = \boxed{A}(LB)^2 - \boxed{B}$

Having defined the correlation between length, width and gross tonnage, the connection with auxiliary power is examined. This is done by calculating the ratio between the auxiliary power and gross tonnage for the vessels in the database. The results are shown in Figure 6.11. Investigation of the grouping of the results leads to an additional distinction, based on the different climates the ferries operate in. The lower light blue area shows ferries operating in a moderate climate such as Western Europe and areas along the American-Canadian border. In these areas, heat from the engines can be used for heating in the winter and the moderate summers result in a limited need for cooling. Therefore the amount of auxiliary power needed per GT is limited. Higher ratios for auxiliary power versus gross tonnage occur when the climate deviates from this moderate climate. The red areas show ferries operating in hotter climates, such as the Mediterranean, where the HVAC system is dominated by the year-round operation of the cooling system. The result is a higher auxiliary power need per GT than in moderate climates. The dark blue areas show values for vessels sailing in areas with significantly colder winters than in moderate climates. The extra required heating results in more installed auxiliary power.

The $\frac{\text{Auxiliary power}}{\text{Gross tonnage}}$ ratios used in the exploration tool are shown directly below. For the moderate and warm climate an approximate average was determined. The option of a cold climate was not implemented. Having only one data point in combination with it giving a significantly higher value that the other points, drove the decision not to implement the option.

Moderate climate: Auxiliary power = $GT \cdot \boxed{A}$
Hot climate: Auxiliary power = $GT \cdot \boxed{A}$

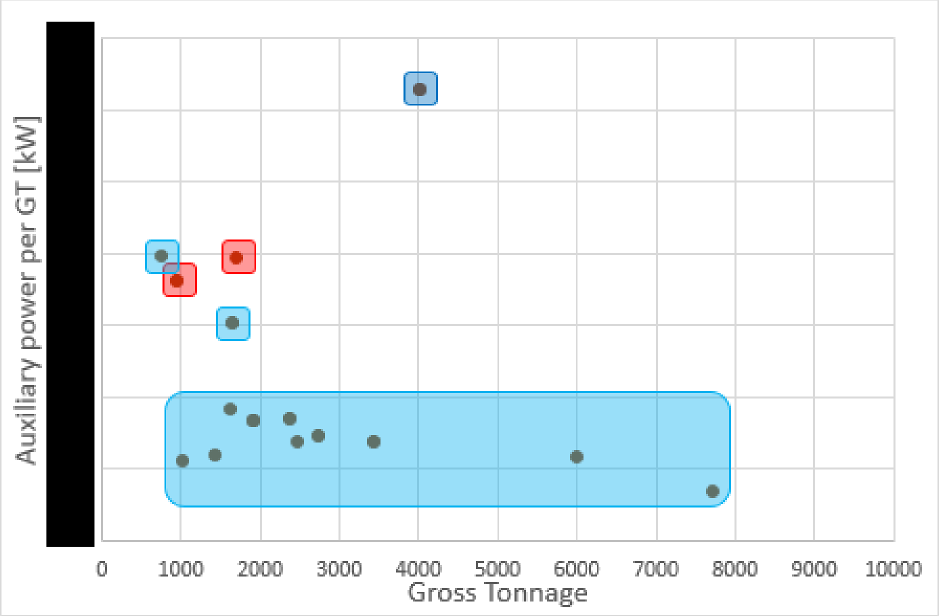


Figure 6.11: Auxiliary power per Gross Tonnage vs Gross Tonnage

6.2.6. Operational profile input

The operational profile used as input for converting the propulsion and auxiliary power to energy is given by the user of the exploration tool. Double ended ferries are assumed to have a general operational profile applicable to the majority of the vessels. This starts with starting up the energy system, during which energy is consumed but the vessel does not necessarily move. This is followed by manoeuvring away from the dock, after which the vessel accelerated to its service speed. The acceleration is followed by transit at service speed. After the transit, the vessel decelerates. The vessel then manoeuvres to the dock and shuts down after securely docking. The format in which the input is to be given is shown in Figure 7.1, a screen-shot of the user interface of the exploration tool. This shows that the user provides the speed in percentage of the service speed sailed at each phase of the trip. The

Double ended ferries rarely sail 24 hours per day. To account for this in the model, the user needs to provide the idle night time in hours. This is the time during the night that the ferry does not sail. For the unloading time, the user provides the amount of time available per car for loading and unloading.

6.2.7. Energy consumption

The energy consumption during one trip is the sum of the energy consumed for propelling the vessel and the energy consumed by auxiliary systems. The energy consumed for propulsion of the vessel is calculated by determining the sum of the energy used during each of the phases of transit, described by subsection 6.2.6. From the speed or speed-equivalent energy consumption, the power needed during each phase is determined. Multiplying this by the time allocated to each phase, yields the energy consumption.

The auxiliary energy consumption is assumed to be constant over the entirety of each trip, with shore power delivering the energy during loading and unloading. The amount of auxiliary power during the trip is given by the user in the form of a percentage of the total installed auxiliary power. Multiplying this percentage with the total installed power and the trip time, yields the auxiliary energy consumption per trip.

6.3. Energy system types

The second part of the model development is the addition of the algorithms that determine the technical and economical aspects of the energy systems and corresponding vessel concepts. Knowledge gained in chapter 4 is used to determine which aspects of the energy systems are essential for a realistic the concept exploration and how they should be captured in an algorithm. Adding the developed algorithms to the previous part, yields a model resembled by the partial model diagram shown in Figure 6.12.

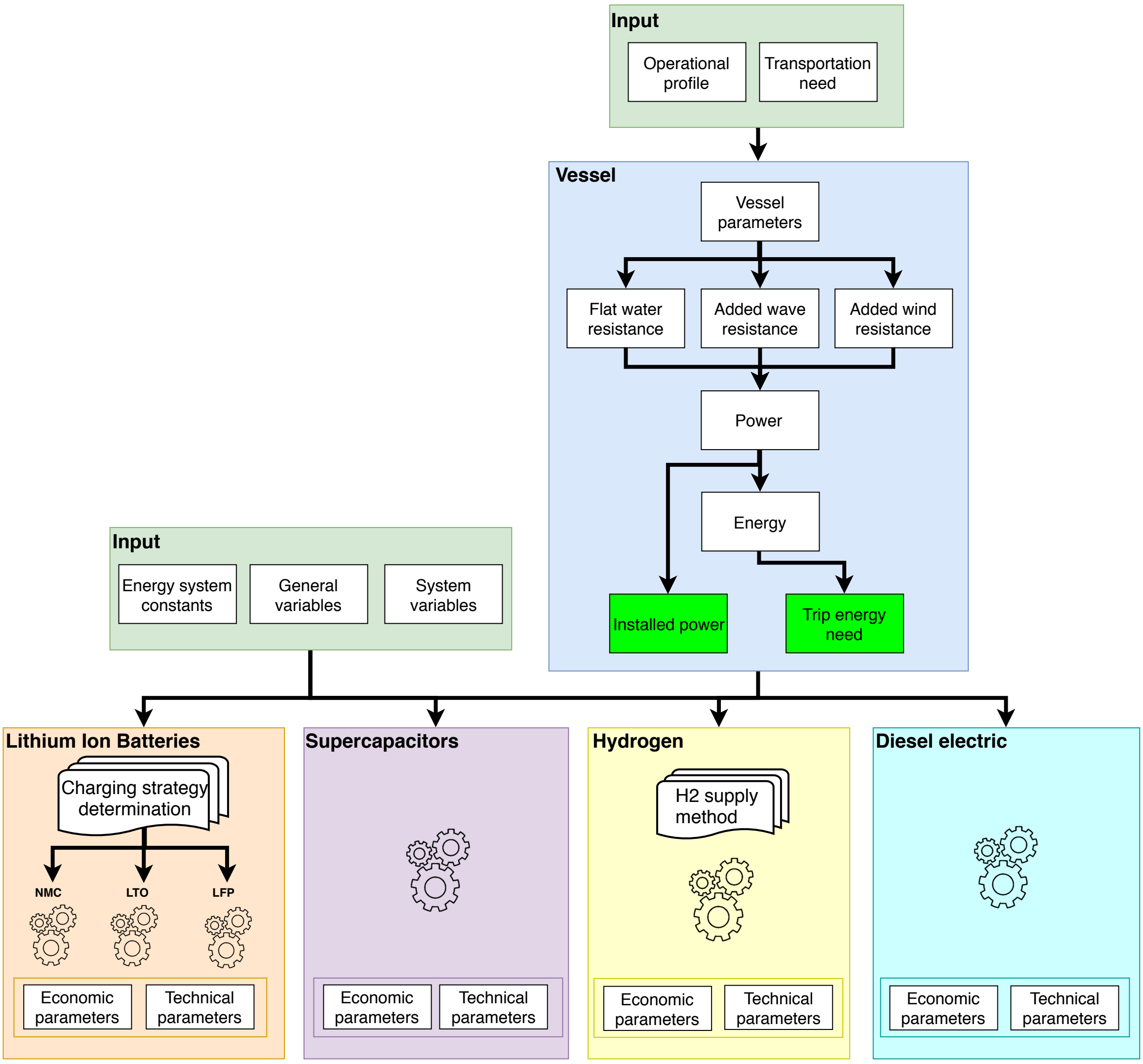


Figure 6.12: Model diagram - partial 2

6.3.1. Lithium-ion batteries algorithms

The algorithm that determines the technical and economical parameters of the battery energy system uses the general variables, battery-system variables and battery-energy system constants as input. The first step is to determine the desirable charging strategies and the corresponding battery types, using a sub-algorithm. Using these charging strategies, the technical aspects of the battery energy systems are determined. The technical parameters are then used to determine the economical parameters.

Charging strategy The mass and volume of a battery system are not only dependant on the amount of energy a ferry needs for one trip. The power available to charge the batteries and the resulting charging strategy are just as influential. When a ferry uses batteries for energy storage, batteries need to be charged using power provided by a connection at the terminal. As an integral part of the local energy grid, there is a limitation to the power that this connection can supply. This is the limiting factor for how much energy can be transferred from the grid to the batteries on the vessel during the available charging time. The preferred option is to be able to charge the vessel with energy for one trip during each birthing.

If the shore power is insufficient, a solution is to add extra batteries at the terminal. These charge the whole period that the ferry is sailing to the other side, loading/unloading and sailing back. When the ferry returns, the built up energy from the shore batteries is transferred to the batteries on the vessel. With this system, the time available to extract the trip energy from the local grid is greatly enlarged. This enhances the possibilities of battery energy systems being feasible. If the shore power is even less, there is an option to install a high capacity battery, that fully charges over night and recharges partially during the day using the available charging time at each birthing. The energy charged overnight and battery capacity is the difference between the energy charged during each birthing and the energy required per trip, multiplied by the daily amount of trips. Depending on the shore power it might also be desirable to only add shore batteries at one of the terminals that the ferry sails between.

All of the possible charging strategies for a ferry using batteries are shown in Figure 6.13, with the explanation of each charging strategy discussed above the figure. The assumption is that there is an equal amount of shore power available at both terminals. The algorithm that determines which charging strategies need to be considered, is based on having the lowest cost. In Figure 6.13 the charging strategies are roughly sorted from cheapest to most expensive, from top-left to bottom-right. Roughly because the relative costs of batteries versus charging stations can influence the cost of the overall system. An example is a more elaborate system with relatively cheap components being cheaper than a simple system with relatively expensive elements. In cases where this becomes a factor, the algorithm gives multiple charging strategies as an output. The reason for this is that if the cost difference of two charging strategies is limited, the complexity of the overall system or specifications of the batteries might become important factors in the choice of the naval architect/client. The choice for the more expensive option can be based on multiple reasons such as safety, redundancy or overall reliability.

An example is the comparison of charging strategy 2 and 3. Depending on the cost (purchase, use and replacement) difference between an extra charging station or extra battery, either option could be the cheapest. However other factors such as possible extra permits for an extra charging station or extra complexity of adding an extra battery might outweigh small cost differences between the charging strategies, for the user. This illustrates the reason for not defining an optimal charging strategy. It is still possible however to narrow down, as charging strategy 4 will never be more desirable than charging strategy 2. If charging strategies 2 and 3 are not possible due to insufficient shore power, strategies 4, 5 and 6 will be considered. If these are not possible, the strategies with overnight charging, strategies 7 to 11, are considered. The flow chart with the algorithm that determines the charging strategies is shown in Appendix C. If none of the strategies are possible due to the low shore power, a pop-up showing this message pops up on the screen of the user.

Charging strategy 2: The vessel battery has energy for one trip. The vessel battery is recharged directly from the local grid with the required energy for one trip, after each trip.

Charging strategy 3: The vessel battery has energy for two trips. The vessel battery is recharged directly from the local grid with the required energy for two trips, after each second trip.

Charging strategy 4 The vessel battery has energy for one trip and there are shore batteries at each terminal with the energy capacity for one trip. The shore batteries are continuously charging from the local grid. The vessel battery is recharged from the shore batteries with the required energy for one trip, after each trip.

Charging strategy 5: The vessel battery has energy for more than one trip and less than two trips. At one terminal there is a shore battery with an equal capacity. The shore battery is continuously charging from the local grid. The vessel battery is recharged from the shore batteries every time it is at the corresponding terminal and recharged directly from the grid at the other terminal.

Charging strategy 6: The vessel battery has energy for two trips and at one terminal there is a shore battery with an equal capacity. The shore battery is continuously charging from the local grid. The vessel battery is recharged from the shore batteries with the required energy for two trips, after each second trip.

Charging strategy 7: The vessel battery has energy for more than two trips, but less than the total daily energy requirement. There are shore batteries at each terminal with the energy capacity for less than one trip. The shore batteries are continuously charging from the local grid. When the vessel is not sailing during the night, the vessel battery is fully charged using the grid. The vessel battery is also recharged from the shore batteries with the required energy for less than one trip, after each trip.

Charging strategy 8: The vessel battery has energy for more than two trips, but less than the total daily energy requirement. There is a shore battery at one terminal with the energy capacity for less than one trip. The shore battery is continuously charging from the local grid. When the vessel is not sailing during the night, the vessel battery is fully charged using the grid. The vessel battery is also recharged from the shore battery with the required energy for less than one trip at the corresponding terminal and recharged directly from the grid at the other terminal with energy for less than one trip.

Charging strategy 9: The vessel battery has energy for more than two trips, but less than the total daily energy requirement. There is a shore battery at one terminal with the energy capacity for less than one trip. The shore battery is continuously charging from the local grid. When the vessel is not sailing during the night, the vessel battery is fully charged using the grid. The vessel battery is also recharged from the shore battery with the required energy for less than one trip, at the corresponding terminal.

Charging strategy 10: The vessel battery has energy for more than two trips, but less than the total daily energy requirement. When the vessel is not sailing during the night, the vessel battery is fully charged using the grid. The vessel battery is also directly charged from the grid after each trip, with energy for less than one trip.

Charging strategy 11: The vessel battery has energy for more than two trips, but less than the total daily energy requirement. When the vessel is not sailing during the night, the vessel battery is fully charged using the grid. The vessel battery is also directly charged from the grid after each second trip, with energy for less than one trip.

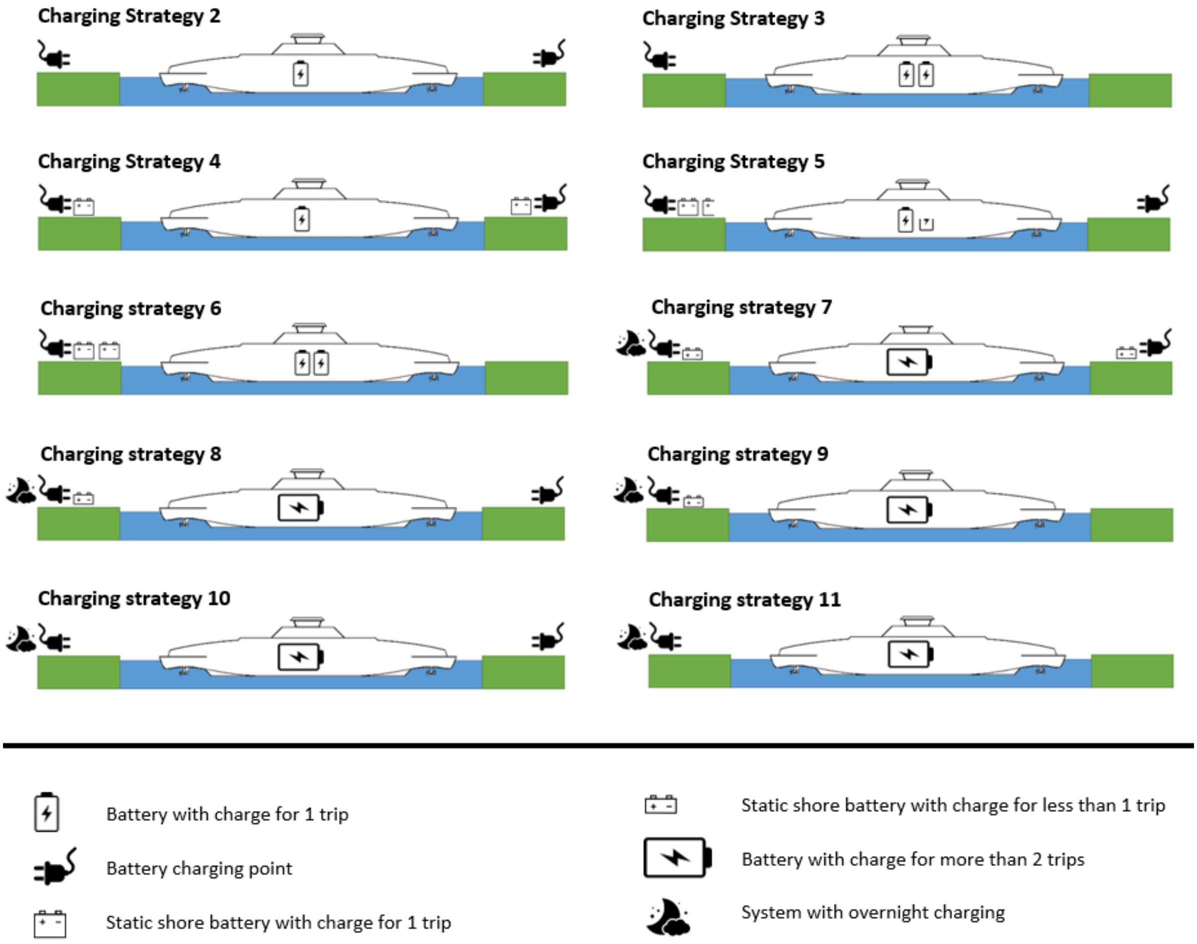


Figure 6.13: Battery charging strategies

Battery swapping

The battery energy systems discussed in this thesis are under the assumption that the batteries are fixed in the vessel. Batteries can however also be used in a non fixed manner. This works as follows: when a battery is empty it is removed and replaced by a fully charged one. In the transportation sector this is called battery-swapping. For a ferry this would mean that, at a certain interval, a battery charged at the terminal is swapped for the empty battery on board the vessel. In the discussed charging strategies, such a system can be implemented in charging strategies 4, 5 and 6. This would not change any of the technical and economical output used or results calculated in this thesis.

C-rates and battery types

Another factor influencing the feasibility of the battery systems is the maximum C-rate of the batteries. The C-rate is a normalised value for how fast a battery is charged or discharged. At a C-rate of 1 (dis)charging the battery takes one hour. At a C-rate of 2, 30 minutes and at a C-rate of C/2 2 hours. Battery manufactures specify a maximum continuous C-rate for the operation of batteries. If the desired amount of energy cannot be charged within the available time using this maximum continuous C-rate, the corresponding battery type is not feasible. Within lithium-ion batteries, there are multiple types differentiated on specific chemical composition. Each of these types has different characteristics concerning energy density, ageing and maximum C-rates. Therefore three types of lithium-ion batteries are considered in this thesis NMC, LTO and LFP. The characteristics of each of these types is shown in

Figure 4.6.

Cost parameters To compare each energy system the initial CAPEX, total CAPEX, daily OPEX and Net Present Value are to be determined. The first two are greatly influenced by the costs of the battery system and the lifetime. Depending on the charging strategy the battery system will include the batteries on the ship, possible shore batteries and one or two charging stations. The finite lifetime of the batteries might mean that the batteries need to be replaced one or multiple times over the lifetime of the vessel. Depending on the cost of replacing the system, the frequency with which this is needed has a large influence on the feasibility of a battery system. The daily OPEX is a combination of the costs of electricity and maintenance. The electricity costs are an input provided by the user. The maintenance is expressed as a yearly percentage of the initial CAPEX, a characteristic of the battery type. The total net present value is the calculated over the lifetime of the vessel using a discount rate from user input and all of the capital en operational expenses related to the operation of the energy system.

6.3.2. Supercapacitor algorithms

The technical and economical parameters of supercapacitors are calculated using a simplified version of the lithium-ion algorithm. Supercapacitors have the lowest energy density (mass and volume) of the considered energy systems and also the highest cost. This results in the assumption that installing supercapacitors with more capacity than needed for one trip, is not feasible economically. Therefore only the charging strategy similar to charging strategy 2 from subsection 6.3.1, is used. Adding the general variables, supercapacitor-system variables and supercapacitor-energy system constants, returns the technical parameters of the supercapacitor energy system and corresponding economic values. The flow chart of the supercapacitor energy system is shown in Appendix C

6.3.3. Hydrogen algorithms

The technical and economical parameters of a hydrogen energy system are dependant on the needs for hydrogen for operating the ferry and the possibilities for obtaining the hydrogen. The cost of obtaining the hydrogen is a crucial factor in choice for which system is used to supply the vessel. The first step is thus to create an algorithm that determines these costs and the technical parameters of the corresponding system. The second step is to incorporate the results to an algorithm that gives the specifications of the hydrogen system installed on the vessel. The final results are the technical and economical aspects of the total system, from supply to usage.

Hydrogen source Hydrogen can be made available at the ferry terminal using three methods; a pipeline, truck delivery or electrolysis. The method where a pipeline supplies hydrogen to the ferry was not explored in this thesis. The reason for this is that hydrogen pipeline infrastructure is rarely part of the local infrastructure and the building/development cost of new pipelines is largely location dependant. The second method is truck delivery. Trucks fill up with hydrogen at a centralised hydrogen production plant and transport this to the ferry terminal. There the trucks directly fill up the hydrogen tanks installed on the ferry or dispense the hydrogen to separate tanks installed at the terminal. The third option is to install an electrolysis unit at the terminal that uses electricity and water to produce hydrogen. The workings of such a system are explained in section 4.2.

To sole goal of the hydrogen source algorithm is to determine which method provides hydrogen with the lowest net present value over the lifetime of the ferry. When hydrogen is delivered by truck an transferred directly to the tank on the ferry, the only costs are the actual costs of the hydrogen. A second option for refuelling by truck, is that the truck fills up hydrogen tanks at the terminal. Which option is used depends on the desired refuelling interval given by the user. The hydrogen refuelling interval is chosen such that per refuelling, the hydrogen needed is far less than can be provided by one truck, it makes more sense to have the truck dispense the excess to a tank a the terminal and have the ferry refuel from this tank until empty. The size of this tank is related to the capacity of the truck, hydrogen ferry refuelling interval and capacity of the tank on board the ferry. The costs of having hydrogen delivered by truck and the capacity of the truck are given by the user, as this is highly location dependant.

At most ferry terminals the access to water and electricity creates the possibility to produce hydrogen on site. Depending on the cost of electricity, the amount of hydrogen needed, discount rate at which investments are made and the costs related to purchasing and maintaining the equipment, it can be possible that producing hydrogen is cheaper than purchasing it. In the algorithm, the amount of energy needed in 24 hours expressed in mass of hydrogen, is used to determine the size of the electrolysis unit. In addition to this unit a storage tank for the produced hydrogen is needed. The size of this tank is determined by the refuelling interval and capacity of the ferry. The flow diagram of the resulting algorithm is shown in Appendix C.

Hydrogen fuel cell and fuel tank The hydrogen energy system on board of the vessel consists of two main components; the fuel cell and the fuel tank (section 4.2). The fuel cell is the power generating component and its size is thus derived from the power needed by the ferry to sail at the desired maximum speed. The fuel tank, containing compressed hydrogen, is the energy storage component and thus dependant on the energy needed by the ferry for the amount of trips in between each refuelling.

The requirements for the power needed for the maximum speed and the energy required for one trip are combined with the technical characteristics of hydrogen energy systems to calculate the technical parameters of the hydrogen energy system to be installed on the ferry. Combining the costs related to such a system with the costs of obtaining the needed hydrogen results in the economic parameters of the total hydrogen system.

6.3.4. Diesel-electric algorithms

To provide insight into the performance of zero-emission energy systems from a technical and economical perspective relative to systems currently used, a fossil fuel benchmark is introduced. The diesel-electric energy system was chosen as it the layout is similar to that of zero-emission energy systems. In diesel-electric energy systems, the diesel generators provide electricity to the electrical engines. Whereas in the zero-emission energy systems this is done by batteries, fuel cells or supercapacitors. Thus from electrical engines to propellor, the propulsion system has the same configuration. Obviously the diesel-electric energy system algorithm also considers the fuel tanks.

Using the required installed power to reach the maximum speed, the power of the diesel engines is determined. The fueling interval provided by the user is combined with the amount of energy required per trip to find the volume and mass of diesel to be carried on board of the vessel. An added mass factor and added volume factor for this weight and volume are used to account for the volume and mass of the tank itself.

Cost of carbon

For the diesel benchmark an extra cost parameter is added: the cost of carbon dioxide emissions.

Emissions resulting from burning fossil fuel accumulates in the environment and atmosphere. The unwanted effects of this accumulation on the climate are borne by society. The cost related to these effects is called the social cost of carbon. Without a carbon tax, neither the producers or consumers of fossil fuels bare these social costs. Introducing a tax changes this and adds the reflection of the damages caused in the form of a higher price of usage. The idea being that the generated income is used by the government to compensate or mitigate the damages to society. The net result is that it becomes more expensive for consumers to consume fossil fuels, which increases the incentive to explore zero-emission options. Some cities and countries currently have such a carbon tax implemented. For double ended ferries using diesel-electric energy systems, the carbon tax increases the operational cost and influences the economic outputs of the model.

6.4. Output generation

In this section the details of the output of the model are discussed. Also, the method of iterating the designs is discussed. Adding the output and the iterations yield the model shown in Figure 6.1.

6.4.1. Economic outputs

The economic feasibility of a zero-emission energy system cannot be expressed in a single value. This is because economic feasibility depends on the financial status and preferences of the client purchasing the vessel. As described in section 6.1 this is when the desirability comes in to play. Some clients might prefer higher initial costs and lower operating costs or vice verse. The prospect of certain components needing replacement over the lifetime can also influence the choice for a certain system, that might initially not be the cheapest. This unknown factor in the preferences of the client is the reason for the multiple economic outputs given by the tool:

Initial CAPEX
The initial CAPEX for the energy system are the costs for the initial purchase of the energy system at the beginning of the vessel lifetime. Based on the funds available to the client this value can be used to determine if it is financially feasible for a client to purchase a certain energy system.

Total CAPEX
The total CAPEX is the total amount of capital expenses during the lifetime of the vessel. This value differs from the initial CAPEX as some components of the energy system have a limited lifetime and need to be replaced before the end of the vessel life. An example is batteries, where it might be the case that they need to be replaced multiple times. Together with the initial CAPEX, the total CAPEX indicates the to be expected replacement costs over the lifetime of the vessel. Based on the forecast of the financial status of the client, it can be determined if the client is able to pay the replacement costs in the future. If the initial and total CAPEX are equal, the expectation is that the life of the components of the energy system is greater than or equal to the life of the vessel.

OPEX
The OPEX consists of the costs for maintenance and fuel/electricity/hydrogen, given in €per day. They are important to a client, as sufficient funds need to be available during the vessels lifetime, to pay for these expenses. Based on their financial status, the ratio between CAPEX and OPEX can influence the financial feasibility of the energy systems.

Net present value

The net present value is a measure of the current value of money spent and received over a future period of time. The discount rate is the interest rate used to determine the current value of future cash flow. The basic principle is that having a certain amount of money today, is worth more than having that same amount in the future. Along that same principle money spent in the future is worth less than that same amount spent today. This is because that money could have been used to make more money in the mean time. A simplified example related to ferry energy system purchasing;

An operator, possessing €100, has the choice between two systems with the exact same performance. System 1 costs €100 at the beginning of the 30 year lifetime and does not need replacement. System 2 costs €50 at the beginning of the lifetime and needs replacement after 15 years, at the same initial costs. So for the first 15 years the operator has €50 unspent. The decision is made to put this in a bank at a yearly interest rate or discount rate of 5.0%. After 15 years there is €104 in the bank account of the operator. At this moment the operator spends the €50 on the replacement energy system and still had €54 left in the bank account. In absolute terms both systems will cost the operator €100 over the lifetime of the vessel. But after 30 years, with system 1 the operator has €0 in the bank account and with system 2 €112, without having any difference in the performance of the vessel. This illustrates why it is more desirable to spend money later.

