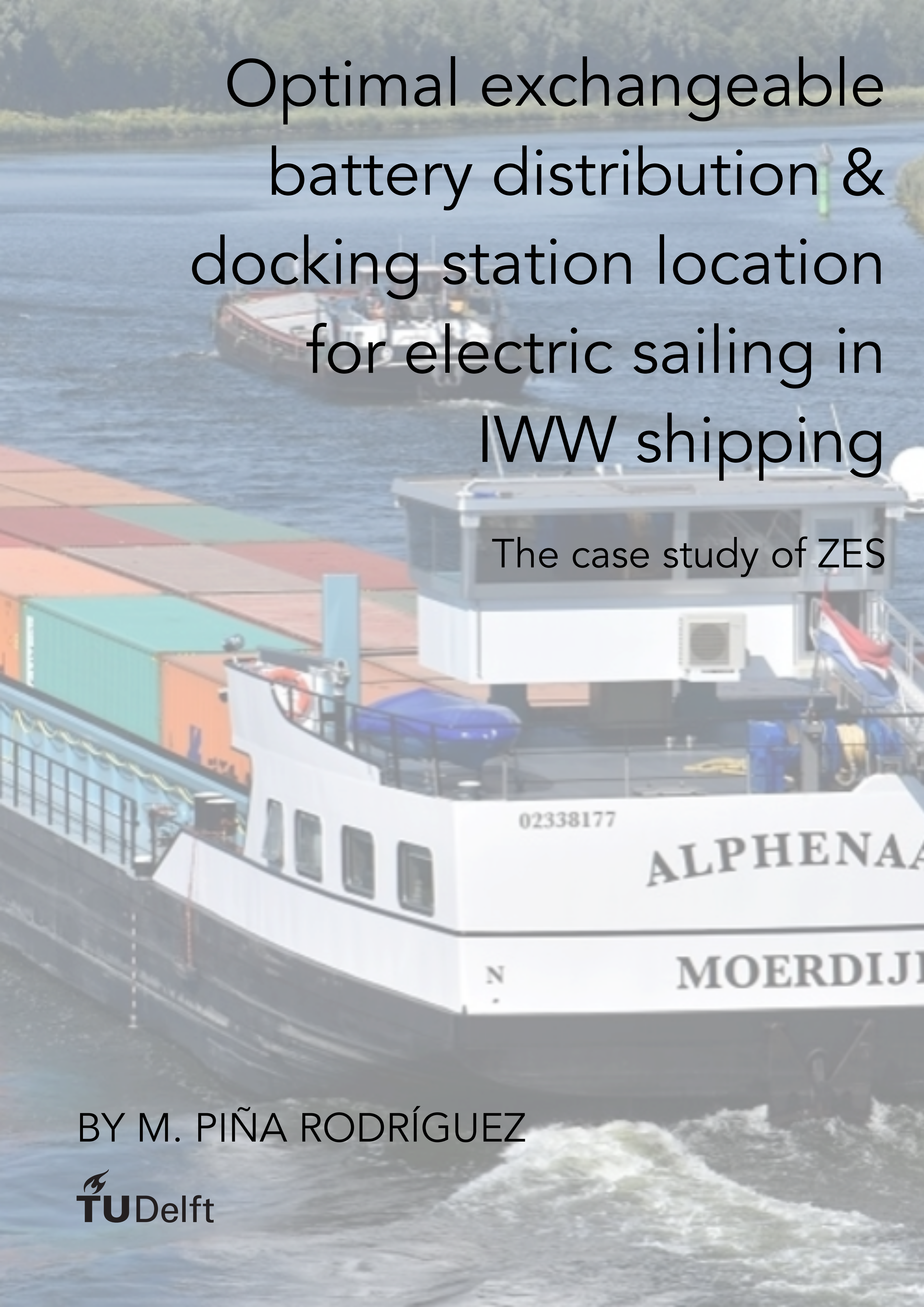
Optimal exchangeable battery distribution & docking station location for electric sailing in IWW shipping

The case study of ZES

BY M. PIÑA RODRÍGUEZ

TUDelft



Optimal exchangeable battery distribution and docking station location for electric sailing in IWW shipping:

The case study of ZES

by

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to obtain the degree of
Master of Science Transport, Infrastructure and Logistics
at the Delft University of Technology,
to be defended publicly on the 23rd of August, 2021.

Student number:	5077613	
Project duration:	February 15, 2021 – August 23, 2021	
Thesis committee:	Prof. dr. ir. L.A. Tavasszy,	TU Delft chair
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Preface

This thesis represents the outcome of over six months of hard work and the end of my Master of Science in Transport, Infrastructure and Logistics at Delft University of Technology. My personal interests in inland waterways (IWW) transportation, optimisation and sustainability were perfectly reflected in the topic of this thesis and gained my interest from day one.

Electrification of IWW by using an exchangeable battery system is a greenfield in research. Many challenges need to be overcome for this concept to be successfully implemented, some of which were addressed in this research. Sustainable transportation is of great interest for society as a whole, and therefore research in this direction is of extreme importance.

Firstly, I would like to thank Lori for helping me find a thesis research topic that fulfilled my academic interest, as well as, my desire to work at a company. Moreover, I want to thank my supervisors Bart and Mark for their support during the course of this research. Bart's comments and feedback on the academic side of the research were extremely useful and helped me to write a well-structured and concise report. Mark's guidance on the model development was of undoubtful value and, without it, the outcomes would not have been the same.

Secondly, I would like to express my gratitude to everyone at ZES who despite being extremely busy always found the time to answer my questions and helped me gain insights into the system which were crucial elements for my research. In particular, I want to thank my weekly supervisor Koen for believing in my work from the beginning. His support and enthusiasm were fundamental to fulfil this research. Moreover, I want to thank Nynke, whose encouraging conversations were key to overcome the drawbacks during the research and made working from home much easier.

Finally, I want to thank my family and friends in Uruguay and my friends in The Netherlands for their unconditional support and for motivating me throughout the course of this research and my studies at the TU Delft.

I really hope this research can work as an initial step towards IWW shipping electrification and that can inspire many others to research innovative concepts to make it fully achievable in the near future.

Mariana Piña Rodríguez
Delft, August 2021

Summary

The Netherlands has recently committed to very challenging environmental targets regarding transportation. One of which is to become carbon-neutral by 2050. Nowadays, inland waterways (IWW) shipping accounts 5% of the total transportation emissions. This urges the need to achieve long-term full decarbonisation of IWW transport. Many different measures can be applied for this, however, to successfully create an impact on emissions, zero-emission energy concepts (ZEECs) need to be developed.

This research focuses on one of these concepts which is the electrification of IWW transport using exchangeable batteries. This ZEEC was designed by the company ZES (Zero Emission Services), and it consists of three main components: batteries, docking stations and vessels. The exchangeable batteries are designed to fit in 20ft containers and are charged at docking stations. Then, the charged batteries are used to power the vessels. The batteries do not belong to a specific vessel but to the whole system. With this, batteries can power a vessel and once the vessel arrives at a terminal with a docking station it can leave the batteries to charge. The vessel can load another battery and sail, saving time. The batteries that were left at the terminal can be used by another vessel or for other businesses. The concept of sharing batteries among vessels results in the need for fewer batteries per vessel as vessel demand increases. To this end, the usage of fewer batteries becomes an advantage of this system as the battery cost is a major constraint in the system.

The implementation of such a system does not come without several logistic challenges. The problem becomes more complex as the three main components of the system interact. So far, no research has been done in this specific domain, and an exchangeable batteries system was not implemented before in IWW shipping.

The aim of this research is, therefore, to develop an optimisation model to help assess the implementation of an exchangeable batteries system for IWW shipping. For this, the docking station locations from a set of terminals, and the number of batteries and their deployment in the network in order to fulfil the vessels' power requirements, need to be determined. The battery movement through the network needs to match the vessels' routes. All the input parameters (vessels routes, power requirements and terminal locations) are precisely known. Also, the problem objective function and constraints can be formulated as linear equations. Therefore, to meet the requirements of the system, a time-discrete mixed-integer linear programming (MILP) optimisation model with deterministic inputs is developed. Formulating problems as MILP has the advantage that optimal solutions are found. The network used as input for the model is simplified so as to be easily scalable and flexible to be adapted to other networks.

The model is first applied to a set of fictitious sailing profiles to show the optimisation potential, and then it is applied to the study case of ZES. Though fictitious, the sailing profiles were designed to remain as realistic as possible. Given the computational time constraints, the model runs were limited to a maximum of four vessels and 24 time-steps. The real-life sailing profiles had to be adjusted and simplified so as to fit this constraint.

The obtained results showed the optimisation opportunities and possible synergies that can be achieved when vessels share the batteries and charging infrastructure, for both the fictitious and real case study sailing profiles. It is not trivial to determine beforehand the optimal result for different inputs. It is therefore needed to assess various scenarios. Four scenarios were designed and analysed for both cases (fictitious and real profiles). Three key performance indicators (KPIs), namely, batteries per vessel, docking stations (DS) per vessel and capital expenses (Capex) per vessel, were defined to determine the optimisation potential of the model. The main outcomes obtained are as follows:

- Scenario 1: demand increase
  A demand increase with the same sailing profile showed the highest battery per vessel reductions. When combining routes, the results become more unpredictable and they largely depend on which terminals are shared by the vessels routes, as these are the battery exchange points.
- Scenario 2: battery capacity variations
  Battery capacity variations did not show great improvements for the need of batteries per vessel. Only a small improvement in DS per vessel for batteries of 3.000kW was seen. Despite this, larger batteries are also more expensive, then the trade-off of less DS is not compensated, leading to larger Capex per vessel.
- Scenario 3: docking stations design
  The combination of DS designs did not prove to have better results than the base case, regarding the above-mentioned KPIs. Only smaller designs for the case study proved to have a reduction in Capex per vessel.

- Scenario 4: variation in docking spots on vessels
  Adding docking spots on board of the vessels led to less DS. However, further analysis on the shipper's costs side is needed to determine if the gain is relevant for all stakeholders.

In general, better results in terms of batteries reduction per vessel were found with the fictitious sailing profiles than with the real case study ones. This can be expected as the former were built to show most of the model potential. In real life, it can be expected to have fewer synergies.

This research can be considered as the first step to investigate the implementation of this promising zero-emission concept, as it contributes to help assisting the strategic decision of the system implementation from a logistics perspective. Although the model outputs do not directly answer whether to implement the ZEEC, they give useful information to assist this by analysing different scenarios with different input parameters.

Several assumptions and simplifications were made when developing the model which limit this research. First, the model aims at minimising the investment costs for the batteries and docking stations, leaving outside the operational costs and other costs like vessel's retrofit. Moreover, the battery capacity was modelled in a simplistic way. A fixed number of maximum available battery capacity was used per battery and a linear charge/ discharge was considered. In a real-life setting, the available battery capacity can be lower than the one modelled. Apart from this, the vessels' power consumptions were assumed fixed per time step using an average consumption. This is also not realistic, as weather conditions, waves, wind, among other factors modify the power requirement from the vessel.

To conclude, it is recommended to perform further research in terms of model improvement (optimisation of running times), incorporation of operational costs and shipper's costs (vessel retrofit and loss of revenue for carrying batteries instead of cargo), incorporation of vessel speed, model non-linear batteries charge/ discharge, model charge regimes and battery ageing. Another recommendation regards the possible use of vessels to reallocate batteries in the system and adding possible extra stops to the vessels' routes to exchange batteries.

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List of Abbreviations

AC	Alternating Current
Capex	Capital expenses
DC	Direct Current
DS	Docking Station
EV	Electric Vehicle
FCR	Frequency Containment Reserves
HFO	Heavy Fuel Oil
IWW	Inland Waterways
KPI	Key Performance Indicator
MEC	Modular Energy Concept
MILP	Multi integer linear programming
Opex	Operational expenses
PoC	Proof of Concept
TEU	Twenty Equivalent Unit
ZEEC	Zero-Emission Energy Concept
ZES	Zero Emission Services

Contents

1 Introduction

1.1 Background

Today, the Dutch transport sector is collectively responsible for 21% of all CO_2 emissions in The Netherlands. Within the transport sector, inland navigation makes up 5% of these emissions. Through The Green Deal Zeevaart, Binnenvaart en Havens (Maritime, Inland Shipping and Ports) The Netherlands has committed to very challenging environmental targets to reduce CO_2 emissions. Which includes a reduction of 40% of CO_2 emissions by 2030 and to become climate-neutral by 2050. [1]

In order to achieve these long-term challenging targets, a combination of policies with new future-proof energy concepts needs to be implemented. [38] This leads to the development of new Zero-Emission Energy Concepts (ZEECs). Several projects in this direction have been promoted by the Dutch government in the last few years.

One of them is the Modular Energy Concept (MEC) powered by Heineken and developed by a group of very important stakeholders (Port of Rotterdam, Engie, ING and Wärtsilä) who set up a new start-up company, ZES, to implement this concept. This ZEEC consists of lithium-ion interchangeable batteries arranged in 20 feet containers which can provide energy to inland waterways vessels. The batteries are charged at docking stations and can be used for other purposes apart from powering inland barges, such as providing grid stabilisation and energy market applications, like FCR (Frequency Containment Reserve). [20]

The implementation of exchangeable batteries at swapping stations or docking stations has the advantage of mitigating the drawback of the long battery charging times, as it allows the replacement of a depleted battery with a previously full-charged one at a significantly less time. [4] Apart from this, the batteries, while idle at the docking stations, can be used to provide stability to the electric grid (FCR). [44]

1.2 Problem Definition

The incorporation of the exchangeable battery concept for electric vehicles is not entirely new, and several authors have studied the implications of using such a concept in already existing systems like electric buses. Most of the research is focused on the optimisation of the number and location of the battery swap stations [53][4], optimisation of the electric vehicle routing considering battery driving range limitations and battery swapping stations limitations [53][47][26] and vehicle scheduling and battery reservation strategies. [3][27][4]

As far as this research concerns, the implementation of interchangeable batteries in the field of inland waterways has only been researched by I.M.W. Hilverda in his master thesis. [15] In it the author investigated the needed decentralised battery network for the electric waterbus sailing in the Port of Rotterdam.

So far, ZES is the only company working on implementing the interchangeable battery concept on a large scale. They aim to make all inland vessels be able to sail electric within The Netherlands and beyond. This implies the use of batteries on large vessels with high power demands and a docking station network that allows the system to work properly.

ZES has developed a Proof of Concept (PoC) for the first ship sailing the Alpherium-Moerdijk corridor, which took place during this thesis. For this PoC, three batteries (ZES-packs) were used, one ship (the Alphenaar) was retrofitted and one docking station was constructed at Alphen aan den Rijn. [49] The logistics design for the PoC is pretty straightforward, including the ship's schedule, battery distribution and the decision of the location of the docking station. Nevertheless, for the new ZEEC to effectively cause an impact in CO_2 emissions a large scale implementation is needed [39] the scaling-up scenarios to more corridors and more ships is, however, not that clear.

Despite some similarities that can be drawn from already studied problems there are some peculiarities of the implementation of the new ZEEC in inland waterways which have not yet been researched. For example, the extremely high costs of the batteries do not allow to have a large stock of batteries to ensure a certain service level like proposed by [53]. On the contrary, their optimisation is a key aspect for the new energy concept to be economically feasible and, hence, successful. Moreover, assuming a fully-charged battery is available at all times to be loaded on a vessel [15] can lead to the need for extra batteries. Therefore, the battery level should be monitored to optimise the charging times and the number of needed batteries. Apart from this, vessels' routes and schedules are fixed making it not realistic for vessels to choose the docking station at where to load/unload the batteries according to the possible queue as studied by [3] and [47]. The problem needs to be seen from the battery side perspective assuming the vessel's routes as given.

Therefore, the definition of a plausible scale-up scenario from the Proof of Concept that is logistically and economically feasible is needed to ensure a successful implementation of the new ZEEC in inland waterways.

In order for a ZEEC to operate successfully a fleet of exchangeable batteries needs to be optimally deployed in the network. Moreover, docking stations need to be placed to guarantee that the batteries can be charged to provide the needed energy to the vessels. At each time step, the batteries can be either providing logistic services by powering vessels with electric energy or being idle at docking stations waiting to be placed on a vessel. Battery movement throughout the network (from one terminal to another terminal) is restricted to the vessels routes and vessels availability.

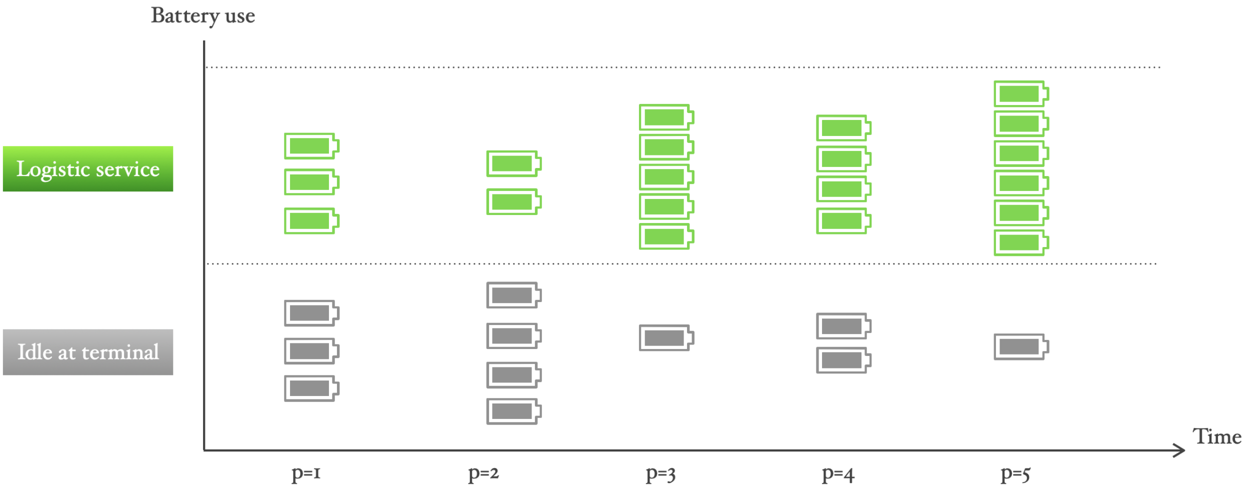


Figure 1: Example of battery fleet deployment per usage.

When providing energy to vessels a revenue is generated. Therefore, it is needed to determine the optimal allocation of the fleet of batteries, to have enough batteries to guarantee the logistic service to vessels at all times. This fleet can not be too large, as it will lead to many idle batteries that do not bring income to the system.

This leads to the problem statement that this research aims to solve:

Define the optimal exchangeable battery distribution and docking station locations for electric sailing in IWW shipping, to help assess the scalability of the system from one single corridor to a network.

This research will look into this problem and will develop an optimisation model that includes all the elements of the new ZEEC, its boundaries and its interrelations. Through different scenario analyses, the output of this research will give answers to questions such as how many batteries and docking stations are needed, where should the docking stations be located and how should the batteries be distributed in the network to guarantee the logistic service to the vessels demand.

1.3 Objective & Research Question

The objective of this research is to determine the optimal logistics design for the battery distribution and docking station location of the new ZEEC to achieve a first scale-up phase from one single corridor (Proof of Concept) to a network of four corridors (scale-up phase 1) for different scenarios.

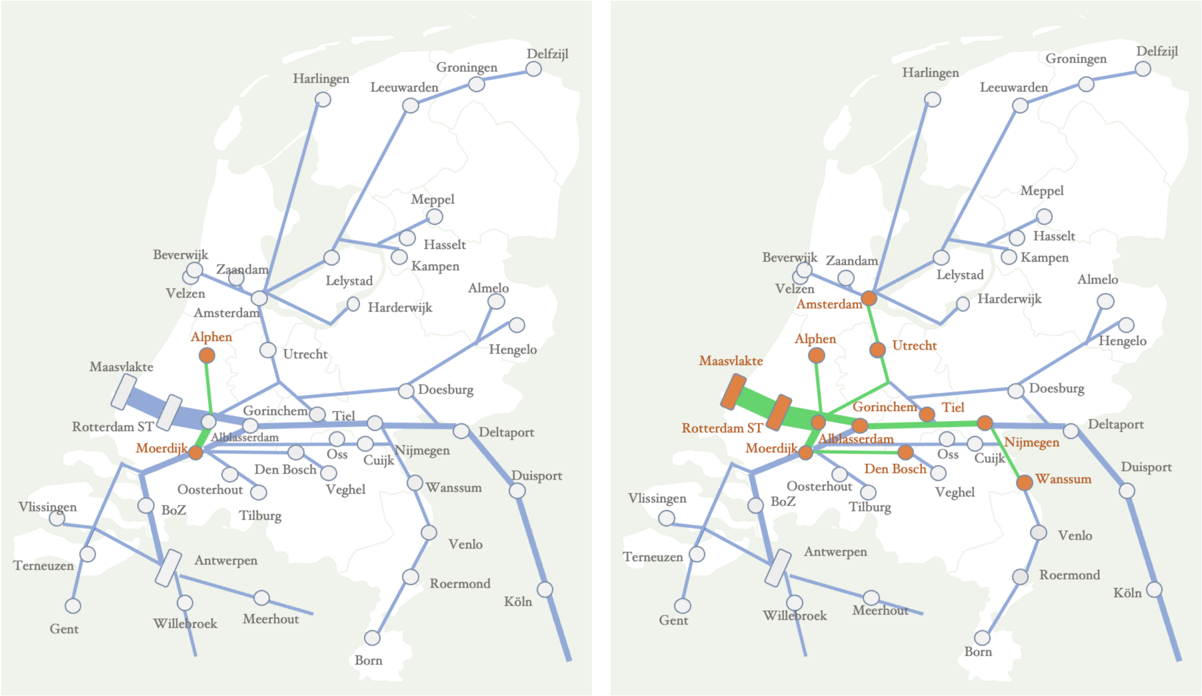


Figure 2: Proof of Concept (left) and scale-up phase 1 (right). Source: ZES internal document [50]

The logistics design should include:

- The needed number of batteries;
- The needed number and location of the docking stations;
- The battery distribution plan, specifying where and when batteries should be charged to ensure their availability with the required charge level at the right place and time.

The aim is to minimise the total costs and guarantee a minimum service level, given an identified potential vessel demand (including the number of ships, their routes, the loading & unloading terminals and the power requirements), and a set of possible pre-identified docking station locations determined by the company. The logistics design will be constrained to the vessel autonomy reduction (compared to diesel fuel), and the availability of docking places at the docking stations and vessels.

To achieve this objective the following main research question is defined:

How can exchangeable batteries distribution and docking stations locations be optimised to guarantee electric sailing for a certain demand of IWW vessels?