The formula for calculating the net present value is shown in Equation 6.31. Using the example the net present value for both systems is calculated. As shown in Equation 6.32 and Equation 6.33, the net present value of system 2 is €25.9 higher than the NPV of system one, and therefore more desirable - as the performance is exactly the same. How this can also be explained is that in order to have the €50 needed for the replacement, 15 years after the initial purchase, the buyer needs to set apart €24.1 at the beginning - which needs to stay at the bank and cannot be spent. The initial cost is then €74.1

$$NPV = \sum \frac{\text{Net cash flow}}{(1+\text{discount rate})^{\text{number of time periods}}} - \text{initial investment} \tag{6.31}$$

$$NPV_{system1} = €-100 \tag{6.32}$$

$$NPV_{system2} = \frac{-50}{(1+0.05)^{15}} - 50 = €-74.1 \tag{6.33}$$

For an investment the NPV is usually a positive value, as an investment will result in returns over time. In this case, any assumptions concerning ferry ticket sales and pricing only adds insecurity to the results. Therefore returns were not included in the calculations and the calculated NPV is always negative. It should therefore be read that **the system with the smallest absolute value of NPV is the cheapest over the life of the vessel**. This includes; initial CAPEX, replacement CAPEX, maintenance costs and electricity/diesel/hydrogen costs. All other costs are excluded in the calculation.

6.4.2. Technical output

The aspects determining if a zero-emission energy system is technically feasible are governed by the current status of technology and boundaries within which an energy system needs to operate. A clear example of such a boundary is the available shore power available. With this boundary in place, certain charging strategies are not technically possible for certain combinations of charging time and required energy transfer.

In the case where multiple energy systems are technically feasible, the desirability of certain technical aspects can influence the final choice for an energy system. This desirability is not definable black-and-white and thus not practical to implement in the model. Therefore it is not implemented in an algorithm. Technical output from the concept exploration tool can be used to let the user make such decisions.

Another reason for providing technical information on the various energy systems and iterated designs, is to provide users with insight regarding the technical performance of the energy systems. In chapter 7, a practical use for such insights is explained. The technical output provided by the tool is:

- Energy system mass
- Energy system volume
- Propulsion energy consumption per trip
- Auxiliary energy consumption per trip
- Total energy consumption per trip
- Vessel length
- Vessel displacement

An example of the desirability of a technical aspect is the desirability of a short vessel length. The exploration tool iterates the vessel parameters to "custom" vessel concepts for each energy system, possibly having different lengths. Examples of reasons for a short length being desirable might be easier manoeuvring or the maximum dry-dock length of a nearby maintenance yard.

6.4.3. Iteration of designs

The iteration of the vessel designs is based on the difference in mass and volume between the diesel-electric benchmark and zero-emission energy systems. These differences are added to the mass and volume of the vessel from the prior iteration. This makes the resulting vessel parameters deviate from the values derived from the initial vessel parameter algorithm. This algorithm is based on a database containing diesel powered double ended ferries.

The implementation of the mass difference is quite simple. If the zero-emission energy system is heavier than the benchmark the difference and thus vessel displacement increase is positive. Vice verse the difference is negative and the vessel displacement decreases. Being a direct input to the Telfer resistance prediction method, this displacement difference results in an increase or decrease of the resistance of the vessel.

Accounting for the volume difference of the less simple. This is due to the volume being a result of multiple vessel parameters; length, width, draught and block coefficient. Multiple assumptions are the basis for deciding which of these parameters change due to a volume increase or decrease. The first assumption is that the draught of the vessel does not change, because this is an input value provided by the user. Any applicable draught restrictions on the sailing route cannot be changed which means that a vessel exceeding the depth would be per definition in-feasible. The second assumption is that the block coefficient is not varied. As the value is provided by the user and (as discussed earlier) a reliable method for predicting it is not available.

The two parameters left are the vessel width and length. Changing these will be used to result in decreases or increases in vessel volume. However, for volume decreases they cannot change. Due to the vessel length and width governing the deck area, which in turn dictates car capacity, a decrease will lower the car carrying capacity of the vessel and make it infeasible according to the clients' wishes. This results in the third assumption that if the volume of a zero-emission energy system is lower than that of the benchmark, vessel volume does not change. The fourth assumption is that the width of the vessel does not change. The main reasoning behind this is that the Telfer resistance prediction method, which is used to determine the vessel resistance in the model subsection 6.2.2, does not directly take width into account. An increase of the width would then not influence the vessel resistance, an unrealistic scenario. The final result is that a volume increase, due to a zero-emission energy system having a larger volume than the benchmark, results in an increase of the length of the ship. This increase in length results in an increase of the vessel resistance resulting from prediction with the Telfer resistance method.

The amount of iterations that the tool performs for each case is 5. This constant is determined empirically by varying the amount of iterations for a large number of cases. The result is that after five iterations the results have converged.

6.5. Model discussion

This section contains the discussion of the mode. First, the model assumptions are explained. Subsequently the verification is discussed. Third, the validation of the model is examined.

6.5.1. Model assumptions

The developed model is a combination of algorithms that creates concept designs of double ended ferries. The process of creating concept designs is a dynamic process with many facets that are subject to change. This change can occur within projects or between different projects. By limiting some changes, assuming that the user has certain knowledge and simplifying certain aspects of the process, it is possible to represent the complexity of the concept design process using a set of algorithms. A full list of assumptions is provided in Appendix F. The main assumptions of the model are are:

- The tool is only applicable to double ended ferries that carry cars and passengers
- The tool is intended for early stage concept design
- The tool is only intended for mono-hull ships
- The energy system starts with energy transfer systems at the terminal
- The energy system ends where electrical energy has been made available on board of the vessel, from the energy storage system
- The net present value is only applicable to the energy system

6.5.2. Verification

The aim of verification is to show that the calculations in the algorithms in the model are solved correctly. To understand how the model was verified, a small explanation of how the concept exploration tool is programmed follows. In order to make the concept exploration tool expandable and adjustable for future use, the algorithms in which the model is divided are coded in functions. In an executable script, these functions are called and coupled with each other. In this script the input is called from the graphical user interface (GUI) and the results are written to it. By programming in such a manner functions can easily be adjusted in their respective and relatively short scripts. New functions can be developed separately and coupled to their others in the executable when satisfactory. These can be added to the model, replace existing functions or can be used case dependant. In this way, the model can be expanded to account for more factors and variables or be made applicable to other vessel types.

The functions are:

- Added resistance upwind
- Added resistance downwind
- Battery specifications
- Battery specifications iteration
- Diesel specifications
- Hydrogen source
- Hydrogen specifications
- Supercapacitor specifications
- Energy consumption
- Energy consumption iteration
- Vessel parameters and resistance
- Vessel parameters and resistance iteration

For verification purposed such a system enables for separate verification of the calculations in each function. This was done by using static and dynamic verification methods. The static verification was done by checking that the implemented calculations matched the flowcharts which they are meant to mirror. As the algorithms in each function are relatively short, the results of each function were subsequently compared to manual calculations. The verification of each function being complete if the results of the function were identical to those from manual calculations. Dynamic verification of the results was done by testing each function and experimenting with the input values. The expected results of changing certain input values were compared with with the actual results from the functions. With this comparison it could be confirmed if the calculations were performed correctly. A simple example being that an increase in the amount of required car capacity should logically lead to a larger vessel length and width. The manual verification being the manual calculation of length and width using the derived trendlines. By checking for multiple single cases and variations of input, each function was verified before moving on to the development of the next.

During the process of coupling the functions in the executable file, a similar process was used to determine if the coupling was implemented correctly. By starting with the functions mirroring the beginning of the model diagram, adding the next function according to the diagram, verifying the intermediate results and repeating until the end of the model, a second check was done to ensure the verification of the final result.

6.5.3. Validation

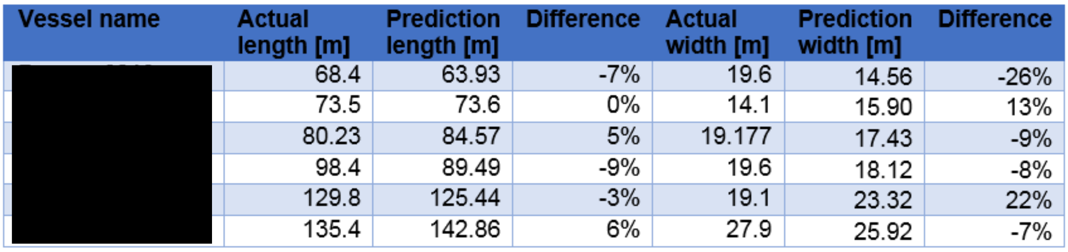
In the concept exploration tool, multiple algorithms are used that predict or estimate certain aspects of double ended ferry design and performance. Some of these algorithms are developed by third parties and others are developed as part of this thesis. The algorithms developed by third parties, their general use and the source where the validity of the algorithms is proven are shown in the list directly below.

- Added wind resistance - Brix [11]
- Added wave resistance - Kreitner [16]
- Added wave resistance - STAIMO [38]
- Thrust deduction factor - Harvald [46]
- Wake fraction - Harvald [46]
- Open water efficiency - Kristensen and Lützen [46]

As can be the case with vessel design, some of the algorithms developed by third parties are not specifically designed for double ended ferries. In the research performed during this thesis and the resulting foundation of knowledge was used to determine that these methods were accurate enough to use in the concept exploration tool.

To validate the algorithms developed as part of this thesis, the validation is split into four parts; vessel parameter prediction, resistance prediction method, energy consumption prediction and energy system calculation.

Vessel parameter prediction This first part is aimed at validating the method used to generate the general parameters of the double ended ferries. A data-set consisting of 7 vessels, that are not included in the original database, are used to determine the accuracy of the vessel parameter prediction. For each of these ferries, the variables that influence the general vessel parameters are put in to the concept exploration tool to generate vessel parameters. The draught of the vessel is taken to be equal to the input vessels, as this is an actual input for the exploration tool and decided upon by the naval architect using it. These results of the concept exploration tool are shown next to the actual vessel parameters in Figure 6.14, where the percentages of deviations and average percentages of deviations are also shown.



Vessel name	Actual length [m]	Prediction length [m]	Difference	Actual width [m]	Prediction width [m]	Difference
[redacted]	68.4	63.93	-7%	19.6	14.56	-26%
[redacted]	73.5	73.6	0%	14.1	15.90	13%
[redacted]	80.23	84.57	5%	19.177	17.43	-9%
[redacted]	98.4	89.49	-9%	19.6	18.12	-8%
[redacted]	129.8	125.44	-3%	19.1	23.32	22%
[redacted]	135.4	142.86	6%	27.9	25.92	-7%

Figure 6.14: Vessel parameter predictions vs actual

The prediction of the vessel length is within 10% for each of the vessels, either over or underestimating. This is deemed accurate enough for the use in the concept exploration tool. This accuracy is directly related to the data from the vessel database used to determine the trendline, shown in Figure 6.3. The correlation that this graph shows between the length over all and car capacity follows a clear trend over the whole range. Above a car capacity of approximately 120, the data starts to spread more, leading to the expectation of less accurate length predictions above this car capacity.

Prediction of the vessel width gives less closely grouped and accurate results. The predictions range from 31% over-prediction to 20% under-prediction, but also with some predictions being within 1% from the actual vessel width. This spread can be explained by looking at the data on which the prediction is based, shown in Figure 6.4. The graph shows that there is a quite large variation of vessel widths for given vessel lengths, even from the same ferry operators and shipyards. This indicates there is more freedom or that there are more factors influencing the width of double ended ferries. In discussion with [redacted] it was learned that the vessel width is often limited by factors such as docking facilities and capacities of close-by repair and maintenance yards. This explains the variations in widths and the deviations of the exploration tool from some of the vessels compared. However, this is not always the case and in many cases of newly built double ended ferries, the width is not greatly limited by external factors. By using a data from a large variety of vessels and locations it is determined that the resulting trendline for width prediction is accurate enough for the use of concept design.

The other two vessel parameters, draught and block coefficient, are provided by the user. The main reasons for this are possible draught limitations along the route and that reliable data regarding the vessel draughts was not available. Therefore the choice was made to have the naval architect/user provide the vessel draught. For the block coefficient, the lack of an accurate prediction method was the reason for having the naval architect/user provide a value as input. Multiple conventional methods were tested, as no block coefficient method specifically for double ended ferries currently exists to the knowledge of the author. Comparing the results with some known double ended ferry block coefficients showed that all provided values too high for double ended ferries.

Resistance prediction method

This second part discusses the validity of the resistance prediction method. The validation of the resistance prediction method is based on the fact that it is derived from a data-set of model-test resistance values. The method is elaborately discussed and compared to other resistance methods in subsection 6.2.2.

Energy consumption prediction

This third part is aimed at determining the validity of the combination of the algorithms calculating the resistance and energy consumption. This was done using a data set containing energy consumption predictions. The data set consists of two vessels [redacted]. The difference with results of these calculations and the concept exploration tool is -8% and -14%. The reason for this difference is the method with which the resistance was calculated. The concept exploration tool uses the Telfer method and for the data-set Holtrop-Mennen was used. The vessel parameter prediction function was bypassed for this comparison to isolate the energy consumption prediction from the vessel parameters.

The comparison shows that the output generated by the concept exploration tool is close to the values used en calculated by a reputable shipyard such as Damen Shipyards. Obviously, a comparison with the energy consumption of a currently operable double energy ferry would be a better validation case, but such data was unfortunately not available for this thesis.

Energy system calculation

The algorithms of the energy system types are not algorithms that predict aspects of designs, but rather calculate the parameters. As the physics of the systems can be accurately represented by mathematics, there is little uncertainty requiring validation. The uncertainty in the energy system calculations is traced back to the uncertainty of the input. When using the concept exploration tool it is the responsibility of the user to determine the validity of the input and implications on the results. The input used in the general analysis subsection 7.2.3 was obtained through research and investigation of the various energy system types, with data from systems that can currently be purchased by shipbuilders as is discussed in chapter 4.

Confirmation for the correct implementation of the energy system calculations was obtained from the fact the parameters varied in the general analysis section 7.2 did not influence any output values that they should not influence according to the model diagram flowchart in Figure 6.1 and Appendix C. This was the case in all the iterations performed during the general analysis (section 7.2). During this analysis, the tool was ran through approximately 400.000 iterations without any discrepancies in the results.

6.6. Conclusion

The development of a concept exploration tool for zero-emission double ended ferries is the main goal of this thesis. This is achieved by developing a theoretical model and transforming this into an exploration tool, through implementing of the set algorithms from the model in the Python programming language. Input is provided through a graphical user interface coupled to this set of algorithms. The result of the algorithms are coupled back to the user through another part of the interface when the execution button is activated.

III

Results and conclusions

7

Results Extractions

This chapter describes how results and insights can be extracted from the developed concept exploration tool. The concept exploration tool is developed in such a way that it can be used in two ways. Firstly, for daily use within the operations of a shipyard. Secondly for the general analysis of the possibilities of using zero-emission energy systems in the double ended ferry market and the influence of internal and external variables on these possibilities. With both uses, there is a different way to extract the results from the concept exploration tool. The first part of this chapter briefly explains how the concept exploration tool is to be used for daily use. The second part focuses on how the general analysis is set-up, what is of interest for this analysis and the variations investigated. In the next chapter the results of the analysis are discussed.

7.1. Single case analysis

In daily operation at a shipyard, the concept exploration tool can be used in the early design stage to evaluate the feasibility of different types of zero-emission energy systems for double ended ferries. By providing a relatively limited amount of input, the concept exploration tool provides multiple economical en technical output values for the different types of energy systems and corresponding vessels. These results can be used for a multitude of applications. Regardless of the specific application, the main advantage is that decisions following from the concept exploration tool can be supported by data, thus creating data driven decision making. With the technical characteristics and technical variables developing rapidly, human experience regarding the feasibility of certain system is quickly outdated or different per naval architect. By adjusting/updating the constants of the energy systems in the tool (see subsection 7.1.1 for a visual representation) a whole design department is able to use the same values when making choices regarding energy systems.

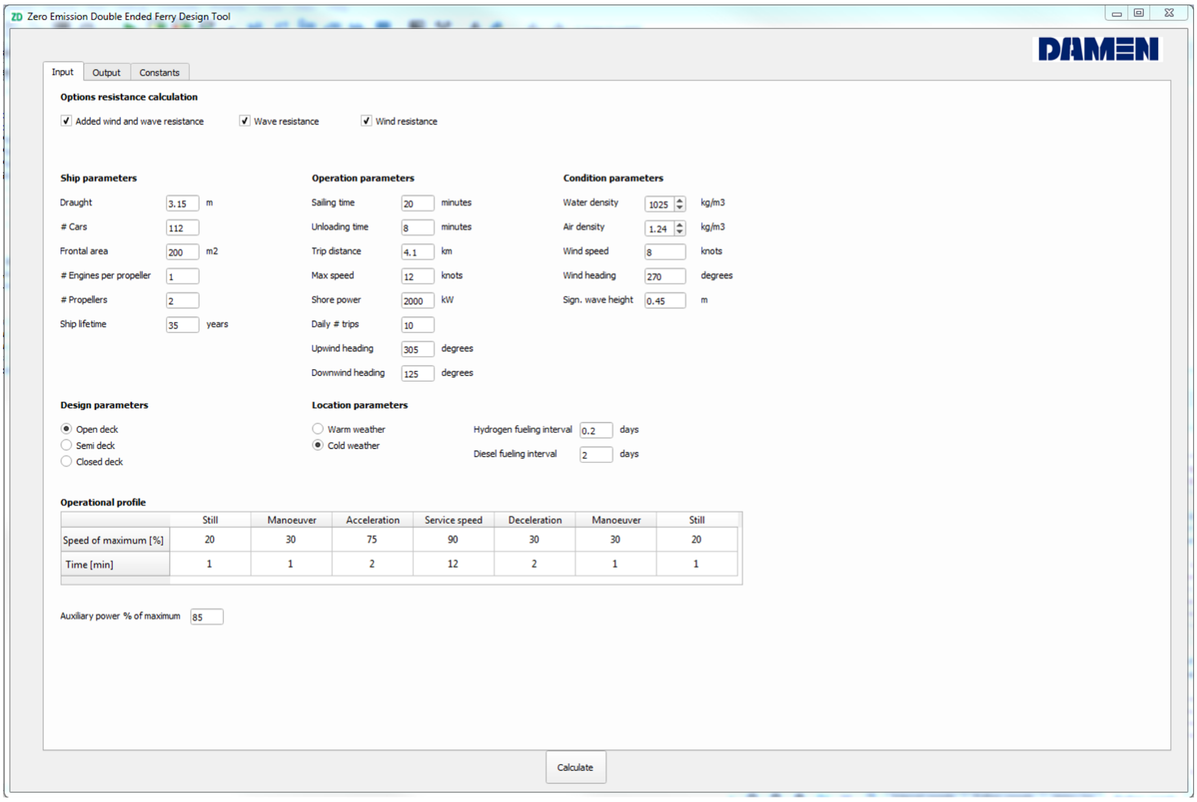
When specifically designing a double ended ferry that has a zero-emission energy system, the concept exploration tool can firstly be used to narrow down the possible energy system types based on the types calculated to be feasible by the tool. As a result, the early design process can be much more efficient than if all types need to be investigated in detail. If multiple systems are feasible the output of the tool can be used to asses the desirability of the different options.

A second use is the quick comparison of zero-emission energy systems with the diesel-electric energy system. This is useful in cases where a zero-emission energy system is not specifically required. Based on the economical and technical output of the tool, a decision can be made regarding the further investigation of certain energy systems. As zero-emission energy systems are rapidly developing and becoming cheaper, more often the argument for such a system is based on financial grounds than environmental.

Thirdly the concept exploration tool can be used to rapidly investigate the performance of various concept designs. This is useful in cases where the boundaries of the transportation need, that the ferry needs to fulfil, are not yet strictly defined. With the run-time of five iterations being under two minutes, the influence of varying certain input can be quickly assessed for specific cases.

7.1.1. Graphical interface use

The user interacts with the concept design tool through a graphical user interface that is coupled to the back-end of the model. This user interface consists of a screen with three tabs: input, output and constants. The input tab with example input data is shown in Figure 7.1. All boxes in white require input by the user. The tick boxes give the user the choice to include added wave resistance and/or added wave resistance aspects in the resistance calculation. Depending on which aspects are included, the corresponding input boxes are hidden or displayed. The radio buttons are used to provide information about the location of operation of the vessel and general information about the design. This information is used in the calculation of the auxiliary power and energy consumption.



Options resistance calculation

☑ Added wind and wave resistance ☑ Wave resistance ☑ Wind resistance

Ship parameters

Draught 3.15 m
Cars 112
Frontal area 200 m2
Engines per propeller 1
Propellers 2
Ship lifetime 35 years

Operation parameters

Sailing time 20 minutes
Unloading time 8 minutes
Trip distance 4.1 km
Max speed 12 knots
Shore power 2000 kW
Daily # trips 10
Upwind heading 305 degrees
Downwind heading 125 degrees

Condition parameters

Water density 1025 kg/m3
Air density 1.24 kg/m3
Wind speed 8 knots
Wind heading 270 degrees
Sign. wave height 0.45 m

Design parameters

● Open deck
○ Semi deck
○ Closed deck

Location parameters

○ Warm weather
● Cold weather

Hydrogen fueling interval 0.2 days
Diesel fueling interval 2 days

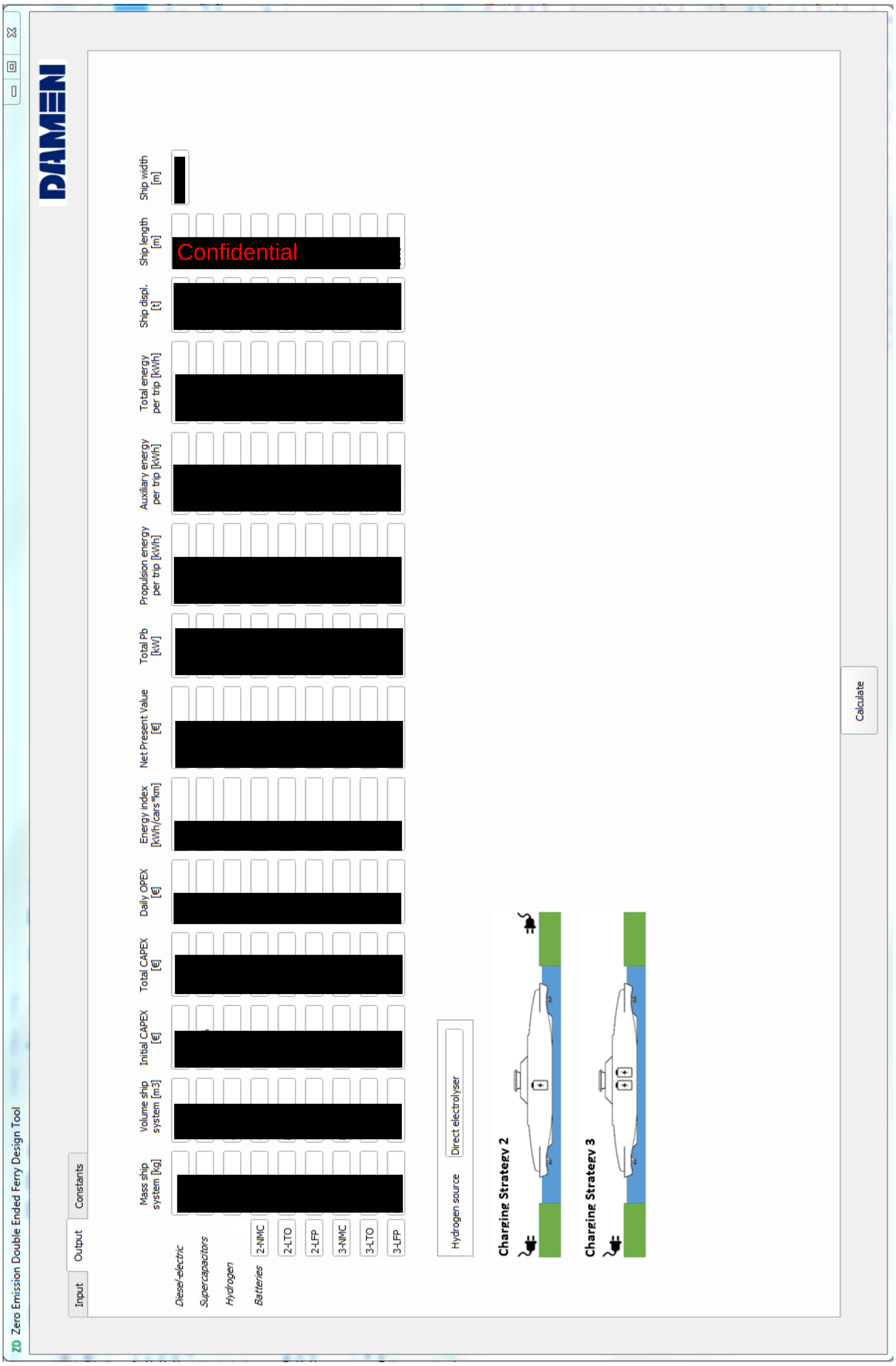
Operational profile

	Still	Manoeuver	Acceleration	Service speed	Deceleration	Manoeuver	Still
Speed of maximum [%]	20	30	75	90	30	30	20
Time [min]	1	1	2	12	2	1	1

Auxiliary power % of maximum 85

Figure 7.1: GUI Concept exploration tool - input tab

The output tab with example output data, is shown in Figure 7.2. This tab displays the feasible energy systems and corresponding economical and technical parameters when the "Calculate" button is clicked.

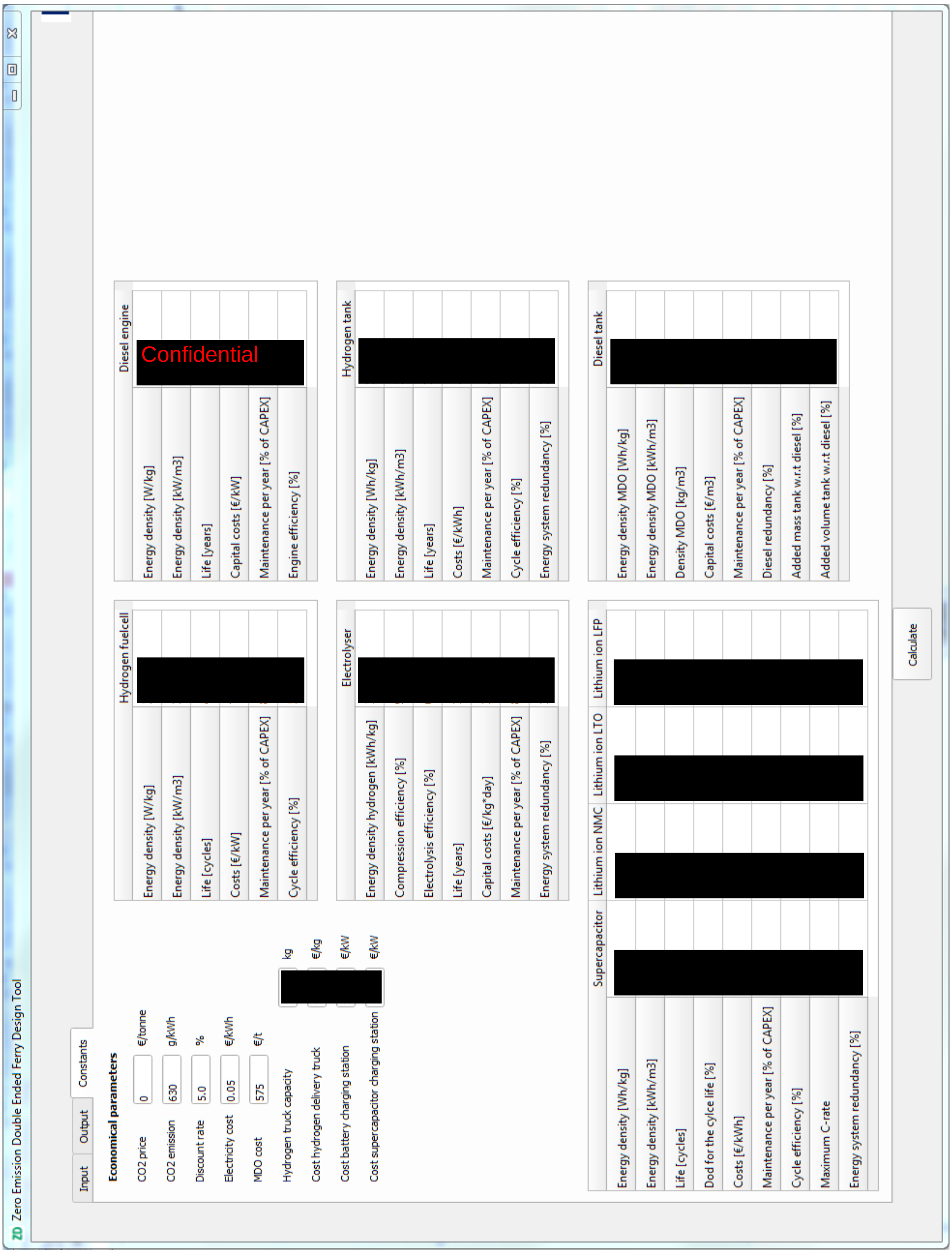


Confidential

[redacted]

Figure 7.2: GUI Concept exploration tool - output tab

The constants tab, shown in Figure 7.3 contains all system characteristics used in the algorithms. There are no hidden constants regarding the performance of the energy systems anywhere in the scripts of the model. By default, the values in this tab are set to currently deemed accurate values. If changes are desired by the user, the value in the boxes can simply be changed, after which clicking the "Calculate" button will calculate new results using the alteration and display them in the output tab.