To answer the main research question a set of sub-questions are stated:

- Which are the main components involved in the new ZEEC? What are their attributes, boundaries and interrelations?
- To what extent can the existing developed models to overcome the logistic challenges of transport electrification be applied to IWW shipping?
- How can the components and attributes of the new ZEEC be incorporated in an optimisation model?
- What would be the needed number of batteries and docking stations, and the optimal battery distribution, in order to minimise total costs, considering different input scenarios?

1.4 Research Methodology

The methodology used to answer the abovementioned research questions is summarised in the framework below which is adapted from [35].

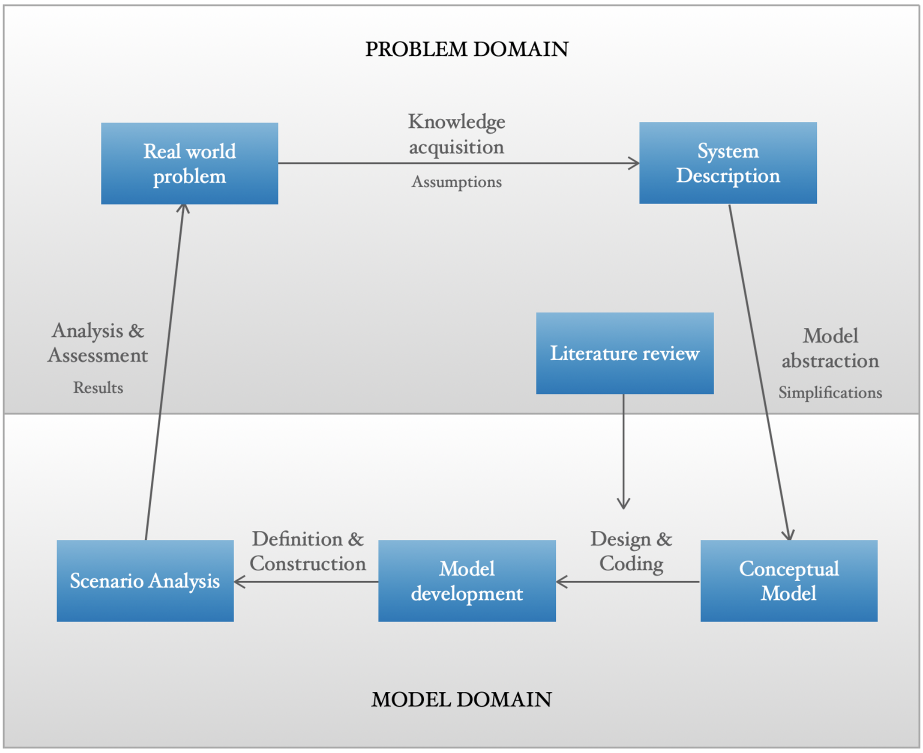


Figure 3: Research framework. Adapted from [35]

This framework will structure the research, while also help answer the sub research questions. Starting with the defined problem in 1.2, the objective of this research is to find the optimal number of batteries and docking stations with which build a logistics design that should include the battery distribution and allocation plan to successfully provide the vessels with electric energy.

In order to achieve this objective the first research phase that needs to be fulfilled is the system description. This includes describing the problem, as well as, those elements from the real world that relate to the problem. [35] This phase of the research involves knowledge acquisition and making assumptions when a knowledge gap needs to be filled in. Moreover, a general understanding of the system proposed by ZES is required. In particular, understanding the attributes and boundaries of the three main components of the system, namely batteries, docking stations and vessels.

The outputs of this first phase of the research enable the determination of a set of validated attributes and parameters needed to model the system components (i.e. vessels, docking stations, charging capacities and battery types) and their corresponding boundaries or limitations and interrelations.

Following the system description, and using simplifications, those parts of it that are going to be modelled need to be described in a conceptual model. The main components of the conceptual model are the model objectives, inputs, outputs, assumptions and simplifications. [35] To do this, firstly, a literature review has to be performed to understand the current state of the art of the modelling of transport electrification and to determine to what extent these models can be applied to IWW shipping. In particular what opportunities and limitations these models have.

After the conceptual model is done, the model needs to be designed and the computational model needs to be coded. The model to be developed in this research is an optimisation model that looks at minimising the total investment cost of batteries and docking stations. The problem is seen from the battery perspective, hence modelling the battery location, battery charge level at every time step and docking station location, to guarantee battery availability at the right place and time assuming fixed vessels routes.

Once the model is developed and verified, the model will be validated with the PoC of the study case of ZES. After that, it will be implemented to a set of experimental scenarios to prove the optimisation opportunities that can be achieved. Then, some of the scenarios will also be implemented in the study case to see to what extent optimisation can be done with real-life data. To build the scenarios to analyse, the framework for scenario development proposed by [31] is used. The authors state four phases for scenario analysis, starting by the scenario definition, followed by scenario construction, scenario analysis and finally, scenario assessment.

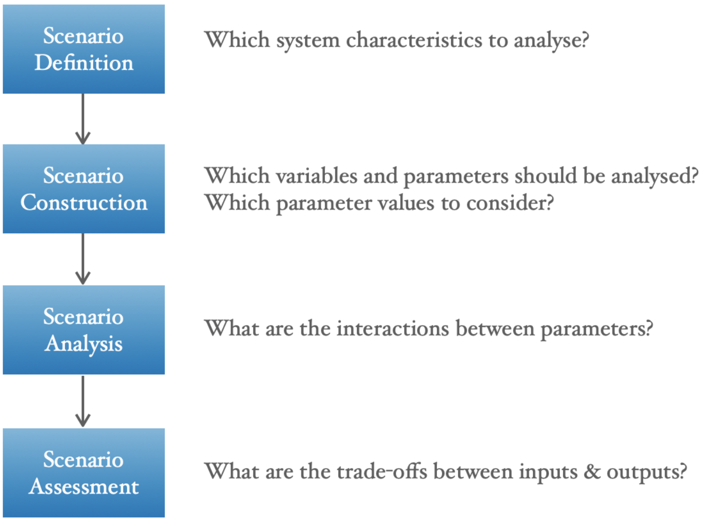


Figure 4: Scenario development framework. Adapted from [31]

For the scenario definition, the specific characteristics of the scenarios that are of interest need to be identified. Then, the scenarios need to be constructed, determining the variables and parameters to consider and the input values. After that, the scenarios are run in the model and the obtained results are analysed. The main objective of this phase is to identify the consequences of the interactions among the modelled components and attributes. [31] Finally, the different scenarios are assessed in order to identify the trade-offs between the inputs. For each scenario assessed the outputs are the number and location of the docking stations and the number of batteries required.

1.5 Contribution to science & society

This research can be considered of relevance from a scientific perspective, as it looks to solve the complexity of scaling up a logistics design from one single corridor to a network. It also looks into the interaction of the transportation and energy systems, in a sector that has not been thoroughly researched before: inland shipping.

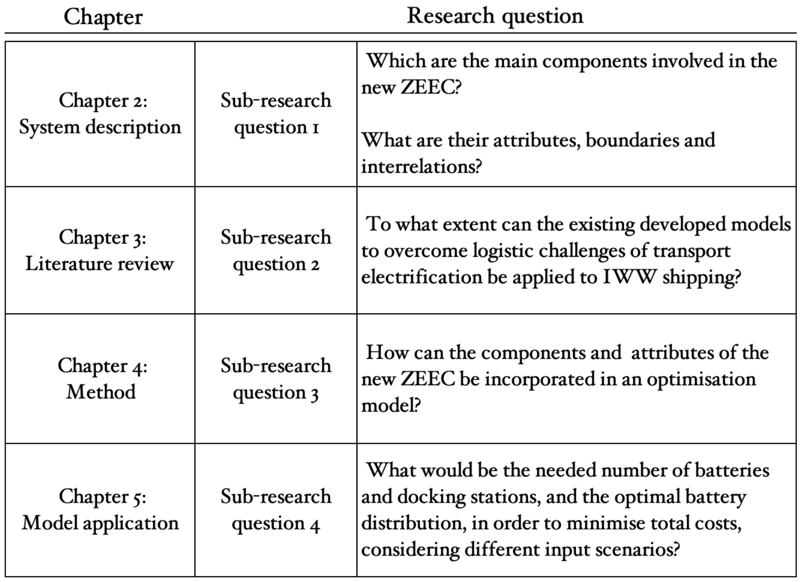
From a societal perspective, this research is of relevance as it aims to facilitate the implementation of the first scale-up phase of a new energy system in inland navigation that will lead to a reduction of CO_2 emissions, PM, noise, among others, which is of great interest for the society as a whole. Moreover, the outputs of this research can be of interest as they will help The Netherlands to achieve the national targets for inland waterway transportation (Green Deal Binnenvaart) in particular and of the Paris Agreement in general.

This research will leave the door open for further research on several topics regarding inclusion or more technical aspects like non-linear charging/ discharging of the batteries and battery ageing, as well as, research on policies or regulations that need to be implemented to decrease the financial gap of the large-scale implementation of the system and the incorporation of other business to the model.

1.6 Thesis Structure

In Chapter 2 the sub-research question 1 is answered by describing the system of exchangeable batteries and docking stations to electrify IWW shipping main components, their attributes and interrelations. In Chapter 3 a literature review is conducted to answer sub-research question 2. For this the state of the art of existing models use to address the logistic challenges of transport electrification and how can these be implemented in the particular case of IWW shipping will be determined. Chapter 4 aims at answering sub-research question 3 by stating the method to analyse the implementation of exchangeable batteries and docking stations to electrify IWW shipping is addressed. Firstly, a conceptual model will be stated and then the model will be developed. In Chapter 5 sub-research question 4 is answered by analysing the results of the application of the developed model to numerical experiments and the case study of ZES. The research finalises with a chapter of conclusions and recommendations.

In the following table, the structure of the thesis and the sub-research question answered in each sub-chapter is shown.



Chapter	Research question	
Chapter 2: System description	Sub-research question 1	Which are the main components involved in the new ZEEC? What are their attributes, boundaries and interrelations?
Chapter 3: Literature review	Sub-research question 2	To what extent can the existing developed models to overcome logistic challenges of transport electrification be applied to IWW shipping?
Chapter 4: Method	Sub-research question 3	How can the components and attributes of the new ZEEC be incorporated in an optimisation model?
Chapter 5: Model application	Sub-research question 4	What would be the needed number of batteries and docking stations, and the optimal battery distribution, in order to minimise total costs, considering different input scenarios?

Figure 5: Thesis structure

2 System description for the implementation of exchangeable batteries and docking stations to electrify IWW shipping

The inland waterway shipping in Northwest Europe is a traditional sector, which has been largely incentivised by the Mannheim Agreement. This agreement aimed to increase the use of IWW for transportation. One of the articles of this agreement states there will not be taxation on diesel fuels. This helped the sector grow in the past years, but also to lag behind in incentives towards a greener and more sustainable energy sources. Summed to the absence of strict regulations on environmental impact, the propulsion technologies for shipping have not kept the pace of road transport in terms of reducing pollution. [42] Now that the Dutch government has agreed upon specific targets for emission reductions for the transportation sector, a change in the maritime power generation is needed. The use of electricity as an alternative to combustion fuels is one direction to achieve this.

Electrification of IWW transport proposes several opportunities as well as challenges. This chapter is divided into three parts, firstly an overview of the different options to electrify IWW shipping, namely hybridisation, fuel cells and batteries, is given and their advantages and disadvantages stated. Then, the focus will be made on the electrification of IWW with batteries, which is the scope of this research. The second subchapter will give a general description of the application of exchangeable batteries to power IWW vessels. Followed by a subchapter describing the system components and their attributes and interrelations. This chapter finalises with the description of how the system will be implemented.

2.1 Electrification options for IWW shipping

Electrification can be used to produce energy to power berthing ships (cold ironing) and to charge batteries for full-electric or hybrid ships. The power system of full-electric ships is usually based on batteries charged from the onshore grid while at berth, [38] though fuel cells could also be implemented. [45]

2.1.1 Hybridisation

In hybrid ships, either batteries or fuel cells can be used. These batteries do not bunker electricity from shore but use any excess power generated by the ship's engines and store it to be used for any purpose. [24] Several degrees of hybridisation using batteries can be realised between a full-electric system and a traditional system. Hybrid solutions are believed to have significant potential for energy efficiency and are suitable for applications on different types of ships. [38] Moreover, they require moderate infrastructure adaptation for its implementation. [5] However, there is a limit to the emission reduction that can be obtained with hybridisation.

Hybridisation by use of fuel cells or batteries is considered an abatement option in the category of renewable fuels and can be used to deliver the auxiliary power supply of vessels. [28] An advantage of this is that there is no reduction in the vessels' autonomy, as the vessel uses the fuel engine for the main power requirements. Another advantages of hybrid systems is that the vessels can run electric when entering in the harbours to berth, as the maneuvering happens usually at low speed. Therefore, propulsion power can be provided exclusively with the batteries for this, saving fuel and reducing emissions and noise levels close to the shore. [9]

A way of improving the hybridisation benefits regarding emissions is to combine the battery-electric systems with biofuels, and in this way replace fossil fuels. [6] Despite not being completely emission free, hybrid propulsion allows more flexible designs that enable vessels' configurations which balance financial constraints and environmental considerations [16] On the one hand, hybrid marine engines offer fuel savings, which also lead to emission reductions. On the other hand, they also have relatively fast payback times, which is of high interest for shippers. [32]

2.1.2 Fuel cells

Fuel cells can efficiently produce electricity by using the chemical energy of hydrogen or another fuel. [38] In conventional diesel generators, chemical energy is converted into electricity via thermal and mechanical energy. Whereas in fuel cells the chemical energy is directly converted into electricity. [42] Fuel cells can replace the traditional auxiliary engines partly or completely. [28] A diverse variaty of fuels can be used in fuel cells. Hydrogen is an interesting fuel option since the combustion outputs only water and energy, and hence no CO_2.

[28] Moreover, the refueling times are rapid. In buses and trucks hydrogen fuel cells have achieved refueling times very similar to diesel refueling. [7]

However, there are several challenges to overcome for its use on a large scale. Firstly, the use of hydrogen still requires research and development, particularly to make it commercially viable. So far, there is no standardised design and fuelling procedures for hydrogen-powered ships and their bunkering infrastructure. [28] Furthermore, remaining safety design issues with regards to the volatility of the fuel need to be solved for a safe storage and transportation. [16]

From a volumetric density perspective, a fuel cell system usually takes up more space than conventional diesel generators, reducing the vessels' cargo capacity. One possible solution is the low-temperature fuel cells using liquefied hydrogen. However, this system is only feasible to a limited refuelling interval, [34] therefore, decreasing the vessel autonomy. For a wide refuelling cycle, the total system size with sufficient hydrogen storage could result in a significantly larger volume. [34]

Another issue regards the storage of the hydrogen. It can be compressed, for which it requires very high-pressure tanks, that would lead to considerable changes to storage and refuelling systems, both onboard and in bunkers. [17]. Moreover, additional infrastructure to maintain the pressure is needed, which involves complex structural considerations. [33] Hydrogen can also be stored as a liquid at very low temperatures (below -240°C). This would require significant energy to maintain this temperature, increasing the costs. [33]

Regarding the costs on the shippers side, the low energy density requires very large fuel tanks, which increases the capital cost and reduces cargo space, leading to revenue losses [16] Fuel-cell powered ships are currently much more expensive than comparable diesel ships. For newbuilds, a fuel-cell powered ship can cost from 1,5 to 3,5 more than a comparable diesel vessel, and operation costs can be up to eight times higher. [38]

Finally, if relevant volumes of hydrogen are to be used on a large scale, it would be essential to ensure that the production processes are based on renewable electricity generation. Otherwise, no improvement in CO_2 emissions compared to conventional HFO could be guaranteed. [16][17] Most of the industrial hydrogen is obtained from steam-methane reforming, oil and coal gasification, which are methods that generate greenhouse gases. Only a very small percentage of hydrogen supply is produced via electrolysis, which is a clean method regarding emissions. However, it requires large quantities of energy. Another way of producing sustainable hydrogen is via biological processes (biohydrogen). Although this method is an environmentally friendly and less energy intensive alternative, it is an expensive procedure and has safety issues regarding the H_2 (hydrogen) and C_2 (dicarbon) explosive combination. [14]

2.1.3 Batteries

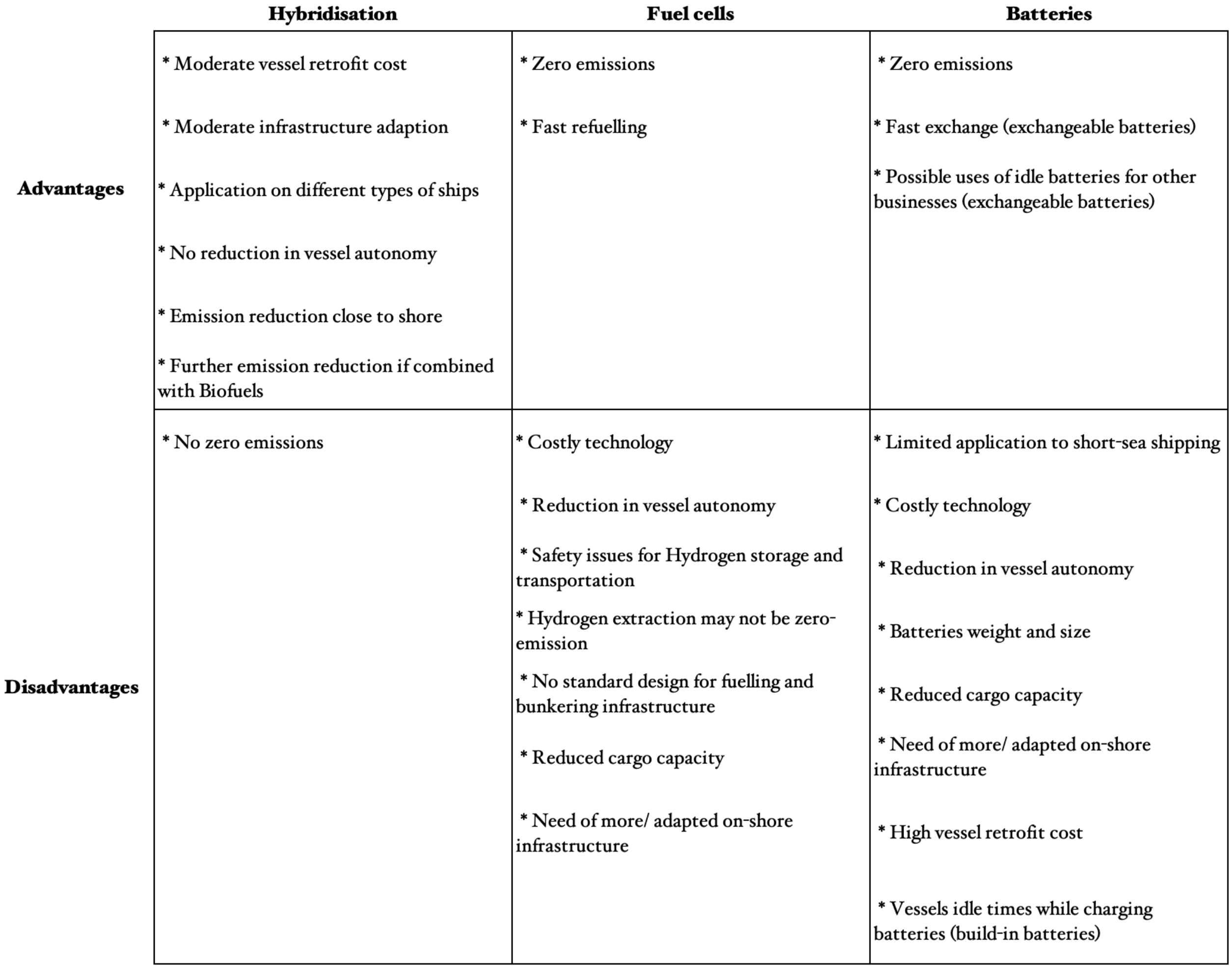
The use of batteries for fully electric sailing is another way of obtaining zero emissions, however their use has also several barriers. Firstly, the energy storage systems remain a relatively costly technology. Electric motors are assumed to be cheaper than conventional engines, but the cost of the needed batteries per unit of energy and their accommodation on ships makes the implementation of these engines an expensive option. [16] Although, rapidly falling costs of battery technology for electric vehicles suggest that the technology might become a more viable and readily available option also for other transport sectors such as shipping [16], the technology of current batteries has not sufficient energy density to be considered for applications other than short routes at modest speeds. [11] This is a barrier also stated by [38], who stated that batteries capacity reduce vessel's autonomy and require more charging places compared to diesel fuel. The authors also state that the full-electric operation seems currently relevant only for the short-sea shipping segment where the shorter distances can make electric propulsion systems more efficient than traditional ones. Apart from this, the integration of large battery spaces represents a challenge, as ships designs are constrained either by weight or volume, limiting the maximum size and weight of the batteries. [10] The needed space for batteries also causes a reduction in the carrying capacity of the vessel, which indirectly leads to a loss of revenue for shippers, as they carry batteries instead of cargo.

Regarding the costs of implementing full-electric vessels, it does not only link to the batteries. The investments in essential shore-based charging facilities are far from negligible. The electrification of modern ships brings a number of challenges concerning the need for more shore-based facilities for battery charging. [38] Fully electric ships depend on charging infrastructure in harbours, which requires access to the electricity grid, limiting the possible locations for the charging stations or increasing the costs for connections. [5] Moreover, in the case of existing vessels, high retrofit costs to be able to sail electrically have also to be considered.

A possible way of mitigating some of the issues regarding batteries implementation in IWW shipping is by using exchangeable batteries. These batteries require another type of charging infrastructures that can provide the energy demand for the vessels, such as the battery swapping station (BSS) [48] With exchangeable batteries, vessels do not need to wait to charge their build-in batteries, but simply arrive at a battery swapping station, also called docking station (DS), and swap the depleted battery for a fully charged one. The main obvious advantage of this system is the reduction in the time the vessel is idle while charging. Moreover, compared with the traditional charging stations, the DS operators can flexibly arrange battery charging and discharging plans, and in this way participate in the power market making extra profit. [48] Also, the exchangeable battery concept can reduce the cost for shippers, as they do not own the batteries, but only pay for their use. [37]

In the table below the main advantages and disadvantages of each electrification system are stated.

Table 1: Electric sailing options advantages and disadvantages. Sources: [38][5][24][28][7][16][34][33][17][14][11][10][5][48]



	Hybridisation	**Fuel cells**	**Batteries**
Advantages	* Moderate vessel retrofit cost * Moderate infrastructure adaption * Application on different types of ships * No reduction in vessel autonomy * Emission reduction close to shore * Further emission reduction if combined with Biofuels	* Zero emissions * Fast refuelling	* Zero emissions * Fast exchange (exchangeable batteries) * Possible uses of idle batteries for other businesses (exchangeable batteries)
Disadvantages	* No zero emissions	* Costly technology * Reduction in vessel autonomy * Safety issues for Hydrogen storage and transportation * Hydrogen extraction may not be zero-emission * No standard design for fuelling and bunkering infrastructure * Reduced cargo capacity * Need of more/ adapted on-shore infrastructure	* Limited application to short-sea shipping * Costly technology * Reduction in vessel autonomy * Batteries weight and size * Reduced cargo capacity * Need of more/ adapted on-shore infrastructure * High vessel retrofit cost * Vessels idle times while charging batteries (build-in batteries)

As mentioned before, this research is based on the use of exchangeable batteries to electrify IWW shipping. In the following subchapters, this system will be further explained.

2.2 General description of exchangeable batteries system to electrify IWW shipping

As stated by several authors [38][12][5] despite there being many measures that can be applied and combined to contribute to reducing CO_2 emissions in the transport sector, long-term full decarbonisation will require a consistent switch from fossil fuels to alternative energy options. No one independent measure should be applied to obtain the needed results, but a set of measures. This leads to the development of new energy systems concepts, such as the application of exchangeable batteries to IWW transportation. This involves not only the design, development and manufacture of the large interchangeable batteries but also the design and construction of the needed infrastructure to allow the battery swap (the docking stations or swapping stations) and guarantee battery availability for sailing vessels.

For the implementation of exchangeable batteries to power IWW vessels on a large scale to be successful, it needs to be based on a flexible and easily scalable technology. [51] Which can be achieved by open access and standardisation. With open access, any vessel carrying an exchangeable battery must be able to switch it at any docking station, allowing the ship to have minimum stop time and decoupling it from the charging speed of the battery. With the standardisation of the batteries and interfaces (connections between batteries and docking stations and batteries and vessels) the system can be upscaled easily. [52]

In the picture below the system description for the exchangeable batteries application to IWW is shown.

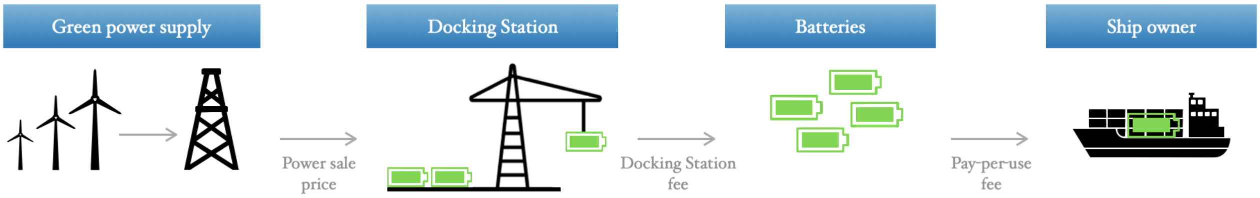


Figure 6: Exchangeable batteries for IWW vessels system description. Source: adapted from ZES internal document [51]

As it can be seen in the figure, the exchangeable batteries system is composed of batteries, docking stations and vessels, which interact as follows. The batteries are charged at docking stations, for which they pay a power sale price for the power supply. The charged batteries can then be used to power the vessels, for which the shippers pay a pay-per-use fee for the battery usage.

The docking stations are the locations at which depleted batteries can be exchanged for full ones, enabling ships to sail on quickly with minimal waiting time. For the proper functioning of the whole system, a network of open access charging points or docking stations needs to be set. [51] Apart from providing energy to charge the batteries, at the docking station, idle batteries could be used to provide grid stabilisation and for energy market applications[20] such as Frequency Containment Reserve (FCR). This means using the charged batteries that are idle at the docking stations to balance the electricity grid.

Despite the abovementioned advantages of the proposed new concept, there are also disadvantages that can make its large-scale implementation less feasible. One of them is the costs for shippers to retrofit their existing vessels in order to allocate the batteries on board. In the case of new vessels, a new design that includes the required infrastructure to withstand and couple the batteries is needed, which can also mean larger costs for shippers.

2.3 Attributes & interrelations of the exchangeable batteries system components

The three main components needed to implement exchangeable batteries to power IWW vessels are the batteries, the docking stations and the vessels. In this subchapter, their main characteristics are described. These would comprise the main technical inputs for the model to develop.

2.3.1 Batteries

The designed batteries proposed by ZES to apply for the exchangeable battery system to power electric vessels are modular, independent lithium-ion batteries arranged in 20 feet containers. The battery total weight was limited to 25 tons so they can be loaded, unloaded and transported with current terminal equipment. Moreover, the connection between the battery and the docking station or vessel should be as simple as possible. [49]

Lithium-ion exchangeable batteries have several advantages over ship built-in batteries. Firstly, lithium-ion batteries use existing developed technology and have a relatively high energy density, allowing them to store more energy than other types of batteries. [8] Secondly, the system can be used on both, new or retrofitted vessels. Finally, build-in batteries require the vessel to be idle while charging making the operations less efficient or require very large batteries which reduce the vessel capacity for carrying goods.

Despite the abovementioned advantages, these batteries present several challenges that limit their implementation to IWW vessels, such as the relatively high energy density and power requirement from vessels. Batteries sizes are constrained by the ship design as the integration of large batteries, is limited either in weight or volume. [10] Moreover, batteries capacities are not constant and depend on several factors, and they deteriorate with time. Below some of the main challenges regarding batteries implementation are further explained.

Battery Capacity

It is expected that with more technology developments batteries capacities could be increased maintaining the dimensions (size and weight). This will lead to larger sailing ranges and fewer costs for the whole system. If compared with lithium-ion batteries development for cars, between a 15 and 25% capacity in kW/kg increase is expected by 2030 if the current trends continue. [21] However, maximum battery capacity is not the only aspect to consider as the usable capacity has not a fixed value but depends on several factors such as temperature and charging and discharging regimes. Both battery capacity and charging performance deteriorates at extremely low or high temperatures [8] Lithium-ion batteries are capable of operating over a relatively wide temperature range, however, batteries achieve optimal service life when used at 20°C or slightly lower. [8] Different temperature conditions result in different adverse effects. [30] For example, the effect of temperature is higher during charging than discharging. [8]

At higher temperatures, one of the effects on lithium-ion batteries is greater performance and increased storage capacity of the battery. A study performed by [25], showed that an increase in temperature from 35°C to 45°C led to a 20% increase in maximum storage capacity. However, there is a side effect to this increased performance, the life cycle of the battery is decreased over time. On the contrary at lower temperatures, lithium-ion batteries lose capacity. At 0°C the lithium-ion battery capacity loss is about 10-20% of its rated capacity at 25°C. [8] For low temperatures, the performance of the batteries is reduced. Which results in lower efficiency, lower available capacity, higher internal resistance, and reduced allowable power levels (particularly for charging). [10] The graph below shows the relation between temperature and the relative battery capacity for 25°C for lithium-ion batteries.

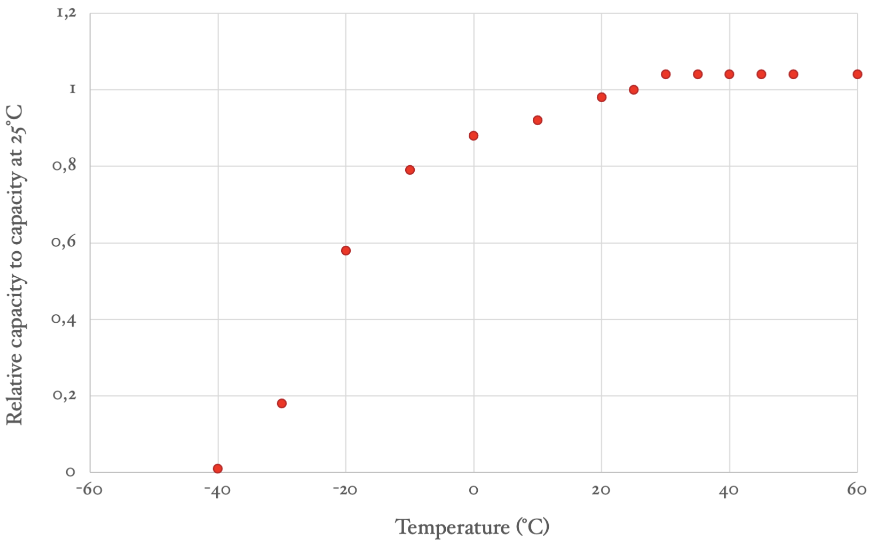


Figure 7: Relative battery capacity and temperature for lithium-ion batteries. Source:[8]

As it can be seen, useable battery capacity is a very complex parameter to estimate. In this research a maximum usable capacity value will be used as an input parameter per battery. No effect of temperature and charging regime will be considered.

Battery power losses & Ageing

There are several sources of power loss in lithium-ion batteries due to their use, the most relevant ones are losses due to heat and losses for DC to AC power transformation. Apart from power losses, batteries deteriorate with time and lose power capacity. It is estimated that the decrease of the battery capacity due to ageing is about

20% in 10 years. Ageing in lithium-ion batteries is a complex issue and depends on several factors like the charging regime and the number of cycles. [2] In other words, the speed at which a battery is charged (fast or slow), as well as the number of charges/discharges it has, affect its ageing. In general, lithium-ion batteries are more sensitive to fast charging than fast discharging.[10]

As mentioned before, another source of increased ageing or life cycle degradation for lithium-ion batteries is the temperature. In the study by [25], it was found that when the battery is charged at 45°C versus 25°C the life cycle degradation was much more significant. A way to counteract the battery ageing process and increase battery lifetime is not to use the entirely installed energy, meaning avoid fully discharge of the batteries. [21] However, to evaluate the overall effect of these various degradation mechanisms simultaneously is extremely difficult. [10]

Costs

Another major boundary for the system is the battery cost. Lithium-ion technology development has been primarily driven by consumer electronics and automotive markets. For comparison, the entire maritime market to date comprises less than 1% of the total amount of lithium-ion batteries produced yearly and to some extent, this has driven the higher cost of a comparative marine battery system. [10]

If batteries costs were low, then the system could be more easily optimised assuming a large fleet of batteries and having them available for the vessels to use at all times. However, this is not so. Given there is not yet a significant business for maritime batteries, as mentioned before, their cost is high and a huge boundary to the system. Despite this, it is expected that the battery cost will decrease in time, once the system is implemented on a large scale and benefits from economies of scale can be obtained. Again, how much the price reduction would be or when is uncertain, but a look into car batteries can be done to see the estimated cost decrease for the coming years. As estimated by [8] in his research, the decrease would be around 14% from 2025 to 2030. Still, this is an estimation and for a more well-known market, cars. Therefore, it is difficult to draw direct parallelism for IWW vessels. In this research, only the battery Capex will be considered and it will be modelled as an input parameter. If different battery capacities are considered, then different Capex should be inputted.

2.3.2 Docking Stations

For the implementation of exchangeable batteries to be successful, users need to be able to trust the system. This means that the availability of charged batteries to power vessels at the right time needs to be guaranteed. For this to happen a network of docking stations at or near existing container terminals needs to be set. These docking stations need to be designed in order to provide the required docking spots and power to charge batteries. Moreover, the docking stations should be as standard as possible, allowing for replication in different locations and easy scale-up if demand increases. The designed docking stations by ZES are modularly constructed from various parts and are based on open standards as it can be seen in the picture below. [51]

Figure 8: Docking Station layout. Source: ZES internal document [52]

1. Grid connection station
2. Power Distribution Container
3. Power Interface Container: AC / DC conversion
4. Docking platform for placement of ZES-packs
5. Connector: fully-automated plug for energy and data communication between ZES-packs and docking station
6. Optional: DC Charging column for E-trucks, E-Reach stackers, OV-buses, among others, with standard CCS (Combined Charging System) connection.

As in the case with batteries, there are several challenges to overcome regarding the docking stations. These mainly regard operational and strategic decisions like the docking station design, which will influence the investment costs as well as operational costs, and their locations.

Location

As mentioned in 2.1.3, vessels powered electrically with batteries suffer autonomy reduction due to batteries lower ranges. Meaning that vessels require to stop to charge the batteries more often than to refuel diesel. Therefore, more docking stations locations in the network than diesel refuelling stations are needed. The docking stations will be located at existing container terminals to take advantage of the infrastructure and equipment available. The best locations for the stations will depend on several factors which can be intrinsic or extrinsic. In the first case, DS locations depend on the distance to container terminals quays, the availability of grid connection, as well as the availability of land (space) to build them. These will limit the options of possible terminals where DS can be located. Apart from this, the locations will depend on the number of batteries that are in the system, the battery capacity, the number of docking places at the vessel and the vessel's power requirements. This will establish the docking station demand and, hence, the needed locations

Therefore, once the possible locations for docking stations are found in terms of feasibility (land availability, grid connection), a model is needed to assess which of these locations to use to guarantee a proper service considering the interaction of the other system components characteristics. In this research, DS will be considered as possible in all the terminals at which the vessels stop in their routes. It will be assumed that land and grid connection is available in all the possible sites.

Docking design: charging spots & charging capacities

The design of the docking station refers to the number of needed charging spots and the power that each charging spot supplies to charge the batteries. For each location, the demand profile needs to be determined to decide upon the number of docking places required and the energy contract to have with the energy provider. [51]

The docking station investment and operational costs are linked to the location (cost of land, cost of building), as well as to the number and power capacity of the charging spots chosen. The docking station operational costs include energy purchase from power supplier, network costs for connection to the grid, logistical costs for the loading, unloading and transportation of the batteries to and from the vessel, and operational costs for maintenance, insurance, among others. [49]

As it can be seen the definition of docking stations locations and design, namely size and power, are interconnected. Therefore, an iterative process needs to be performed to find the most optimal combination of parameters. This will be exemplified in chapter 5. In this research, the design of the DS will be represented by two parameters the number of charging spots and the power of each spot. Each design will imply a different Capex. Operational costs will not be considered.

2.3.3 Vessels

The last component of the exchangeable batteries system are the vessels. For the whole system to work, batteries need to guarantee sufficient electric power to vessels at all times. The battery movement throughout the network, as well as the charge level, is then linked to vessels' routes, schedules and power consumption. The implementation of batteries to power vessels guarantees shippers zero-emission sailing and, therefore, coping with the environmental targets set. However, the lower sailing range provided by batteries and the high investment costs can be major drawbacks for the system from the shippers' perspective, which need to be considered.

Retrofit costs & loss of revenue per container

When installing state-of-the-art or innovative components or systems on board of ships, retrofit is needed. Thus retrofit can be driven by the need to meet new regulations or emissions standards or by the shipowner interest to upgrade to higher operational standards. [22] In the implementation of exchangeable batteries for fully electric sailing, vessels need to be retrofitted to fit the exchangeable batteries. This signifies a cost for shippers, which is composed by [29]:

- The cost for purchasing and installing the connector and convector ([49]) to fit the batteries on board;
- The potential loss of income during the time off the vessel is being retrofitted;
- The cost for sailing to the shipyard for retrofitting;
- The cost to train the crew for the new operations.

The cost of sailing to the shipyard is not as significant as the others. A way of decreasing the total cost and the impact on the operations is to schedule the retrofit with maintenance and repair of the vessel. The total retrofit cost depends on the vessel type, age and dimensions. Apart from the retrofit costs for shippers, there is also a loss of revenue for carrying less cargo containers to leave place for the batteries. The number of loss positions in the vessel for carrying the batteries is not limited to one per battery, as no cargo can be loaded on top of the batteries. Therefore, the whole stack of cargo containers is lost.

From a logistics perspective, it can be of interest to consider the option of batteries been relocated in the network, for example, to be charged at a station with low demand or to be available in a route for another vessel. For this relocation, vessels could be used. However, the costs of this should be considered as the battery to be relocated will take the space on the vessel of a cargo container.

In this research, the costs incurred by the shippers namely retrofit costs and loss of revenue, will not be directly modelled. However, the relevance of these costs can be a significant drawback in the implementation of the exchangeable batteries system and therefore need to be assessed. To do so, different scenarios will be analysed showing the trade-offs between more batteries on board versus the total number of batteries and docking stations required in the system.

Vessels' power requirements

An important aspect to consider in the implementation of exchangeable batteries is that the vessels' power consumption depends on several factors like the vessel's speed, climate conditions (wind, waves), the vessel's shape, the vessel's load and whether the vessel is sailing in restricted or unrestricted areas.

The vessel's speed is greatly influenced by the resistance encountered while sailing. Factors like the surface of the hull underwater, vessel's cross-section and width and depth of the waterway affect the total resistance. [43] It is often found in the literature that a vessel speed reduction of 10%, leads to a reduction in required energy of about 19%. [13] This approximation is based on the assumption that power is proportional to ship speed cubed. The cubic relationship between speed and daily bunker consumption is commonly assumed in maritime transportation models. However, several authors have researched that the speed-power curve depends highly on ship size, type, hull form and operating speed. A significant variation in the speed exponent can be observed both among different ships and at different speeds, [40] making it almost case specific to determine it.

Apart from the complexity that the vessel's speed has over the power consumption, additional fuel consumption for a voyage needs to be considered due to waves, which does not depend on the speed of the ship. [40] Moreover, additional power may be required to overcome the effects of wind and currents. This additional power may account up to 15% of the total power under certain circumstances. [43] Another factor affecting power consumption is the vessel's load. Empty vessels require less propulsion power than loaded vessels. This can be seen in the sailing profiles when looking at round trips, when the vessel carries more load the power requirements are larger than when it carries less load. The sailing profiles are therefore a good way to incorporate this factor in the model.

The combination of factors as speed, weather, vessels' hull shape and load on the power requirement is hard to assess. In this research, sailing speed, weather conditions and vessels shape and sate (load or unload) are not directly modelled, therefore the effects of a change of these parameters in power consumption needs to be manually inputted. To do this, the sailing profiles need to be modified, stating the new sailing times and power consumption per time step.

Extra times at terminals & sailing times

Apart from the abovementioned challenges, there are other challenges regarding extra times needed at terminals for the operation of loading/ unloading the batteries as well as possible extra stops needed. As the vessel's autonomy decreases when using batteries, given that their power capacity is less than with fuels, this can lead to the need for more stops for the vessels to swap depleted batteries with new ones or change their sailing speed to reduce power consumption. Both options lead to extra sailing times and indirectly to profit loss. In this research extra vessel's stops will not be considered, in case the power supplied by batteries is not enough to power the vessel between two terminals, the model will be infeasible. Larger batteries capacities would need to be considered.

In the table below a summary of the main challenges of the system components and the model implications are described.

Table 2: System components' challenges and model implications

Component	Attribute	Challenge	Model implication
Batteries	Usable battery capacity	External temperature	* Maximum usable capacity is modelled as a parameter for each battery. * No variations of maximum usable capacity are considered due to external circumstances, such as temperature or charging regimes. Capacity reductions due to ageing and power losses can be analysed by changing the maximum usable capacity of the batteries individually.
		Charging regime	
		Ageing	
		Power losses (heat, AC to DC transformation)	
	Costs	Cost variation with time and battery increase	* Batteries Capex are modelled as a parameter for each battery. Different Capex for different battery capacities or ages can be modelled. Opex are not considered.
Docking station	Location	Land availability, grid connection	* The terminals at which the vessels stop in their route are considered as possible DS locations and are given as input. It is assumed that there is land availability and grid connection in them.
	Design	Docking spots	* Modelled as a parameter for each possible DS
		Charging capacity	
	Costs	Cost variation with DS design, location	* Capex is modelled as a parameter for each possible DS design. * Opex are not considered.
Vessel	Retrofit	Cost	* Not considered in the model. * The retrofit cost and loss of revenue can be assessed considering the number of docking spots on board, which is a parameter for each vessel in the model.
		Loss of revenue	
	Power requirement	Speed	* Speed and external conditions are not included directly in the model. *The power requirements are defined per time step for each vessel. Speed variations, wind or waves can be assessed by modifying the power requirements.
		External conditions: weather, waves	
	Route	Extra times at terminals	* No extra times at terminals or more stops in the vessels' routes are considered in the model.
		More stops	

2.4 Implementation of the exchangeable batteries system for IWW shipping

As explained before, in order to obtain positive environmental impacts by using an exchangeable batteries system for IWW shipping, it needs to be implemented on a large scale. To do so, proper charging infrastructure and batteries need to be available to provide vessels with electric power to sail.

There are several ways to implement the exchangeable batteries system to IWW shipping. For example, each vessel could be assigned with a set of batteries to use. Once the vessel arrives at a terminal with a docking station, the batteries can be downloaded, charged and uploaded to the vessel again. All this is executed while the vessel is at the terminal. This will imply that there are a fixed number of batteries per vessel (depending on its power requirement) and, therefore, battery demand and vessel demand grow together. Moreover, vessels will need to be at the terminal at least the time that is required to download, charge and upload the batteries again. In this case, the needed problem to solve is the docking station locations to charge the batteries.

Another way of implementing the exchangeable battery system implies sharing the batteries among vessels. This is the concept designed by ZES and analysed in this research, in which the batteries do not belong to a specific vessel but to the system. In this case, batteries can power a vessel and once the vessel arrives at a terminal with a docking station it can leave the batteries to charge, load another one, and sail, saving time. The batteries that were left at the terminal can be used by another vessel or for other businesses, such as FCR. Sharing batteries among vessels results in the need for less batteries per vessel as vessel demand increases, which becomes an advantage of this system, as battery costs are far from neglectable. This implementation has more logistic challenges when more vessels and larger networks with more routes and terminals are considered. Not only the DS locations needs to be determined, but also the needed batteries, including their routing. The movement of the batteries through the network has to match with the different vessels' routes, as they do not depend on one exclusive vessel. Synergies between the charging infrastructure, vessels routes and batteries are needed.

Therefore, the implementation of the system proposed by ZES has the challenge of determining how many batteries are needed, how they should move through the network to properly power vessels and charge at the needed time, and where to locate the docking stations from the set of terminals available, so that vessels can have an available charged battery to sail at all times. All this considering the restrictions imposed by the limited battery capacity, the design of the DS (charging points and power), and the available docking spots, power requirements and routes of the vessels.

2.5 Summary

There are several ways to reduce emissions in IWW transportation and achieve the environmental goals set in the Green Deal. One of them is through electrification of the IWW transport. This can be achieved by vessel hybridisation, fuel cells or batteries, either build-in or exchangeable. Every option has advantages and disadvantages, and implementation challenges to overcome in order to be successfully applied on a large-scale and cause an actual impact on emissions.

This research focuses on the electrification of IWW transport using exchangeable batteries. The implementation of such a system has several challenges, and the problem becomes largely complex as the three main components of the system, namely, batteries, docking stations and vessels, interact.

Batteries limit the autonomy of vessels as they provide less power than diesel fuels. Therefore, battery capacity is a key parameter of the system. However, battery capacity is not a fixed value. On the contrary, it depends on several factors like temperature and charging/ discharging regimes. Moreover, batteries suffer power losses due to heat and DC to AC power transformation, and capacity losses due to ageing. Ageing is also a very complex factor to assess. Finally, battery investment costs are a big drawback for the exchangeable batteries system implementation. It is expected that costs will drop, as it happened in road transport, once the system in IWW is implemented on a large scale. However, to what extent or when this will happen is not clear.