Economical parameters

CO2 price	0	€/tonne
CO2 emission	630	g/kWh
Discount rate	5.0	%
Electricity cost	0.05	€/kWh
MDO cost	575	€/t
Hydrogen truck capacity	[redacted]	kg
Cost hydrogen delivery truck	[redacted]	€/kg
Cost battery charging station	[redacted]	€/kW
Cost supercapacitor charging station	[redacted]	€/kW

Diesel engine

Confidential

Energy density [W/kg]	[redacted]
Energy density [kW/m3]	[redacted]
Life [years]	[redacted]
Capital costs [€/kW]	[redacted]
Maintenance per year [% of CAPEX]	[redacted]
Engine efficiency [%]	[redacted]

Hydrogen tank

Energy density [Wh/kg]	[redacted]
Energy density [kWh/m3]	[redacted]
Life [years]	[redacted]
Costs [€/kWh]	[redacted]
Maintenance per year [% of CAPEX]	[redacted]
Cycle efficiency [%]	[redacted]
Energy system redundancy [%]	[redacted]

Diesel tank

Energy density MDO [Wh/kg]	[redacted]
Energy density MDO [kWh/m3]	[redacted]
Density MDO [kg/m3]	[redacted]
Capital costs [€/m3]	[redacted]
Maintenance per year [% of CAPEX]	[redacted]
Diesel redundancy [%]	[redacted]
Added mass tank w.r.t diesel [%]	[redacted]
Added volume tank w.r.t diesel [%]	[redacted]

Hydrogen fuelcell

Energy density [W/kg]	[redacted]
Energy density [kW/m3]	[redacted]
Life [cycles]	[redacted]
Costs [€/kW]	[redacted]
Maintenance per year [% of CAPEX]	[redacted]
Cycle efficiency [%]	[redacted]

Electrolyser

Energy density hydrogen [kWh/kg]	[redacted]
Compression efficiency [%]	[redacted]
Electrolysis efficiency [%]	[redacted]
Life [years]	[redacted]
Capital costs [€/kg*day]	[redacted]
Maintenance per year [% of CAPEX]	[redacted]
Energy system redundancy [%]	[redacted]

	Supercapacitor	Lithium ion NMC	Lithium ion LTO	Lithium ion LFP
Energy density [Wh/kg]	[redacted]	[redacted]	[redacted]	[redacted]
Energy density [kWh/m3]	[redacted]	[redacted]	[redacted]	[redacted]
Life [cycles]	[redacted]	[redacted]	[redacted]	[redacted]
Dod for the cylce life [%]	[redacted]	[redacted]	[redacted]	[redacted]
Costs [€/kWh]	[redacted]	[redacted]	[redacted]	[redacted]
Maintenance per year [% of CAPEX]	[redacted]	[redacted]	[redacted]	[redacted]
Cycle efficiency [%]	[redacted]	[redacted]	[redacted]	[redacted]
Maximum C-rate	[redacted]	[redacted]	[redacted]	[redacted]
Energy system redundancy [%]	[redacted]	[redacted]	[redacted]	[redacted]

Figure 7.3: GUI Concept exploration tool - constants tab

7.2. General analysis

The use of the concept exploration tool for single cases at a shipyard is a very practical use, yet focused very specifically. The fact that the concept exploration tool consists of a set of computer algorithm makes it greatly suitable for the analysis of large amounts of input data. This ability is used to create and vary input data with the goal of answering the two research questions related to Parameter analysis (section 1.2).

The general analysis is divided into two phases; the **full range analysis** and the **boundary range analysis**. Each phase focuses on a different range of combinations of car capacity and trip distance. In short, the full range analysis focuses on the full operational range of car capacity/trip distance combinations of the double ended ferry market and the boundary range analysis focuses on specific trip distances or car capacities. For both phases, the starting values of all other variables are the same. These initial values are shown in Figure 7.8.

To make the concept exploration tool more practical for the analysis of large amounts of input data, the graphical user interface described in section 7.1 was decoupled from the back-end script. Having to put each case into the user interface not very efficient. In the back-end script the possibility to generate large strings of input was added, as well as various manners to graphically display the resulting output.

7.2.1. Phase 1: Full range analysis

The first aim of the full range analysis is to provide insight into which types of energy system have the lowest absolute net present value, in which areas of the operational range of the double ended ferry market. The lowest absolute net present value means that, discounted to the present, the energy system has the lowest total cost of ownership over the lifetime of the vessel. By varying the economical, technical and operational parameters from the initial values, their influence on the financial performance is investigated. Which parameters are varied and with which values, is explained in subsection 7.2.3.

The input data of the full range analysis is made up of all combinations of: car capacity ranging from 20 to 150, with a step size of 5 and trip distance ranging from 5km to 50km with a step size of 5km. For each combination of car capacity/trip distance, the concept exploration tool is run. From the results, the energy system type with the least negative NPV is identified and a point with the corresponding colour is plotted in the graph. An example of such a graph is shown in Figure 7.4, with the colour legend shown below. The cut-off above which the graph remains white shows combinations where the amount of daily trip cannot be accomplished within 24 hours, with the given speed, trip distance, car capacity and minimum (un)loading time per car.

- Red = Diesel-electric
- Yellow = Supercapacitor
- Blue = Hydrogen
- Green = Lithium-ion batteries

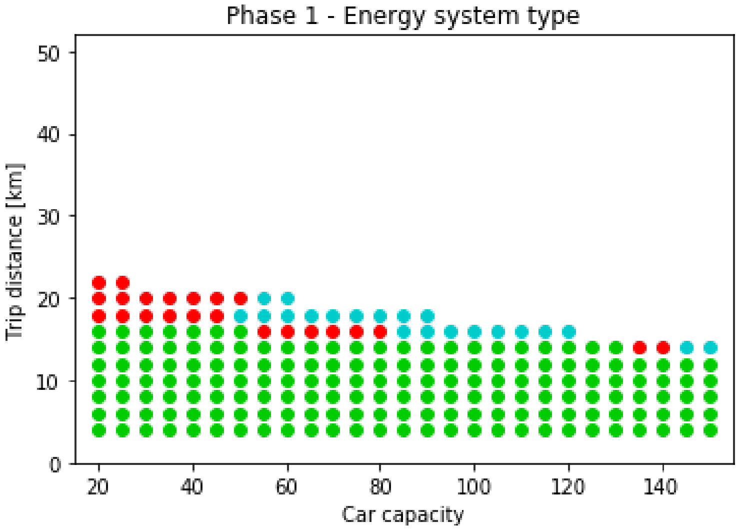


Figure 7.4: Phase 1 - Energy types

There is a second option within the full range analysis that does not focus on energy system choice, but rather on the comparison of the resulting vessel concepts. This can be done by having the colours of the points correspond with a value, through the introduction of a legend. An example is the displacement change of the concept vessels when using a battery energy system. By comparison of the displacements of the concepts using battery energy systems and diesel-electric energy systems, the percentage increase/decrease of one with respect to the other can be calculated. These percentages can then be plotted in a graph for the full range of trip distance/car capacity combinations. The resulting graph is shown in Figure 7.5

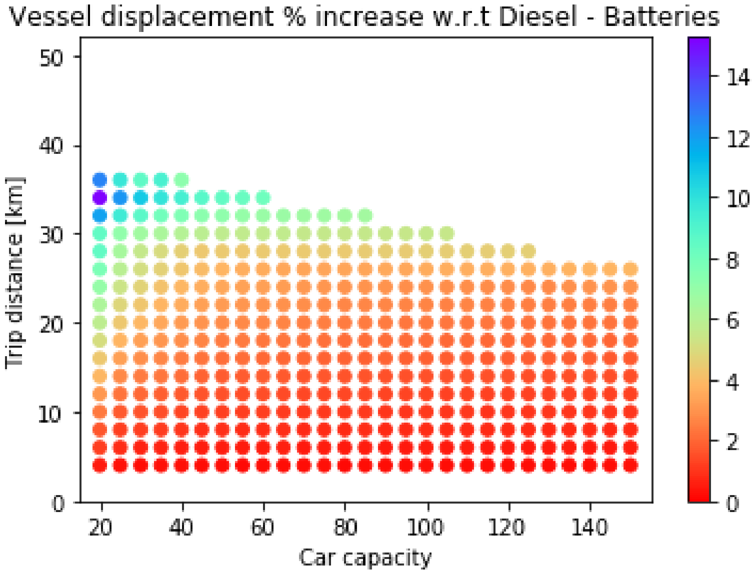


Figure 7.5: Phase 1 - Vessel displacement % increase w.r.t Diesel - Batteries

7.2.2. Phase 2: Boundary range analysis

The graphs from the full range analysis show clear boundaries where which type of energy system that has the lowest absolute NPV. Along these boundaries, the values of these outputs for the different types of energy systems are close together. In phase 2, graphs are created showing the development of the systems along these boundaries, to gain insights into what dictates these boundaries. Depending on the propagation of the boundary in the full range analysis, either the trip distance or car capacity is fixed in these graphs. The remaining value is plotted against the NPV. The energy system with the lowest absolute NPV or the lowest dot along the y-axis of the graph, has the lowest total cost of ownership over the lifetime of the vessel discounted to present value. Examples of the resulting graphs are shown in Figure 7.6 and Figure 7.7.

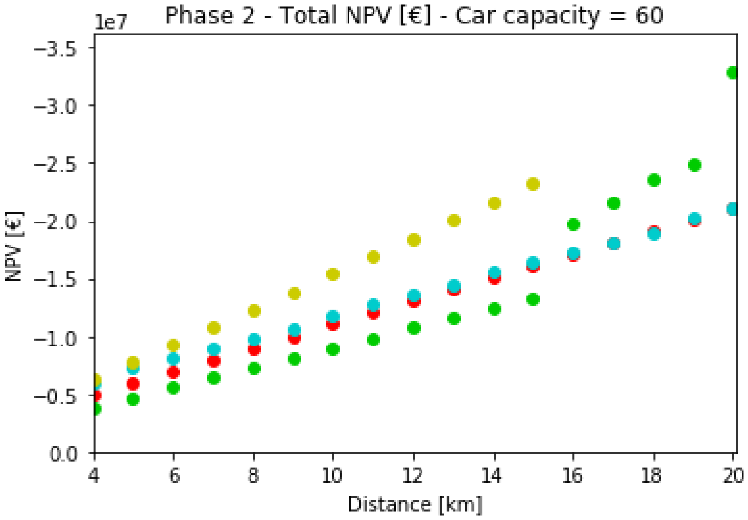


Figure 7.6: Phase 2 - Net Present Value for constant car capacity

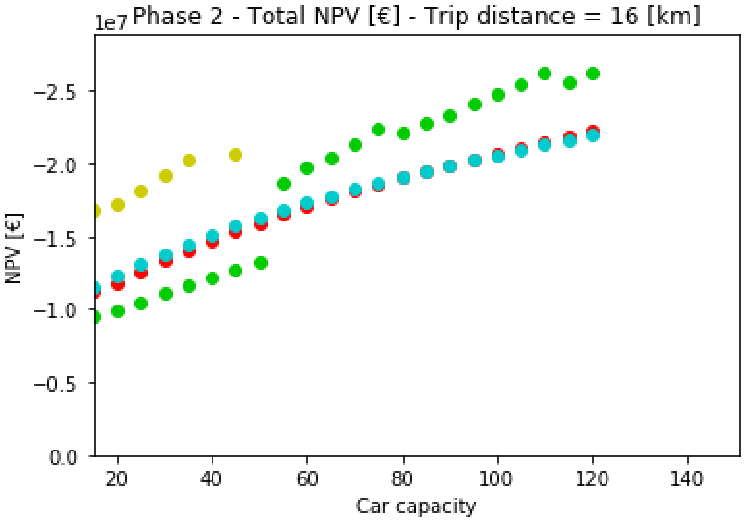
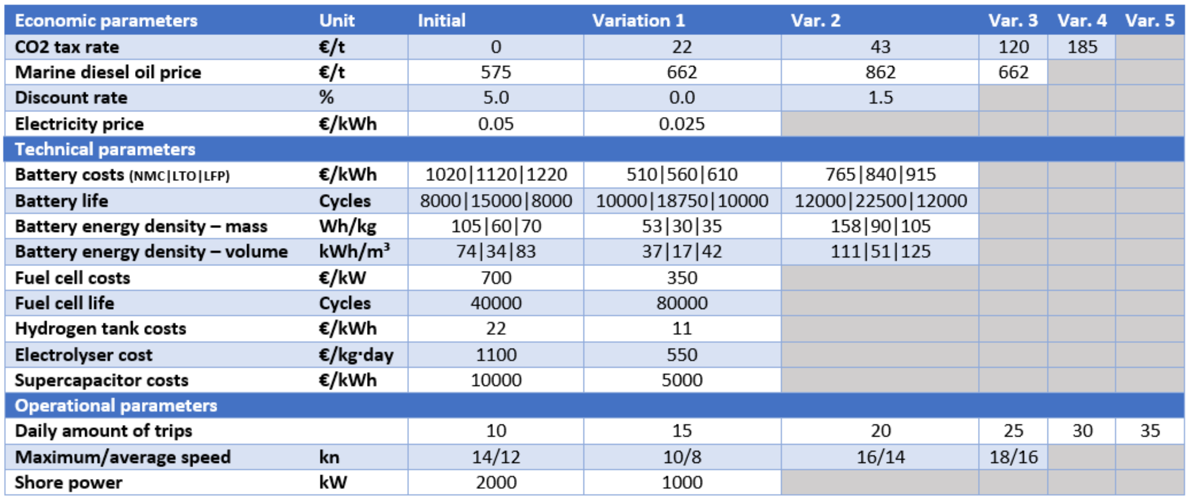


Figure 7.7: Phase 2 - Net Present Value for constant distance

7.2.3. Parameter variations

With the possibility of analysing large amounts of input data in the general analysis, there is the opportunity to investigate the effect of varying the input. This is done by systematically varying single input parameters. The results from analysing the produced data are discussed in chapter 6.

The input variations investigated are based on the varying of three types of parameter: economical, technical and operational. Large amounts of data and variations of input can be analysed by the tool. If all possible variations would be investigated, this would result in amounts of data far greater than is possible to analyse and discuss in this thesis. Based on the knowledge gained in Step I of this thesis, the choice was made to analyse the data resulting from the parameter variations shown in Figure 7.8. The reasoning behind the parameter specific variations are explained in Appendix H.



Economic parameters	**Unit**	**Initial**	**Variation 1**	**Var. 2**	**Var. 3**	**Var. 4**	**Var. 5**
CO2 tax rate	**€/t**	0	22	43	120	185	
Marine diesel oil price	**€/t**	575	662	862	662		
Discount rate	**%**	5.0	0.0	1.5			
Electricity price	**€/kWh**	0.05	0.025				
Technical parameters							
Battery costs (NMC|LTO|LFP)	**€/kWh**	1020|1120|1220	510|560|610	765|840|915			
Battery life	**Cycles**	8000|15000|8000	10000|18750|10000	12000|22500|12000			
Battery energy density – mass	**Wh/kg**	105|60|70	53|30|35	158|90|105			
Battery energy density – volume	**kWh/m^3**	74|34|83	37|17|42	111|51|125			
Fuel cell costs	**€/kW**	700	350				
Fuel cell life	**Cycles**	40000	80000				
Hydrogen tank costs	**€/kWh**	22	11				
Electrolyser cost	**€/kg·day**	1100	550				
Supercapacitor costs	**€/kWh**	10000	5000				
Operational parameters							
Daily amount of trips		10	15	20	25	30	35
Maximum/average speed	**kn**	14/12	10/8	16/14	18/16		
Shore power	**kW**	2000	1000				

Figure 7.8: Table parameter variations investigated

8

Conclusion deductions

In this chapter the results of the parameter variation analysis, performed using the concept exploration tool, are discussed. The results are expressed as conclusions, with the reasoning and corresponding data being discussed per conclusion. These conclusions are divided into four sets, for each party identified to be involved in the design and development chain of double ended ferries. These are Energy system manufacturers, Governments, Ferry operators and Shipyards. The assumed role that each party has is discussed in the first section of this chapter. This section also includes the explanation of the structure of the results. Subsequently, the conclusions are discussed in four sections, corresponding to the four sets they are divided into.

8.1. Parameter variation results structure

The influences of the variations are determined through a comparison with the initial starting point. The starting point is based on the variables shown in Figure 7.8, Figure 7.3 and Figure 7.2, obviously with the sailing distances and car capacities varying. For the energy system characteristics these values, determined in Step I of this thesis, are assumed to be the current state of systems. The other values, derived from the knowledge gained in Step I, are determined to be realistic for an average double ended ferry. Using these initial variable values, the graph shown in Figure 8.1 is yielded.

The graphs resulting from having one or two parameters varied from this base case are used to derive the sets of conclusions. Each variation graph contains text stating the parameter varied and the percentage with which it is varied from the original or the new value. How the graphs should be interpreted is explained in section 7.2.

It is important to note that if multiple parameters are changed simultaneously, the severity of the effects can change. Some might strengthen each others' effects and some might weaken them. Due to it being impractical to investigate all possible combinations, the structure is to clearly state the effects per parameter - only incidentally drawing conclusions from two simultaneous variations. The reasoning behind the chosen variations is discussed in chapter 7 and Appendix H. Obviously it would be possible to investigate far more variations, but time and resources are limited for this thesis.

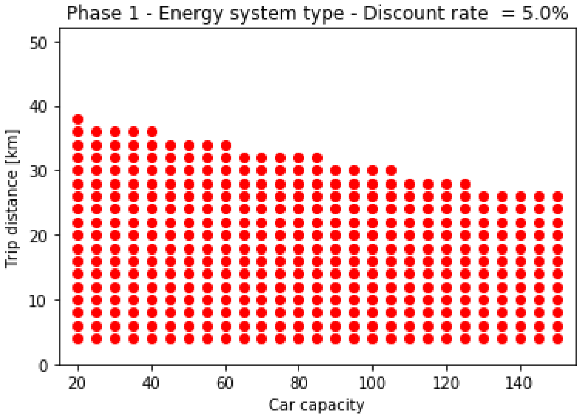


Figure 8.1

The role of the parties for which the conclusions are divided into sets are discussed below. Understanding which definition of their role is used helps to understand how the conclusions are relevant to their practice.

Energy system suppliers are viewed as third party companies supplying systems and system components to shipyards. Their aim is developing their systems as such that they are technically and financially attractive for shipyards to use or ferry operators to request to be installed in their vessels.

Governments are assumed to have a dual role. Firstly they are clients to the ferry operators and secondly they are influencers of certain economic and operational parameters. As clients to the ferry operators governments decide which route the ferry has to sail and influence what the transportation requirement over this route is. Some operational aspects are chosen in deliberation with ferry operators, as the government benefits from financially stable operators capable of providing the service for an extended period. The second role of the governments, as influencers, stems from the desire to provide its people with zero-emission transportation. From this role the governments can influence certain parameters to make zero-emission operation more financially attractive for ferry operators. Examples of this is their influence on CO2 taxes. The challenge for the governments is the balance between stimulating zero-emission double ended ferry services and creating a situation where ferry operators can run a financially sustainable operation.

Ferry operators are viewed as the owners of double ended ferries and the suppliers of transport over water to a (local) government. Their aim is to make profits from their ferry operations. Thus the current and future projected costs are of interest to them. The assumption is made that ferry operators have influence on some of the operational requirements of the ferry service, such as car capacity and vessel speed. The exact operational requirements are assumed to be determined together with the (local) governments.

Shipyards are the parties building the vessels. They create the vessel designs and decide which exact systems are installed in the vessel. They advise their clients on the advantages and disadvantages of the feasible energy systems. As shipyards are responsible for performance, the technical characteristics of the energy systems and their influence on the vessel is also of interest.

Class societies are parties that determine and maintain technical standards for the design and construction of vessels. As described in section 4.7 their influence on the concepts in the concepts exploration phase is limited. As none of the conclusions resulting from the parameter variations leads to clear recommendations for their practices, class societies are not discussed beyond this paragraph. It is acknowledged that their presence in the maritime industry is of great importance and certainly not to be overlooked. During this thesis research, their influence was unlined during the many conversations with maritime professionals. During these one theme frequently emerged; the delay of the application of zero-emissions energy systems due to the lack of clear regulations.

8.1.1. Energy system suppliers

Battery cost decrease has a large impact on the energy system choice
Current battery price assumptions of 1020 €/kWh, 1120 €/kWh and 1220 €/kWh for the different chemical compositions of lithium-ion batteries are used in this thesis. If prices decrease with 25% or 50%, in many transportation cases battery energy systems become the cheapest energy system based on net present value. Such price changes are in line with the trend of battery prices decreasing over the past decade. The effect of such decreases is shown in Figure 8.2 and Figure 8.3.

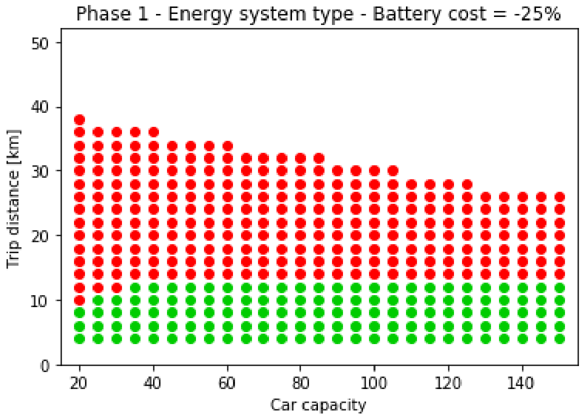


Figure 8.2

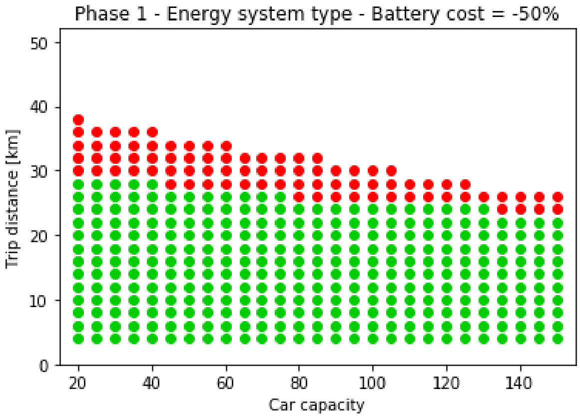


Figure 8.3

Battery life increase has a large impact on the energy system choice
For battery life current assumptions used in this thesis are 15000 FEC at 50% DOD, 8000 FEC at 40% DOD and 8000 FEC at 40% DOD for the different chemical compositions if lithium-ion. If this is increased by 25% or 50%, the batteries need to be replaced less often, leading to an increase of the net present value. The result is the battery energy system having the highest NPV in much more cases than the initial (Figure 8.1) as shown in Figure 8.4 and Figure 8.5.

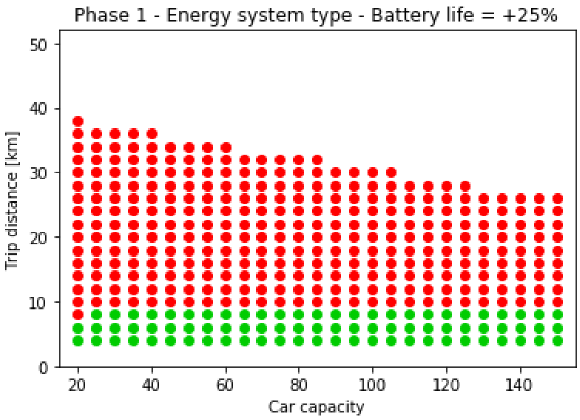


Figure 8.4

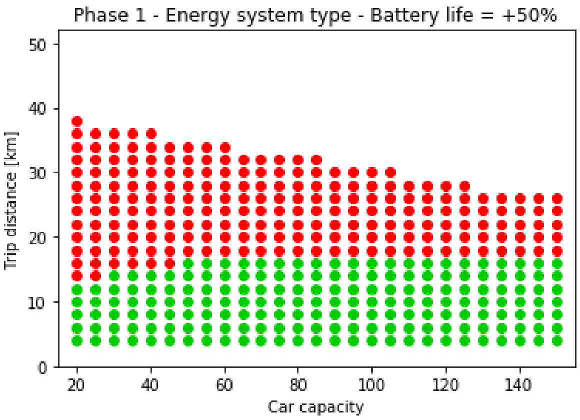


Figure 8.5

Battery life increase and battery cost decrease are not weighted equally when determining the NPV of a battery energy system
When battery life is decreased the factor with which this is done directly multiplies with the battery costs, resulting in a higher NPV. When battery life is increased, the initial capital costs are not influenced. Resulting in no NPV increase. However, battery life increase does have an influence on the weighting of future battery replacements. This weight is determined by dividing the cost of replacement by the discount rate to the power of the amount of years to replacement. This amount of years is increased when the battery life is increased. The combined NPV decrease from dividing the replacement cost by the discount rate to a higher power for all replacements is not equal to the NPV decrease resulting from an equal percentage battery cost decrease. Depending on the amount of battery replacements over the lifetime of the vessel, the used discount rate and the moment of the battery replacements during the lifetime of the vessel, either can result in a higher NPV decrease.

For realistic discount rates combined with frequent battery replacements, (intervals less than 10 years combined with discount rates lower than 10%) a battery cost decrease generally has more effect than an equal percentage of battery life elongation. The term generally is inserted because there are cases where an increase in battery life has a larger impact than a decrease of the battery costs. This occurs in situations where the battery is replaced relatively short before the end of life of the vessel. When this last replacement is not needed due to a battery life increase, the impact on the NPV can be higher than a battery cost reduction, equal to the percentage of battery life increase.

For reference, 10 year replacements intervals occur for a trip distances higher than 10 km, assuming 10 daily trips, a 15000 FEC battery life at 50% DOD and an average speed of 12 knots. If the used discount rate decreases the replacement intervals can increase. If the discount rate stays at 10%, the replacement interval time will decrease if daily trips is increased, speed is decreased or battery life is lower.

Realistic battery mass increase/decrease and volume increase/decrease have a low impact on energy system choice and vessel design
In this thesis it came to light that the energy system is only a small part of a double ended ferry when viewed from the mass and volume perspective. An increase thus has a small effect on the volume and mass of the vessel and resulting energy consumption. Figure 8.6 to Figure 8.11 show the effect of halving the volume and mass energy density of the battery energy system, next to the initial values. The effect on the economical attractiveness is little to negligible. An equal effect occurs if battery energy

density is increased. The graphs supporting this can be found in Appendix G.