Regarding docking stations, their location and design, namely the number of charging spots and the power of each spot, are highly interconnected. Moreover, docking station location depends on the number and capacity of batteries in the system and the number of docking spots and power requirements from vessels.

The environmental targets set by the Green Deal, force shippers to look for alternative options to comply with the emissions restrictions, one of them being vessel electrification with batteries. From shippers' perspective, adopting the exchangeable battery system means great investment in retrofit, revenue loss for carrying batteries instead of cargo containers, possible extra times at terminals and possible need for speed reductions. Sailing slower means less power requirements and, hence, less battery capacity required. Leading to the need for fewer batteries onboard or less stops to swap them. However, this increases the sailing times. Therefore, it is not straightforward what is the best ratio of vessel speed with required battery capacity.

The interrelation seen between the different components of the system and the complexity of some of their attributes requires assumptions to be made in order to simplify the problem and be able to model it. For this, battery capacity and Capex will be modelled as individual parameters per battery. Allowing to test a fleet of batteries with different useable capacities to resemble a heterogeneous fleet of batteries ages and sizes. Docking stations locations will be determined by the model given a set of possible locations with specified DS designs. Different options can be assessed by inputting different scenarios. Vessels' routes and power consumption will be represented by the sailing profiles. The speed of the vessels and the effects of weather conditions will not be directly modelled, the inputted sailing profiles (route and power requirement) can be changed to evaluate different sailing speeds and power requirements per time step.

The scope of this research is limited to the logistic implementation of the exchangeable battery system and therefore, no in detail evaluation of the shippers' costs will be done. However, in chapter 5 the trade-off between docking places on board and number of batteries is performed.

Finally, the implementation of the system proposed by ZES implies the sharing of the batteries and the infrastructure by the vessels. This adds logistic challenges to the problem as not only the docking station locations need to be determined from the set of terminals, but the number of needed batteries and the deployment of these batteries in the network, in order to fulfil the vessels' power requirements, while matching the batteries movement and vessels' routes.

3 Literature review of modelling transport electrification

The aim of this chapter is to provide a review of the models developed to tackle the main logistic challenges that electrifying the transport have and to conclude on the applicability of these models to the particular case of IWW shipping electrification.

Given the fact that, as far as this research concerns, there is no specific literature on optimisation models for IWW shipping electrification, a literature review on other modes of transport was performed. Then a comparison with IWW was made to determine the applicability and limitations of existing models to IWW shipping. In particular, buses were chosen as the mode of transport to compare. The reasons for this are the availability of literature and the similarity of bus road transport and IWW transport in terms of type of vehicles and operations. Buses are large vehicles with higher power demands if compared to cars and have fixed routes and schedules, like IWW vessels. Trucks could have been another option to compare, as they are also large vehicles with relatively high demands of power, long routes and less stops than buses, similarly to IWW vessels. However, literature on trucks electrification is also limited.

To perform this literature review Scopus and Science Direct were used to find suitable papers. The terms ‘buses’, ‘electrification’, ‘challenges’ and ‘model’ were used in different combinations. Moreover, backward snowballing was used to expand the number of papers considered in this literature review.

The results of the literature review are structured starting with the challenges that electrifying buses transport have and how these can also apply to IWW transport. Followed by a description of the models developed to address these challenges for buses, discussing the possible applicability and limitations if implemented for IWW vessels. Finally, conclusions are made on the need to develop a specific model for IWW shipping to analyse the possibility of electrification with exchangeable batteries.

3.1 Logistic challenges of transport electrification

As mentioned before, in this subchapter, the logistic challenges that electrifying buses have will be described. At the end of this section a parallelism of these challenges to IWW vessels will be done.

In the implementation of any innovation there are always challenges to overcome. In the case of buses electrification these can be of many types, such as users’ reluctance to change and high implementation costs. The reliability of the system becomes a key aspect to successfully implement buses electrification. For this, a proper combination of charging infrastructure and batteries that provides a reliable energy supply to maintain a stable operation, even under demanding conditions, is needed. [23] As study by many authors, securing system reliability leads to logistic challenges to overcome.

The first challenge, regards the number and location of the charging infrastructure. [53][19] The strategic location of charging stations is key for the system to properly work and for users to trust it. The charging infrastructure will be in place in the network for many years. Therefore, the location decisions will also affect tactical and operational decision for these charging stations.[18] Moreover, the large capital costs involved in installing charging infrastructure, make the decision on number and locations of charging stations not straightforward. [19]

Apart from the location problem, decisions need to be made on the charging stations capacities and charging regimes. The size or capacity of the recharging stations affects the transportation planning as stations cannot serve more than their installed capacity. [19] Electric buses have higher power demands than electric cars, and they operate under fixed routes and daily schedules, therefore subject to more constraints in relation to where the charging infrastructure can be placed. [46] Moreover, a charging station can be fast or slow charging. Standard charging is performed with a moderate charging power mainly in the bus depot overnight and during longer brakes. [36] Charging schedules can be implemented in buses electrification, for example use overnight charging to avoid the need of fast charging stations. [31] However, this causes a high battery capacity and a high weight of the system, when the bus shall be operated the entire day. Fast charging on the track during operation can reduce the battery capacity and therefore the weight significantly.[36] However, there is a trade-off between charging speed/time and the damage to the battery, making this type of charging to have their own limitations. [54] [19] To overcome this, battery exchange schemes/stations can be implemented. This avoids the bus to be idle while recharging [31] as well as battery deterioration, as battery life can be extended by charging at slower speed. [54] Some drawbacks of battery swap stations include the need of unified battery standards among vehicles and stations. [19] Decisions on the station type will directly affect the charging times and will depend on the buses power demand, size of batteries,[19] the location of the stations, but also on the buses schedules to see if their provide sufficient charging times at certain locations. [36] As it can be seen the charging station design (size, power and type) and location decisions are interrelated, making it not trivial to decide upon the best option.

The second main challenge of bus electrification regards the limited driving-range capabilities of the vehicles which are restricted by the amount of electricity stored in their batteries. [19] This challenge has been address by several authors, as it is a key barrier that reduces the attractiveness of bus electrification [31] and imposes non-trivial additional constraints when designing efficient distribution routes. [19] Maximum battery capacity is linked to technological limitations, but also to size, weight and cost limitations. Batteries can make up to one-third of the total cost of an electric bus. [23] Therefore, a balance between battery capacity and range needs to be made. The restriction in driving range imposed by the batteries to the buses, has also an impact on buses schedules, as additional times and stops might be required to charge the batteries. [19] Again this problem is linked to the charging infrastructure location problem.

When thinking of the possible challenges that the electrification of IWW vessels can have, a parallelism can be drawn with some of the abovementioned challenges of buses electrification. For example, the charging infrastructure location, number and design (size and power) will also be an issue with IWW vessels. Charging stations, as in the case of buses, need to be in the route of the vessels, because their routes are fixed. Detouring a vessel to go to a charging station outside its route is not economically feasible. The problem for IWW vessels will have the added constraint that charging stations need to be at the terminals at which the vessels stop, near the cranes for the loading and unloading of the batteries and need to have access to power grid and ensure land availability. The challenge concerning the charging time will also be present in IWW vessels. In an optimal operation the vessel should not have to be idle at a terminal longer than if sailing with diesel fuel. Therefore, the system needs to provide either fast charging infrastructure to built-in batteries or available charged batteries to swap if an exchangeable battery system is implemented. The possibility of overnight charging seems quite infeasible as shipping is usually a 24/7 operation. Moreover, the challenge of battery range will also be present in IWW vessel electrification. The power requirement of a vessel is huge in comparison with a bus, making the need of either very large built-in batteries or sufficient swapping stations on the route a must for the system to work. Additional vessels stops and extra times for charging or swapping batteries need to be minimised.

3.2 Models developed to overcome the logistic challenges of transport electrification

In this subsection a selection of models developed to overcome the abovementioned logistic challenges that can be found in literature for buses electrification will be reviewed. In the following subsection the applicability of these models to IWW vessels will be addressed.

When looking into the researched models to address the logistic challenges for electrifying buses, it is usual to find authors addressing more than one logistic challenge combined. In particular battery range restrictions are usually used as a constraint to the problem.

Starting with the number and location of charging infrastructure challenge, the research performed by [18] addresses this problem and proposes a mixed-integer problem decomposed in two subproblems. The first one aims to solve the uncapacitated fixed charge facility location to find the optimal station location and the demand of each station. Whereas the second one, aims at finding the optimal configuration of the localised charging system, in particular the charger type and battery inventory. The problem is solved for a fleet of battery electric buses and aims at minimising the total investments, by determining the needed number of swapping stations and their locations and the demand assigned to each of them. The buses go to the swapping station from the depot, meaning they do not need a swapping service on during the route. The main limitations of the model are that it is assumed that a battery will be available at a station when a bus arrives, busses will only reach swapping stations from depot, meaning they can finish their whole route without recharging their batteries and swapping stations are assumed uncapacitated, meaning there is no limit of batteries the stations can charge and no charging time. Moreover, the model solves the location of the stations and the demand assigned to each station first, and then determines the number of needed batteries. Therefore, the interrelation between stations number and location and the needed batteries is not modelled.

In this same line of research, [46] studied the optimal distribution of charging infrastructure for electric buses. The model they developed is a mixed-integer linear programming (MILP) that aims to assess upscaling the implementation of electric buses by identifying the optimal spatial distribution of charging infrastructure to minimise costs and energy consumption. The model is based on balancing the energy at arrival of a stop as the energy the bus had when leaving the previous stop minus the required energy to travel the distance between stops. The main limitation of the model regards to the location of the charging stations being limited to starting and end stops in the buses routes, meaning that the battery capacity should be enough to do the whole trip.

Another research which looks to the interaction of an efficient layout of the charging infrastructure and an appropriate dimensioning of battery capacity is the one performed by [23]. The authors propose an advanced mixed-integer linear optimisation model that solves a capacitated set covering problem to determine the number and location of charging stations and the required battery capacity for each bus line, minimising costs and without altering the original operational schedule. Some key aspects of the model proposed in this research are the network perspective which allows to identify synergies when the charging infrastructure is shared by several bus lines at once, the incorporation of the trade-off between battery capacity and charging infrastructure and the nodal energy balance. One limit that this model has is that the charging time is limited to the time the bus it at the stop.

To tackle the battery charging times challenge for buses electrification, research has focused on vehicle schedules and battery reservation strategies to properly match the power demand from the vehicles with the available resources (batteries). Research in this direction include the one done by [4], in which the authors find the optimal location of the EV charging among the swapping stations available in the network. This is done by scheduling the arrival of the buses at the swapping stations, and by determining the charging priority of the depleted batteries at the stations. The scheduling allows to guarantee that a fully charged battery will be available and ready to deploy when the vehicle arrives at the station. Therefore, there is no waiting time of the bus for charging. The authors developed a time-discrete multi-objective optimisation algorithm to solve the problem.

3.3 Conclusions & reflections of the application of existing models to electrify the IWW shipping with exchangeable batteries

As it was mentioned before, as far as this research concerns, the application of exchangeable batteries to power vessels has not been in depth researched before. Many questions need to be answered for such a concept to be fully implemented on a large scale. Some of which regard the logistics challenges of the exchangeable batteries and the docking stations. Despite some parallelisms can be drawn from studied problems on buses electrification and the developed models to solve them, there are some peculiarities of the implementation of this concept in inland waterways vessels which make the direct applicability of these models not possible.

For example, the extremely high costs of the needed batteries and docking stations for IWW vessels make their optimisation a key aspect for the exchangeable battery concept to be economically feasible and, hence, successful. Therefore, the interrelation between the both need to be considered when finding their optimal number and location, contrary to what is suggested by [18].

Moreover, assuming a fully-charged battery is available at all times to be loaded on a vessel as proposed by [18] is not realistic, as the needed charging times at the docking stations are not being considered. Docking stations also have a limit amount of charging spots and, therefore, a limited charging capacity. [18] This is why the time needed to charge batteries needs to be considered, in order not to overload the stations with batteries that cannot be charged. Apart from this, it is not realistic to limit the charging time as suggested by [23], as the batteries needed to power IWW vessels are very large, and the charging times are not neglectable. Battery level is a key parameter that should be tracked so as to optimise the charging times and number of needed batteries.

Allowing the possible vessels to use exchangeable batteries only to those which power requirements are low enough to be fulfilled with the power of batteries on board is a major limitation. [18] [46] The combination of docking stations locations and batteries in the network should allow the fleet of vessels analysed to sail electric regardless of the power requirement. If needed more docking stations should be placed in the system to swap the depleted batteries for fully charged ones. Therefore, all vessels stops at terminals should be considered as a potential docking station to allow possible batteries swapping in the route and not only on end terminals as proposed by [46]. Finally, vessels' routes and schedules are fixed making it not realistic for vessels to choose the docking station at where to load/ unload the batteries according to the possible queue or battery charging schedules as studied by [4].

Despite the abovementioned limitations for the applicability of the assessed models to IWW vessels, there are some concepts developed by the authors that can be applied in the development of a new model for IWW shipping. In particular the cost minimisation perspective suggested by [18], [46] and [23] for the optimisation of the exchangeable battery system is of interest for this research. Apart from this, the time-discrete modelling approach developed by [4] is of relevance for this research. Developing a model with discrete time-steps to represent the power requirements of vessels, their locations and the battery charge level seems reasonable. Moreover, the nodal energy balance concept used by [46] and [23] has potential applicability. The battery charge level needs to be determined at all times, therefore, a energy balance between time steps is needed. Finally, the network perspective to develop a MILP as done by [23] is also of relevance for this research. Finding possible synergies between the charging infrastructure, the needed batteries and the vessels will lead to better results in terms of DS and batteries optimisation.

The table below summarises the assessed models and their limitations and potentials to their applicability to IWW vessel electrification.

Table 3: Assessed models review: limitations and potential application to IWW vessels. Sources: [18][46][23][4]

Challenge	Model	Limitations to IWW vessels' application	Potential to IWW vessels' application	Paper
Number & location docking stations	Mixed-integer problem to solve optimal facility location, demand for swapping stations and needed batteries	* Battery availability at a station at bus arrival. * Battery charge enough to perform whole trip without recharging * Service capacity of a station is unlimited * Interrelation between swapping stations number and location and the needed batteries is not modelled.	* Cost minimisation perspective	Jing, W., Kim, I., & An, K. (2018). The uncapacitated battery swapping facility location problem with localized charging system serving electric bus fleet.
	Mixed-integer linear problem to find optimal spatial distribution of charging infrastructure to minimise costs and energy consumption.	* Charging infrastructure locations limited to beginning or end of buses route. * Battery charge enough to perform whole trip without recharging	* Cost minimisation perspective * Nodal energy balance	Xylia, M., Leduc, S., Patrizio, P., Kraxner, F., & Silveira, S. (2017). Locating charging infrastructure for electric buses in Stockholm.
Number & location docking stations & battery capacity	Mixed-integer linear problem to determine the optimal number and location of charging stations and the required battery capacity for each bus line	* Limited charging time	* Cost minimisation perspective * Nodal energy balance * Network perspective: synergies possibilities	Kunith, A., Mendelevitch, R., & Goehlich, D. (2017). Electrification of a city bus network—An optimization model for cost-effective placing of charging infrastructure and battery sizing of fast-charging electric bus systems.
Number & location docking stations & battery charging times	Multi-objective Optimization algorithm to find optimal location of the charging infrastructure and schedule arrivals and battery charges	* Changing schedules	* Time-discrete modelling	Amiri, S. S., Jadid, S., & Saboori, H. (2018). Multi-objective optimum charging management of electric vehicles through battery swapping stations.

In this research, the problem aimed at solving, requires to incorporate not only the swapping stations or docking stations optimisation but also the battery optimisation. For which battery location and battery charge level are two parameters that need be tracked at all times. Therefore, this research aims to extend the existing literature and propose an optimisation model for the implementation of exchangeable batteries in IWW shipping in order to minimise costs, by optimising the needed number and locations of docking stations and the number of batteries, so as to satisfy a given demand of vessels, with their specific routes and power requirements. For this, the following concepts of the assessed models will be used: energy balance, synergies possibilities by using a network perspective of the system allowing batteries to be shared by vessels sailing in different routes, time-discrete modelling and cost minimisation approach. [40]

4 Method to analyse the exchangeable batteries distribution and docking stations location for IWW shipping

In this chapter the method used to analyse the implementation of an exchangeable batteries system to IWW shipping is explained. Starting by the description of the conceptual model that sates the model objectives, project requirements, inputs and outputs and the assumptions and simplifications made. Followed by a subchapter with the description of the optimisation model developed to assess the abovementioned system implementation. In this subchapter the modeling concepts, the mathematical formulation, the model verification and validation are explained.

4.1 Conceptual model for the implementation of exchangeable batteries and docking stations to power IWW vessels

A conceptual model is a specific description of the computational model that is been developed. [35] The components of the conceptual model described in this chapter are the model objective, the project requirements, the model inputs and outputs, the assumptions and the simplifications made.

In the figure below a general overview of the model with the inputs and outputs is shown.

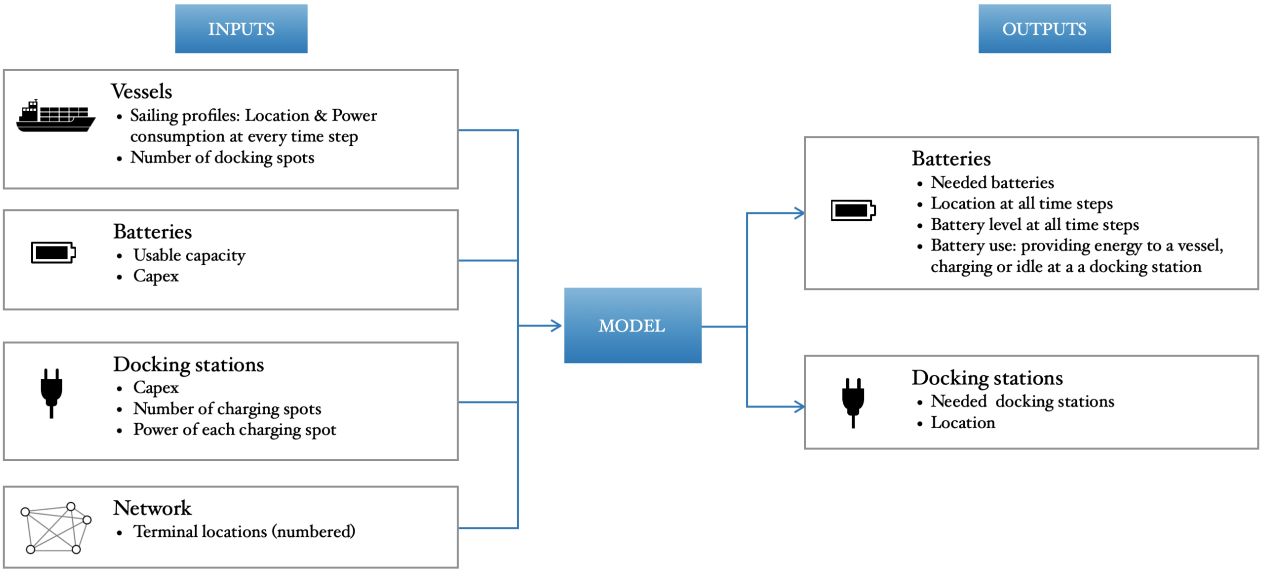


Figure 9: Model overview

4.1.1 Model objectives

The model objective is to find the optimal combination of batteries and docking stations to successfully provide the required power to all vessels, minimising batteries and DS investment costs, in order to implement exchangeable batteries to IWW shipping. To do so several scenarios are analysed varying: battery capacity, docking spots on vessels and docking station power and docking stations spots.

4.1.2 Project requirements

- **Time scale**: the duration modelled needs to account for the longest round trip of the fleet of vessels considered. For the case study of ZES the longest round trip is 61,5 hs corresponding to the vessel Nijmegen Max.
- **Flexibility**: the model should allow to analyse different fleet composition (vessels with different routes and power consumption), different corridors and terminal locations.

- **Scalability**: the model should allow easy scalability to more terminals, more vessels and potentially more time steps.
- **Scenario analysis**: the model needs to easily allow to analyse different input scenarios such as different battery capacity, charging spots at docking station and their power, and docking spots in vessels. Moreover, the model should allow to analyse DS locations at specific terminals. Therefore, the DS locations need to be able to be fixed.

4.1.3 Model assumptions

Batteries

- Fleet composition: all batteries are assumed to be lithium-ion. Therefore, no heterogeneous battery technologies is considered, for example a mix of hydrogen cells and lithium-ion batteries.
- Battery ageing and power losses: given the added complexity that modelling battery ageing will give to the problem, and the fact that only a short period of time will be modelled, it was decided not to include ageing directly. All the power losses and power variability due to use or temperature, as well as ageing, are included in the maximum usable battery capacity. Each battery is modelled individually so different scenarios with different capacities can be modelled to account for different battery ageing and charging regimes.
- Battery capacity: as it was mentioned before, there is variability of the battery capacity due to different factors such as the temperature and the charging regimes. This combined variability is not easy not model. Therefore, an average value of usable battery capacity is assumed in the model. However, given the relevance that battery capacity has as a restriction to the system, it was decided to model capacity as a parameter that will allow to assess scenarios with different battery capacities.
- Batteries need to be fully charged before they are placed on a ship.
- A minimum battery level is set to avoid batteries to fully discharge and to keep a safety margin to account for unforeseen events that might require larger power consumption from the vessel, than those stated in the sailing profiles.

Docking stations

- The locations of the possible docking stations are limited to the terminals at which the vessels stop in their routes. For the case study, the possible DS locations are at terminals that have been pre-identified by the company. It is assumed that these locations can guarantee space and availability of connection to the electric grid.

Vessels

- The sailing profiles (routes and power consumption) used for the study case are those given by the vessels owners for an average day sailing on diesel fuel.
- Vessel speeds and distances are not modelled. These can indirectly be accounted for by altering the energy consumption per time period of the sailing profiles (model input).
- The time the vessel stops at a terminal is enough to load or unload a battery. No extra time is considered for swapping batteries at a docking station.

Others

- The only costs considered in the model are those for the batteries and docking stations Capex. In other words, no operational costs are considered.
- The costs for vessels' retrofit and shippers revenue losses for having fewer containers on board to accommodate the batteries are not considered.

The reason for this is to reduce the complexity of the model, as introducing another variable to account for used docking spots on board of the vessels will increase complexity and computational times. However, analysing costs on shippers' side is also of importance. Therefore, the number of needed batteries and docking stations versus the number of docking spots on board will be analysed as a scenario in 5.

- The considered period of time for the model correspond to the longest vessel round trip of the fleet modelled.
- A service level of 100% is considered, meaning all the vessels' power demands need to be satisfied. The model looks for the needed batteries and docking stations so that the whole fleet sails electric.

4.1.4 Model simplifications

- Running time is a huge limitation to the model, the selected time scale and time steps need to allow to obtain results within reasonable time yet relevant to make conclusions. Therefore, the maximum number of vessels model is limited to four and the vessels' sailing profiles are simplified so as to describe the vessels' routes and power requirements in a maximum of 24 time steps.
- The batteries are linearly charged/ discharged in time.
- The batteries supply energy to the vessel alternatively in each time step. Meaning, that if more than one battery is on a vessel, at a time step p only one battery is used to power the vessel.
- Battery age and size heterogeneity, as well as, energy losses and battery degradation, are indirectly represented by different maximum battery capacity.
- Vessels' sailing profiles (sailing times and power consumption) are not changed due to external factors like sailing speed, the weather or currents.

4.2 Optimisation model development for the implementation of exchangeable batteries and docking stations to power IWW vessels

In this chapter the optimisation model developed in this research is explained. Starting by a general explanation of the model and the modelling concepts used, followed by the mathematical formulation of the model and its verification and validation.

4.2.1 Model description & Modelling concepts

The problem that is aimed to solve in this research requires to develop an optimisation model for the exchangeable battery fleet and docking stations locations. As explained in 1.2 is not possible to have a large fleet of batteries available for vessels at all times. The problem needs to be modelled from the battery perspective, as it needs to keep track of the batteries location and battery charge level in order to match them with the fixed sailing routes of the vessels.

As the demand of vessels, including the sailing routes and the power requirements, as well as, the terminal locations are precisely known, the model is optimised as deterministic. Moreover, given the nature of the problem to model, discrete time representation comes as a straightforward representation of it. The vessels' locations and power requirements, as well as, the batteries locations and battery charge levels can be easily represented in hourly time steps. This makes it also easier to understand the outputs, as well as, to modify the input values, which can be useful for the company later on.

Given the project requirements from the conceptual model stated in 4.1.2, the developed model needs to be flexible and scalable. Therefore, it was decided to simplify the network and represent the terminals with numbers. Then the sailing profiles of the vessels are adjusted so as to show in each time step their location (at a terminal or sailing). In this way no specific node-arc representation is needed, allowing for the model to be adapted and or extended to any other network.

In this research a mixed integer linear programming (MILP) model with discrete time is proposed to find the optimal number of batteries and docking station number and locations to make the vessels demand be effectively powered by electric energy. Formulating problems as MILP has the advantage that optimal solutions can be found. [41] As all the equations that represent the problem of this research (objective function and constraints) can be formulated in linear equations, this is the chosen method, which is solved by using the commercial solver Gurobi.

4.2.2 Mathematical formulation

Sets

$b \in B$ $\{1,2,3,\dots S\}$	Set of batteries
$v \in V$ $\{1,2,3,\dots,M\}$	Set of vessels
$t \in T$ $\{1,2,3\dots T\}$	Set of terminals
$p \in P$ $\{1,2,3,\dots H\}$	Set of time periods

Variables

$$\mathrm{n}_b = \begin{cases} 1, & \text{if battery } b \text{ is being used} \\ 0, & \text{otherwise} \end{cases}$$

$$\mathrm{u}_t = \begin{cases} 1, & \text{if terminal } t \text{ is used as docking station} \\ 0, & \text{otherwise} \end{cases}$$

$$\mathrm{x}_{b,t,p} = \begin{cases} 1, & \text{if battery } b \text{ is at terminal } t \text{ at time } p \\ 0, & \text{otherwise} \end{cases}$$

$$\mathrm{y}_{b,v,p} = \begin{cases} 1, & \text{if battery } b \text{ is on vessel } v \text{ at time } p \\ 0, & \text{otherwise} \end{cases}$$

$$\mathrm{k}_{b,t,p} = \begin{cases} 1, & \text{if battery } b \text{ is being charged at terminal } t \text{ at time } p \\ 0, & \text{otherwise} \end{cases}$$

$$\mathrm{m}_{b,v,p} = \begin{cases} 1, & \text{if battery } b \text{ is providing energy to vessel } v \text{ at time } p \\ 0, & \text{otherwise} \end{cases}$$

$l_{b,p}$	Battery level of battery b at time p

Parameters

Terminals

cds_t	Capex for installing a DS in terminal t [€]
chp_t	Number of charging points of a DS installed at terminal t
pw_t	Power of each charging spot [kW]

Batteries

cb_b	Capex of battery b [€]
cap_b	Maximum battery capacity of battery b [kWh]
mlv	Minimum battery level charge required to be used in vessel
mlb	Minimum battery level at all times to avoid batteries to be fully discharged (safety margin)

Vessels

$sp_{v,t,p}$	Sailing route. If vessel v is at terminal t at time step p, then $sp_{v,v,p}$=1, and 0 otherwise.
$pv_{v,p}$	Power consumption of vessel v at time step p [kWh]
chv_v	Number of batteries that can be fitted in vessel v (docking spots)

Initial values

$Lb_{b,0}$	Battery level of battery b at start of period (p=0)

$$\mathrm{Ut}_{b,t,0} = \begin{cases} 1, & \text{if battery } b \text{ is at terminal } t \text{ at p=0} \\ 0, & \text{otherwise} \end{cases}$$

$$\mathrm{Uv}_{b,v,0} = \begin{cases} 1, & \text{if battery } b \text{ is on vessel } v \text{ at p=0} \\ 0, & \text{otherwise} \end{cases}$$

$$\mathrm{k0}_{b,t,0} = \begin{cases} 1, & \text{if battery } b \text{ is at terminal } t \text{ and is being charged at p=0} \\ 0, & \text{otherwise} \end{cases}$$

$$\mathrm{m0}_{b,v,0} = \begin{cases} 1, & \text{if battery } b \text{ is on vessel } v \text{ and the battery is being used at p=0} \\ 0, & \text{otherwise} \end{cases}$$

Others

M_1	Large number
M_2	Small number

Objective function

The objective is to minimise the total investment cost of the batteries and docking stations.

$$min\left(\sum_{b\in B} n_b.cb_b + \sum_{t\in T} u_t.cds_t\right) \tag{1}$$

The first term of the objective function represent the battery investment costs (Capex) and the second term the docking station the investment costs (Capex).

Constraints

$$n_b.M_1 \geq \sum_{t \in T} \sum_{p \in P/p>0} x_{b,t,p} + \sum_{v \in V} \sum_{p \in P/p>0} y_{b,v,p} \ ; \ \ \forall b \in B \tag{2}$$

$$u_t.M_1 \geq \sum_{b \in B} \sum_{p \in P/p>0} x_{b,t,p}.n_b \ ; \ \ \forall t \in T \tag{3}$$

$$1 \geq \sum_{b \in B} m_{b,v,p} \geq pv_{v,p}.M_2 \ ; \ \ \forall v \in V \ ; \ \ \forall p \in P \ ; \ \ \forall p > 0 \tag{4}$$

$$l_{b,p} \leq l_{b,p-1} + \left(\sum_{t \in T} pw_t.k_{b,t,p} - \sum_{v \in V} pv_{v,p}.m_{b,v,p} \right) \ ; \ \ \forall b \in B \ ; \ \ \forall p \in P \ ; \ \ \forall p > 0 \tag{5}$$

$$cap_b.n_b \geq l_{b,p} \geq cap_b.n_b.mbl \ ; \ \ \forall b \in B \ ; \ \ \forall p \in P \ ; \ \ \forall p > 0 \tag{6}$$

$$(y_{b,v,p} - y_{b,v,p-1}).mlv.cap_b \leq l_{b,p} \ ; \ \ \forall b \in B \ ; \ \ \forall v \in V \ ; \ \ \forall p \in P \ ; \ \ \forall p > 0 \tag{7}$$

$$\sum_{t \in T} x_{b,t,p} + \sum_{v \in V} y_{b,v,p} = n_b \ ; \ \ \forall b \in B \ ; \ \ \forall p \in P \ ; \ \ \forall p > 0 \tag{8}$$

$$x_{b,t,p} \leq x_{b,t,p-1} + \sum_{v \in V} (y_{b,v,p-1}.sp_{v,t,p}) \ ; \ \ \forall b \in B \ ; \ \ \forall t \in T \ ; \ \ \forall p \in P \ ; \ \ \forall p > 0 \tag{9}$$

$$y_{b,v,p} \leq y_{b,v,p-1} + \sum_{t \in T} (x_{b,t,p-1}.sp_{v,t,p}) \ ; \ \ \forall b \in B \ ; \ \ \forall v \in V \ ; \ \ \forall p \in P \ ; \ \ \forall p > 0 \tag{10}$$

$$\sum_{b \in B} x_{b,t,p} \leq cht_t \ ; \ \ \forall t \in T \ ; \ \ \forall p \in P \tag{11}$$

$$\sum_{b \in B} y_{b,v,p} \leq chv_v \ ; \ \ \forall v \in V \ ; \ \ \forall p \in P \tag{12}$$

$$k_{b,t,p} \leq x_{b,t,p} \ ; \ \ \forall b \in B \ ; \ \ \forall t \in T \ ; \ \ \forall p \in P \ ; \ \ \forall p > 0 \tag{13}$$

$$m_{b,v,p} \leq y_{b,v,p} \ ; \ \ \forall b \in B \ ; \ \ \forall v \in V \ ; \ \ \forall p \in P \ ; \ \ \forall p > 0 \tag{14}$$

$$x_{b,t,0} = Ut_{b,t,0}.n_b \ ; \ \ \forall b \in B \ ; \ \ \forall t \in T \tag{15}$$

$$y_{b,v,0} = Uv_{b,v,0}.n_b \ ; \ \ \forall b \in B \ ; \ \ \forall v \in V \tag{16}$$

$$k_{b,t,0} = k0_{b,t,0}.n_b \ ; \ \ \forall b \in B \ ; \ \ \forall t \in T \tag{17}$$

$$m_{b,v,0} = m0_{b,v,0}.n_b \ ; \ \ \forall b \in B \ ; \ \ \forall v \in V \tag{18}$$

$$l_{b,0} = Lb_0.n_b \ ; \ \ \forall b \in B \tag{19}$$

$$k_{b,t,p} \geq 0 \ ; \ \ \forall b \in B \ ; \ \ \forall t \in T \ ; \ \ \forall p \in P \tag{20}$$

$$m_{b,v,p} \geq 0 \ ; \ \ \forall b \in B \ ; \ \ \forall v \in V \ ; \ \ \forall p \in P \tag{21}$$

$$x_{b,t,p} \in \{0,1\} \ ; \ \ \forall b \in B \ ; \ \ \forall t \in t \ ; \ \ \forall p \in P \tag{22}$$

$$y_{b,v,p} \in \{0,1\} \; ; \; \forall b \in B \; ; \; \forall v \in V \; ; \; \forall p \in P \tag{23}$$

$$n_b \in \{0,1\} \; ; \; \forall b \in B \tag{24}$$

$$u_t \in \{0,1\} \; ; \; \forall t \in T \tag{25}$$

$$k_{b,t,p} \in \{0,1\} \; ; \; \forall b \in B \; ; \; \forall t \in t \; ; \; \forall p \in P \tag{26}$$

$$m_{b,v,p} \in \{0,1\} \; ; \; \forall b \in B \; ; \; \forall v \in V \; ; \; \forall p \in P \tag{27}$$

Constraints 2 and 3 determine the usage of the batteries and the terminals as docking stations. Constraint 4 limits to one the number of batteries that can supply energy to a vessel at each time step. Constraint 5 determines the battery charge level at every time step. It also guarantees that the power requirement from the vessel at each time step is satisfied. Constraint 6 bounds the battery level between the maximum capacity and a minimum battery level to avoid batteries to fully discharge (safety margin). It also guarantees non-negative values for the battery level. Constraint 7 sets a minimum battery level for the battery to be placed on a vessel. Constraint 8 limits the battery location to either a terminal or on a vessel, whereas constraints 9 and 10 match the vessels' routes to the batteries. Not allowing for a battery to move in the network if it is not on a vessel. Constraints 11 and 12 limit the maximum number of batteries that can be at a docking station and on a vessel according to the number of charging and docking spots respectively. Constraints 13 and 14 force the battery to be at a docking station to be charged and to be on a vessel to provide it with energy respectively. Constraints 15, 16, 17, 18 and 19 set the initial battery location, battery usage and battery charge level values. Finally, constraints 20 and 21 set the variables to be non-negative and constraints 22, 23, 24, 25, 26 and 27 defines the binary variables.

4.2.3 Model verification

To verify the model, this is to check if the model works correctly, two verification were performed. Starting with a base model, different parameters were modified and the new results compared against the base model to check if they were logical. Due to limitations given by large computational times, small scenarios needed to be designed for the verification.

Base Model

The base model consists of a simplified network with seven possible terminals that can be potential docking stations, three vessels, sailing different routes and a fleet of twenty possible batteries. A time period of 24 hours with time steps of 1 hour is modelled. The initial locations of the batteries are two on each ship and two on each of the possible docking stations. All the batteries are fully charged at p=0.

In the picture below the terminal locations are shown.

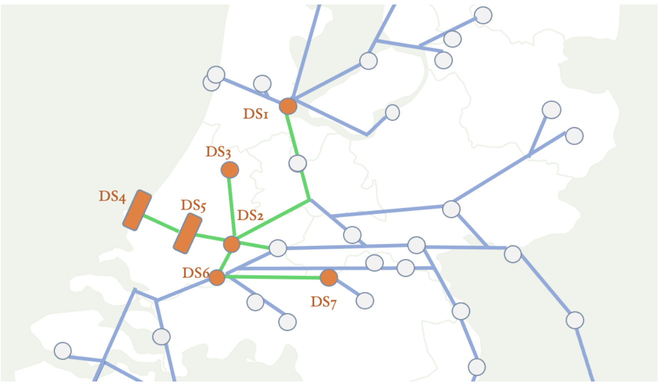


Figure 10: Model verification network

Verification 1: increase in the batteries capacities

Increasing battery capacity will lead to the need of fewer batteries in the system as the vessel's autonomy increases. Moreover, it should lead to the need of less docking stations. If the capacity increases so as to cover the whole 24 hours modelled with one battery, the output of the model should be that only one battery is used for each of the vessels and no docking stations to recharge the batteries are needed. To run the first verification, only the battery capacity was altered. It was increased from 2.000kW to 8.600kW.

Verification 2: increase in the number of docking spots in the vessels

If more docking spots are available on the vessels, it means that the vessels can carry more batteries and, therefore, have larger autonomy. For this verification the number of docking spots was increased to four. Then, twelve batteries were modelled, initially located on the vessels fully charged, plus fourteen batteries located at the terminals (two in each terminal).

As the battery Capex is lower than the DS Capex, it is expected to have an output with more batteries and less or even no DS used.

Verification outputs

In the table below the base case and the two verification outputs, as well as, the expected outputs are shown.

Table 4: Verification outputs

	Base Case	**Verification 1** Increase battery capacity	**Verification 2** Increase vessel docking spots
Number of batteries	6	3	9
Number of DS	6	---	3
Location of DS	DS 1 DS 2 DS 3 DS 4 DS 5 DS 6	---	DS 2 DS 3 DS 5
Expected output		* No DS used * Only 3 batteries used	* Increased number of batteries * Less DS
Check		OK	OK

As it can be seen, the obtained results match the hypothesis made for each of the verifications. It can be said that the model works correctly.

4.3 Model validation

The Proof of Concept (PoC) of the ZEEC implementation is used to validate the model, this is to check the model is an accurate representation of the reality. The PoC was carried out with the first long term contract that ZES has obtained. This contract is with the beer brewer Heineken and their transport operator CCT, who have signed a 10-year contract for transporting beer emission-free from the terminal Alphen an der Rijn to Moerdijk. [51] The sailing route is in the Zoeterwoude - Alpherium - Moerdijk corridor between the CCT harbor in Alpherium and Moedijk. The trip is about 60km and takes approximately 6 hours.

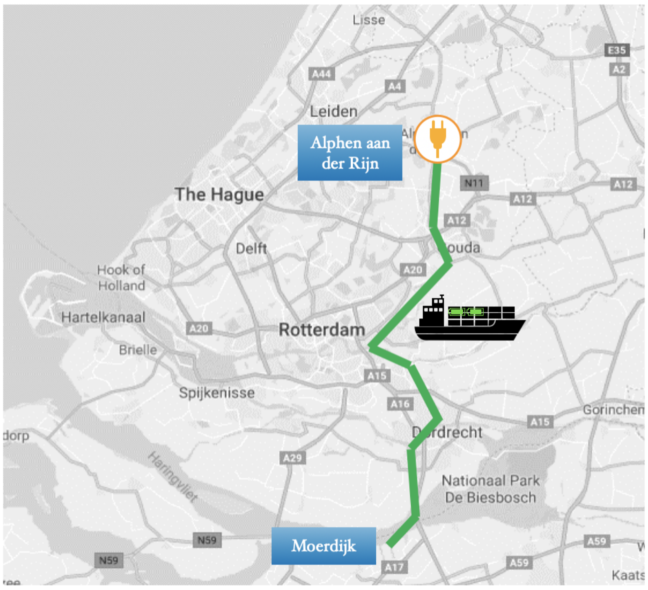


Figure 11: Sailing route of the Alphenaar (PoC). Source [50]

The vessel used for this route is the containership Alphenaar, with a 104 TEU capacity. This vessel sails about 12 hours a day and spends the other 12 hours loading or unloading. The energy consumption of a single trip is 2,1MWh, which is almost the energy a ZES-pack can deliver. [50]

During the time of this research, the Alphenaar was retrofitted in order to accommodate two ZES-packs. At the same time, the first docking station was built in Alphen an der Rijn. [51] Moreover, three ZES-packs were assembled for the PoC operation.

The company is aware that with the current sailing profile, the Alphenaar cannot sail fully electric the round trip abovementioned if it only carries two batteries with useful capacity of 2MWh on average. Therefore, until the battery capacity is not increased, the vessel will have to sail hybrid or adapt its sailing profile so as to reduce power consumption, for example by sailing slower. It is, therefore, expected that the output of the model in the validation will be infeasible for only one docking station, while a possible solution should be to have two docking stations.

For the validation it was assumed that two batteries were available at time p=0 in the vessel, and two batteries were at each of the terminals at which the vessel Alphenaar stops at in its route (terminals 3 and 6). All the batteries were assumed to be fully charged at the initiation of the model run. The modelled time was 48 hs in 2-hour time steps.

The outputs obtained were the need of 2 batteries and 2 docking stations placed in Alphen aan der Rijn and Moerdijk. As explained before the expected output of the model is to have two docking stations that will allow the vessel to complete each one-way trip with the power of two batteries. Then the batteries are recharged while the ship is at the terminal.

4.4 Summary

In this chapter the method used to analyse the implementation of the exchangeable batteries and docking stations to electrify IWW vessels was presented. Firstly, the conceptual model is defined. The objective of the developed model is to find the optimal combination of batteries and docking stations to successfully provide electric power to a certain demand of vessels. For this, the inputs used for the model are the capacity and Capex of the batteries, the DS design and Capex, the vessels' sailing profiles and docking spots on board and the network represented by the terminals in the routes of the vessels. The outputs of the model are the needed batteries and docking stations, specifying the DS locations and the battery charge level, location and use at all times. To develop the model some project requirements needed to be considered which are the time scale, flexibility, scalability and scenario analysis. Some of the most relevant assumptions and simplifications made to conceptualise the model are that the battery capacity is modelled as a fix parameter per battery and that no ageing or power loss are modelled. Different battery capacities can be modelled by inputting different values to the batteries of the fleet available. Moreover, the batteries are modelled to be charged and discharged linearly. Apart from this, vessels' speeds are not directly modelled, neither changes in sailing profiles due to external factors such as weather. Alterations on the vessels' speed can be introduced by changing the sailing profiles. Finally, the only costs considered in the model were the batteries and docking stations Capex.

The optimisation model developed is a time-discrete mixed integer linear programming model with deterministic inputs. The network used as input for the model is simplified so as to be easily scalable and flexible to be adapted to other networks. For this the terminals that are part of the vessel's routes are numbered, and the sailing profiles are written so as to fit with this numbered terminals.

The model is verified for two cases against a base case of three vessels sailing routes using seven different terminals, with two fully charged batteries available at every terminal and on the vessels at p=0. The first verification varies the battery capacity and the second one the number of docking spots on the vessels. In the first case very large battery capacities are given as inputs and in the second four docking spots are set per vessel instead of two. The results obtained in both cases were coherent with the hypothesis. For the first verification only one battery per vessel was required and no docking stations, whereas, in the second verification, more batteries but less docking stations are needed.

Finally, the model is validated using the PoC developed by the company. After running the model with the inputs of the PoC, the results obtained showed, as expected, that two docking stations and two batteries were needed to satisfy the power requirements of the vessel.

5 Application of exchangeable batteries distribution and docking station location optimisation model for IWW shipping

5.1 Model implementation

There are many programs in which the MILP can be developed and implemented. For this research, Python was the language used for the programming and Spyder the program to run the code. Moreover, as mentioned before the optimiser Gurobi was chosen as the solver for the optimisation problem.

Given the amount of binary variables that the model has, computational time is an issue when solving the optimisation problem. Though Gurobi has very fast solvers as it first reduces the size of the problem using a pre-solver, the running times proved to be an issue for the modelled problem when more than four vessels and 24 time steps were modelled. For this reason, analysing the whole fleet of vessels of the first scale-up phase was not directly possible.

Therefore, it was decided to firstly analyse numerical experiments with fictitious sailing profiles with which to prove the main opportunities that the optimisation model can bring to the system. For this, three key performance indicators (KPIs) were defined: number of batteries per vessel, DS per vessel and investment cost per vessel. The sailing profiles are designed so as to show the possible gains that can be obtained in each case. Though the profiles are not real they attempt to be as realistic as possible. For this, a consistent network of locations and connections was considered with vessels sailing closed-loop routes. Moreover, the sailing and docking times tried to resemble the case data. The specific assumptions used will be further explained in 5.2.1.

The idea is to analyse how increases in the demand for zero emission vessels affect the different KPIs for two scenarios, the same corridor and multiple corridors. Moreover, the impact of battery capacity variations, docking stations design (number of charging spots and power of each charging spot) and number of docking spots on the vessels, will also be assessed. Secondly, experiments will be run with the real sailing profiles simplified and adapted to fit in 24 hours to see to what extend the KPIs changed in real-life cases. For this the ZES case study is presented.

5.2 Numerical experiments

As mentioned before, firstly numerical experiments will be run with fictitious sailing profiles. In the next subchapter the designed network with its terminals, sailing routes and vessel power requirement will be explained. Following this comes the scenario analysis. This analysis will be done following the methodology explained in 1.4. Starting by the definition and construction of the scenarios. Firstly, a base cases that will be used to compare the other scenarios is introduced and the four scenarios that will be analysed are described. Then, the model is run with each scenario and the results are analysed. The subchapter finalises with the discussion of the obtained results.