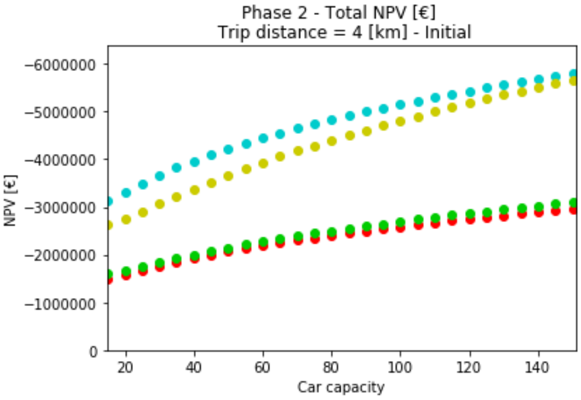


Figure 8.6

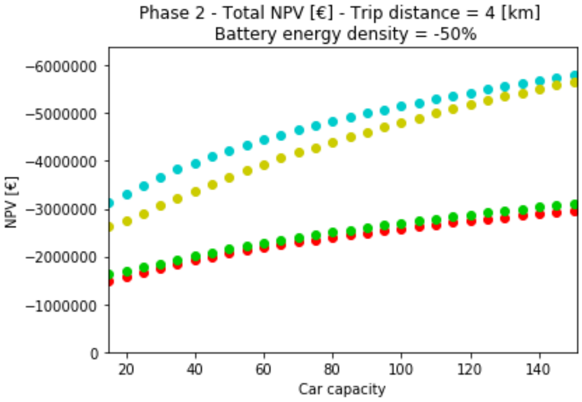


Figure 8.7

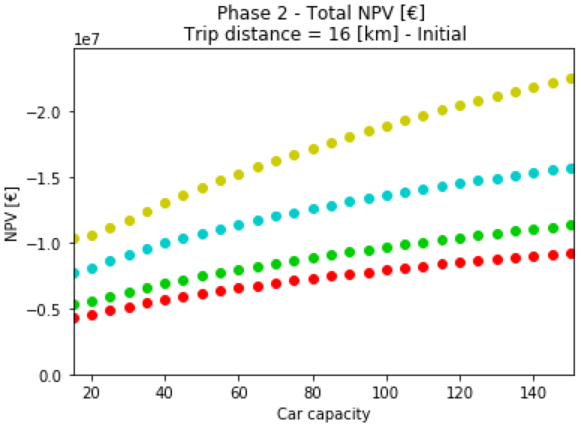


Figure 8.8

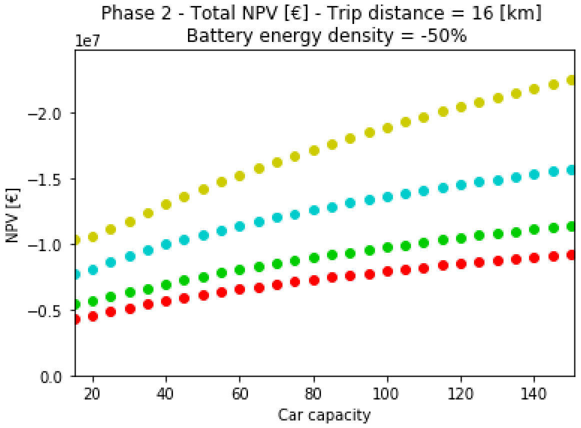


Figure 8.9

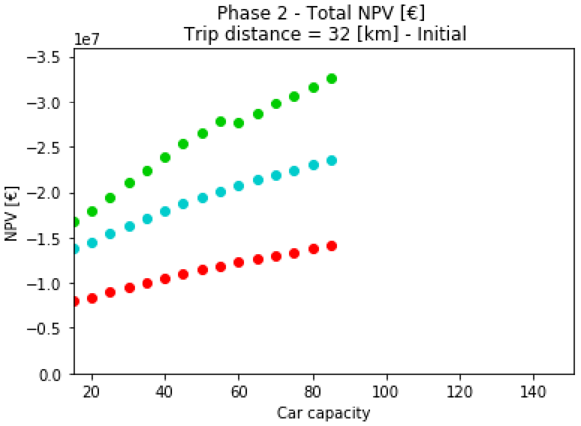


Figure 8.10

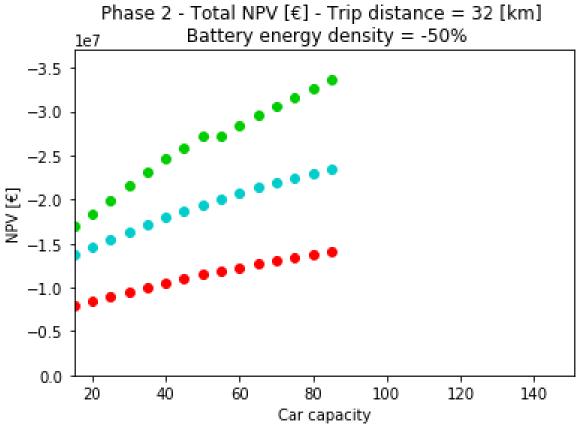


Figure 8.11

Hydrogen energy system costs need to drastically decrease for a hydrogen energy systems to be economically attractive
Current hydrogen energy systems have a net present value lower than battery and diesel energy systems and lower than supercapacitors for short distances (below 5 km). The difference is significant, as indicated by Figure 8.12, Figure 8.13 and Figure 8.14. For hydrogen energy systems to become economically comparable with the other energy system types, the NPV and thus costs need to decrease.

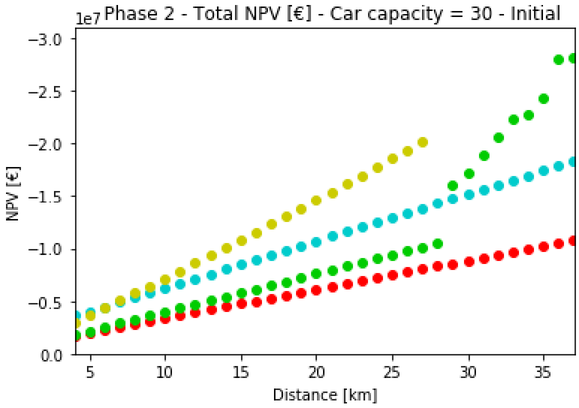


Figure 8.12

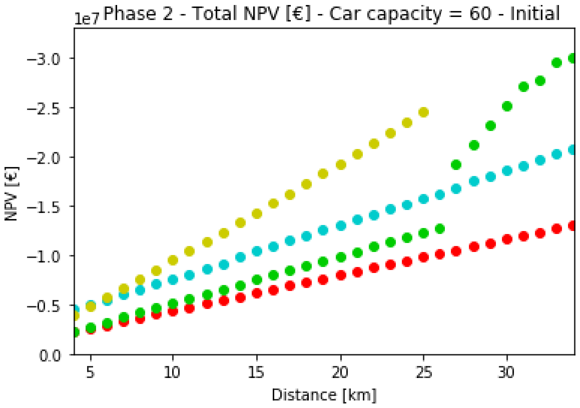


Figure 8.13

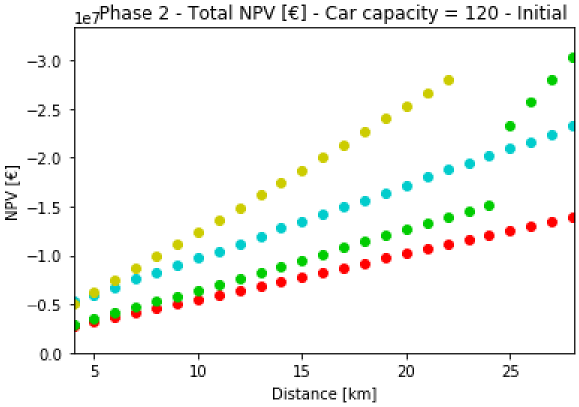


Figure 8.14

The order of influence of an equal percentage cost decrease on net present value for hydrogen systems is: hydrogen cost, fuel cell cost, electrolyser cost, hydrogen tank cost
The influence of the costs of the different components of the hydrogen system can be derived from the independent variation of these costs and analysing the resulting NPV decrease. For car capacities of 30, 60, 120 and the full range of sailing distances, the graphs showing the result of decreasing the cost of each component by 50% were extracted. For a car capacity of 30 these are shown in Figure 8.16, Figure 8.17, Figure 8.18 and Figure 8.19. The resulting blue dots depicting the hydrogen system are compared with the initial case shown in Figure 8.15. The electricity cost has the largest influence on the NPV. The electricity costs are directly proportional with the bare hydrogen costs when using an electrolyser at the terminal to obtain hydrogen. This method of obtaining hydrogen is the cheapest over the full range in the initial case. The second most influential cost decrease is that of the fuel cell, followed by the electrolyser cost decrease and hydrogen tank cost decrease. For car capacities of 60 and 120, the trends are the same. The corresponding graphs are shown in Appendix G.

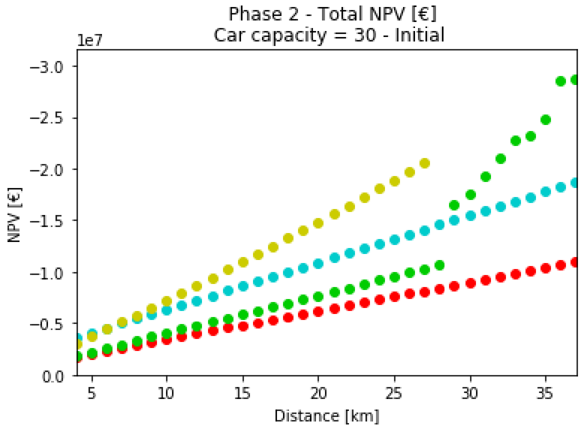


Figure 8.15

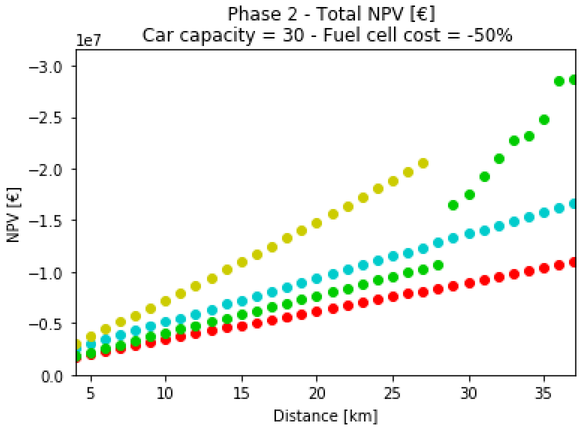


Figure 8.16

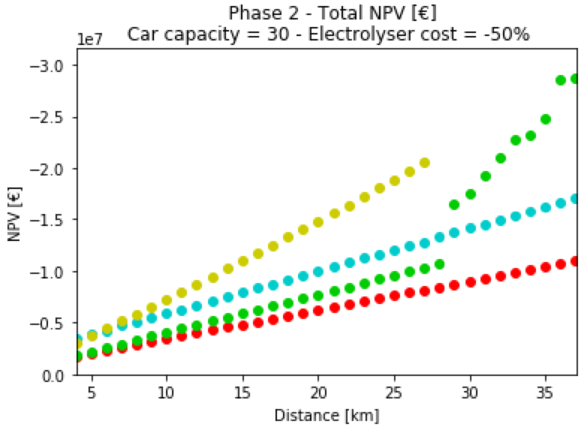


Figure 8.17

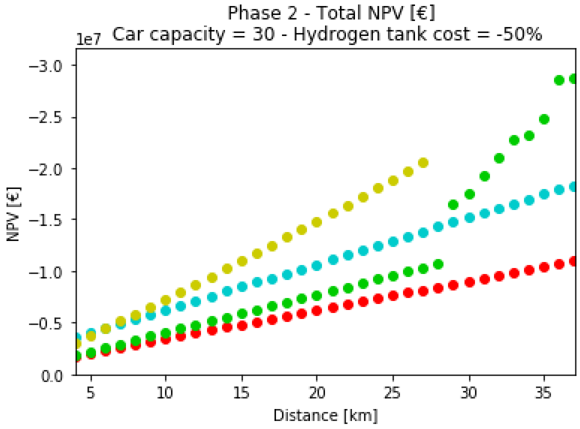


Figure 8.18

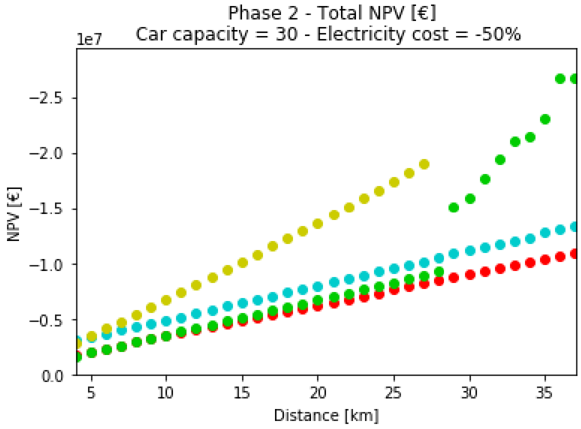


Figure 8.19

Supercapacitor costs need to decrease to expand the current niche of economic attractiveness
With current supercapacitor energy system costs of 10000 €/kWh, there is a niche where supercapacitors have the highest NPV of all energy systems. This is when the amount of daily trips is 30 or higher. This niche greatly expands if supercapacitor costs decrease by 50%, as is shown by the difference between Figure 8.20 and Figure 8.21.

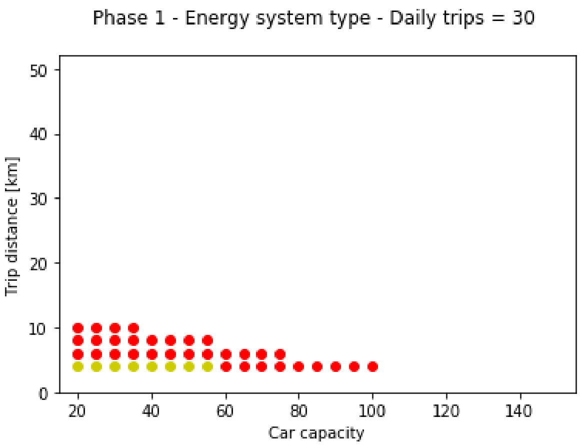


Figure 8.20

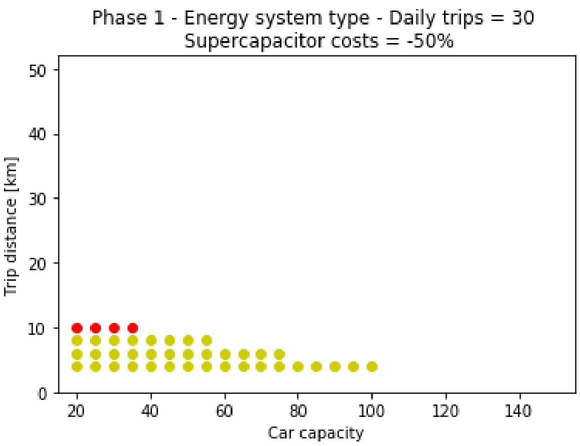


Figure 8.21

8.1.2. Governments

Shore power available can have a large impact on the economical attractiveness of battery energy systems
Battery energy systems ideally use the charging strategy where the trip energy consumption can be charged directly from the grid, during the (un)loading time. When this is not possible additional batteries on shore or in the vessel are needed for a battery energy system. The capital expenses of these extra batteries have a large effect on the NPV, visually shown by a step in the graph. An example of such a step occurring due to a shore power change is illustrated in Figure 8.22 and Figure 8.23.

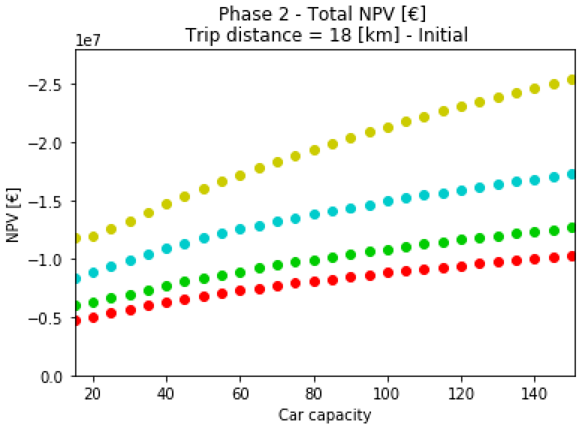


Figure 8.22

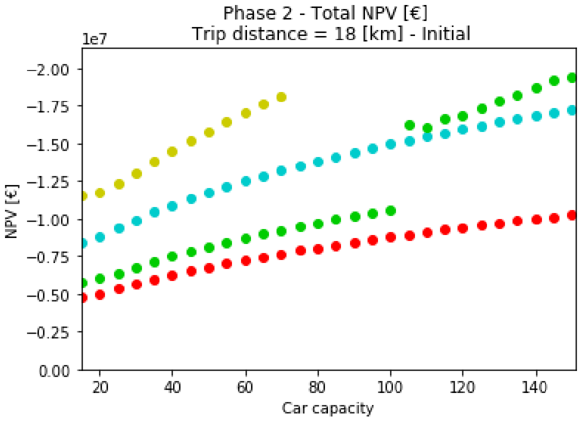


Figure 8.23

CO2 taxes need to increase beyond current values to have a significant impact on energy system choice

The large majority of carbon taxes, if implemented at all, are below 22 €/tCO2. Their effect on NPV based preference of double ended ferry energy systems, is very little. When taxes of 43 €/tCO2 are implemented, the impact increases significantly. The effect start at short trip distances, as shown in Figure 8.25. When the taxes are increased to 120 €/tCO2 the effect becomes dominant, as is shown in Figure 8.26. For the full range of trip distance and car capacity combinations to have a higher NPV with zero-emission energy systems, the CO2 tax needs to increase to 185 €/tCO2. Using this value, hydrogen becomes the energy system of choice for the larger trip distances. Hydrogen energy system surpass battery energy systems in this region due to the step increase in capital expenses associated with a change in charging strategy, illustrated by Figure 8.28. The effect visualised in Figure 8.27.

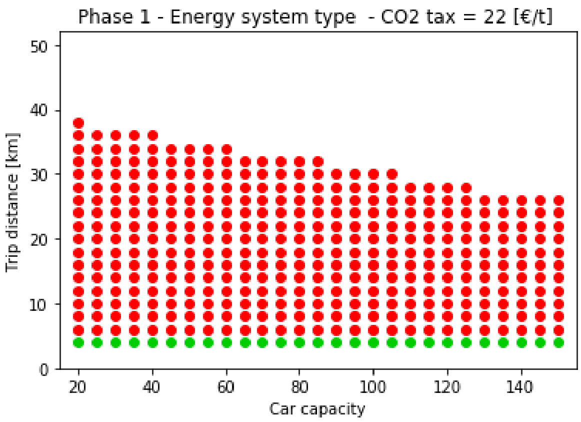


Figure 8.24

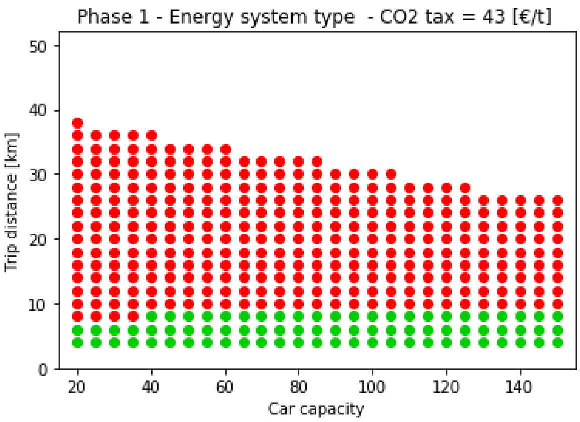


Figure 8.25

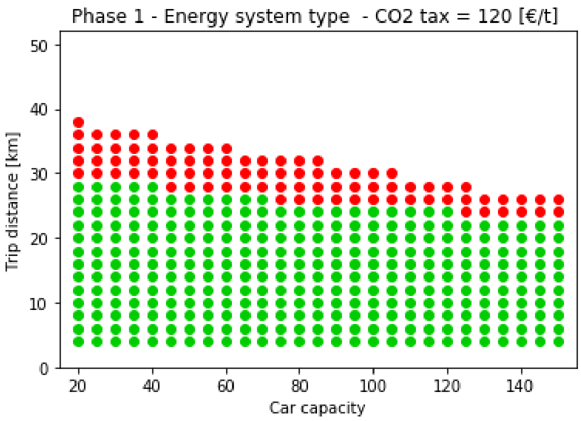


Figure 8.26

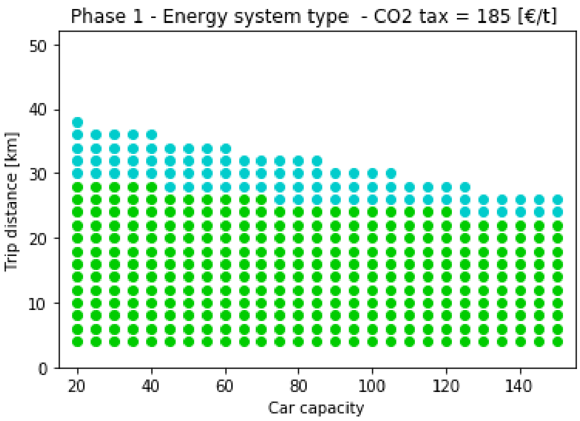


Figure 8.27

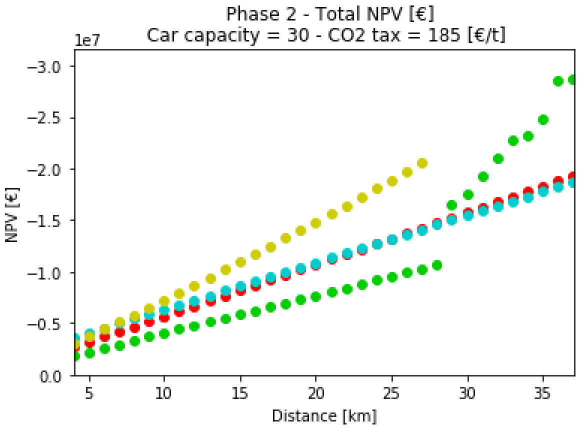


Figure 8.28

Exact trip distance can have a large influence on the economical attractiveness of battery energy systems

Battery energy systems ideally use the charging strategy where the trip energy consumption can be charged directly from the grid, during the (un)loading time. When the trip distance exceeds a certain distance (for a given car capacity), the energy consumption per trip increases beyond the point where this charging strategy is no longer possible and extra shore and/or vessel batteries are needed. This results in a significant step in the net present value of the battery energy system. An example of such a step for a car capacity is shown in Figure 8.29. When the trip distance increases beyond 25 km there is a significant decrease in the NPV of the battery system.

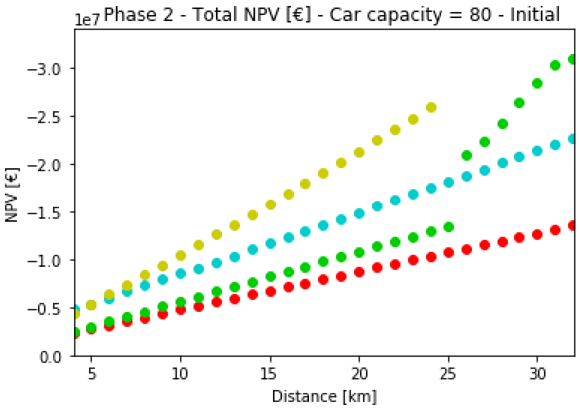


Figure 8.29

The combination of shore power, trip distance and car capacity has a large influence on the economical attractiveness of battery energy systems

The step in net present value of battery energy systems resulting from extra shore and/or vessel batteries is a result of the combination of shore power, trip distance and car capacity. This can be concluded from the previous two conclusions for the government, the conclusions for the ferry operators and their corresponding explanations.

8.1.3. Ferry operators

Exact car capacity can have a large influence on the economical attractiveness of battery energy systems

Battery energy systems ideally use the charging strategy where the trip energy consumption can be charged directly from the grid, during the (un)loading time. When the car capacity exceeds a certain value (for a fixed trip distance), the energy consumption increases to the point where extra shore and/or vessel batteries are needed. The result is a step decrease in NPV of the battery energy system. Such a step is shown in Figure 8.30, where the NPV of the battery energy system decreases significantly when the car capacity is increased beyond 40.

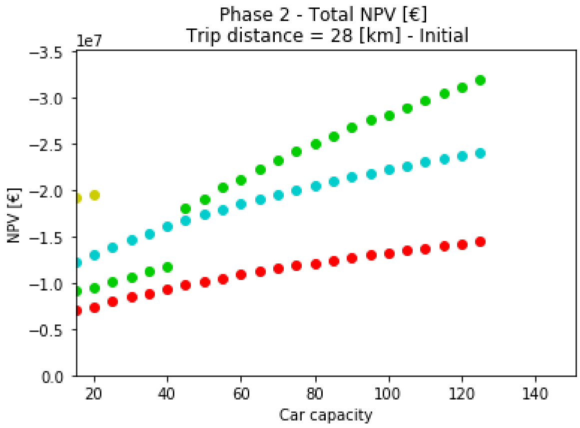


Figure 8.30

Exact discount rate has a large impact on the economic attractiveness and decisions regarding the energy systems

A higher discount rate results in a higher weighting of initial investments and investments made early on in the vessel lifetime, compared to the total investments over the lifetime. A lower discount rate does the opposite. Thus with a higher discount rate, energy systems with a large initial CAPEX and lower OPEX, such as battery energy system, yield a lower net present value than systems that have the opposite diesel such as diesel energy systems. This the explanation for the results shown in Figure 8.31, Figure 8.32 and Figure 8.33. These indicate that the chosen discount rate has a large impact on energy system attractiveness.

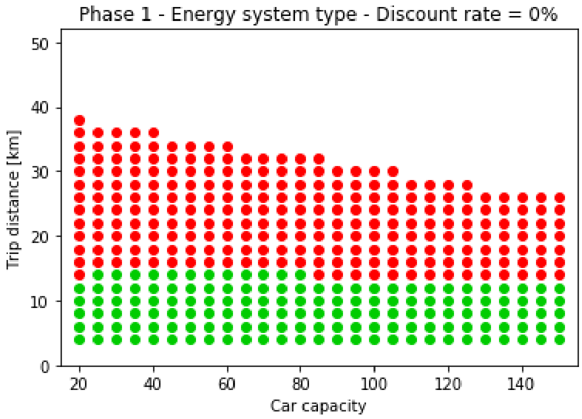


Figure 8.31

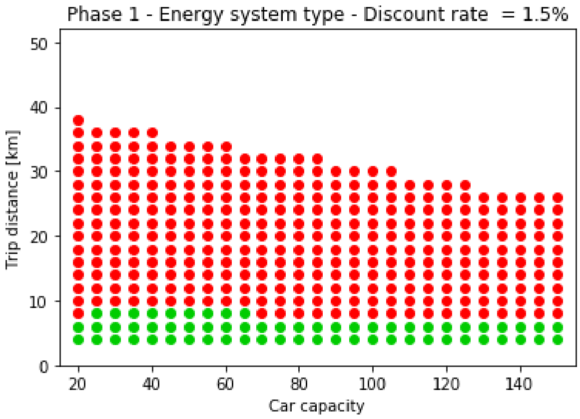


Figure 8.32

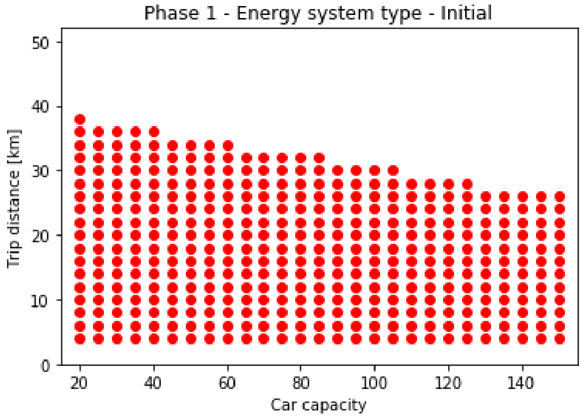


Figure 8.33

Amount of trips sailed daily has a large impact on the economic attractiveness and decisions regarding the energy systems

The amount of trips sailed daily is a parameter that directly influences the amount of daily cycles the energy system undergoes and the daily amount of energy needed. Increasing the amount of daily trips and thus cycles results in more frequent replacements of energy systems where the cycle capacity is limited, such as batteries and fuel cells. Also, the daily amount of energy consumed increases, thus requiring diesel powered vessels to carry more fuel. The result is a shift in economic attractiveness between the energy system types. This is derived from Figure 8.34 to Figure 8.37, which show the NPV for a car capacity of 30 over the range of sailing distances for 10, 15, 20 and 25 daily amount of trips. For car capacities of 60 and 120 similar graphs were obtained, supporting the conclusion. These can be found in Appendix G.