5.2.1 Network & sailing profiles

The fictitious sailing profiles were build in order to show the potential that the model can have in terms of battery and docking station number and location optimisation. Though fictitious, these profiles tried to resemble a logical sailing profile of a real vessel of the case study. Meaning that the following considerations were made when building them:

- 24/7 operation: not allowing a vessel to use the batteries during the day and another during the night. This is the sort of operation the case study container barges have;
- Sailing times larger than times at terminals;
- Total power consumption per trip between terminals similar to real profiles of the vessels (see B);
- Closed-loop routes;
- Round trips shorter than the 24 hours modelled so as to guarantee that the battery at the end of the time period is enough to start a new trip.

A network of five terminals and vessels with four different routes were considered as it can be seen in the figure below.

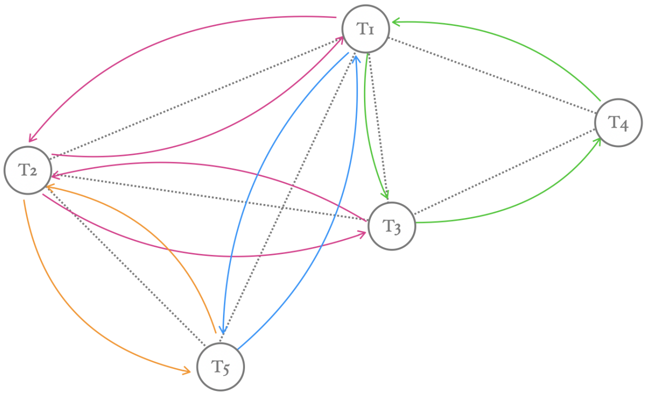


Figure 12: Fictitious routes

- Route A (red): T1 - T2 - T3 -T2 -T1
- Route B (green): T1 - T3 - T4 - T1
- Route C (orange): T2 - T5 - T2
- Route D (blue): T1 - T5 – T1

With the abovementioned considerations and network the following profiles were designed.

Table 5: Fictitious sailing profiles

	Sailing profile A		Sailing profile B		Sailing profile C		Sailing profile D	
Time [hs]	**Location**	**Power [kW]**	**Location**	**Power [kW]**	**Location**	**Power [kW]**	**Location**	**Power [kW]**
1	T1	0	Sailing	700	T5	0	Sailing	600
2	Sailing	800	Sailing	700	T5	0	Sailing	600
3	Sailing	800	T1	0	T5	0	T1	0
4	T2	0	T1	0	Sailing	550	Sailing	600
5	T2	0	Sailing	700	Sailing	550	Sailing	600
6	Sailing	800	Sailing	700	Sailing	550	T5	0
7	Sailing	800	Sailing	700	Sailing	550	Sailing	600
8	Sailing	800	T3	0	Sailing	550	Sailing	600
9	Sailing	800	T3	0	Sailing	550	T1	0
10	T3	0	Sailing	700	T2	0	Sailing	600
11	T3	0	Sailing	700	T2	0	Sailing	600
12	Sailing	800	Sailing	700	T2	0	T5	0
13	Sailing	800	T4	0	Sailing	550	Sailing	600
14	Sailing	800	T4	0	Sailing	550	Sailing	600
15	Sailing	800	Sailing	700	Sailing	550	T1	0
16	T2	0	Sailing	700	Sailing	550	Sailing	600
17	T2	0	Sailing	700	Sailing	550	Sailing	600
18	Sailing	800	T1	0	Sailing	550	T5	0
19	Sailing	800	T1	0	T5	0	Sailing	600
20	Sailing	800	Sailing	700	T5	0	Sailing	600
21	Sailing	800	Sailing	700	T5	0	T1	0
22	T1	0	Sailing	700	Sailing	550	Sailing	600
23	T1	0	T3	0	Sailing	550	Sailing	600
24	Sailing	800	T3	0	Sailing	550	T5	0

5.2.2 Base Case

The aim of the base case is to have reference values to which to compare the outputs of the different scenarios. For each vessel a base case is modelled. The following assumptions and considerations were made for the base case inputs:

- All vessels will be modelled considering the same time horizon of 24 hours;
- The time step is 1 hour;
- Fully charged batteries are available on the vessels and on the terminals of the vessel's routes at the beginning of the first time period (p=0);
- Every terminal of the route of the vessel is a possible docking station with 2 charging spots that provide 1.000kW each;
- Battery capacity: 2.000kWh/battery;
- Battery capex: 955.500€/battery;
- Docking station capex: 1.350.000€/DS;
- The minimum battery level to be place on a vessel is 100% and batteries should have at least a 10% of battery level at all times.

5.2.3 Scenario 1: increase in number of vessels

In the first scenario the vessels' demands will be modified. Firstly, one single route will be considered. The model will be run for one up to four vessels of the same characteristics and sailing profiles. The sailing profile chosen for this test is the sailing profile A. This sailing profile was selected because it visits three terminals and also has the largest power consumption per sailing period. This led to the best results in terms of battery per vessel and cost per vessel reduction with vessel demand increase, compared to sailing profiles B, C and D. To simulate the added demand (more vessels with the same profile) the profiles are offset one of the other every 6 hours. The second scenario considers all routes. In this case, four vessels with different routes and sailing profiles were modelled, one per corridor. All the other parameters will be kept as explained for the Base Case.

The idea of this scenario is to show the reduction of batteries per vessel and docking station per vessel when vessel demand increases. Therefore, to show the benefit in terms of Capex, of having shared batteries between vessels instead of assigned batteries to each vessel.

5.2.4 Scenario 2: capacity variations of batteries

For the second scenario variations in battery capacity are implemented for the whole battery fleet for a vessel demand of 3 vessels, sailing the profile D (see table 5). As mentioned in 2.3.1 it is expected that battery capacity will increase over time, leading to larger sailing ranges. Therefore, it is very relevant to analyse how battery capacity increases might affect the model outputs.

An increase in the battery capacity will have an impact on the needed number of batteries but also can affect the possible docking station locations, as the larger the power the batteries can supply the larger the vessel autonomy and the less docking stations are needed. On the other hand smaller batteries are cheaper, therefore, it might be of interest to have more smaller batteries if vessels do not require so much power.

The values of the different battery capacity and Capex analysed in each case of this scenario are shown in the table below. The values were provided by the company. All the other parameters will be kept as explained for the Base Case.

Table 6: Batteries capacity and Capex. Source: ZES internal meeting

Battery capacity [kWh]	Capex [€]
1.500	817.000
2.000	955.500
2.500	1.107.000
3.000	1.252.000

5.2.5 Scenario 3: number & capacities of charging spots in Docking Stations

The base case is run assuming all docking stations to be equal as the one being built for the Proof of Concept at Alphen aan der Rijn. However, depending on the actual demand of charging spots and power, the DS could be larger or smaller. Therefore, several scenarios varying the DS design (number of charging spots and power per spot) are analysed. The different DS designs will also imply different Capex. This scenario can be useful to assess possible trade-offs between number and size of the docking stations.

The values analysed in each case of this scenario are shown in the table below, the different docking stations possibilities have different Capex. A demand of three vessels sailing the profiles A, B and C was considered. All the other parameters will be kept as explained for the Base Case.

Table 7: Docking stations charging spots, power and Capex. Source: ZES internal meeting

Charging spots	Power per charging spot [kW]	Capex [€]
2	1.000	1.350.000
2	500	1.080.000
1	750	840.000
1	1.000	950.000

A fifth and sixth case of this scenario were run considering a combination of docking stations designs of two charging spots with 1.000kW and two charging spots of 500kW. Firstly the number of needed DS and charging times of each DS is determined for the first scenario (two charging spots of 1.000kW) then smaller DS are set as input parameters for those stations with less charging demand.

5.2.6 Scenario 4: number of docking spots on board of vessels

As mentioned in 4.1.3, the vessels' retrofit costs and revenue loss for carrying batteries instead of cargo are not considered in the model. To analyse the total system costs of implementing the exchangeable batteries system these costs need to be accounted for. Therefore, different scenarios with different number of docking spots on vessels will be analysed. All the other parameters will be kept as explained for the Base Case.

The idea is to determine the optimal number of batteries and docking stations to have the least total costs, including the vessels retrofit costs and profit loss for carrying batteries instead of cargo, which are determined by the number of docking spots. Cases with two and three vessels sailing the profile D will be compared. A fully charged battery will be placed per docking spot in the vessel at p=0.

5.2.7 Results

In this subchapter the obtained results for the Base Case and the different scenarios will be shown and discussed.

Base Case

Table 8: Base Case results for the fictitious sailing profiles

	Scenarios			
Number of vessels	1	1	1	1
Sailing profile type	A	B	C	D
Number of batteries required	5	2	2	3
Number of docking stations	3	3	2	1
Locations	T1, T2, T3	T1, T3, T4	T2, T5	T5
Total Capex [€]	8.827.500	5.961.000	4.611.000	4.216.500

Scenario 1: increase in number of vessels

The obtained results for this scenario are shown in the tables below for both cases, same route and different routes. In the second table the results are presented as follows. For each vessel demand, the first column are the summed results of the independent sailing profiles (as in the base case). The second column shows the results of the combined case.

Table 9: Results of Scenario 1: increase in demand in the same route for the fictitious sailing profiles

	Scenarios			
Number of vessels	1	2	3	4
Sailing profile type	A	A	A	A
Number of batteries required	5	7	9	11
Number of docking stations	3	3	3	3
Locations	T1, T2, T3	T1, T2, T3	T1, T2, T3	T1, T2, T3
Total Capex [€]	8.827.500	10.738.500	12.649.500	14.560.500
Batteries per vessel	5,0	3,5	3,0	2,8
DS per vessel	3,0	1,5	1,0	0,8
Shared batteries	0	3	8	8
	---	3 by 2 vessels	8 by 2 vessels	6 by 2 vessels 2 by 3 vessels
Cost per vessel [€/vessel]	8.827.500	5.369.250	4.216.500	3.640.125

Table 10: Results of Scenario 1: increase in demand in different routes for the fictitious sailing profiles

	Scenarios					
Number of vessels	2		3		4	
Sailing profile type	A+B	A, B	A+B+C	A, B, C	A+B+C+D	A, B,C, D
Number of batteries required	7	5	9	7	12	11
Number of docking stations	4	4	5	5	5	4
Locations	T1, T2, T3, T4	T1, T2, T3, T4	T1, T2, T3, T4, T5	T1, T2, T3, T4, T5	T1, T2, T3, T4, T5	T1, T2, T3, T5
Total Capex [€]	12.088.500	10.177.500	15.349.500	13.438.500	18.216.000	15.910.500
Batteries per vessel	3,5	2,5	3,0	2,3	3,0	2,8
DS per vessel	2,0	2,0	1,7	1,7	1,3	1,0
Shared batteries	0	2	0	4	0	5
	---	2 by 2 vessels	---	4 by 2 vessels	---	5 by 2 vessels
Cost per vessel [€/vessel]	6.044.250	5.088.750	5.116.500	4.479.500	4.554.000	3.977.625

In both cases, an increase in demand in the same corridor and in different corridors led to a decrease of needed batteries and docking stations per vessel. This is due to sharing of batteries and infrastructure. In the case of the same corridor, the need for batteries for only one vessel is very high, but as soon as more vessels of the same type sail the same route, battery sharing occurs, reducing the needed number of battery per vessel significantly. Every time a new vessel is added to the route, the battery per vessel requirement decreases steadily.

For different routes, a decrease of batteries per vessel can be seen when comparing to the sum of the sailing profiles independently (as in the base case). The decrease depends on the routes that have been shared. The decrease is also not constant, as the different routes combinations do not allow the sharing in all terminals. Regarding the DS per vessel only for the combined case of profiles type A, B, C and D, a decrease in needed DS is seen compared to the scenario of summing the independent profiles.

As for the investment cost in batteries and DS per vessel a decrease is seen in both cases as demand increases. Showing that a better scenario in terms of Capex can be obtained if more vessels use the installed infrastructure, as benefits from synergies between the routes can be reached.

Scenario 2: capacity variations of batteries

The obtained results for this scenario are shown in the tables below for the same route.

Table 11: Results of Scenario 2: battery capacity variations in the same route for the fictitious sailing profiles

	Scenarios			
Number of vessels	3	3	3	3
Sailing profile type	D	D	D	D
Battery capacity [kWh]	1.500	2.000	2.500	3.000
Battery cost [€]	817.000	955.500	1.107.000	1.252.000
Number of batteries required	8	7	7	7
Number of docking stations	2	2	2	1
Locations	T1, T5	T1, T5	T1, T5	T5
Total Capex [€]	9.236.000	9.388.500	10.449.000	10.114.000
Batteries per vessel	2,7	2,3	2,3	2,3
DS per vessel	0,7	0,7	0,7	0,3
	8	7	6	6
Shared batteries	4 by 2 vessels 4 by 3 vessels	6 by 2 vessels 1 by 3 vessels	5 by 2 vessels 1 by 3 vessels	2 by 2 vessels 4 by 3 vessels
Cost per vessel [€/vessel]	3.078.667	3.129.500	3.483.000	3.371.333

It can be expected that an increase in battery capacity will lead to a reduction on the total number of needed batteries per vessel. However, this depends on the case as larger battery capacity can lead to less docking stations, maintaining the number of batteries. This is the case for a fleet of batteries with 3.000kWh the same number of batteries but less docking stations than with 2.000kWh is needed. This reduction however, does not lead to a benefit in terms of costs per vessel, as the increase in battery cost per unit does not compensate the reduction in docking stations costs. Despite the above, a scenario like this can be of interest as one less docking station will also mean less operational costs (which are not included in the model, but need to be assessed) and more income to that one station, as all batteries need to be charged there.

For the case of a battery capacity decrease, one more battery is needed but the same docking stations. Given the cost reduction of the smaller battery, this scenario is better than the original in terms of costs. Regarding the shared batteries not a significant difference is seen between the scenarios.

Scenario 3: number & capacities of charging spots in Docking Stations

The obtained results for this scenario are shown in the tables below for the different routes.

Table 12: Results of Scenario 3: docking stations design variations in different routes for the fictitious sailing profiles

	Scenarios							
Number of vessels	3	3	3	3	3		3	
Sailing profile type	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C		A, B, C	
DS spots	2	2	1	1	2	2	2	1
Power per docking spot [kW]	1.000	500	750	1.000	1.000	500	1.000	750
DS Capex [€]	1.350.000	1.080.000	840.000	950.000	1.350.000	1.080.000	1.350.000	840.000
Number of batteries required	7	Infeasible	Infeasible	Infeasible	10		9	
Number of docking stations	5	---	---	---	3	2	3	2
Locations	T1, T2, T3, T4, T5	---	---	---	T2, T3, T5	T1, T4	T2, T3, T5	T1, T4
Total Capex [€]	13.438.500	---	---	---	15.765.000		14.329.500	
Batteries per vessel	2,3	---	---	---	3,3		3,0	
DS per vessel	1,7	---	---	---	1,7		1,7	
Shared batteries	4	---	---	---	4		4	
	4 by 2 vessels	---	---	---	4 by 4 vessels		4 by 4 vessels	
Cost per vessel [€/vessel]	4.479.500	---	---	---	5.255.000		4.776.500	

It can be seen that when changing all the docking stations types for two charging spots of 1000kW, one charging spot of 750kW and one charging spot of 1.000kW, no result is feasible. Meaning that the charging infrastructure considered cannot satisfy the charging demand of the battery fleet.

To design the fifth and sixth cases, the charging demand required for the DS of the first scenario (two charging spots of 1.000kW) was determined and two of them were significantly less demanded than the other three (stations in T1 and T4). Then, these two stations were set with a smaller design. The results obtained do not show an improvement in both cases in terms of cost per vessel, batteries per vessel or docking stations per vessel. However, it can be of relevance to assess this scenarios as smaller DS will have fewer operational costs.

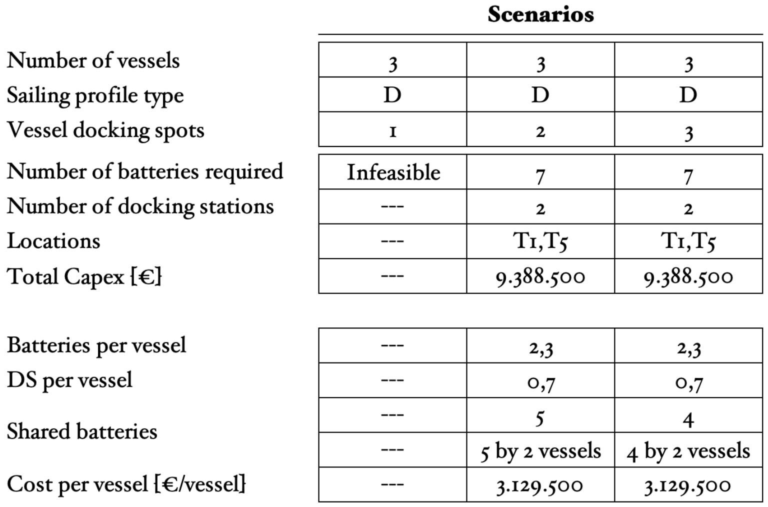
Scenario 4: number of docking spots on board of vessels

The obtained results for this scenario are shown in the tables below for the same route for two and three vessels.

Table 13: Results of Scenario 4: number of docking spots on board variations for 2 vessels sailing same fictitious route

	Scenarios		
Number of vessels	2	2	2
Sailing profile type	D	D	D
Vessel docking spots	1	2	3
Number of batteries required	Infeasible	5	6
Number of docking stations	---	2	1
Locations	---	T1,T5	T1
Total Capex [€]	---	7.477.500	7.083.000
Batteries per vessel	---	2,5	3,0
DS per vessel	---	1,0	0,5
Shared batteries	---	5	4
	---	5 by 2 vessels	4 by 2 vessels
Cost per vessel [€/vessel]	---	3.738.750	3.541.500

Table 14: Results of Scenario 4: number of docking spots on board variations for 3 vessels sailing same fictitious route



	Scenarios		
Number of vessels	3	3	3
Sailing profile type	D	D	D
Vessel docking spots	1	2	3
Number of batteries required	Infeasible	7	7
Number of docking stations	---	2	2
Locations	---	T1,T5	T1,T5
Total Capex [€]	---	9.388.500	9.388.500
Batteries per vessel	---	2,3	2,3
DS per vessel	---	0,7	0,7
Shared batteries	---	5	4
	---	5 by 2 vessels	4 by 2 vessels
Cost per vessel [€/vessel]	---	3.129.500	3.129.500

The results of the fourth scenario show that no significant improvements are obtained when adding more docking spots on board. In the case of a two vessel demand on the same corridor adding one more docking spot on board of the vessels leads to a trade-off of less DS but more batteries, that leads to a reduction of the total investment cost per vessel. However, as mentioned in 2.3.3, more docking spots on board mean larger retrofit costs and more revenue loss for carrying batteries instead of cargo containers. Therefore, the improvement found needs to be compared against this cost increase on the shippers side. Very likely it will not compensate the retrofit and revenue loss costs.

In the case of three vessels on the same corridor no benefit is observed when increasing the number of batteries on board as this does not compensate the need for the investment in two DS. For both cases, a reduction in docking spots on board made the model not feasible, meaning that there is no possible combination of charging infrastructure and battery fleet that to guarantee electric sailing for the vessels.

5.3 ZES study case

As mentioned before, the developed model will also be implemented to the real case of ZES to assess what possible synergies can be obtained regarding the charging infrastructure and the batteries needed. This subchapter starts with a brief description of the case study, which includes the expected vessel demand, sailing profiles and the used network representation. Followed by the scenario analysis, results and discussion.

ZES is a start-up company, whose main stakeholders are the Port of Rotterdam, Engie, ING and Wärtsilä. It has received a subsidy of the Dutch government to develop and implement a new energy concept for IWW shipping based on exchangeable batteries (ZEEC). ZES relies also on the support of a large shipper, in this case Heineken, who has signed a 10-year contract with the company for the transport of beer from the brewery in Zoeterwoude, via the inland shipping terminal Alpherium to Moerdijk.

The modular batteries, called ZES-packs, were designed to fit in a 20ft containers and are used to provide the vessels with electric power. The batteries are charged at docking stations, where they could also be used to provide grid stabilisation when used for the FCR market or used as generators for other business opportunities, for instance, at building sites or festivals.

The first ZES-packs designed by the company were assembled during the first months of this research and are the ones currently being used by the Alphenaar, Heineken's vessel. These ZES-packs were built with lithium-ion batteries and they can provide an average usable energy of up to 2MWh, allowing an approximate 100km shipping range for vessels, or two hours of sailing efficiency. [49] During this research, the first docking station was built in Alphen aan den Rijn and the Alphenaar vessel was retrofitted, in what constitutes the Proof of Concept phase of the ZEEC implementation.

5.3.1 Vessel demand

The vessel demand of the case study of this research is the one estimated by ZES for the first scale up phase of the exchangeable batteries system implementation. It involves seven vessels sailing in four corridors, namely, the Groene, Oost Brabant, Noord Nederland and Maas corridor. The corridors with the terminals that are current stops of the mentioned vessels are shown in the map below.

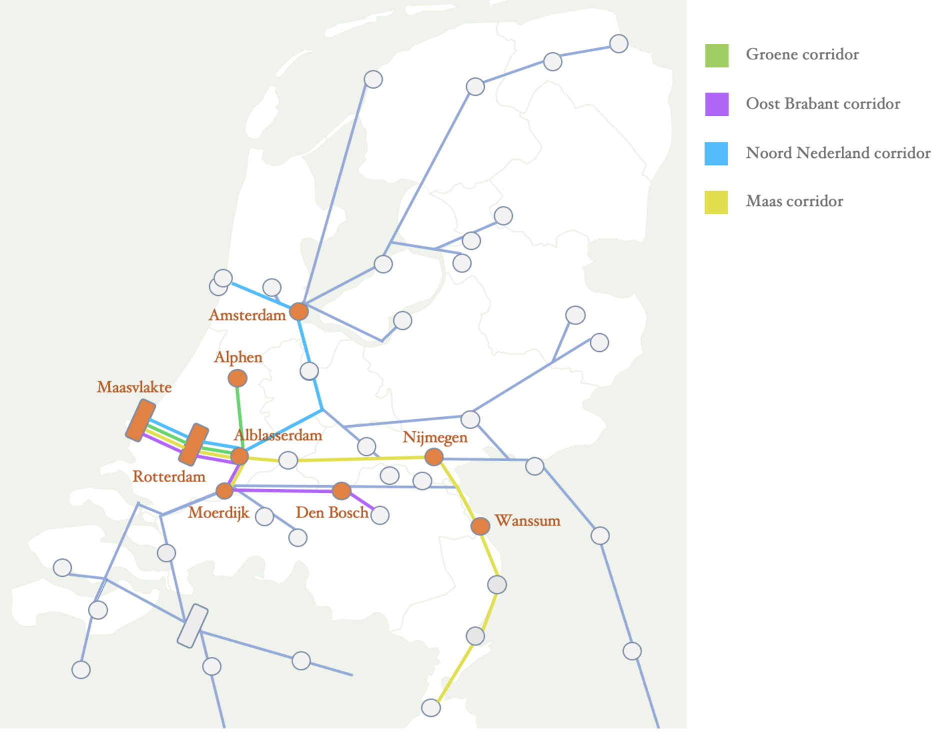


Figure 13: Scale-up phase 1 corridors and terminal locations.