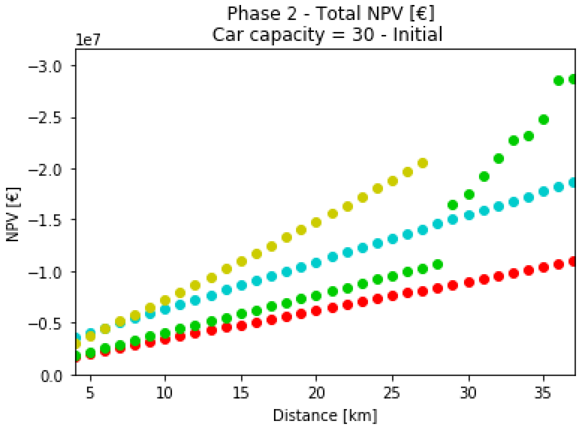


Figure 8.34

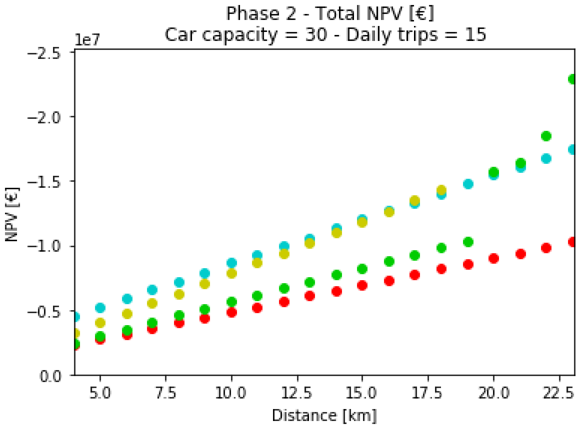


Figure 8.35

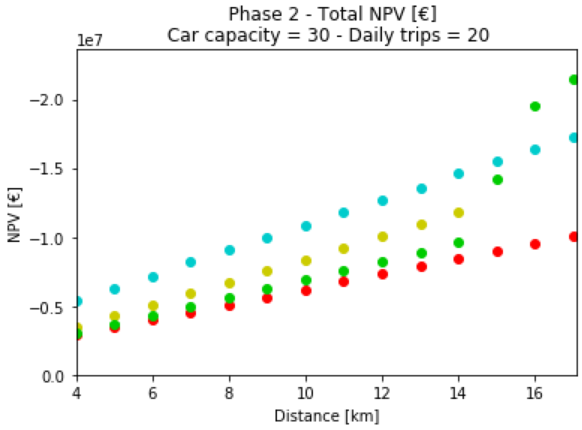


Figure 8.36

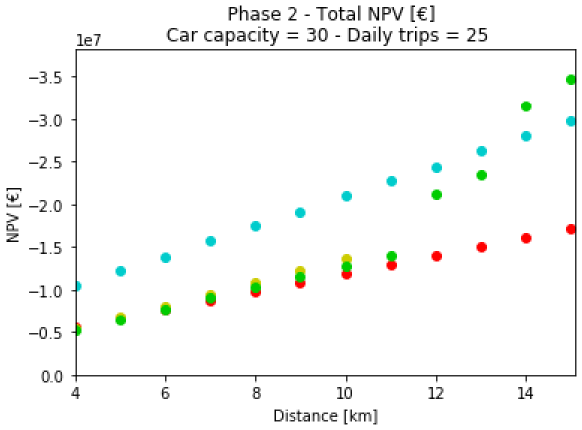


Figure 8.37

Sailing speed has a large impact on the economic attractiveness and decisions regarding the energy systems

Zero-emission energy systems can become more economically attractive if sailing speed is increased

Due to the different energy system characteristics, the result of a speed increase or decrease differs per energy system type. When speed is increased more power and energy is needed. Batteries and supercapacitors only need to increase their energy storage capacity as their power is governed by the speed at which energy can be discharged. Diesel and hydrogen energy systems need to store more energy in diesel and hydrogen, but also need larger engines and fuel cells, which are the most costly components of the system.

These differences result in a smaller decrease of the NPV of battery energy systems than diesel energy systems in the low distance range. This gives the battery energy systems a higher NPV when speed is increased from the initial situation. This is shown in Figure 8.38 and Figure 8.39. For completeness also one variation was run with a speed decrease: 10 knots maximum and 8 knots average. In this case the opposite effect occurs. Diesel-electric systems become more attractive, resulting in a fully red graph.

The effects of the speed decrease and increase are also visualised for a car capacity of 60, in Figure 8.40 to Figure 8.43. For car capacities of 30 and 120 similar graphs with similar trends are shown in Appendix G

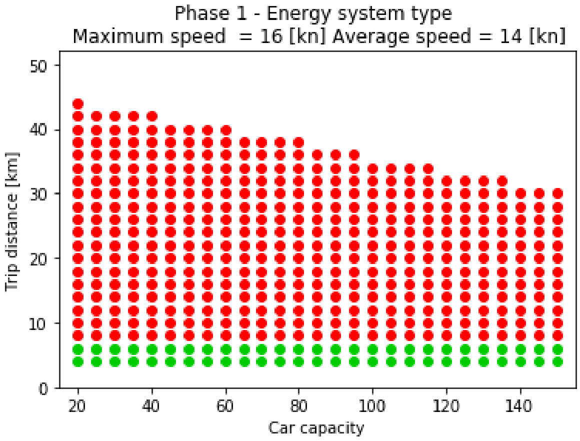


Figure 8.38

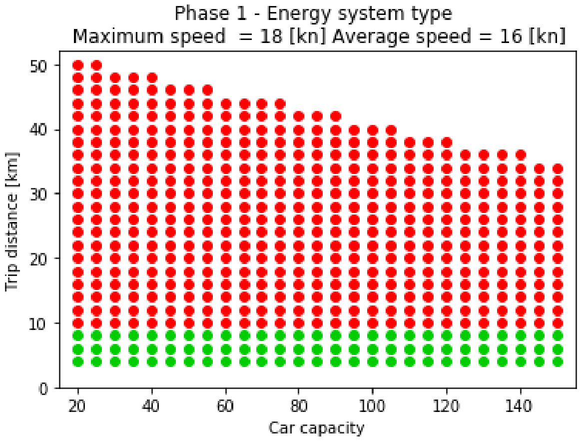


Figure 8.39

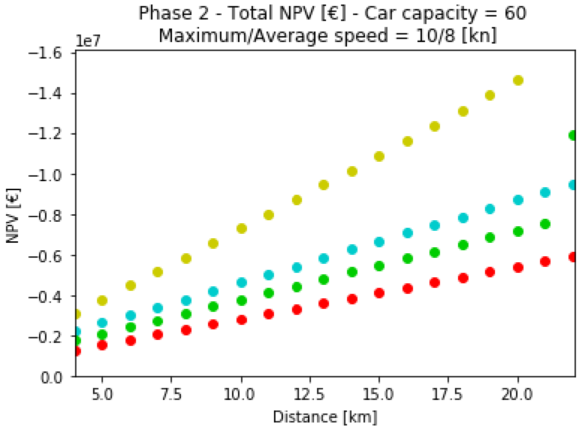


Figure 8.40

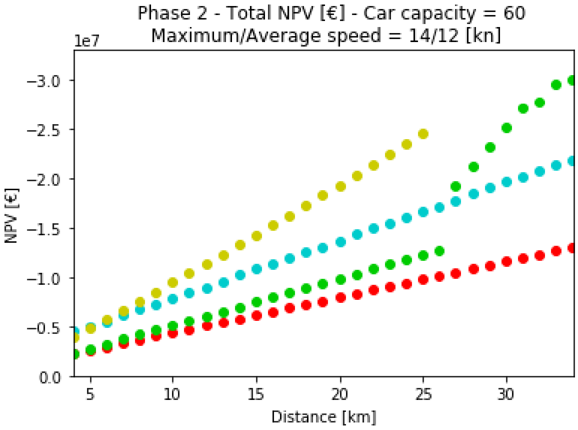


Figure 8.41

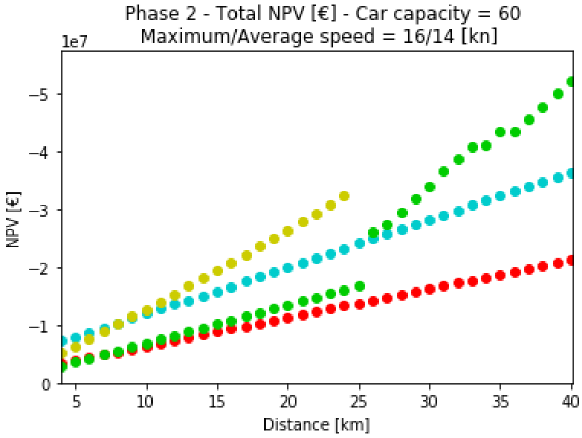


Figure 8.42

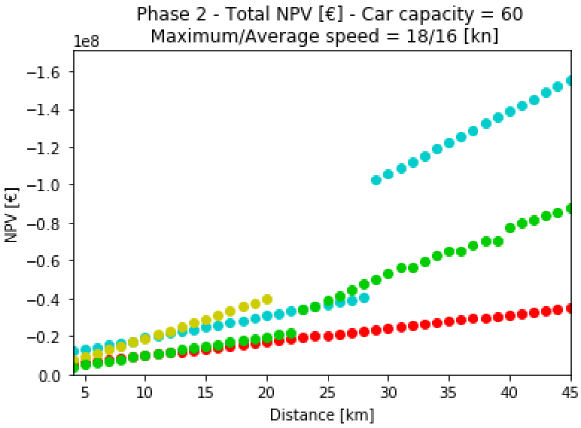


Figure 8.43

Fuel price increase has a large impact on the energy system choice
The initial fuel price used is 575 €/t. An increase has a large impact on the economical attractiveness of diesel-electric systems with respect to the other energy system types. With an increase of 25%, the effect

is still relatively small as shown in Figure 8.44. When fuel prices increase by 50%, batteries have a higher NPV in the majority of cases, as shown in Figure 8.45. The same effect occurs when the amount of trips is increased, as illustrated by Figure 8.46 and Figure 8.47.

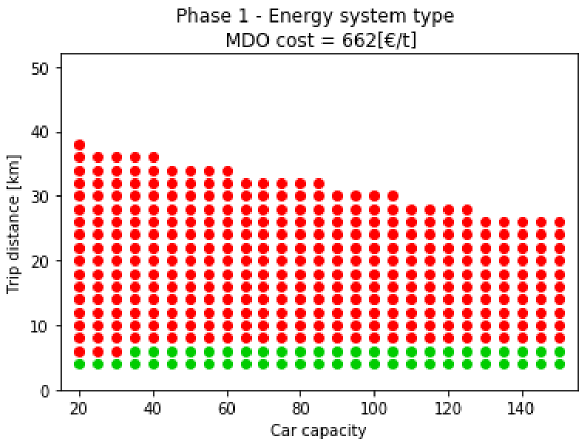


Figure 8.44

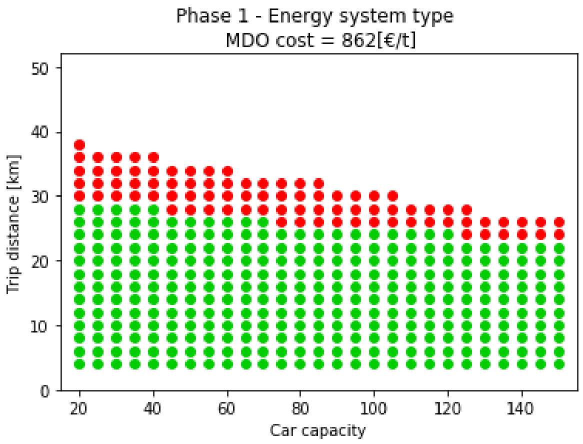


Figure 8.45

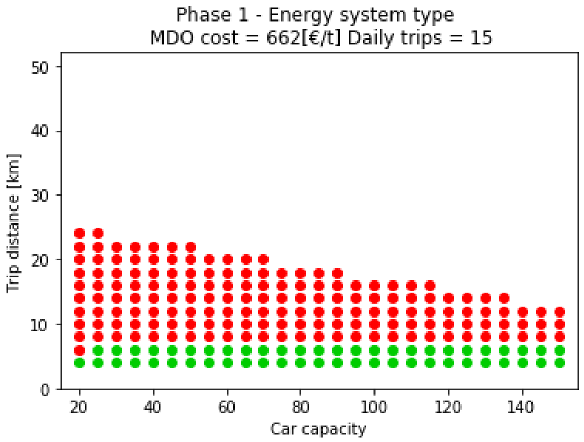


Figure 8.46

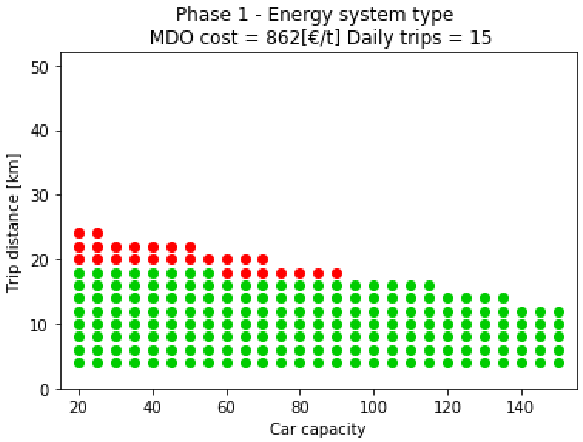


Figure 8.47

Electricity price decrease has a large impact on energy system choice, but not as large as fuel price increase

Electricity is the source of energy for all zero-emission energy systems investigated in this thesis. When the initial electricity price of 0.05 €/kWh is halved, the battery energy system concepts have the highest NPV at the low-end of trip distances. This is illustrated in Figure 8.49. However, the impact is much lower than an equal percentage increase of fuel prices. An explanation is that for battery energy systems are less OPEX driven than diesel energy systems. Thus a decrease of a factor influencing the OPEX has less impact on battery systems than an increase has on diesel systems.

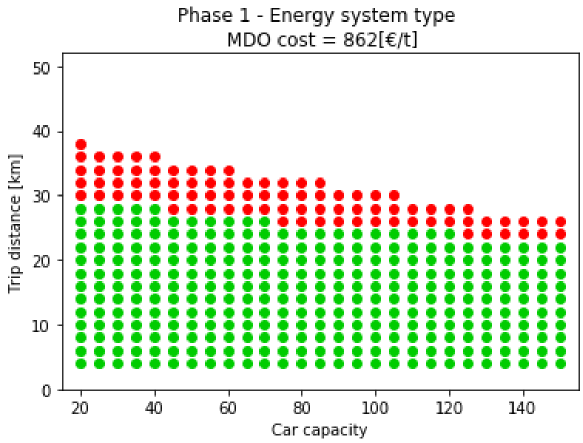


Figure 8.48

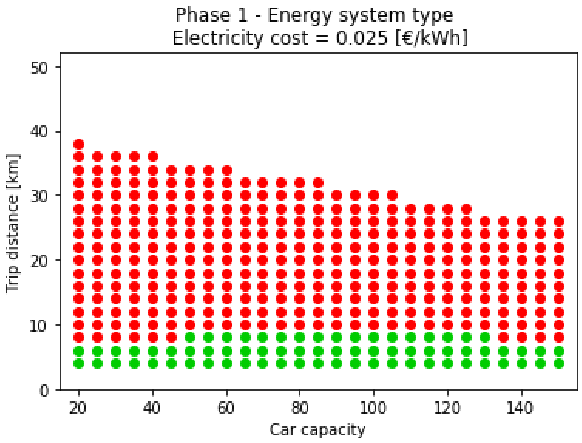


Figure 8.49

Producing hydrogen at the terminal from electrolysis is a cost competitive alternative to centralised production and supply

The concept exploration tool calculates that, with realistic input in the initial case, producing hydrogen at the terminal using an electrolyser is cheaper than obtaining hydrogen by truck for all car capacity/trip distance combinations. In Figure 8.50 the full range analysis is shown for the hydrogen supply methods. In the graphs a yellow dot represents the use of electrolysis at the terminal and a black dot the supply of hydrogen by truck. The displayed colour corresponds to the method that has the higher NPV for the supply of hydrogen over the life of the vessel. In the comparison, for electrolysis the NPV is calculated including the electrolyser costs, replacements, maintenance, electricity costs storage tank costs, replacements and maintenance. For supply by truck, the NPV is calculated including hydrogen cost, possible storage tank cost, replacement and maintenance. The point where hydrogen from supply by truck becomes cheaper is at 3.2 €/kg, a factor 3 lower than current prices. The available shore power also needs to be sufficient to produce the daily required amount of hydrogen. When it is halved from the 2000 kW in the initial case to 1000 kW, the shore power is insufficient for larger distances, as is shown in Figure 8.51.

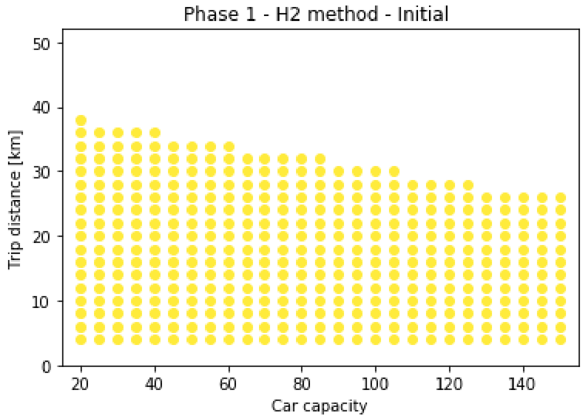


Figure 8.50

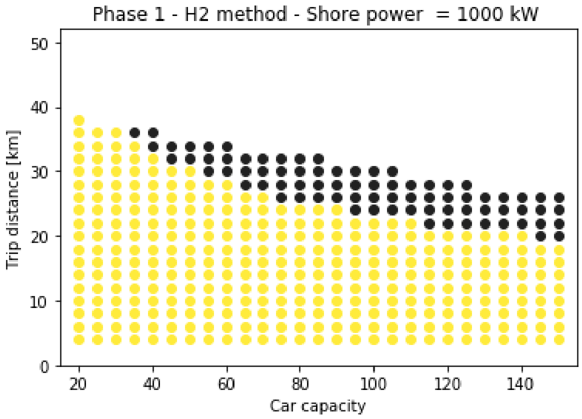


Figure 8.51

8.1.4. Shipyards

Zero-emission energy systems are technically feasible for double ended ferries
The energy storage that zero-emission energy systems are able to supply is in the range required to operate double ended ferries. Also, the corresponding system mass and volume are not an obstacle for the use of zero-emission energy systems. Technologies of the different types of systems are mature and already used in double ended ferries or similar applications. Figure 8.58 to Figure 8.68 show that the vessel displacement, volume and energy consumption of vessels using zero-emission energy systems are close to those of vessels using diesel energy systems. For supercapacitor and battery energy systems the shore power and (un)loading time can limit the feasibility. To illustrate the effect, Figure 8.52 to Figure 8.55 are compared. The graph showing the diesel systems illustrates the initial range of feasibility cut-off due to it not being physically possible to sail with more cars or a longer distance within 24 hours, for the chosen speed, daily trips and (un)loading time. The battery and hydrogen graphs show that, for the initial input values, battery and hydrogen energy systems are technically feasible in all cases where diesel systems are feasible. Supercapacitor systems are not feasible in all cases, as the graph shows them to be infeasible at certain longer trip distances.

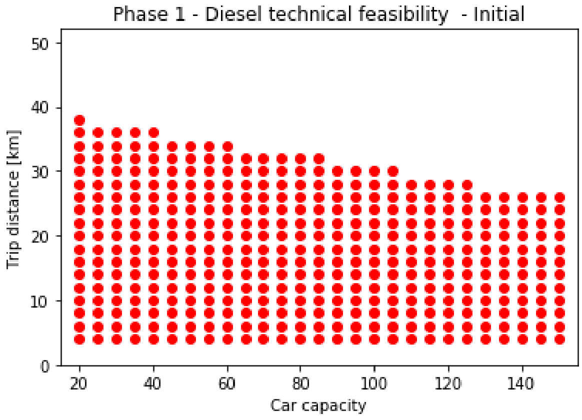


Figure 8.52

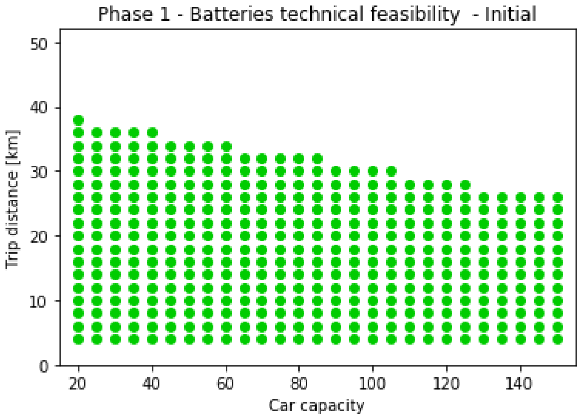


Figure 8.53

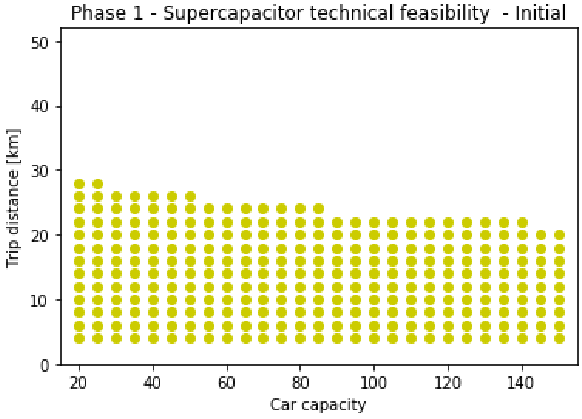


Figure 8.54

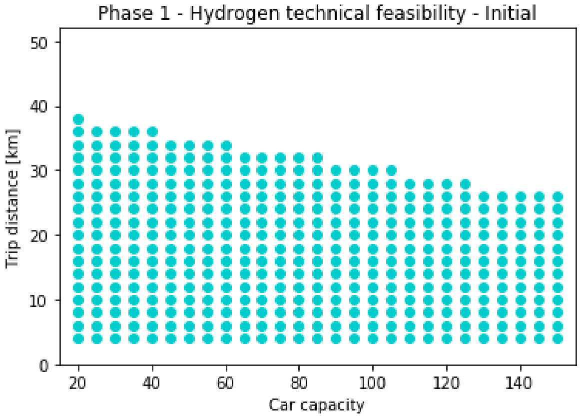


Figure 8.55

Zero-emission energy systems are currently cost competitive with fossil fuel energy systems for double ended ferries

The net present values of zero-emission energy systems are able to compete with the net present values of fossil fuel energy systems for double ended ferries. Which system has the lower net present value in which cases, depends on the exact input values used. The general ranking is that diesel and battery system net present values are very close to each other. Supercapacitors are cost competitive when the daily amount of trips increases above approximately 30. Hydrogen energy systems have CAPEX and OPEX a level higher than battery and diesel systems.

Supercapacitor energy systems are economically attractive when short distances are sailed with high daily frequency

The initial amount of daily trips is 10. When this is increased beyond 30, supercapacitors have the highest net present value of all energy system types. This is shown in Figure 8.56 and Figure 8.57. The high cycle life of supercapacitors means that even with a high sailing frequency and resulting system cycles, the system does not need replacement over the life of the vessel. This is not the case for battery and hydrogen systems. High amounts of cycles make them more expensive due to frequently required replacement. As the daily amount of trips is increased, the daily amount of energy consumed also increases, resulting in an increase in operational expenses. This means that for diesel energy systems the fuel expenses increase and that the electricity expenses increase for supercapacitor energy systems. The data that the concept exploration tool provides shows that this increase is steeper for diesel energy systems than for supercapacitor energy system. This is explained through understanding that diesel energy systems are OPEX driven, having relatively low capital expenses with respect to the operational costs of the system. Supercapacitor systems, on the other hand, are CAPEX driven. In comparison to the high initial cost of purchase, the operation of supercapacitors is relatively cheap. Therefore increasing the time of operation only has a relatively small contribution to the NPV. The consequence is that the NPV of supercapacitor systems becomes higher than that of diesel energy systems, as the daily amount of trips surpasses 30.

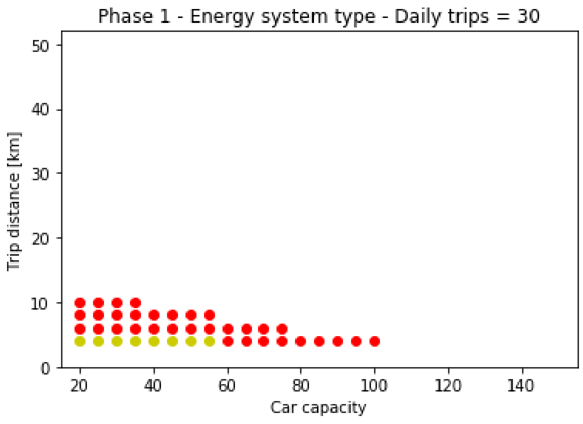


Figure 8.56

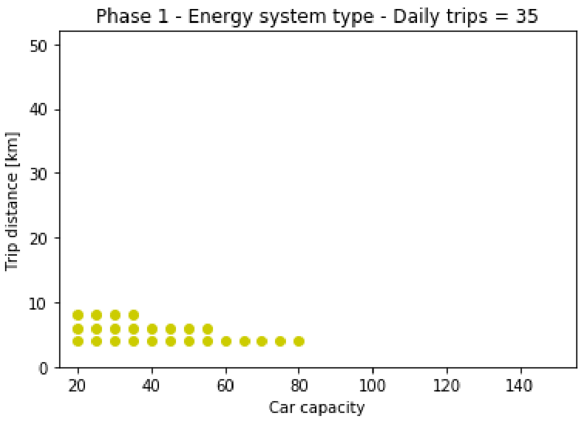


Figure 8.57

Displacement, length and energy consumption do not drastically increase due to the use of zero-emission energy systems, in the majority of the cases

The use of a hydrogen energy system results in the least displacement, length and energy consumption increase with respect to diesel, followed by batteries and supercapacitors

As described in section 1.4, the energy system definition used in this thesis is the system that stores energy and converts it to electricity to be used by the electric engines. Considering the mass and volume of a whole double ended ferry, this energy system is only a small part of the whole. Therefore the influence of a mass and volume increase of this system on the vessel parameters and energy consumption is limited. In Figure 8.58 to Figure 8.60 the percentage increase of the vessel mass, length and energy consumption relative to a diesel energy system, are shown for battery systems. Increases above 3% only occur at larger trip distances. This is not coincidentally the region where the net present value difference between the energy systems is the highest, favouring the diesel energy system. This is illustrated by Figure 8.61. Large battery systems relative to vessel size also result in a relatively high energy system cost. Other than in these regions, the influence is minimal.

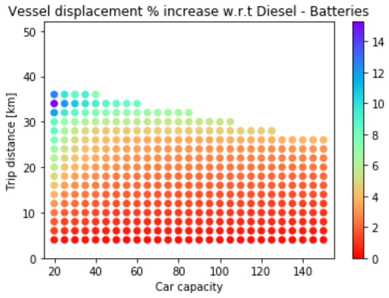


Figure 8.58

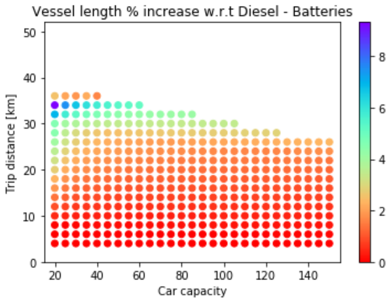


Figure 8.59

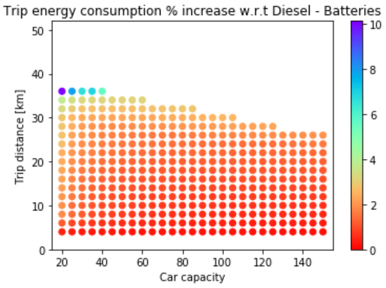


Figure 8.60

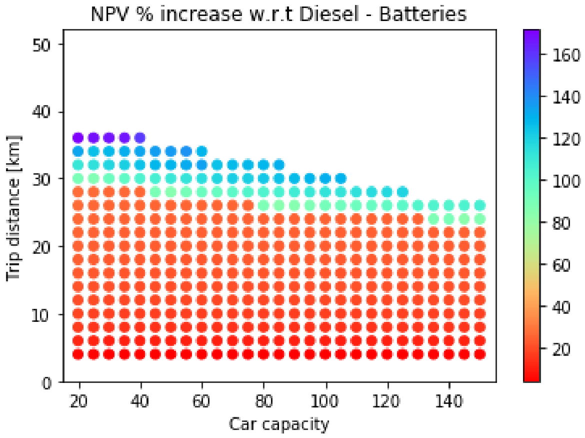


Figure 8.61

Pure to illustrate the effect of the mass of the battery energy system on the performance of the vessel, a similar plot was made for halved values of mass and volume battery energy density. The graph in Figure 8.62 shows a limited effect on the trip energy consumption for the majority of the range. This indicates that a heavier and larger battery only has a limited effect on the vessel performance.