Vessels' sailing profiles

The sailing profiles were provided by the shippers (see Appendix B for the detailed sailing profiles). These include the vessel location, power consumption when sailing and the time to sail from one terminal to another. The sailing profiles had to be adapted in order to fit the layout of the inputs for the model. Firstly, the locations and power consumption were written per the defined time step. Then, the locations were rewritten with the terminal numbering described in 5.3.2. When the vessel is sailing then the location is 0.

As the routes of the real-life vessels are quite long, and the model running times restrict the maximum time steps to 24, it was decided to adapt the sailing profiles with time steps of 2 hours. In this way, 24 time steps represent 48 hours of sailing time. Some adjustments and simplifications had to be done to fit all the profiles in the abovementioned template. For example, if a vessel power requirement was of 3.280 kWh for a sailing time of 10 hours, and it was assumed a 2-hour time step, then the power requirement per time step is 656kWh.

The figures below show the vessels' main characteristics and their routes.

Alphenaar & Gouwenaar

Characteristics	Vessel type	Inland container barge	
	Beam	11	m
	Length	90	m
	Capacity	104	TEU
Round trip	Length	122	km
	Time	23,5	hs
	Avg. energy	4.100	kWh

Figure 14: Alphenaar & Gouwenaar characteristics and route.

Nijmegen Max

Characteristics	Vessel type	Inland container barge	
	Beam	11,4	m
	Length	110	m
	Capacity	220	TEU
Round trip	Length	382	km
	Time	61,5	hs
	Avg. energy	13.000	kWh

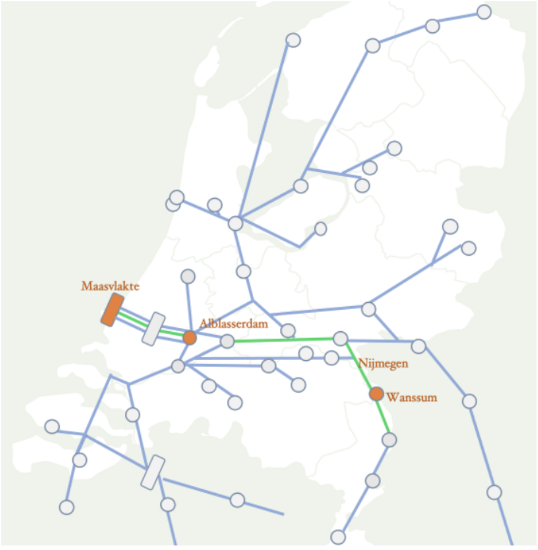
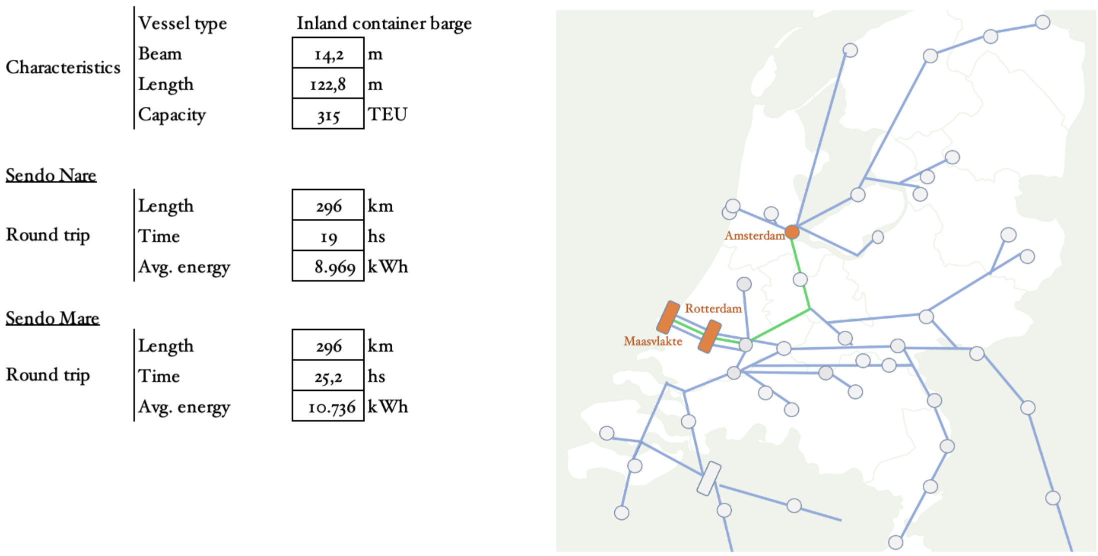


Figure 15: Nijmegen Max characteristics and route.

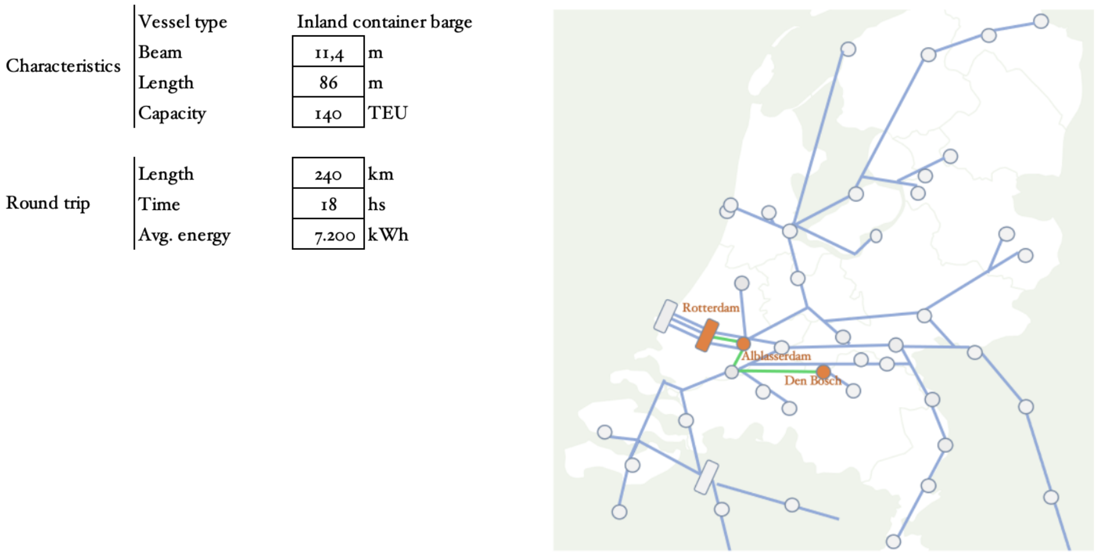
Sendo Mare & Sendo Nave



Characteristics	Vessel type	Inland container barge	
	Beam	14,2	m
	Length	122,8	m
	Capacity	315	TEU
Sendo Nare			
Round trip	Length	296	km
	Time	19	hs
	Avg. energy	8.969	kWh
Sendo Mare			
Round trip	Length	296	km
	Time	25,2	hs
	Avg. energy	10.736	kWh

Figure 16: Sendo Mare & Sendo Nave characteristics and route.

Den Bosch Max Groen & Den Bosch Blauw



Characteristics	Vessel type	Inland container barge	
	Beam	11,4	m
	Length	86	m
	Capacity	140	TEU
Round trip	Length	240	km
	Time	18	hs
	Avg. energy	7.200	kWh

Figure 17: Den Bosch Max Groen & Den Bosch Blauw characteristics and route.

5.3.2 Network representation

As mentioned in 5.3.1 the vessel demand for the first scale-up phase sails in four corridors. These vessels have currently nine terminals as stops in their sailing profiles. In these locations ZES determined it was feasible to place the docking stations. However, it is expected to have different space availability, accessibility to the electric grid and distance to the mooring docks for each terminal. Though these aspects will not be modelled, they need to be considered in future analysis as different locations will have different capital and operational costs. For the model inputs, the terminals were represented by numbers, as shown in the figure below.

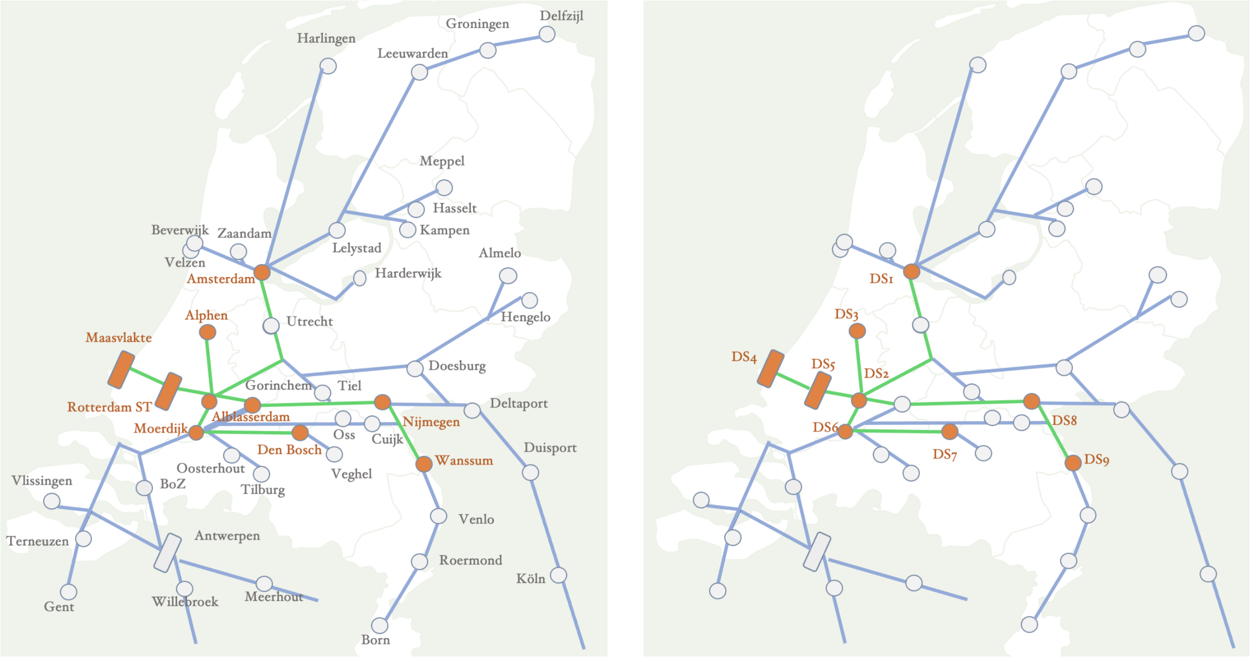


Figure 18: Study case scale-up phase 1 network representation

5.3.3 Scenario analysis

The same scenarios as presented in 5.2 were implemented for the study case of ZES with the abovementioned sailing profiles and routes. Firstly, the independent vessels are modelled to set up the base cases against which the different scenarios will be compared.

Base case:

The input assumptions made for the base case are:

- All vessels will be modelled considering the same time horizon of 48 hours;
- The time step is 2 hours;
- Fully charged batteries are available on the vessels and on the terminals of the vessel's routes at the beginning of the first time period (p=0);
- Every terminal of the route of the vessel is a possible docking station with 2 charging spots that provide 1.000kW each;
- Battery capacity: 2.000kWh per battery;
- Battery capex: 955.500€ per battery;
- Docking station capex: 1.350.000€ per DS;
- The minimum battery level to be place on a vessel is 100% and batteries should have at least a 10% of battery level at all times.

Scenario 1: increase in number of vessels

For the vessel demand increase the same corridor and sailing profile of the DB Max was used and an increase from one to four vessels was performed. Moreover, a combination of four vessels sailing the Alphenaar, Gouwenaar, DB Max Blauw and DB Max Groen was done. The reason for selecting these vessels is that this combination allows to see the benefits of the optimisation by sharing infrastructure and or batteries, while complying with the limitation of modelling maximum four vessels due to computational time restrictions.

Scenario 2: capacity variations of batteries

Battery capacity variations were modelled to analyse the changes of batteries and docking stations required for four vessels sailing the combination routes of the Alphenaar, Gouwenaar, DB Max Blauw and DB Max Groen. The values of battery capacities and corresponding Capex used for the scenario, are those of table 6.

Scenario 3: number & capacities of charging spots in Docking Stations

For the changes in DS design the combined sailing of four vessels with the Alphenaar, Gouwenaar, DB Max Blauw and DB Max Groen routes was used. Then different DS designs, charging points and capacity, were studied. The DS designs used for the cases of this scenario are those shown in table 7.

Scenario 4: number of docking spots on board

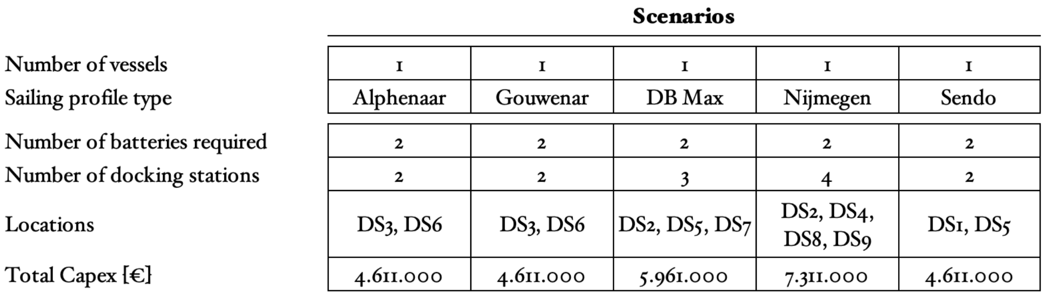
A reduction and increase in docking spots on the vessels were performed for the case of four vessels with the Alphenaar, Gouwenaar, DB Max Blauw and DB Max Groen routes. A fully charged battery is considered per docking spot in the vessel at p=0.

5.3.4 Results

Base case:

The table below shows the results obtained for the individual vessels.

Table 15: Results of the Base Case for the case study

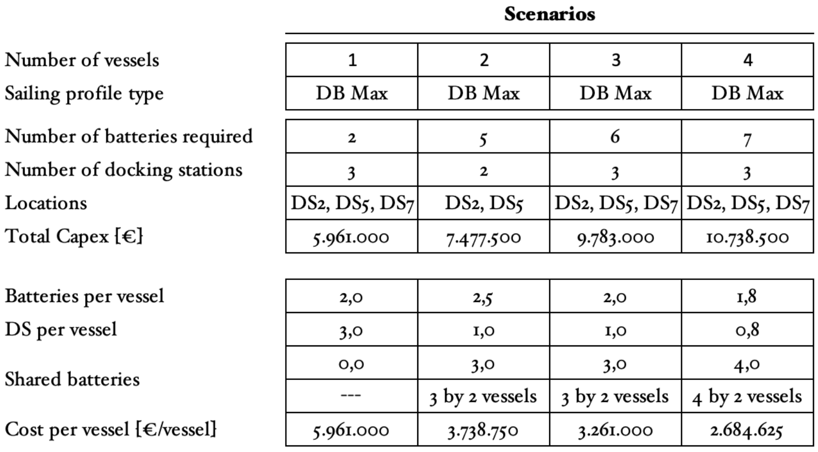


	Scenarios				
Number of vessels	1	1	1	1	1
Sailing profile type	Alphenaar	Gouwenar	DB Max	Nijmegen	Sendo
Number of batteries required	2	2	2	2	2
Number of docking stations	2	2	3	4	2
Locations	DS3, DS6	DS3, DS6	DS2, DS5, DS7	DS2, DS4, DS8, DS9	DS1, DS5
Total Capex [€]	4.611.000	4.611.000	5.961.000	7.311.000	4.611.000

Scenario 1: increase in number of vessels

The table below shows the results obtained for vessel demand variations for the same sailing profile and for a combination of profiles. For the second table, the first column shows the summed results of the independent sailing profiles (as in the base case), whereas the second column shows the results of the combined profiles.

Table 16: Results of Scenario 1: increase in demand for the same sailing profile for the case study



	Scenarios			
Number of vessels	1	2	3	4
Sailing profile type	DB Max	DB Max	DB Max	DB Max
Number of batteries required	2	5	6	7
Number of docking stations	3	2	3	3
Locations	DS2, DS5, DS7	DS2, DS5	DS2, DS5, DS7	DS2, DS5, DS7
Total Capex [€]	5.961.000	7.477.500	9.783.000	10.738.500
Batteries per vessel	2,0	2,5	2,0	1,8
DS per vessel	3,0	1,0	1,0	0,8
Shared batteries	0,0	3,0	3,0	4,0
	---	3 by 2 vessels	3 by 2 vessels	4 by 2 vessels
Cost per vessel [€/vessel]	5.961.000	3.738.750	3.261.000	2.684.625

Table 17: Results of Scenario 1: increase in demand for the different sailing profile for the case study

	Scenarios	
Number of vessels	4	4
	Alphenaar + Gouwenaar + DB Max B +DB Max G	Alphenaar, Gouwenaar DB Max B, DB Max G
Number of batteries required	8	9
Number of docking stations	5	4
Locations	DS2, DS3, DS5, DS6, DS7	DS2, DS3, DS5, DS6
Total Capex [€]	14.394.000	13.999.500
Batteries per vessel	2,0	2,3
DS per vessel	1,3	1,0
Shared batteries	0,0	3,0
	---	3 by 2 vessels
Cost per vessel [€/vessel]	3.598.500	3.499.875

As it can be seen in table 16 a reduction of costs per vessel is gained as demand increases for the DB Max vessel. Deploying a second DB Max vessel (column 2) results in an increase in batteries per vessel but in a reduction in DS per vessel. This can be of interest as for a first stage might be more convenient to invest in one DS and more batteries and then expand to one more DS once more demand is guaranteed (columns 3 and 4). From two to four vessels the increase in demand represented a reduction of both, batteries and DS per vessel.

In the case of combining the sailing profiles of the four vessels, a total Capex reduction per vessel was observed if compared to the sum of the individual vessels. Moreover, a trade-off of one less DS but one extra battery is seen.

Scenario 2: capacity variations of batteries

The table below shows the results obtained for battery capacity variations for a combination of profiles.

Table 18: Results of Scenario 2: capacity variations for the case study

	Scenarios			
Number of vessels	4	4	4	4
Sailing profile type	Alphenaar, Gouwenaar DB Max B, DB Max G	Alphenaar, Gouwenaar DB Max B, DB Max G	Alphenaar, Gouwenaar DB Max B, DB Max G	Alphenaar, Gouwenaar DB Max B, DB Max G
Battery capacity [kWh]	1.500	2.000	2.500	3.000
Battery cost [€]	817.000	955.500	1.107.000	1.252.000
Number of batteries required	Infeasible	9	8	8
Number of docking stations	---	4	3	3
Locations	---	DS2, DS3, DS5, DS6	DS3, DS5, DS7	DS5, DS6, DS7
Total Capex [€]	---	13.999.500	12.906.000	14.066.000
Batteries per vessel	---	2,3	2,0	2,0
DS per vessel	---	1,0	0,8	0,8
Shared batteries	---	3	0	0
	---	3 by 2 vessels	---	---
Cost per vessel [€/vessel]	---	3.499.875	3.226.500	3.516.500

A reduction in battery capacity proved to be unfeasible for the combination of vessels. Both capacity increases, to 2.500kWh and 3.000kWh, proved to require less batteries and less docking stations than the base case. However, for an increase of 3.000kWh the cost per vessel is slightly larger than for 2.000kWh. These results should be further analysed to determine the strategic investment decisions, as reducing one docking station signifies less operational costs that were not considered in the model.

Scenario 3: number & capacities of charging spots in Docking Stations

The table below shows the results obtained for different DS designs for a combination of profiles.

Table 19: Results of Scenario 3: DS designs variations for the case study

	Scenarios			
Number of vessels	4	4	4	4
Sailing profile type	Alphenaar, Gouwenaar DB Max B, DB Max G	Alphenaar, Gouwenaar DB Max B, DB Max G	Alphenaar, Gouwenaar DB Max B, DB Max G	Alphenaar, Gouwenaar DB Max B, DB Max G
DS spots	2	2	1	1
Power per docking spot [kW]	1.000	500	750	1.000
DS Capex [€]	1.350.000	1.080.000	840.000	950.000
Number of batteries required	9	8	8	8
Number of docking stations	4	5	5	5
Locations	DS2, DS3, DS5, DS6	DS2, DS3, DS5, DS6, DS7	DS2, DS3, DS5, DS6, DS7	DS2, DS3, DS5, DS6, DS7
Total Capex [€]	13.999.500	13.044.000	11.844.000	12.394.000
Batteries per vessel	2,3	2,0	2,0	2,0
DS per vessel	1,0	1,3	1,3	1,3
Shared batteries	3,0	—	—	—
	3 by 2 vessels	—	—	—
Cost per vessel [€/vessel]	3.499.875	3.261.000	2.961.000	3.098.500

For all the assessed DS designs one less battery but one more DS were needed compared to the base case. From costs perspective the DS design with one charging point of 750kW of capacity is the most optimal. However, it is important to consider possible further vessel demand increase or expansion to other routes to decide which option is the most suitable, as charging infrastructure will remain in place for many years.

Scenario 4: number of docking spots on board

Table 20: Results of Scenario 4: number of docking spots on board variations for the case study

	Scenarios		
Number of vessels	4	4	4
Sailing profile type	Alphenaar, Gouwenaar DB Max B, DB Max G	Alphenaar, Gouwenaar DB Max B, DB Max G	Alphenaar, Gouwenaar DB Max B, DB Max G
Vessel docking spots	1	2	3
Number of batteries required	Infeasible	9	9
Number of docking stations	---	4	2
Locations	---	DS2, DS3, DS5, DS6	DS2, DS3
Total Capex [€]	---	15.972.000	14.061.000
Batteries per vessel	---	2,3	2,3
DS per vessel	---	1,0	0,5
Shared batteries	---	3	3
	---	3 by 2 vessels	3 by 2 vessels
Cost per vessel [€/vessel]	---	3.993.000	3.515.250

Finally, regarding variations in docking spots on board of the vessels, an unfeasible model is obtained when a reduction to 1 docking spot is modelled (first column of table 20). If more docking spots are available, the results show an improvement in terms of DS per vessel. This is an expected result, as DS Capex is larger than battery Capex. When more docking spots are available on the vessel the more battery capacity can be carried and less stops at DS are required.