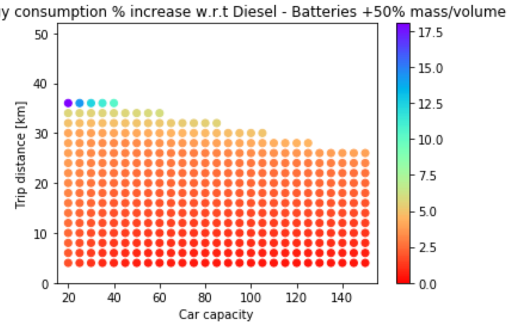


Figure 8.62

In Figure 8.63 to Figure 8.65 the same graphs are shown for hydrogen energy systems. Most obvious is the graph showing the length increase. This indicates that the volume of the hydrogen energy systems is lower than that of the diesel energy system, in the cases depicted by the graph. Also the vessel displacement increase when using the hydrogen energy system is minimal, having a maximum of 0.25%.

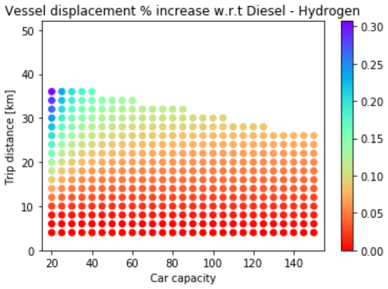


Figure 8.63

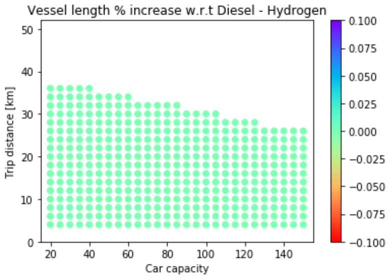


Figure 8.64

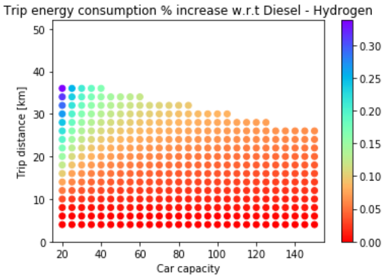


Figure 8.65

The vessel mass, volume and energy consumption increase when using supercapacitors is shown in Figure 8.66 to Figure 8.68. Of all zero-emission energy systems, the increases when using supercapacitors are the largest. This is due to the very low energy densities compared to the other systems, the differences being in the order of factor 7. However, when sailing short distances the effects are still minimal, being in accordance with the niche of supercapacitors for short distances.

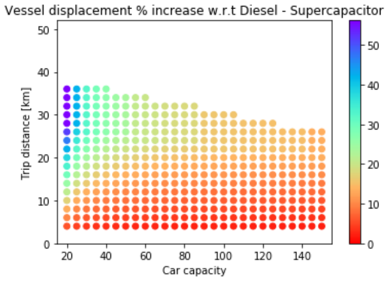


Figure 8.66

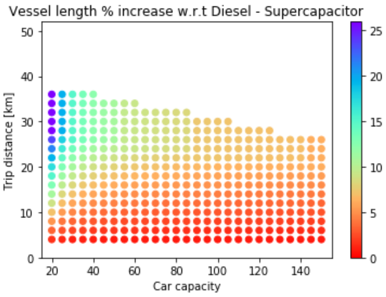


Figure 8.67

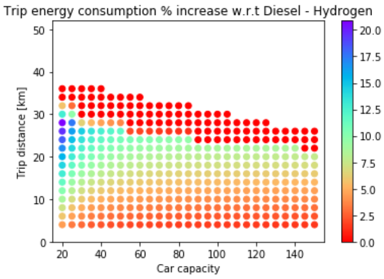


Figure 8.68

9

Conclusions and recommendations

The results of this thesis are the concept exploration tool and the conclusions from the parameter variation analysis performed with this tool. This chapter firstly describes the concept exploration tool and how it is to be used in daily operations. Secondly, the conclusions resulting from the parameter variation analysis are given, answering the research questions related to the parameter analysis, given in section 1.2. They are structured by the parties involved in the building of new double ended ferries; Energy system manufacturers, Governments, Ferry operators and Shipyards. These parties each influence certain aspects of the design and development of double ended ferries and their energy systems. By having the conclusions written up per party, each party can easily identify the conclusions applicable to their practice. For the majority of the conclusions, a corresponding recommendation is provided. Lastly, recommendations for future research are given.

9.1. Concept exploration tool

The intention of the concept exploration tool is to determine the feasibility of zero-emission energy systems for double ended ferries and create corresponding design parameters of vessel concepts using these systems. The tool is intended to be used in the early design stage, where it will help decide between different zero-emission energy types and benchmark them against a diesel-electric option. The tool will not make choices for the naval architect, make the naval architect obsolete, generate finished vessel designs or remove the need for critical evaluation of results and input values. The quality of the outcome of the concept exploration tool depends on the quality of the input it receives. The concept exploration tool will provide technical and economical characteristics of double ended ferry concept designs. For the feasible energy system types, the tool generates the concepts within minutes. By comparing their characteristics and combining them with designer and client preferences, the naval architect gains insights into which energy systems and corresponding vessel concepts are likely to satisfy the clients' wishes, based on data. This aids efficient allocation of resources for the detailed vessel design, detailed investigation of the energy systems and ensures the consideration of all energy system types implemented in the tool.

9.2. Parameter analysis conclusions

9.2.1. Energy system suppliers

Firstly, battery cost decrease has a large impact on the energy system choice. For the manufacturers of batteries this indicates a logical phenomenon; if the price of their product decreases, it becomes more cost-competitive with, and eventually cheaper than, fossil fuel options. This increasing the market for their product. Secondly, battery life increase has a large impact on the energy system choice. If battery life increase results in less frequent battery replacement, the system becomes more financially attractive. Regarding the development of batteries for double ended ferries, it depends on the operations of the ferry if a battery cost decrease or battery life increase has more effect on NPV. Therefore, for energy system suppliers, it is recommended to focus equally on both battery characteristics but to also keep in mind at which cost the characteristics are developed. In some cases, a cheaper battery with a shorter life will result in the most financially attractive energy system, and in other cases, a more expensive battery with a longer life will be more financially attractive. Thirdly, the increase or decrease of battery mass and volume has a relatively low impact on the energy system choice and vessel design. This leads to the recommendation of reviewing the balance between battery cost and energy density in relation to market demand. For double ended ferries, cheaper batteries with higher energy densities are more desirable than more expensive batteries with higher energy densities.

For hydrogen energy systems, the costs need to drastically decrease for them to be financially attractive. Therefore, for double ended ferries, manufacturers of the system components are advised to focus on cost reduction. To do this efficiently, the influence of the cost reduction of each component is crucial information. Parameter variation analysis revealed that the order of influence of cost decrease on net present value for hydrogen systems is: hydrogen cost, fuel cell cost, electrolyser cost, fuel tank cost. Focusing on reducing the cost of obtaining or producing hydrogen has the highest effect on NPV for equal percentages of cost reduction. As a combination of reductions will also yield a significant NPV reduction, the required resources to achieve reductions per component should be considered in the strategy of cost reduction.

Supercapacitor costs need to decrease to expand the current niche of financial attractiveness. The recommendation for supercapacitor manufacturers is to focus on decreasing the price of their product in order to expand their possible market share in the double ended ferry business.

9.2.2. Governments

The first conclusion for governments is that CO2 taxes need to increase beyond current values to have a significant impact on energy system choice of double ended ferries. Taxes only start to have a significant influence when increased to the order of 100 €/t. The recommendation is for governments to evaluate the effect and resulting incentives of their CO2 tax policy.

A second conclusion is that the available shore power at the ferry terminal can have a large impact on the financial attractiveness of battery energy systems. This is the zero-emission energy system that is most frequently economically competitive with diesel energy systems. If it is desired by (local) governments to have zero-emission double ended ferries, more shore power at the terminal will increase the possibility of battery energy system based ferries being financially attractive. The shore power available should thus be considered when choosing the terminal locations.

A third conclusion is that the exact trip distance can have a large influence on the financial attractiveness of battery energy systems. Due to energy consumption having a large influence on the charging strategy choice, a small increase in trip distance can trigger the need for a more complex charging strategy (subsection 6.3.1). This results in extra costs and has a large impact on the economical characteristics of the ferry concept. Therefore, if local governments are deciding upon new ferry routes and have the desire to use zero-emission double ended ferries, they are advised to take into account the influence of trip distance on charging strategy.

Lastly, from data variations discussed in subsection 8.1.2, it is concluded that also the specific combination of shore power, trip distance and car capacity has a large influence on the financial attractiveness of battery energy systems. When governments are investigating new ferry routes or extending contracts on current routes, it is recommended to pay extra attention to the employed charging strategy of battery powered double ended ferry concepts. If the initial result is that a charging strategy with shore batteries is required, the advice is to determine the effect of slight alterations to shore power, trip distance or car capacity. If these can be changed such that shore batteries are no longer needed, this results in a very large NPV decrease of the project.

9.2.3. Ferry operators

The first conclusion for ferry operators is that exact car capacity can have a large influence on the financial attractiveness of battery energy systems. As more cap carrying capacity results in a larger vessel and a higher energy consumption per trip, a change to a more complex battery charging strategy might be needed. The costs accompanying the more complex strategy are significant and have a large influence in the NPV. It is recommended to consider the car capacity at which the charging strategy needs to be changed when considering for battery energy systems.

Secondly, the exact discount rate has a large impact on the economic attractiveness and decisions regarding the energy systems. For ferry operators, this conclusion underlines the importance of determining/choosing the discount rate applicable to investments made. The discount rate influences which types of energy systems fit into the financial strategy and future of the operator.

Thirdly concluded, is that the amount of trips sailed daily has a large impact on the economic attractiveness and decisions regarding the energy systems. The advice to ferry operators is to keep in mind the effects of the amount daily trips on the NPV of the energy system types. Also if a ferry is tailored to a trip distance/daily amount of trips combination, the NPV will change if used for a different combination.

Fourthly, the sailing speed has a large impact on the economic attractiveness and decisions regarding the energy systems. Zero-emission energy systems do not necessarily become less financially attractive with respect to diesel-electric energy systems, if sailing speed is increased. Zero-emission energy systems can become more financially attractive if vessel speed is increased, due to having different energy storage and generation characteristics than diesel-electric energy systems. For ferry operators, it is recommended to consider this when determining the average and maximum vessel trip speed.

The fifth conclusion is that fuel price increase has a large impact on the energy system choice. The ferry operators' expectations for future fuel prices should play a large role in the decision process of the energy systems of new ferries. With the volatility of fuel prices, increases of 50% are not unrealistic. This elaborated upon in Appendix H.

From analysing the results of electricity price variations, the sixth conclusion is derived: An electricity price decrease has a large impact on energy system choice, but not as large as an equal fuel price increase. For the ferry operator, this conclusion indicates that the expectations for future electricity prices are important in the decision making process for energy systems of new ferries. That higher impact of fuel price changes does mean that the focus should be more based towards accurate predictions of fuel prices than electricity prices, as deviations have a higher impact.

The last conclusion for ferry operators is that hydrogen obtained from electrolysis at the terminal, is a cost competitive alternative to centralised production and supply. Ferry operators considering hydrogen energy systems are advised to investigate the possibility of producing hydrogen at the terminal, even if a centralised hydrogen supplier is located nearby. Producing hydrogen at the terminal can result in significant financial savings over the lifetime of a double ended ferry.

9.2.4. Shipyards

For shipyards, the most important conclusion is that zero-emission energy systems are currently technically feasible and cost competitive with diesel-electric energy systems for double ended ferries. It is therefore recommended to invest money and effort in gaining knowledge and experience in designing zero-emission double ended ferries. Likely future decreases of the costs of zero-emission energy systems will increase the demand for zero-emission ferries in the future and open up possibilities for the prepared shipyards to exploit. In cases where cost competitive, zero-emission energy systems are not only better for the environment during their operation, but can also result in significant monetary savings for the operator, with respect to a fossil fuel options. Being able to offer vessels with these advantages to their clients, can help the shipyards sell vessels.

The second conclusion is that displacement, length and energy consumption do not drastically increase due to the use of zero-emission energy systems, in the majority of the cases. The use of a hydrogen energy system results in the least displacement, length and energy consumption increase with respect to diesel, followed by batteries and supercapacitors. The influence of larger and heavier zero-emission energy systems only has a limited effect on the general parameters of double ended ferries and their performance. It is therefore advised not to dismiss zero-emission energy systems based on mass and/or volume in the early design stage, unless very obviously unfeasible. Also, it is advised to consider the balance between the cost of components and their power production/energy storage capacities. In some cases, it could be financially wise to use technologically less advanced systems, with lower energy and power densities, but also lower costs than vice verse.

A final conclusion useful for shipyards is that supercapacitor energy systems are financially attractive at high-frequency sailing schedules in combination with short trip distances. It is recommended to consider the use of supercapacitors when the amount of daily trips approaches 30. If prices decrease beyond the current 10000 €/kWh this value becomes lower.

9.3. Recommendations for future research

During the research performed in this thesis, some recommendations for future research were identified. These are split into three categories; parameter analysis expansion, model expansion and future concept exploration.

9.3.1. Parameter analysis expansion

The parameter variation analysis performed in this thesis does not use the full potential of the concept exploration tool. Many more parameter variations are possible, potentially leading to many more insights and conclusions. More in-depth research into the variations of certain parameters or the influence of simultaneous parameter variations can provide are examples of this. It is recommended to expand the research into which parameters the involved parties are able to influence and to which extent they are able to do so. From this, their influence in the feasibility and desirability of zero-emission energy systems for double ended ferries can be fully understood.

9.3.2. Model expansion

The developed concept exploration model can be expanded in three ways: in series, in parallel and in detail. Series expansion of the model refers to incorporating into the model, algorithms that describe the generation of energy. Parallel expansion refers to the addition of more energy system type algorithms, parallel to the ones currently implemented. Detail expansion refers to adding algorithms that go into more detail than the current ones. Thereby increasing the resemblance of the model to reality.

Series Currently, the system modelled described the energy system from the necessary systems at the terminal to energy being available for usage by electrical engines on board a vessel. This definition can be expanded by expanding through additional algorithms. In front of current algorithms, new ones can be added that model the generation of electricity from renewable energy sources. Thereby adding the options to compare the cost of obtaining electricity from a centralised supplier with generation at the terminal from wind or solar power. This provides a more insight into a possible complete zero-emission solution. Secondly, new algorithms can be added after current ones, calculating the costs of the vessels hull and remainder of the drive-train. As each zero-emission energy system results in a slightly different vessel concept, the cost differences in these areas due to less/more installed power or a smaller/larger vessel can be accounted for in the comparison of the concepts.

Parallel Comparison of more energy system options can be achieved by implementing corresponding algorithms parallel to the current selection. A recommendation is to add algorithms for hybrid configurations combining the different zero-emission energy systems. Energy systems consisting of combinations of hydrogen fuel cells/batteries or hydrogen fuel cells/supercapacitors can benefit from the advantages that both systems have in certain parts of the operational spectrum. This would provide insight into the desirability of these hybrids with respect to single type zero-emission energy systems.

Secondly, the assumption is made in this thesis that all the ferries sail a shuttle service. Adding the possibility of other sailing profiles would expand the usability of the model. Also, the model could be expanded with an algorithm for the design and performance prediction of double ended ferries with a catamaran hull.

Detail and data The third manner in which the model can be expanded is on the detail level or by using more data/higher quality data for the predictions. Expanding algorithms to predict more than the general parameters of the vessels can form the basis for more accurate performance predictions. Currently, the lack of data regarding the draught and block coefficients of double ended ferries resulted in these being fixed and given by the user. By acquiring data regarding these values and deriving prediction methods, more accurate concepts could be provided by the model.

Another way of expanding the level of detail can be achieved through expanding and categorising the vessel database, on which the current design trendlines are based. This can results in design trendlines for specific types of double ended ferry. In the trend of adding data, the data-set from which the Telfer resistance coefficients are currently determined is recommended to be expanded. Another aspect that could be implemented in more detail is the operational profile of the vessels. More research into the used power over the duration of a trip can be done to aid this.

Regarding the energy system algorithms, these can be expanded to a component level. This would result in more accurate predictions of the technical and economical characteristics of the systems, resulting in a more grounded comparison between the energy systems. This could be aided by obtaining specific technical data and cost values from energy system manufacturers. For the components, it would also make the concepts designs a step more ready for the next phase of design.

It is important to understand that expanding the model on a detail level, does not always make sense. It depends highly on the (un)certainty of the extra input that a new level of detail requires and the amount of input required. If the model is expanded to have a great level of detail, a large increase in required input could firstly reduce the user-friendliness of the model and eventually the frequency of use. Secondly, the addition of a large amount of input can result in a seemingly accurate model, whilst actually achieving the opposite. If a large amount of input variables is used, the certainty of the result is a factor of all the combined uncertainties. Where many uncertain variables will provide a highly uncertain result. It might then be better to have a limited set of input for which the uncertainty and its impact on the end result are much better grasped, even if it means sacrificing a level of detail

9.3.3. Further concept exploration

The concept exploration tool developed in this thesis and insights obtained from the parameter variation analysis are only applicable to double ended ferries. The developed framework, however, can also be applied to other vessel types. A recommendation for future concept exploration is to investigate the possibilities of concept design tools for other vessel types. Such tools are a great asset for implementing data driven decision making within the maritime industry. By systematically and consistently exploring concept variations many insights in the influence of certain design inputs or demands can be obtained. Possibly eventually working towards (partial) automation of ship design. This could be achieved by adding vessel optimisation software in combination with CFD resistance calculations, energy system design software and packing software. The result is a concept exploration tool capable of providing highly detailed concepts for which many parts of the design process are completed automatically.

A

Vessel design

Under the waterline

The hull of a double ended ferry is symmetrical with respect to the mid-ship plane. This is a defining design aspect of double ended ferries and is applicable to all double ended ferries. Within the symmetry aspect, hull design variations are still possible. The most common type of hull is the mono-hull.

When transporting vehicles using a double ended ferry, the deck area is the most limiting factor to the amount of vehicles that the ferry can carry. Double ended ferries generally have a relatively high width to maximise this area. A result of this high width is a small Lwl/B ratio and a large B/T ratio in comparison to other vessel types [1]. This combination of ratios is likely to give a directional unstable vessel when using a monohull design. To compensate for this, many double ended ferries have a centreline skeg on both ends. Improved course keeping is the result.

A second option is to choose for a catamaran hull to provide the directional stability. The two parallel pontoons provide excellent straight line sailing stability. A second benefit is that a rectangular deck can be installed over the full length of the pontoons to maximise the deck surface area. A problem for vessels with this hull shape can be bridgedeck slamming when sailing in rougher waters.

Figure A.1: Catamaran ferry [23]

B

Non-feasible energy systems analysis

Flywheels

Reason for in-feasibility
The reason that flywheel energy storage is not explored further in this thesis is the lack of use for primary energy storage in current portable/transportation systems. The main challenge is that volume energy density is a factor 4 lower than battery and hydrogen energy storage.

Energy storage
Using flywheels, the energy is stored as kinetic energy in the rotating mass of a disk/rotor. The disk is mounted to a shaft, to which an electrical motor is also connected. Such systems are also called flywheel energy storage systems or FESS.

Energy loading
Loading the flywheel is done by the motor/generator unit connected to the shaft. Electrical energy is used to accelerate the motor. Via the shaft this is used to accelerate the angular velocity of the disk.

Energy conversion
The energy conversion of the kinetic energy in the flywheel back to electrical energy is done using the generator option of the motor/generator unit.

Costs
The costs of flywheel energy storage for vessels is difficult to determine as there have been no cases of vessels having long-term (>1 minute) energy storage using flywheels. For flywheels the costs are mostly stated as $/kW and/or $/kWh. A recent start-up manufacturing small 3kW/15kWh (15 kWh at 3kW continuous power) flywheel systems states a cost of $6000 per unit or 400$/kWh [63]. A presentation from Boeing in 2012 stated a cost range of $300-1000/kWh, with the intention to reduce them to $100/kWh [55]. This wide range of cost depends on the material used and which systems of the FESS are included in the costs. The costs of flywheels specifically designed for vessels are not known, as it has never been done.

Technical specifications
The main parameters of the flywheel itself are the radius, thickness and material. The combination of

the three gives the mass of the disk, which is an important factor determining storage capacity. Secondly, the maximum tensile strength and density of the material determine the maximum amount of energy stored per unit mass of the disk. Combined with the radius of the disk the maximum rotational velocity of the disk can be determined. Above this velocity the disk will get damaged and not hold its shape.

Due to its high maximum tensile strength, most modern flywheels are made composite materials. These flywheels are connected to the shaft, supported by magnetic bearings in a vacuum enclosure. The latter uses magnetic levitation to create a non-contact bearing that gives very low friction and wear. The motor/generator unit is a permanent magnet motor/generator. This is connected to a variable voltage, variable frequency direct current (DC) to alternating current (AC) inverter.

The energy and power density with respect to the mass is determined by examining several commercially available flywheels. The examined flywheels are from Beacon Power, EnWheel, Velkness, Amber, Temporal and WattsUp.

Advantages

- High lifetime and charge/discharge cycles
- Limited temperature sensitivity
- No chemical hazards
- Minimal maintenance
- Observable state of charge
- Modular architecture
- Limited capacity decay
- Fast response
- Zero-emission operation

Drawbacks

- Low long-term charge/discharge efficiency
- Complexity of durable and low loss bearings
- Potentially hazardous failure modes
- Not yet used or proven as sole power source for ships
- Not yet used for large-scale portable energy storage
- Uncertain gyroscopic effects
- Uncertain costs
- Low mass energy density
- Low mass power density

Terminal requirements
If a FESS would be installed on a double ended ferry the flywheel would need to be loaded with certain intervals. As the charge/discharge efficiency of flywheels decreases significantly over longer periods, it would be advisable to recharge as often as possible from an efficiency standpoint. As the flywheel uses a permanent magnet motor/generator, the vessel would need an electrical connection to the shore for charging. **Case studies**
Case studies for use of flywheels for energy storage for propulsion have not been performed. There have been FESS developed for stationary land-based use. Examples of this are the 20MW storage facilities

in Stephentown, New York and Hazle Township Pennsylvania. These each use 200 of Beacon Powers 50kW/29.2kWh flywheels, this would allow them to provide 50kW of continuous for 35 minutes.

Compressed Air Energy Storage

Reason for in-feasibility

The reason that compressed air energy storage is not explored further in this thesis is the large uncertainty concerning the parameters of the system. Current compressed air energy storage systems are built on a large-scale and employ some kind of fossil fuel burning to increase energy output. More R&D of the zero-emission and small-scale versions of this system is needed before it can be considered for use in ships.

Energy storage

In compressed air energy storage (CAES) compressed air is stored in cylindrical tanks on-board of the ship.

Energy loading

For CAES energy storage, compressed air is needed. This is loaded into the tanks from an external source through a piping system or through an electrically powered compressor.

Energy conversion

The compressed air is converted to electricity through a generator. This generator is coupled to the tanks through a piping system.

Costs

As there is no vessel currently propelled solely using compressed air for energy storage, no quality estimates can be made for the costs of such a system. Values for large land-based plants are 400–800$/kW and 2–50 $/kWh capital costs [31]. These values can differ vastly for ships.

Technical specifications

The heat created when compressing air can be used to improve the total efficiency of the system. It can be used for heating systems or used to heat the air when it is expanded for energy generation. The re-use of energy improved the efficiency of the energy storage. A second possibility is to use the heat from compression for heating of the vessel and use the need for heat at expansion for cooling of the vessel.

Advantages

- No chemical hazards
- Observable state of charge
- Zero-emission operation
- Limited capacity decay
- Almost absent capacity decay
- Almost unlimited cycling ability
- Capacity unaffected by speed of charge/discharge
- Possibility of centralised energy storage production

Drawbacks

- Not yet used or proven as sole power source for ships
- Not yet used for large-scale portable energy storage
- Uncertain costs
- Uncertain system mass
- Uncertain system volume
- Low energy density

Terminal requirements

At certain intervals, the compressed air tanks need to be refilled from the land-based part of the energy system. This can be done by compressing air into a land-based storage tank using an electrical compressor and transferring this pressure to the ship-based tanks using a piping system. This has the advantage of posing less strain on the local electrical grid, due to more time being available for the compression than if the air was compressed during ferry loading/unloading. In this case, the compressor would only operate during loading/unloading of the vessel and all of the required energy needs to be compressed during this time.

Case studies

Multiple ideas for small-scale portable CAES have been proposed such as air powered cars or a CAES container unit. But none have actually been widely commercially available.

Compressed Air Over Water Energy Storage

Reason for in-feasibility

The reason that compressed air over water energy storage is not explored further in this thesis is the lack of small-scale and commercially available systems. The application for ships and other portable applications still need to be developed and researched.

Energy storage

In compressed air over water energy storage or liquid piston energy storage, the energy is stored in the air. But the medium of energy transfer is water as this is used in the energy conversion.

Energy loading

The loading of energy is done using a water-pump, optionally in combination with an air compressor. Pumping water into the tank is always needed, as this is the energy transferring medium. The pumping of water into the tank will compress the air in the tank and store energy. Additionally, an air compressor can be used to increase the pressure in the tank or speed up the loading process.

Energy conversion

The energy conversion can be done in two ways. The first is to convert the energy into electrical energy by connecting it to a hydro turbine. A second is to use the water flow itself to propel the vessel by using Venturi water pumps and the high-speed water flow to propel a larger volume of water at a lower speed.

Costs

As there are no vessel currently propelled solely using compressed air for energy storage, no accurate estimates can be made for the costs of such system.

Technical specifications

Liquid piston energy storage has isotherm behaviour. The heat that results from the compression of air is transferred to the water and extracted from it during expansion. Thus the net temperature of the tank is quite stable, which is beneficial for the efficiency.

In land-based systems the water is pumped between a second reservoir and the pressure tank, as not to need a continuous water supply. For ships it is not necessarily needed as the body of water provides a practically endless water supply. A side-note to this is that an enclosed fresh water system can be needed to minimise corrosion of the system when sailing on a body of salt water.

Advantages

- No chemical hazards
- Observable state of charge
- Zero-emission operation
- Almost absent capacity decay
- Unlimited cycling ability
- Capacity unaffected by speed of charge/discharge
- Possible efficiency gain over CAES
- Possibility of centralised energy storage production

Drawbacks

- Not yet used or proven as sole power source for ships
- Not yet used for large-scale portable energy storage
- Uncertain costs
- Uncertain system mass
- Uncertain system volume
- Low energy density

Terminal requirements

For this energy storage system, the energy can be compressed/pumped and stored at the terminal and then transferred to the vessel during loading/unloading or compressed/pumped directly into the tanks on the vessel during loading/unloading. The first having the benefit of lower peak strains on the local electrical grid. For the second option, the peak strain on the grid will be higher, but the total system will comprise of fewer components. It also needs to be possible to compress/pump all of the energy into the vessels tanks during the loading and unloading.

Case studies

Using compressed air over water energy storage has not been used for vessel propulsion yet.

Liquid air energy storage

Reason for in-feasibility
The reason that liquid air energy storage is not explored further in this thesis is the large uncertainty concerning the parameters of the system. Liquid air energy storage is being applied for large-scale land-based energy storage, but not portable on a small-scale.

Energy storage
In liquid air energy storage (LAES) the energy is stored in liquefied air. This liquefied air is stored in insulated non-pressurised tanks.

Energy loading
Liquefied air is obtained through the cooling of air until it liquefies at -196 degrees Celsius. LAES is thus a form of thermal energy storage.

Energy conversion
Exposure of the liquid air to heat causes the liquid to turn gaseous and expand by a factor of 700. This volume can be fed to a turbine to generate electricity or to a piston engine to generate mechanical energy directly.

Costs
As there are no vessel currently propelled solely using compressed air for energy storage, no accurate estimates can be made for the costs of such a system.

Technical specifications
The first step for obtaining liquid air is to separate the air from gasses that freeze before -196 degrees Celsius, which would damage the system components. The result is a mixture of mostly nitrogen and oxygen. Next is the liquefaction process using the Hampson-Linde cycle or the Claude cycle. This results in liquefied air that is ready for storage. The generation of energy from the liquefied air is based on its expansion, for which heat is needed. This heat can come from the ambient temperature, a dedicated heat source or low-grade waste heat. This gives the opportunity to re-use waste heat from other systems or provide cooling to certain areas such as electrical engines. Hereby removing the need for dedicated cooling systems. The heat can also be extracted from the input air for the next air liquefaction cycle to improve the cycle efficiency, by cooling that air. Less energy will then be needed to cool that air to cryogenic temperatures.

Instead of using liquefied air for cryogenic energy storage liquefied nitrogen can be used. In the current situation, large industrial gas companies have spare nitrogen production capacity, which could result in cheap filtered nitrogen for liquefaction. This is possible as it has similar thermodynamic characteristics as air. This method thus eliminates the energy intensive process of air separation from the equation, whilst using existing production facilities. A major drawback is that the nitrogen is a by-product of an emission intensive industry. But it could be used to kick-start the technology by increasing the efficiency and lowering the cost until dedicated renewable energy powered production facilities are built.

A drawback that cannot go unmentioned is the low basic efficiency of 25%. When recycling the needed heat for expansion is used to cool the air for the next refrigeration cycle this can increase to 50%. This can increase even further if waste heat is for the expansion, as this heat would otherwise be wasted.

Advantages

- No chemical hazards
- Observable state of charge
- Zero-emission operation
- Limited capacity decay
- Possible use of existing production facilities (nitrogen)
- Use of low-grade waste heat
- Refrigeration/cooling as byproduct
- High energy density
- Possibility of centralised energy storage production

Drawbacks

- Not yet used or proven as sole power source for ships
- Not yet used for large-scale portable energy storage
- Uncertain costs
- Uncertain system mass
- Uncertain system volume
- Low power density w.r.t. other technologies
- Low base efficiency
- Generally low power density

Terminal facilities
The use of cryogenic energy storage depends on the liquefied air (or nitrogen). Obtaining this can be done locally or centralised. Depending on the size of the systems the liquefaction process can be done on the vessel completely and powered by electricity during loading and unloading. This would require the complete installation to be installed on the vessel. A second option is to liquefy the air on land, store it in tanks and to transfer the liquefied air to tanks on the vessel during loading/unloading. Here the liquefaction facility is at the terminal together with a storage tank. This has the benefit of size and mass of the liquefying system being less restricted. A third option is to obtain the liquefied air from a large centralised production facility from which it is transported to storage tanks at the terminal. The last having the efficiency and cost gains due to scale effects of production.

Case studies
Using liquid air energy storage has not been used for vessel propulsion yet.

Flow batteries

Reason for in-feasibility
The reason that flow batteries are not explored further in this thesis is that the usability for ships is not yet fully developed. Further r&d into specific systems for ships and electrolyte refuelling for fast charging is needed before flow batteries can act as the main energy storage system for ships.

Flow batteries are batteries that use liquid electrolytes as the energy carriers. They do not have solid electrodes such as classic batteries. One electrolyte liquid is negatively charged and the other the positively charged when charging the battery. The electrolytes are stored in connected separate tanks, divided by an ion-selective membrane. Depending on if the battery is charging or discharging, certain ions pass through the membrane to complete chemical reactions similar to classical batteries. The corresponding electron pass through an external circuit connected to both sides of the electrolyte. Different types of flow batteries exist o.a redox, iron-chromium, vanadium redox and zinc-bromine. The major drawback of currently available flow batteries is their relatively low charge rates. Currently C-rates in the range of 0.1-0.5C are achieved for larger batteries. For the average of 0.3C, this means that it takes 3 hours and 20 minutes to fully recharge the batteries.

Flow batteries do have the practical aspect of storing the electrolytes in tanks. When the energy capacity of the battery needs to be increased, the size of the tanks can simply be increased. The possibility also exists to replace the electrolyte liquids when they are spent, by new "energised" electrolyte liquid. Recent research has shown that this results in refuelling similar to conventional liquid fossil fuel refuelling. Even though this is not available commercially available, its development can lead to a huge breakthrough in flow battery charging and its possible applications.

C

Complete appendix confidential

Complete appendix confidential

[redacted]

Complete appendix confidential

[redacted]

Complete appendix confidential

[redacted]

Complete appendix confidential

[redacted]

D

Comparison resistance estimation methods

The energy that a double ended ferry consumes for propulsion is a result of overcoming resistance. This resistance can be predicted as a function of vessel parameters, sailing speed and conditional parameters. In this section, various methods for flat water resistance are explained and compared. The comparison is done using data from an available data set at Damen Shipyards. This data set is confidential.

Holtrop Mennen

The Holtrop-Mennen resistance prediction method is widely known and used across naval architecture. Developed in the eighties by Jan Holtrop and Frits Mennen at MARIN, this method still used by shipyards worldwide. As to not to be repetitive, the workings of the method, as described by its developers, can be found in [44].

Guldhammer-Harvald

During the period ranging from 1965-1974, an empirical resistance prediction method was developed by Guldhammer and Harvald. Based on available test data a set of diagrams were established for use in the prediction method. The description of this method can be found in [46].

Telfer resistance coefficient

Discussed in subsection 6.2.2

Total resistance coefficient

The total resistance coefficient from the ITTC-2002 Recommended Procedures is a dimensionless coefficient, calculated using the total resistance, water density, vessel speed and wetted surface area as shown in equation Equation D.1

$$C_{TL} = \frac{R_T}{0.5 \cdot \rho \cdot V^2 \cdot S} \tag{D.1}$$

The procedure for determining the total resistance coefficient is the same as the procedure of the Telfer coefficient subsection 6.2.2. Only when calculating the total resistance, instead of the displacement and length at the waterline, the water density and wetted surface area need to be known.

The curves of the total resistance coefficient are plotted against the displacement-Froude number. The resulting plot is shown in figure Figure 6.5. As with the Telfer curves, the trendline of the average curve was used to determine the total resistance coefficient in the further comparison of the resistance prediction methods.

Resistance method evaluation

Using the resistance prediction methods described in the previous sections, the resistance for the [redacted] vessels in the database was predicted. For Holtrop-Mennen and Guldhammer-Harvald, the values were provided in the initial database. For Telfer and the total resistance coefficient, the derived coefficient trendlines were used. The result is prediction data from all four of the methods and model test data for all [redacted] ships in the database. For each vessel and each prediction method, the prediction method was plotted against the model test data. The set of obtained graphs is confidential [redacted]

Confidential

[redacted]

Figure D.1

Confidential

[redacted]

Figure D.2

Guldhammer-Harvald Comparing the model test resistance data with the resistance prediction using the Guldhammer-Harvald method, the clearest characteristic is that the prediction trend does not follow the model test trend. In two of the four graphs the lines cross, indicating a different correlation between the increase in speed and increase in resistance of the test and prediction. This difference shows that the prediction method will produce unreliable results for further predictions of the resistance of double ended ferries, when reasoning from the available database.

Holtrop-Mennen The results of the Holtrop-Mennen resistance prediction and the model tests do follow a similar trend. Trends are not identical and in absolute sense, there is still a deviation of the prediction from the model tests. The average of the absolute deviation percentage for all speeds and vessels is 14.1% per measurement in comparison to the 8.5% when using the Telfer method. The accuracy, however, is not the only point of interest for this thesis. The aim is to implement the resistance method in a concept exploration tool. This means that the non-standardised input for the resistance prediction needs to be provided by the user of the tool. Of all the methods compared in this thesis, the input parameters for the Holtrop-Mennen prediction are the most elaborate. Obtaining the input for the calculation can be time consuming, reducing the efficiency of the tool and the likelihood that it will be employed.

Another drawback of providing large amounts of input in the concept design phase, is the proneness to errors/inaccuracies/uncertainties in the estimations of the input. These can result in a large anomaly in the end product when subjected to combinations of mathematical operations. The combination of this risk and the fact that the average deviation of Holtrop-Mennen is larger than the Telfer average deviation, makes that the Telfer method is preferred for the aims of this thesis.

Total resistance coefficient Predicting the resistance with the total resistance coefficient yield resistance trends that are similar to the model tests. This is to be expected as the resistance coefficients are derived from the average trend in the model test data. The major issue with this prediction method is the accuracy. The average of the absolute deviation percentage over all ships and vessels is 23.9%, which is nearly triple the average deviation obtained using the Telfer method. A second reason that makes the use of the total resistance coefficient impractical is that the input parameter is the wetted surface area. This firstly requires an accurate estimation of the initial wetted surface area for double ended ferries. Secondly, when the mass and volume of the energy system and thus those of the vessel are varied, the correlation with the wetted surface area must be known to determine the change in resistance when iterating the designs.

Telfer coefficient The resistance prediction method used in this thesis is Telfer. The results of the prediction method follow the trend of the model tests sufficiently, thus making the prediction method useful for new predictions. The accuracy of the average absolute deviation percentage is the best of all prediction methods, with an average deviation of 8.5% per measurement. The input parameters for the resistance prediction also have a clear correlation with the varying mass and volume of different types of energy systems. This is practical when iterating through multiple concept designs.

E

Aage-Brix coefficients

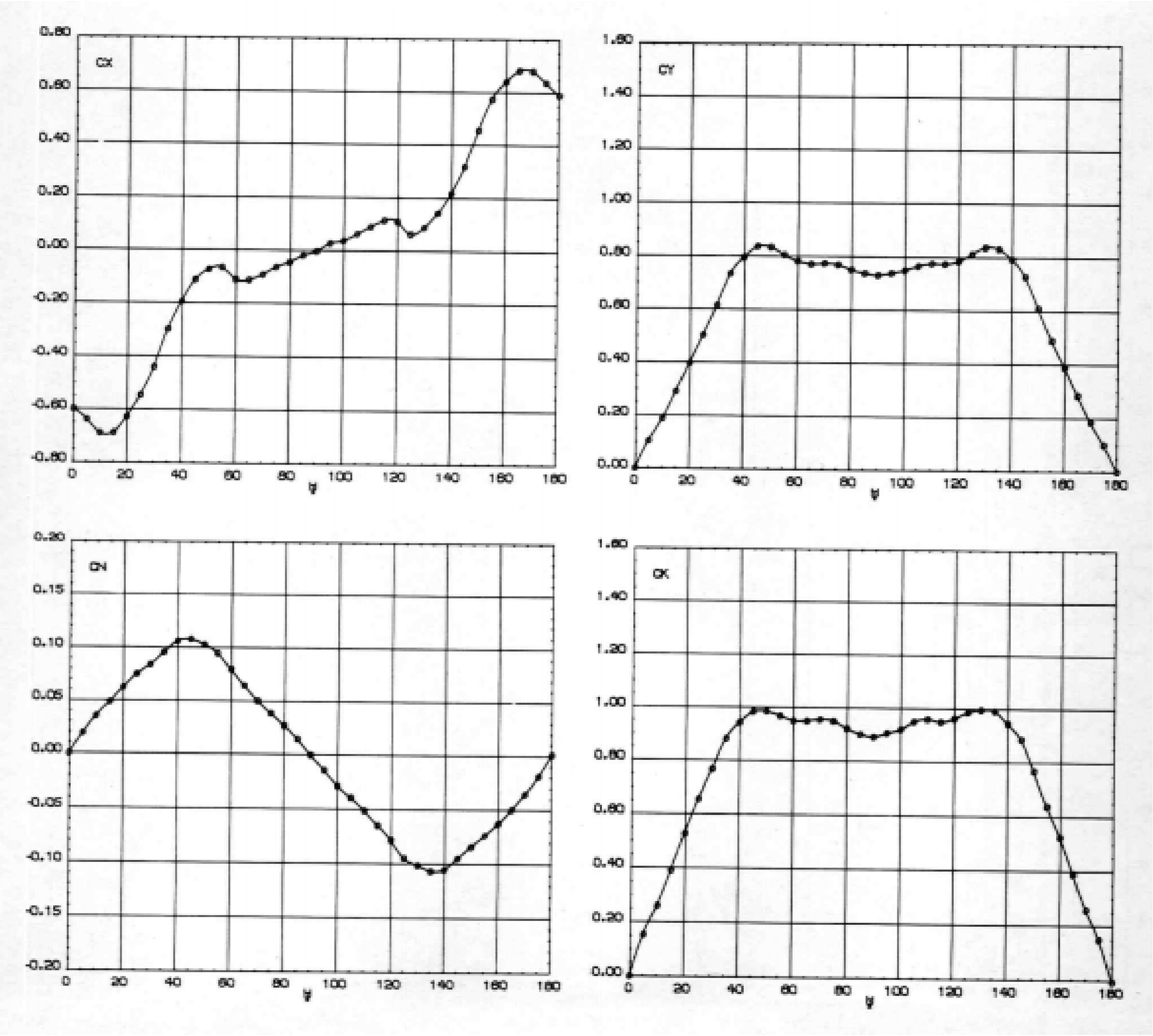


Figure E.1: Aage-Brix coefficients for a double ended ferry [4]

F

Extensive model assumptions

Tool use

- 1. The tool is only applicable to double ended ferries that carry cars and passengers
- 2. The tool is intended for early stage concept design
- 3. The resulting values from the tool are an indication, as with most early concept designs and not definitive
- 4. The tool should be used to narrow down for in-depth research into certain energy systems
- 5. The tool is only intended for mono-hull ships
- 6. The energy system starts with the energy transfer systems at the terminal
- 7. The size and mass of the systems at the terminal is assumed not to be a limiting factor
- 8. The energy system ends where electrical energy has been made available on board of the vessel, from the energy storage system

Energy capacity

- 1. The ships draft is input by the user and fixed
- 2. The required car and passenger capacity is given
- 3. The required sailing time is given
- 4. The trips distance is given
- 5. The required maximum speed is given
- 6. The sailing location and corresponding wind/wave data is known
- 7. The trip speed profile is known
- 8. The trip auxiliary power profile is known
- 9. Resistance is calculated using the Telfer prediction method
- 10. The resulting trip energy capacity is the maximum that the vessel can encounter

Energy systems

- 1. The available charging/refuelling time is known

- 2. The vessel lifetime is given by the user
- 3. The given shore power is available at both shores
- 4. The given shore power is input by the user and fixed
- 5. The energy system data is given in a table, that can be adjusted by the user
- 6. The amount of daily trips is given by the user and fixed over the vessels lifetime
- 7. The hydrogen fueling interval is given
- 8. The diesel fueling interval is given
- 9. Hybrid systems are not investigated at this stage. Would time allow they might be added at the end

Electricity

- 1. The aim is to charge as much as possible directly from the grid
- 2. The desire is to carry as little batteries as possible, whilst not negatively influencing the costs or design
- 3. There are never shore power black-outs
- 4. The battery on-shore and in the vessel are of the same type
- 5. Each configuration contains only one battery type
- 6. There is backup in all options
- 7. Electricity is not cheaper during the night than during the day
- 8. Electricity prices are fixed over the vessels lifetime
- 9. The given depth of discharge is the maximum depth of discharge used outside of emergency situations
- 10. For charging strategies 7, 8, 9, 10 and 11 the overnight charging time is sufficient to not cause problems with C-rates.

Hydrogen

- 1. Only compressed hydrogen is considered
- 2. Direct fueling trucks carry a pumping unit to pump hydrogen to the ship
- 3. Produced water is pure enough to discharge to the environment without harming it
- 4. Hydrogen prices are fixed for the lifetime of the vessel
- 5. Hydrogen fueling speed is not an issue (speeds up to 666 kWh/min are currently possible)

Diesel-electric

- 1. The main alternative for zero-emission energy systems is diesel-electric
- 2. The propulsion plant is diesel-electric with only diesel generators
- 3. Diesel fueling stations are already installed at both ends
- 4. Fuel prices are fixed for the duration of the vessels lifetime

G

Extended data - result analysis

Battery energy density increase - Trip distances 4, 16, 32 km

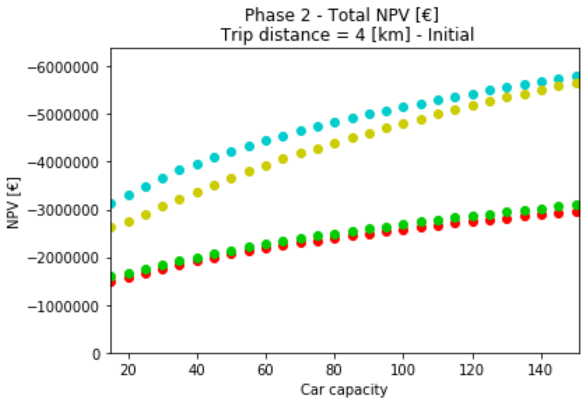


Figure G.1

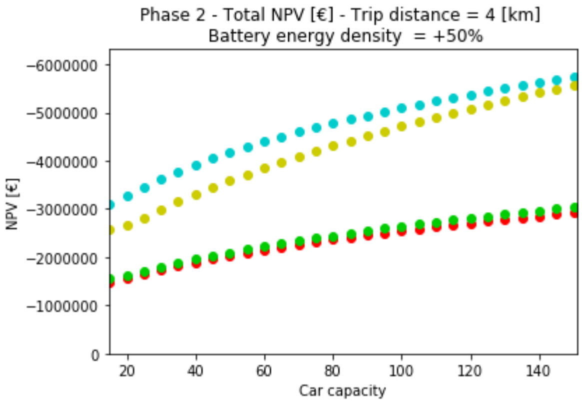


Figure G.2

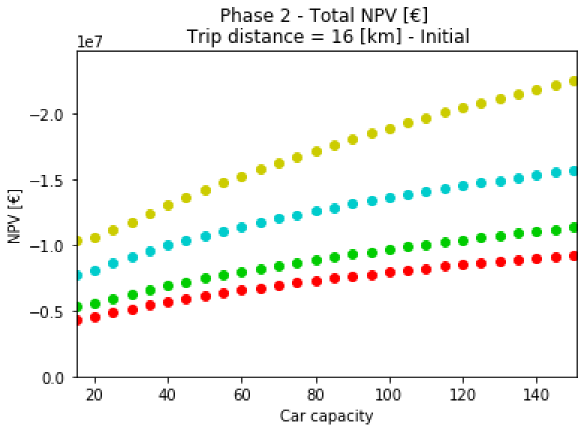


Figure G.3

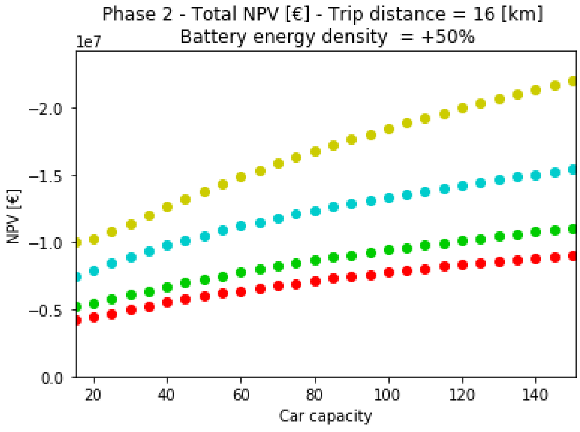


Figure G.4

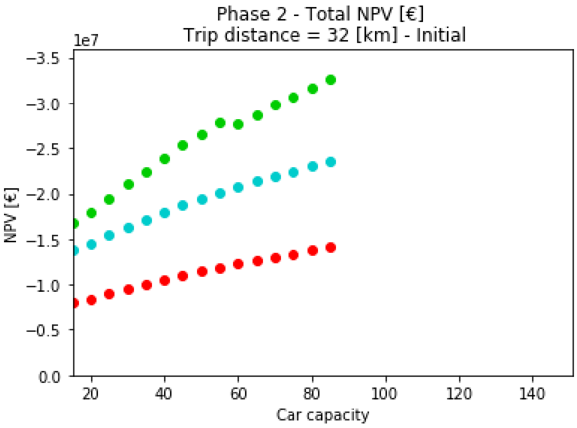


Figure G.5

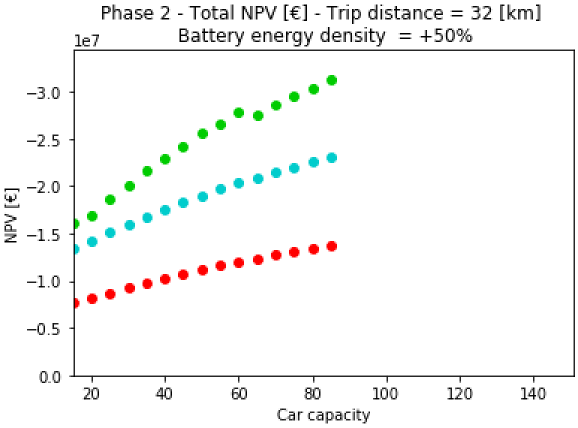


Figure G.6

Cost variation hydrogen energy system - Car capacity = 60

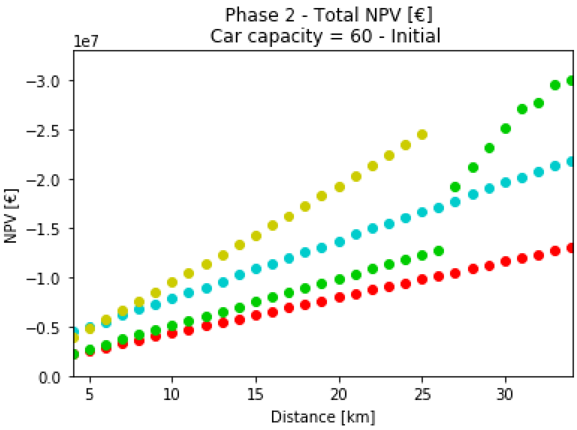


Figure G.7

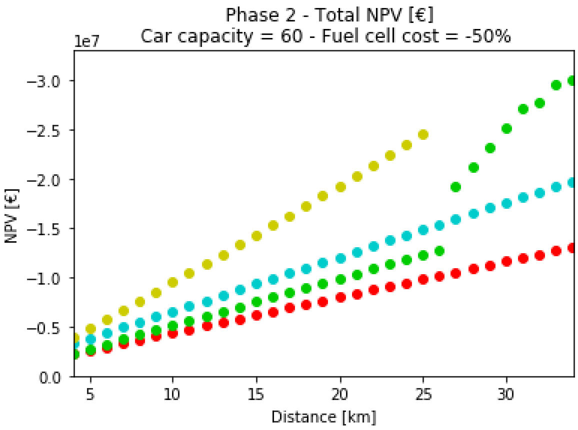


Figure G.8

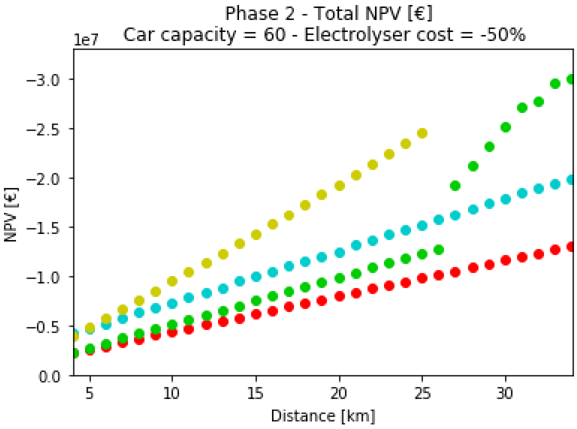


Figure G.9

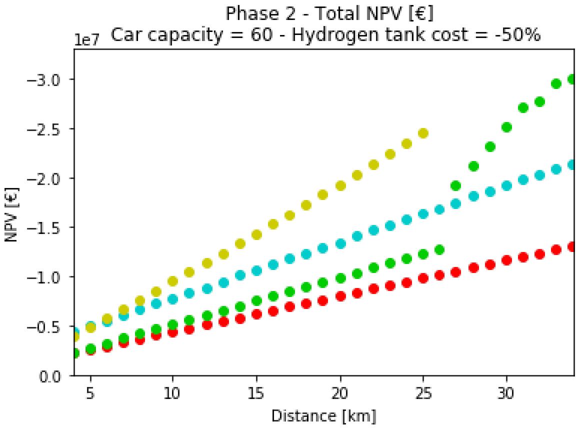


Figure G.10

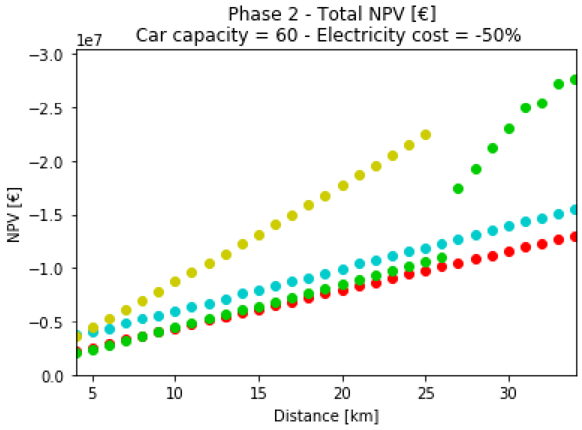


Figure G.11

Cost variation hydrogen energy system - Car capacity = 120

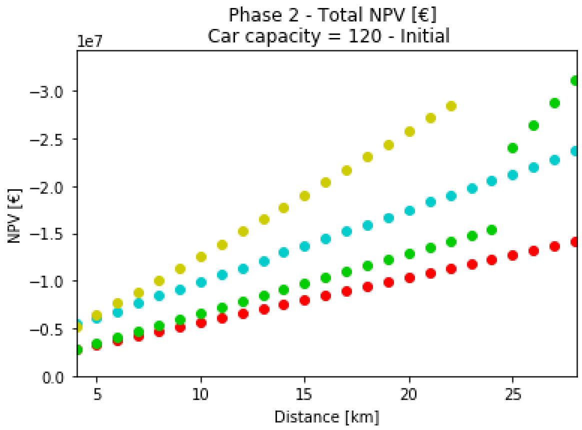


Figure G.12

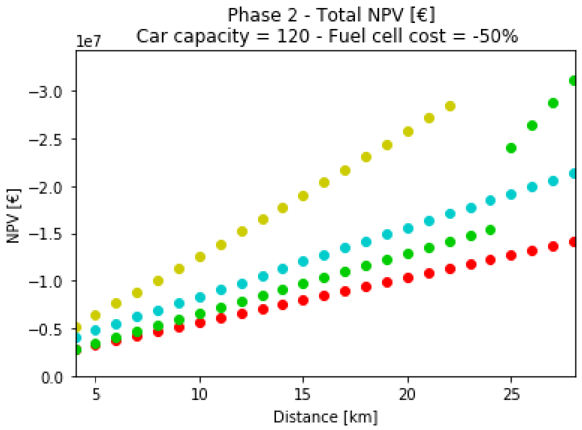


Figure G.13

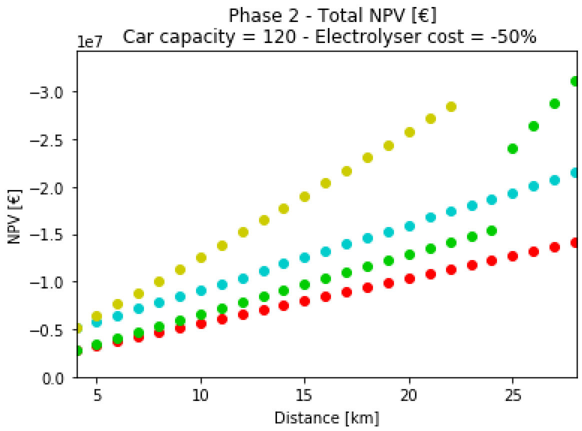


Figure G.14

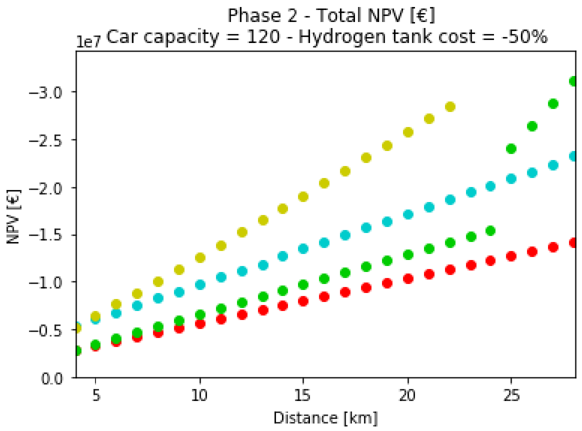


Figure G.15

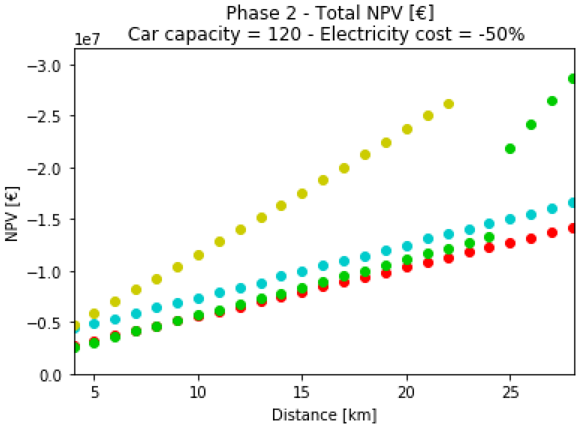


Figure G.16

Daily amount of trips variation - Car capacity = 30

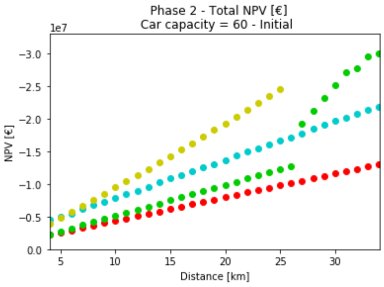


Figure G.17

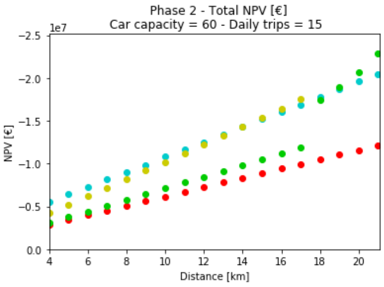


Figure G.18

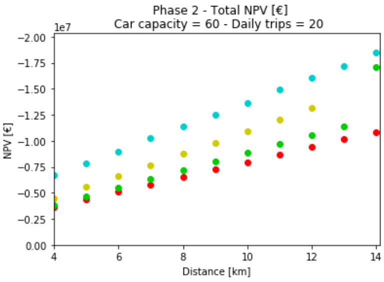


Figure G.19

Daily amount of trips variation - Car capacity = 120

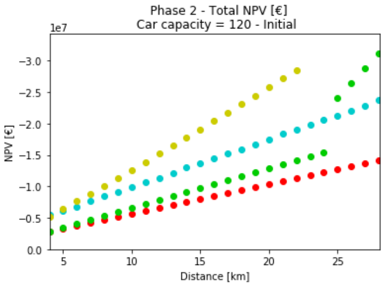


Figure G.20

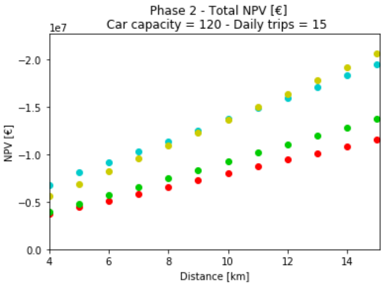


Figure G.21

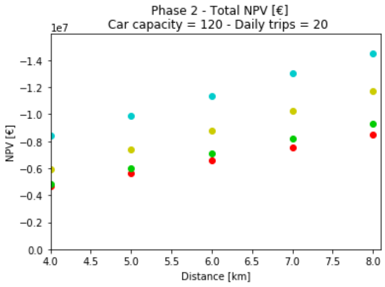


Figure G.22

Speed variation - Car capacity = 30

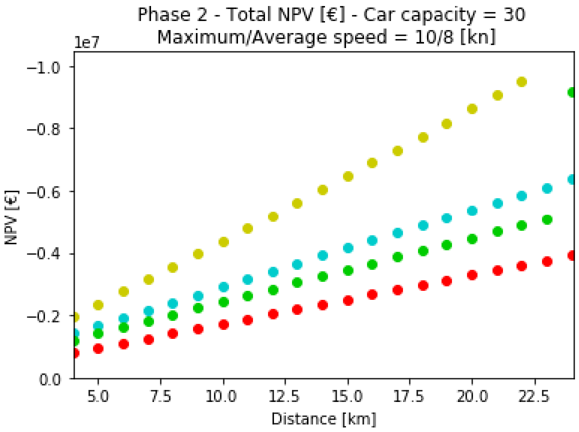


Figure G.23

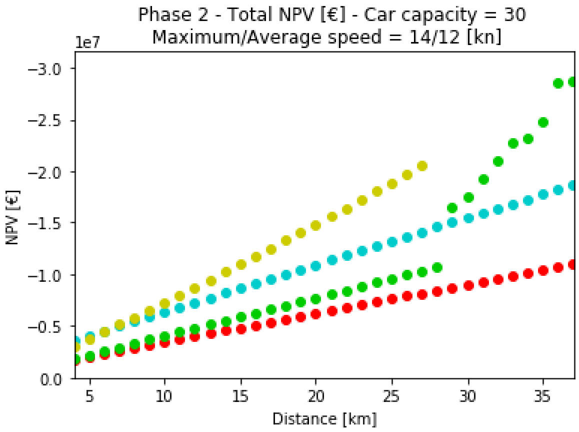


Figure G.24

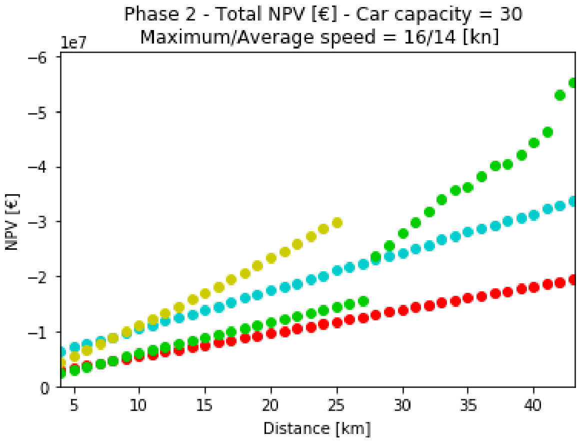


Figure G.25

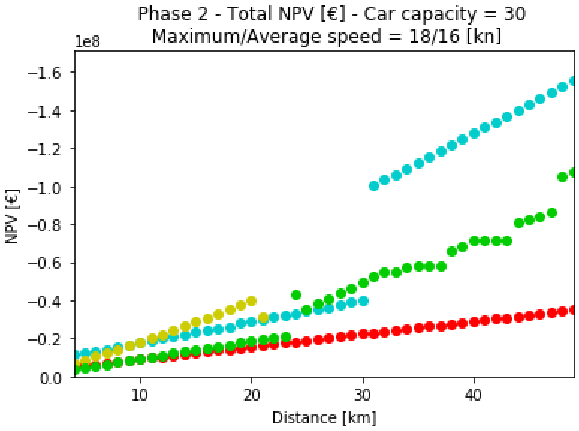


Figure G.26

Speed variation - Car capacity = 120

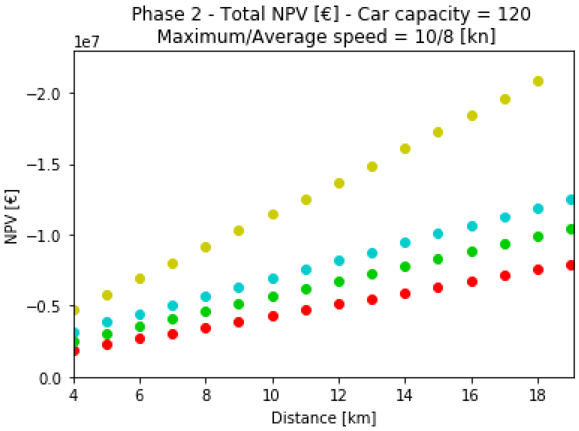


Figure G.27

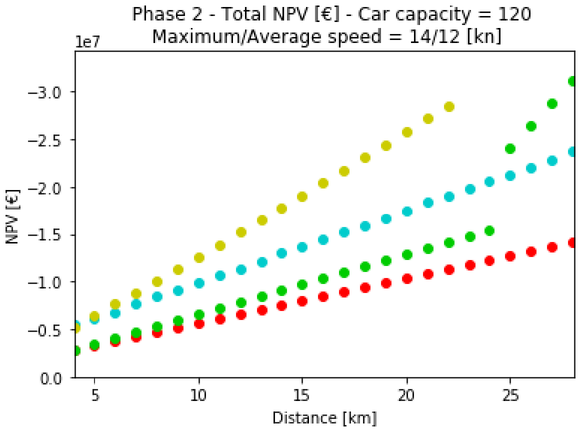


Figure G.28

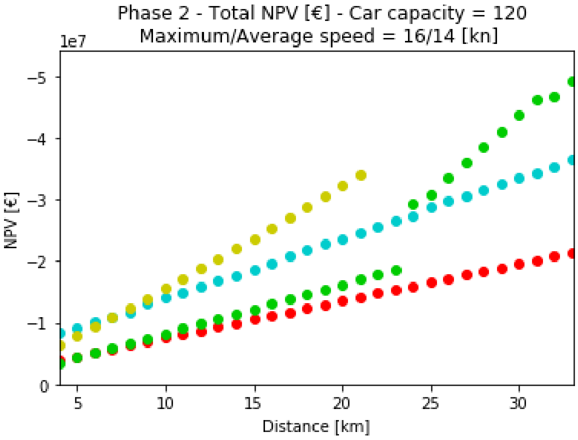


Figure G.29

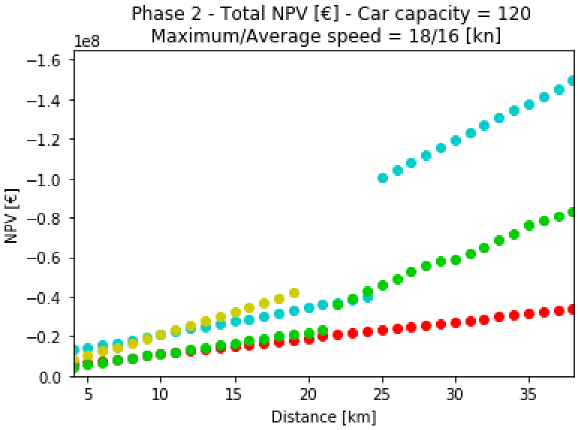


Figure G.30

H

Reasoning parameter variations

Economical parameters

Fuel price: MDO

The price of fuel is closely related to global economical and political developments. The consequence being volatile price developments. The initial price taken into account for Marine Diesel Oil is €575, based on the global average from [12]. Expectations from various sources suggest an increase of the prices in the future Figure C.4. The variations of the MDO price used in this thesis are an increase of 25% and an increase of 50%. This is based on historical values of fuel prices. With respect to current fuel prices (May 2018) fuel has been 50% more expensive in 2011 and 2012, showing that these variations are realistic and have occurred in the recent past. The values for MDO price used in this thesis are global averages and can obviously differ per specific region.

Electricity price

In the near future the price of electricity is undergoing changes with respect to the electricity generation. Electricity generation from renewable sources is becoming competitive with electricity generation from fossil fuels and even cheaper in certain parts of the world. A current global average for the price of electricity for industrial consumers is 5 euro-cents per kilowatt-hour. Forecasts from various sources indicate a bandwidth for future electricity prices [62][48]. The general trend of this bandwidth is a decrease of the prices. In this thesis, one variation of a 50% decrease of the prices is used in the parameter analysis. This is the extreme value of the electricity price forecasts.

Hydrogen cost

The initial value for the hydrogen cost of delivery by truck is based on actual prices of hydrogen at currently operating commercial hydrogen stations. However, Figure 8.50 indicates that producing hydrogen using an electrolyser at the terminal is much cheaper. Therefore the hydrogen price used in the initial case is linked to the electricity price. By reducing the electricity price by 50%, the hydrogen cost variation is introduced.

Discount rate

The discount rate is the value used in the net present value to discount future flows to cash to current value. This makes the discount rate have a very large influence on the resulting net present value. The value of the discount rate is basically equal to the annual return on investment that money would generate if not spent on the project in question, but otherwise invested/allocated. Determining the return on investment of otherwise allocated money is determined greatly by the type of project and the risks associated, as these risks should be equal to the risks of the project in question – for a fair comparison. There are a couple of ways to do this. If zero risk is assumed, the return on investment of a government bond (also assumed to have zero risk) for the same lifetime of the vessel can be used for an indication of the discount rate. This gives a discount rate of 1.5%. Zero risk is however rarely the case, also in government-funded projects. As double ended ferries can be (largely) government-funded, the discount rate that the government uses for its projects can be a reasonable value. Utilitarian projects, such as double ended ferries, are part of what the government provided for its population and not solely motivated by making money. The discount rate used by the Dutch government in utility projects is 5%.

CO2 tax price

The current rate of carbon tax is measured in a cost per metric tonne of carbon dioxide, based on the carbon dioxide content of a fossil fuel. As described in subsection 6.3.4 and subsection 8.1.2 the variations of carbon tax are based on currently used values across the world and the increase of the maximum currently used value by a factor of 3.

Technical parameters

Battery costs, fuel cell costs, hydrogen tank costs, electrolyser costs, supercapacitor costs

The expectations of future developments of the costs of zero-emission energy systems and components range far and wide. Predictions range from low 10% costs decreases to high 75% cost decreases. The latter not being unrealistic, as battery prices have decreased by this percentage in the past decade [59], [19]. It is important to note that the costs in these reports are only the cost of the battery packs and focus on electric vehicles, whilst this thesis uses a value representative for the whole energy system. As more has been invested in battery R&D than hydrogen and supercapacitor R&D [32], such costs decreases are not unthinkable in the future. The reason for using a 50% cost decrease for all the energy systems in the parameter analysis, is that this serves to have clear effects on the net present value. A large cost decrease results in a larger effect on the NPV, making the differences between the energy systems more pronounced.

Battery life, Fuel cell life

For both battery life and fuel cell life an increase of 50% is investigated in the parameter variations analysis. The reason for this value is the comparison with the cost decrease. Equal increases and decreases are compared to indicate where energy system suppliers should focus on in their product developments in order to make their systems more economically attractive for double ended ferries.

Battery energy density

The battery mass and volume energy density variation use half the currently possible volumetric and mass energy density of lithium-ion batteries. This extreme decrease is used to investigate the severeness of the effect on vessel parameters. The effect of decreasing the energy density is clearly shown by the results of this variation. Additionally, graphs showing the energy systems' contributions to the vessel mass and volume, contribute to the understanding. From this understanding, the effects resulting from a further decrease or increase of the energy density can be logically reasoned. Therefore other variations are not investigated.

Operational parameters

Shore power

Zero-emission energy systems need a certain amount of shore power to be feasible. Below a certain value supercapacitors are not feasible and producing hydrogen using electrolysis is not possible. For batteries there is an intermediate step where a different, less desirable, charging strategy needs to be used if the available charging power is below a certain value. With shore power of 2000 kW, the power is above this threshold. To illustrate the effect of going below this threshold, a 50% decrease was introduced as a variation. The values serve a purely illustrative purpose. Although they are realistic, shore power connections vary greatly between ports, countries and regions in the world.

Average and maximum sailing speed

The average speed in the initial case is chosen to be 12 knots in combination with a maximum of 14. These values are derived from the vessel database, as the majority of the vessels sail at these speeds. The speed increase variations investigated are also determined from the speeds of the vessels in the database. For completeness, a speed decrease variation is also investigated. In this variation, the maximum speed is 10 knots and the average is 8 knots. These values correspond with the vessel with the lowest speed in the database.

Daily amount of trips

Ten daily amount of trips are assumed to be the minimum that a double ended ferry is used for. From this minimum variations were investigated with a step increase of 5 until the maximum of 35. At 35 trip the physical limitation of 24 daily ours has largely limited the possible trip distance/car capacity combinations.

List of Figures

Bibliography

[1] Gabriola Island Fixed Link Feasibility Study, 2016. http://www.marinepropulsors.com/smp/files/downloads/smp11/Paper/WA2-2_Minchev.pdf [Accessed: 20-12-2017].

[2] Shipright design and construction:additional design procedures - risk based designs (rbd). 2016. URL https://www.cdlive.lr.org/information/documents/ShipRight/Design%20and%20Construction/Additional%20Design%20Procedures/Assessment%20of%20Risk%20Based%20Designs%20(ARBD)/Risk_Based_Design_(RBD)_January_2018.pdf.

[3] Shipright design and construction:additional design procedures - risk based designs (rbd). 2016. URL https://www.cdlive.lr.org/information/documents/ShipRight/Design%20and%20Construction/Additional%20Design%20Procedures/Assessment%20of%20Risk%20Based%20Designs%20(ARBD)/Risk_Based_Design_(RBD)_January_2018.pdf.

[4] Christian Aage. Wind coefficients for nine ship models. Technical report, Hydro - OG Aerodynamisk Laboratorium Lyngby, Denmark, 05 1971.

[5] Statens Vegvesen/Norwegian Public Roads Administration. E39 Coastal Highway Route, 2017. https://www.vegvesen.no/en/roads/Roads+and+bridges/Road+projects/e39coastalhighwayroute;jsessionid=C30119BDC8F35DA489D3BC2026A056FC [Accessed: 05-12-2017].

[6] Gemeente Amsterdam. Voorgesteld pakket maatregelen Sprong over het IJ, 2017. https://www.amsterdam.nl/bestuur-organisatie/volg-beleid/amsterdam-onderzoekt/maatregelen-sprong/ [Accessed: 05-12-2017].

[7] J. Ayre. Tesla Completes World's Largest Li-ion Battery (129 MWh) In South Australia. https://cleantechnica.com/2017/11/23/tesla-completes-worlds-largest-li-ion-battery-129-mwh-energy-storage-facility- [Accessed: 15-05-2018].

[8] Ballard. FCveloCity-HD Data Sheet. http://www.ballard.com/docs/default-source/motive-modules-documents/fcvelocity_hd_family_of_products_low_res.pdf [Accessed: 15-05-2018].

[9] Ferjer blog. . https://norskeferjer.wordpress.com/category/storm/ [Accessed: 15-01-2018].

[10] Wikipedia Bolivar Bridge. . https://en.wikipedia.org/wiki/Bolivar_Bridge [Accessed: 15-01-2018].

[11] J. Brix. *Manoeuvring Technical Manual*. Seehafen Verlag, 1993. ISBN 3-87743-902-0.

[12] Ship & Bunker. . `https://shipandbunker.com/prices#MGO` [Accessed: 20-05-2018].

[13] D. Carrington. 'Spectacular' drop in renewable energy costs leads to record global boost. `https://www.theguardian.com/environment/2017/jun/06/spectacular-drop-in-renewable-energy-costs-leads-to-record-global-boost` [Accessed: 15-01-2018].

[14] Baltic Workboats Youtube channel. . `https://www.youtube.com/watch?v=RzO7zTOLzRQ` [Accessed: 15-01-2018].

[15] Haisheng Chen, Thang Ngoc Cong, Wei Yang, Chunqing Tan, Yongliang Li, and Yulong Ding. Progress in electrical energy storage system: A critical review. *Progress in Natural Science*, 19(3): 291–312, 2009. doi: https://doi.org/10.1016/j.pnsc.2008.07.014.

[16] International Towing Tank Conference. Full scale measurements speed and power trials. analysis of speed/power trial data. *ITTC – Recommended Procedures and Guidelines*, page 7, 2005.

[17] International Towing Tank Conference. Speed and power trials, part 2. analysis of speed/power trial data. *ITTC – Recommended Procedures and Guidelines*, 1.1:2, 2014.

[18] Green Car Congress. . `http://www.greencarcongress.com/2018/01/20180118-refhyne.html` [Accessed: 15-05-2018].

[19] Claire Curry. Lithium-ion battery costs and market. Technical report, Bloomberg, 07 2017.

[20] Stirling Design. . `https://www.stirlingdesign.fr/en/portfolio/stx-ar-vag-tredan/` [Accessed: 15-01-2018].

[21] Cambridge dictionary. Ferry definition. `https://dictionary.cambridge.org/dictionary/english/ferry` [Accessed: 15-01-2018].

[22] Energy education. . `https://energyeducation.ca/encyclopedia/Supercapacitor#cite_note-6` [Accessed: 30-07-2018].

[23] Corvus Energy, . `http://corvusenergy.com/marine-project/mf-ampere-ferry/` [Accessed: 15-01-2018].

[24] Corvus Energy. All-Electric Car Ferry, . `http://corvusenergy.com/all-electric-car-ferry/` [Accessed: 15-05-2018].

[25] Eno energy. Technical data Eno 82. `http://www.eno-energy.com/fileadmin/downloads/datenblatt/ENO_82_ENG_Datenblatt_AS.pdf` [Accessed: 15-01-2018].

[26] J. Solli T.K. Sandaker E.B.Thorsen E.Sæta, S.O.Simonsen. Technology survey for renewable energy integrated to bridge constructions. *Statens vegvesens rapporter*, 110. URL `https://www.vegvesen.no/_attachment/328171/binary/575808`.

[27] BC Ferries. , . `https://www.bcferries.com/onboard-experiences/fleet/profile-queen_of_new_westminster.html` [Accessed: 15-01-2018].

[28] BC Ferries. BC Ferries Total Vehicle and Passenger Counts by Route for December 2016, 2017. `http://www.bcferries.com/files/AboutBCF/traffic_stats/December_2016_Traffic_Stats.pdf` [Accessed: 04-12-2017].

[29] Lake Champlain Ferries. , . http://ferries.com/vt-ny-ferry-routes/grand-isle-vt-to-plattsburgh-ny/schedules/ [Accessed: 15-01-2018].

[30] Cumberland River Ferry. . https://www.flickr.com [Accessed: 15-01-2018].

[31] European Association for Storage of Energy. Energy Storage Technology Families. http://ease-storage.eu/energy-storage/technologies/ [Accessed: 15-05-2018].

[32] Jafar Rezaei Geerten van de Kaa, Daniel Scholten and Christine Milcaram. The battle between battery and fuel cell powered electric vehicles: A bwm approach. *Energies*, 10(1707):7, 2017. doi: 10.3390/en10111707.

[33] DNV GL. Rules & Guidelines - VI Additional Rules and Guidelines - Chapter 3 Machinery Installations, 2003. http://rules.dnvgl.com/docs/pdf/gl/maritimerules/gl_vi-3-11_e.pdf [Accessed: 15-05-2018].

[34] DNV GL. Rules for Classifications - Ships - Part 6 Additional class notations Chapter 2 Propulsion, power generation and auxiliary systems, 2017. https://rules.dnvgl.com/docs/pdf/dnvgl/ru-ship/2017-01/DNVGL-RU-SHIP-Pt6Ch2.pdf [Accessed: 15-05-2018].

[35] DNV GL. Recommended practice - Safety, operation and performance of gridconnected energy storage systems, 2017. https://rules.dnvgl.com/docs/pdf/dnvgl/rp/2017-09/dnvgl-rp-0043.pdf [Accessed: 15-05-2018].

[36] Tecate Group. Type PBM Data Sheet. http://sunxtender.com/solarbattery.php?id=32 [Accessed: 15-05-2018].

[37] Ioannis Hadjipaschalis, Andreas Poullikkas, and Venizelos Efthimiou. Overview of current and future energy storage technologies for electric power applications. *Renewable and Sustainable Energy Reviews*, 13(6):1513–1522, 2009. doi: https://doi.org/10.1016/j.rser.2008.09.028.

[38] Hans Huisman Henk van den Boom and Frits Mennen. New guidelines for speed/power trials: Level playing field established for imo eedi. *STA-JIP*, 2006.

[39] Lincoln Hexagon. Hydrogen Product Flyer. http://www.hexagonlincoln.com/resources/brochures [Accessed: 15-05-2018].

[40] M. Holder. World's 'first' fully electric ship wins eco award, 14-05-2015. https://www.airqualitynews.com/2015/05/14/worlds-first-fully-electric-ship-wins-eco-award/ [Accessed: 15-01-2018].

[41] Battelle Memorial Institute. Manufacturing cost analysis of 100 and 250 kw fuel cell systems for primary power and combined heat and power applications. 2018. URL https://energy.gov/sites/prod/files/2016/07/f33/fcto_battelle_mfg_cost_analysis_pp_chp_fc_systems.pdf.

[42] Hellas Ships Sales Intl.Co. . https://www.hellasshipsales.com/ [Accessed: 15-01-2018].

[43] J. Louis U. Schabla M. Fischedick K. Arnold A. Pastowski D. Schuwer J. Adolf, C.H. Balzer. Shell hydrogen study: Energy of the future? URL https://www.shell.com/energy-and-innovation/the-energy-future/future-transport/hydrogen/_jcr_

content/par/textimage_1062121309.stream/1496312627865/46fec8302a3871b190fed35fa8c09e449f57bf73bdc35e0c8a34c8c5c53c5986/shell-h2-study-new.pdf.

[44] G.G.J. Mennen J. Holtrop. An approximate power prediction method. *International Shipbuilding Progress*, 29(335):166–170, 1982.

[45] Kokam. Kokam Indoor & Outdoor Rack Data Sheet. http://kokam.com/data/Kokam_Rack_Brochure.pdf [Accessed: 15-05-2018].

[46] Hans Otto Kristensen and Marie Lützen. Prediction of resistance and propulsion power of ships. Technical report, University of Southers Denmark and Technical University of Denmark, 05 2013.

[47] SWZ Maritime. Launch of the Kunta Kinteh. http://www.swzonline.nl/news/8639/video-launch-kunta-kinteh [Accessed: 15-01-2018].

[48] Energieonderzoek Centrum Nederland. National Energy Outlook 2017. https://english.rvo.nl/sites/default/files/2017/11/National%20Energy%20Outlook%202017_Summary.pdf [Accessed: 30-07-2018].

[49] A. Nikiforuk. The Illusion of Progress: China's Electric Cargo Ship To Carry Coal. https://thetyee.ca/Opinion/2017/12/08/Illusion-Of-Progress-Chinas-Electric-Cargo-Ship-To-Carry-Coal/[Accessed: 15-01-2018].

[50] American Bureau of Shipping. Guide for use of supercapacitors in the marine and offshore industries, 2017. https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/288_supercapacitors_2017/Supercapacitors_Guide_e-Dec17.pdf [Accessed: 15-05-2018].

[51] American Bureau of Shipping. Guide for use of lithium batteries in the marine and offshore industries, 2017. https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/275_lithiumbatteries_marineoffshore_2017/Lithium_Batteries_Guide_e-May17.pdf [Accessed: 15-05-2018].

[52] International Maritime Organisation. Sub-Committee on Carriage of Cargoes and Containers (CCC), 4th session 11-15 September 2017 , 2017. http://www.imo.org/en/MediaCentre/MeetingSummaries/CCC/Pages/CCC-4th-session.aspx [Accessed: 15-05-2018].

[53] Panasonic. Batteries catalog for OEM customers. https://industrial.panasonic.com/cdbs/www-data/pdf/ACG4000/ACG4000PE16.pdf [Accessed: 15-05-2018].

[54] T. Powell. Competing in the knowledge economy. http://www.knowledgevaluechain.com/home/ [Accessed: 15-01-2018].

[55] G. Roe. Boeing Flywheel Energy Storage Technology. https://www.uaf.edu/files/acep/BoeingFlywheelOverview_06_20_2012.pdf [Accessed: 15-05-2018].

[56] Damen Shipyards. https://products.damen.com/en/ranges/road-ferry/drfe-8117 [Accessed: 15-01-2018].

[57] Siemens. First electrical car ferry in the world in operation in Norway now, 19-0.5-2015. https://www.siemens.com/press//pool/de/pressemitteilungen/2015/processindustries-drives/PR2015050200PDEN.pdf [Accessed: 15-01-2018].

[58] Sina. China to build the world's first "All-electric ship" with only 2 hours to recharge. http://sina.com.hk/news/article/20171206/5/45/2/%E4%B8%AD%E5%9C%8B%E6%89%93%E9%80%A0%E5%85%A8%E7%90%83%E9%A6%96%E8%89%98%E5%85%A8%E9%9B%BB%E5%8B%95%E8%B2%A8%E8%88%B9-%E5%8F%AA%E9%9C%80%E5%85%85%E9%9B%BB2%E5%B0%8F%E6%99%82-8212980.html [Accessed: 15-01-2018].

[59] P.Hertzke P. Schaufuss Nicholas Laverty Nicolaas Kramer S.M. Knupfer, R. Hensley. Electrifying insights: How automakers can drive electrified vehicle sales and profitability. Technical report, McKinsey & Company, 01 2017.

[60] Norway Statistics. Norwegian Population Statistics 2016, 2017. https://www.ssb.no/en/befolkning/statistikker/folkemengde/aar-berekna [Accessed: 04-12-2017].

[61] Norway Statistics. Norwegian Public Transport Statistics 2016, 2017. https://www.ssb.no/en/transport-og-reiseliv/statistikker/kolltrans/aar [Accessed: 04-12-2017].

[62] Statnett. Long-Term Market Analysis - The Nordic Region and Europe 2016–2040. http://www.statnett.no/Documents/Nyheter_og_media/Nyhetsarkiv/2016/Long-term%20Market%20Analysis%20The%20Nordic%20Region%20and%20Europe%202016-2040.pdf [Accessed: 30-07-2018].

[63] Velkess. . http://www.velkess.com/flywheel.html [Accessed: 15-05-2018].

[64] Bureau Veritas. Guidelines for Fuel Cell Systems Onboard Commercial Ships, 2009. https://www.veristar.com/portal/veristarinfo/files/sites/veristarinfo/web%20contents/bv-content/generalinfo/giRulesRegulations/bvRules/rulenotes/documents/4706.18.547NI%20_2009_04.pdf [Accessed: 15-05-2018].

[65] Det Norske Veritas. Ships / High Speed, Light Craft and Naval Surface Craft - Part 6 Chapter 23, 2008. https://rules.dnvgl.com/docs/pdf/DNV/rulesship/2011-07/ts623.pdf [Accessed: 15-05-2018].

[66] Sun Xtender. Sun Xtender Solar Battery. http://sunxtender.com/solarbattery.php?id=32 [Accessed: 15-05-2018].