Again, it is relevant to mention that more docking spots on the vessels mean higher retrofit costs and revenue losses on the shippers' side. Therefore, these results need to be further analysed to determined the optimal solution for the whole system.

5.4 Discussion & reflection

The aim of this research was to develop a model to help assess the implementation of exchangeable batteries to IWW shipping. After applying the developed model to a set of fictitious sailing profiles and to the case study profiles, the obtained results showed the optimisation opportunities and possible synergies that can be achieved when vessels share the batteries and charging infrastructure. Four scenarios were analysed and three KPIs (batteries per vessel, DS per vessel and Capex per vessel) were defined, in order to show the optimisation potential of the model.

Concerning the obtained results, it is difficult to determine a priori which combination of initial values will bring the best solution. However, it is clear that demand increase with the same sailing profile results in the highest battery reductions per vessel. When combining routes, the results are more unpredictable and they largely depend on which terminals are shared by the vessels' routes, as these are the battery exchange points. Battery capacity variations did not show great improvements for the need of batteries per vessel and only a small improvement in DS per vessel for batteries of 3.000kW. Despite this reduction in DS per vessel, as larger batteries are more expensive, less DS do not compensate for the increase in investment costs per vessel. Regarding the third scenario, a combination of DS designs were the only feasible cases for the fictitious profiles. However, they did not prove to have better results than the base case. Nevertheless, analysing different designs can be of relevance as smaller DS will have less operational costs. As for adding docking spots on board of the vessels, despite it might lead to less DS, further analysis on the shipper's costs side is needed to determine if the gain is relevant for all stakeholders.

In general, better results in terms of batteries' reduction per vessel were found with the fictitious sailing profiles than with the real study case ones. This can be expected as the former were built in order to show most of the model potential while trying to resemble the real profiles as much as possible. In real life, it can be expected to have fewer synergies.

It is important to notice that the results highly depend on the sailing profiles, which for the case study were provided by shippers based on average consumption of diesel. Changes in speed, as well as, changes in weather conditions, can alter the power consumption and trip duration, which may affect the results. Moreover, it needs to be checked beforehand whether the power requirement of the vessels between stops (at terminals) is larger than the maximum usable capacity of the batteries on board. If this is the case, then the model will not be feasible. Therefore, proper analysis of the sailing profiles is needed. Scenario analysis should be performed for the worse, average and best cases of power consumption in order to assess the impact of variations. This will allow to properly adjust the safety margin, to avoid the risk of running out of battery power while sailing.

It is also worth mentioning that the results were obtained for a reduced sample of vessels routes and sailing profiles combinations with a limited time horizon. Though the round trips were significantly different, all these vessels are container barges with relatively similar characteristics in terms of power consumption, sailing times and time at terminals. It can be expected to obtain different results if other vessels types are analysed. Whether these results are better or worse in terms of battery sharing and infrastructure requirement will depend on the sailing profiles, power consumption and terminals at which the vessels stop.

As mentioned in chapter 3, at the time of writing this thesis, no studies were published concerning the implementation of an exchangeable battery system in IWW shipping. This research can be considered as the first step to investigate this promising zero-emission concept, as it contributes to help assisting the strategic decision of the system implementation from a logistics perspective. Through the analysis of different scenarios with different input parameters, information that can be useful to build a business plan can be obtained. Some of the questions that can be answered with the model developed in this research are:

- Where to locate the docking stations for a certain vessel demand (with specific routes and power requirements)?
- How many batteries and docking stations are required if a new vessel is added to the system?
- How does vessel demand increase affect the location of the needed DS? This can help assist the decision of which DS to build first if a certain demand increase is expected.
- Which is the best design (number of charging spots and power of each spot) for each docking station? Scenarios can be modelled with different designs and combinations of them to obtain the best results.
- How does battery capacity variations affect the need for more batteries and docking stations? A heterogeneous fleet of batteries in terms of usable capacity can be modelled. In this way, future year scenarios can be run modelling battery ageing for the batteries that have been longer in the system.
- How do more docking spots on the vessels affect the number of needed batteries and docking stations? Running scenarios with a different number of docking spots on the vessels can also help assess the impact on the shippers' side, in terms of retrofit costs and revenue loss.

The business plan can be used to encourage stakeholders to invest in the new energy concept, governments to give subsidies for the unprofitable years, policymakers to introduce new policies to encourage the adoption of greener systems in IWW shipping, and shippers to trust the system and invest in vessel retrofit. However, there are several other aspects that need to be considered for the implementation of the exchangeable batteries system, like the costs that shippers will incur, which will be further discussed as the limitations to the research.

Limitations

Several assumptions and simplifications were made to develop the optimisation model, which are limitations to this research.

First of all, the model aims at minimising the investment costs for the batteries and docking stations, leaving outside the operational costs and other costs like vessel's retrofit. This limitation needs to be considered especially when comparing scenarios. An output that shows a reduction of cost per vessel does not necessarily mean a better output for the system if the other costs are not properly assessed.

Another limitation is that the sailing profiles need to be built in such a way that more than a round trip is considered. This is to avoid finishing the run of the model with no power on the vessel and no available battery at the terminal to start a new trip. If the model is improved and can be run for more time-steps, this limitation can be overcome, by modelling a couple of round trips per vessel. Moreover, the sailing profiles need to be built making sure that the maximum usable power of the batteries on board is enough to sail from one terminal to the other. If this is not the case, then the sailing profile needs to be adapted. For instance, by reducing the sailing speed. This will reduce the power consumption but also alter the sailing times.

Finally, the battery capacity was modelled in a simplistic way. A fixed number of maximum available battery capacity was used per battery and a linear charge/ discharge was considered. In a real-life setting, neither of these assumptions are representative, and under certain circumstances, the available capacity can be lower than the one modelled. Moreover, the vessels' power consumptions were assumed fixed per time step using an average consumption. This is also not realistic, as weather conditions, waves, wind, among other factors modify the speed and power requirement from the vessel. These limitations were considered in the model through a minimum battery level at all times that worked as a safety margin.

5.5 Summary

In this chapter the developed optimisation model was utilised to (a) run on experimental sailing profiles and (b) simulate a simplified case study for ZES. The reason for this is that the high computational times do not allow the evaluation of more than four vessels and 24-time-steps in a reasonable time. The fictitious sailing profiles used to perform the scenario analysis were defined so as to show the potentials of the model in terms of optimisation of batteries and docking stations while remaining close to reality. In total, four different scenarios were evaluated:

- Increase in the number of vessels for a single route and for a combination of routes;
- Variations in the usable battery capacity;
- Variations in the DS design: number and power of the charging spots;
- Variations in the number of docking spots on board of the vessels.

For the first scenario, a reduction in the needed batteries per vessel and DS per vessel was observed when more vessels sailed the same route and when different vessels were combined in different routes. These results show the interactions that occur when more than one vessel participates in the exchangeable batteries system, as shared batteries and charging infrastructure occurs.

For the second scenario, an increase in battery capacity did not show a reduction in the number of batteries needed. However, for the largest batteries, a decrease in DS needed was seen. This shows how the interactions of the system components do not lead to straightforward conclusions. In the case of battery reduction, more batteries were needed in the system. However, due to the reduction in Capex of these batteries, a better cost per vessel ratio was found for this case.

The third scenario showed that smaller DS designs were not feasible if all terminals were set with the same design for the fictitious sailing profiles. However, when a combination of DS designs was implemented, the model was feasible but no improvements were obtained in terms of costs, DS and batteries per vessel.

Finally, in scenario four, no significant improvements were obtained with the increase of docking spots on board. It is also important to mention that, the overall cost needs to be considered when assessing this scenario, as the vessel retrofit cost and loss of revenue on the shipper's side is not included in the model.

After running the experimental scenarios, they were applied to the ZES study case for simplified sailing profiles and a brief combination of vessels. Despite the results have their limitations, the optimisation opportunities can be seen for the four scenarios, showing the potential of the model to assess strategic and commercial decisions.

6 Conclusions & Recommendations

6.1 Conclusions

The main goal of this research was to assess the logistic side of the implementation of an exchangeable battery system to IWW waterways. The main components of the system (batteries, docking stations and vessels) need to interact in such a way that the power supply to vessels is guaranteed and the system is reliable. The interactions between the charging infrastructure, the depleted fleet of batteries and the vessels need to be combined in one model, which optimises the number of batteries and the number and location of docking stations. It is not trivial to determine beforehand the optimal result when, for instance, vessel demand increases or the battery capacity changes. Therefore, it is important to assess several scenarios independently. Multiple iterations might be required to obtain the input combination that leads to the most optimal results.

In this chapter, the conclusions of this research are summarised while answering the sub-research questions and the main research question. The chapter finalises with the recommendations for future research.

6.1.1 Research questions

The main research question was:

How can exchangeable batteries distribution and docking stations locations be optimised to guarantee electric sailing for a certain demand of IWW vessels?

The answer to the main research question is formulated by answering the sub-questions one by one and then summarising.

Which are the main components involved in the new ZEEC? What are their attributes, boundaries and interrelations?

In order to answer this sub-question, the exchangeable batteries system to power IWW vessels proposed by ZES was analysed. This system has three main components: the batteries, the docking stations and the vessels. For the system implementation to be successful, these components need to interact in such a way that they make the system reliable. This means that the batteries and the docking stations need to guarantee enough power available on board of the vessels for these to sail electric.

The interactions of the components are not straightforward as the attributes from one component affect the decision on the attributes of another component. Moreover, each component has its own peculiarities which add up to the general complexity of the system.

Regarding the batteries, the most relevant attribute of this component is the capacity as it limits the vessels' autonomy and generates charging infrastructure demand. Battery useable capacity is a complex attribute as it varies with temperature and charging regimes. Moreover, batteries suffer power losses due to heat and DC to AC power transformation, and capacity losses due to ageing, which is also a complex attribute to assess. Apart from capacity, battery Capex is also an attribute that largely affects the system and the viability of its implementation.

As for the docking stations, the main attributes are their location and design, namely, the number of charging spots and the power of each spot. These attributes are highly interconnected and dependent on the number and capacity of the batteries in the system, and the number of docking spots and power requirements from vessels.

Finally, concerning the vessels, their routes and power consumption are the attributes that affect the system from a logistic perspective. These will affect the docking station location and the battery requirement to sail electric. Power consumption of vessels is not constant and depends on several external factors like speed, weather conditions, waves and wind. Modifying the vessel's speed to reduce power consumption leads to longer sailing times, which affect the schedules and increase costs. Regarding costs, vessel retrofit to place batteries on board and loss of revenue for transporting batteries instead of cargo are the most significant factors to consider from shippers' perspective.

To what extent can existing developed models to overcome logistic challenges of transport electrification be applied to IWW shipping?

Transport electrification is not a completely new topic and its implementation in road transport dates for years.

However, IWW shipping electrification is a greenfield in research. As mentioned in chapter 3, no application of exchangeable batteries system has been done in IWW shipping before. Consequently, research in this area is still limited. Therefore, to answer this sub-question, a parallelism with bus transport electrification was made. The reason for this is that IWW vessels and buses have similarities in terms of the type of vehicles and operations. Buses are large vehicles with higher power demands if compared to cars and have fixed routes and schedules, like IWW vessels.

In the implementation and scaling-up of the proposed system, several challenges arise. Some of these challenges regard the charging infrastructure (DS) and the batteries. From the literature reviewed, some models that target overcoming the logistic challenges of buses electrification ([18],[46],[23],[4]) can be used as reference and inspiration for the development of a model for IWW vessels. However, some peculiarities of IWW shipping make the applicability of the models not straightforward. For instance, the extremely high costs of the needed batteries and docking stations for IWW vessels make their optimisation a key aspect for the exchangeable battery concept to be economically feasible and, hence, successful. The interrelation between both needs to be considered when finding their optimal number and location. Moreover, charging capacities (docking spots and capacity per spot) at the docking stations are limited.

Apart from this, the time needed to charge batteries needs to be considered in order not to overload the stations with batteries that cannot be charged. Also, limiting the type of vessel that can use the exchangeable battery system to those with low power requirements is not realistic for a full scale-up of the system. Finally, as vessels' routes and schedules are fixed, it is not realistic for vessels to choose the DS where to load/ unload the batteries according to a possible queue or a battery charging schedule.

Despite the above, there are some aspects from the models reviewed that were used or adapted for the model developed in this research:

- Nodal energy balance;
- Network perspective: synergies;
- Cost minimisation perspective;
- Time-discrete modelling.

How can the components and attributes of the new ZEEC be incorporated in an optimisation model?

To answer this sub-research question, a discrete-time MILP (mixed-integer linear programming) optimisation model was developed, aiming at minimising the investment costs of batteries and docking stations. This model integrates the attributes and interrelations of the three main components of the exchangeable battery system.

To develop the model, different assumptions and simplifications were required to model the complex interrelations of the system components and to build a model that can be easy to understand and use. First, the usable battery capacity is modelled as a fix parameter per battery and neither ageing nor power losses were considered. Different battery capacities can be modelled by inputting different values to the batteries of the fleet available. Moreover, the batteries are modelled to be charged and discharged linearly. Regarding the DS, their designs (number of charging spots and power per spot) are introduced as parameters in the model. The DS locations are only possible at terminals which are part of the vessels sailing routes. Apart from this, the vessels are represented in the model through their sailing profiles (location and power requirements) and the number of docking spots on board. Vessels' speeds are not directly modelled, neither changes in sailing profiles due to external factors such as weather. Finally, the only costs considered in the model are the batteries and DS Capex. Meaning operational costs, as well as, retrofit costs and shippers' revenue losses for using batteries instead of carrying cargo, are not included in the model.

The network used as input for the model is simplified so as to be easily scalable and flexible to be adapted to other networks. For this, the terminals that are part of the vessel's routes are numbered and the sailing profiles are written to fit with these numbered terminals.

What would be the needed number of batteries and docking stations, and the optimal battery distribution, in order to minimise total costs, considering different input scenarios?

This sub-research question can be answered by using the developed optimisation model with different input scenarios. In this research, four scenarios were considered:

- Scenario 1: increasing the vessel demand for the same route and for different routes;

- Scenario 2: changing the battery capacity;
- Scenario 3: changing the docking station design (number and capacity of docking spots);
- Scenario 4: changing the number of docking spots on board of the vessels.

The outputs obtained showed that it is not straightforward which input changes can bring the most optimal outputs in terms of minimisation of the investment costs. This shows the complexity of the system components' interactions and the usefulness of a model to assess the different scenarios.

Demand increase was the scenario that showed the most possible optimisation of charging infrastructure as well as the number of batteries, both in the case of the same route and different routes. In the scenario with battery capacity variations, no benefit was seen in terms of investment costs when larger batteries were considered. However, one less DS was required. Therefore, a more in-depth analysis of operational cost reductions with less docking stations needs to be done to determine the real trade-offs of increasing battery capacity. The scenario with variations in DS design did not show any great improvements regarding the defined KPIs. Only smaller designs for the case study led to a reduction in Capex per vessel. Finally, regarding increasing the number of docking spots on the vessel, the improvement was seen when two vessels on the same route were considered. Nonetheless, the costs on the shipper's side need to be investigated, as more docking spots mean higher retrofit costs and less cargo to transport.

Circling back to the main research question, this question can be answered taking into account the answers to the sub-research questions.

The developed optimisation model answers the main research question as it gives as output the needed number of exchangeable batteries and DS locations that optimise the investment costs for a given vessel demand. The proposed model integrates the complexities of the three main components of the system and can be used to evaluate the implementation of an exchangeable batteries system in IWW shipping.

The results obtained for the optimal number and location of batteries and docking stations showed the dependency with the input values of the attributes of each system component. As demand increases, a larger network with more terminals needs to be considered, leading to more complex interactions between the system components. These interactions are not trivial, and different input combinations lead to different optimal solutions. The model helps to assess these interactions, by allowing to analyse different scenarios. For instance, it can be used for selecting the best battery type (capacity) and docking station design (charging spots and capacity) given a certain vessel demand.

The application of the model to the fictitious sailing profiles showed the optimisation opportunities and possible synergies that can be achieved when vessels share the batteries and charging infrastructure. When applied to the case study, the model outputs showed some optimisation opportunities for a selection of vessels routes combination. It is expected that if larger sets of vessels and time steps are combined, more synergies can be obtained.

Despite the usefulness of the obtained results, further analysis into the total costs of the system, including operational costs and shippers' costs, are needed to properly assess each scenario and not to leave any stakeholder interest out of the picture.

6.2 Recommendations

As mentioned before, this research aims to provide a model to assess the logistic side of the implementation of an exchangeable battery system. In particular, to determine the optimal number of batteries and docking stations locations to guarantee the electric sailing of a given vessel demand. To do so, some simplifications and assumptions were made, which will require further research, both in terms of theoretical and practical implications.

6.2.1 Theoretical recommendations

The running times of the model proved to be excessively high when more than four vessels and 24 hours were modelled. Therefore, the first point that is worth researching concerns the optimisation of the model running times. The model developed proved to give useful results regarding the potential optimisations that can be achieved, but only for a limited amount of vessels and time-steps within an acceptable time lapse. If the exchangeable batteries system is implemented on a large scale, a model able to cope with more vessels and more time-steps is needed.

From a technical perspective, modelling non-linear battery charge/ discharge, different charging regimes and battery ageing can be useful to trace and improve the life-cycle of the batteries. Moreover, different battery technologies can be assessed and a heterogeneous fleet of batteries can be modelled.

From the logistic perspective, using vessels to reallocate batteries in the network, for example, on a docking station with free docking spots, can lead to better optimisation results. The extra shippers' cost for revenue loss should be taken into account in this case. Apart from this, vessel's extra stops (within the existing routes) for battery exchange can be further investigated.

From the operational point of view, operational costs at terminals can be added to the model, in particular battery handling costs for loading/ unloading and the energy purchased from the grid. For this last cost, different energy pricing strategies can be compared, for example, stating at what times of the day the energy is cheaper. This can improve the charging of the batteries so as to be charged in those hours when energy is less expensive. Another point to be further researched is the incorporation of the shippers' costs into the model, namely, retrofit cost and loss of revenue for carrying batteries instead of cargo. This will give answers to the needed charging infrastructure and batteries from a system perspective including all stakeholders.

6.2.2 Practical recommendations

Concerning the practical recommendations, it can be relevant to assess combined scenarios, varying the attributes of the three components of the system simultaneously. For example, assess a scenario with a fleet of batteries with different capacities, DS with different designs (number and power of the charging spots) and demand increments. The combination of these aspects was not assessed in this research, but it can be highly relevant as more realistic results in terms of needed batteries and charging infrastructure can be obtained.

The transition from diesel-powered vessels to fully electric vessels can be of interest to analyse. Therefore, the hybrid state adding the possibility of the vessel to use diesel fuel when there is not enough battery power onboard should be added to the existing model. Apart from this, other businesses such as the use of batteries to provide FCR services can be considered when the batteries are charged and idle at the terminals. This can help to assess the system from a financial point of view, evaluating opportunities for improvement.

It can also be relevant to evaluate modifications on the existing sailing profiles in order to generate more synergies, increase battery sharing and, hence, reduce costs. This evaluation needs to be done together with the shippers, as it might alter their sailing speed and, therefore, the sailing times. However, sailing slower can lead to better performances with the batteries and needing less battery charges, which can also be beneficial for shippers. An in-depth analysis of the trade-offs between the vessel costs if slower speeds and less power are used versus the number of docking stations and batteries can be worth studying in further research.

Finally, simulation of the locations of the batteries at all times with a user-friendly output interface could be useful for planners in the future to assess different battery fleet and charging infrastructure scenarios in the network. The current model gives output variables indicating the location and use of the batteries at all times. However, an animated simulation of this output could be easier to interpret.

References

[1] *Green Deals*, (2019). URL https://www.greendeals.nl.

[2] *Lithium-ion battery aging*, (2020). URL https://www.wattalps.com/lithium-ion-battery-aging/.

[3] J. D. Adler and P. B. Mirchandani. Online routing and battery reservations for electric vehicles with swappable batteries. *Transportation Research Part B: Methodological*, 70:285–302, 2014. ISSN 0191-2615. doi: https://doi.org/10.1016/j.trb.2014.09.005. URL https://www.sciencedirect.com/science/article/pii/S0191261514001593.

[4] S. S. Amiri, S. Jadid, and H. Saboori. Multi-objective optimum charging management of electric vehicles through battery swapping stations. *Energy*, 165:549–562, 2018. ISSN 0360-5442. doi: https://doi.org/10.1016/j.energy.2018.09.167. URL https://www.sciencedirect.com/science/article/pii/S036054421831939X.

[5] H. Bach, A. Bergek, Ø. Bjørgum, T. Hansen, A. Kenzhegaliyeva, and M. Steen. Implementing maritime battery-electric and hydrogen solutions: A technological innovation systems analysis. *Transportation Research Part D: Transport and Environment*, 87:102492, 2020. ISSN 1361-9209. doi: https://doi.org/10.1016/j.trd.2020.102492. URL https://www.sciencedirect.com/science/article/pii/S1361920920306799.

[6] H. Bach, T. Makitie, T. Hansen, and M. Steen. Blending new and old in sustainability transitions: Technological alignment between fossil fuels and biofuels in norwegian coastal shipping. *Energy Research & Social Science*, 74:101957, 2021.

[7] Ballard. Fuel cell applications for marine vessels, (2019). URL https://www.ballard.com/docs/default-source/default-document-library/marine-informational-paper-final.pdf?sfvrsn=c1cec080_2.

[8] C. k. Chang. Factors Affecting Capacity Design of Lithium-Ion Stationary Batteries. *Batteries*, 5(3), 2019. ISSN 2313-0105. doi: 10.3390/batteries5030058. URL https://www.mdpi.com/2313-0105/5/3/58.

[9] C. Detloff. *Hybrid Propulsion Delivers Cost and Environmental Benefits*, (2018). URL https://empoweringpumps.com/danfoss-drives-hybrid-propulsion-ships-sea-vessels-marine/.

[10] EMSA European Maritime Safety Agency. Emsa maritime battery study - electrical energy storage for ships., (2020). URL http://www.emsa.europa.eu/publications/item/3895-study-on-electrical-energy-storage-for-ships.html.

[11] European Comission. Electrification of the transport system - studies and reports., (2017). URL https://www.scribd.com/document/435838566/Report-ElectrificationoftheTransportSystempdf-1-pdf.

[12] European Comission. Reducing emissions from the shipping sector., (2017). URL https://ec.europa.eu/clima/policies/transport/shipping_en.

[13] J. Faber, D. Nelissen, G. Hon, H. Wang, and M. Tsimplis. Regulated slow steaming in maritime transport. an assessment of options, costs and benefits. Feb 2012.

[14] D. D. T. Ferraren-De Cagalitan and M. L. S. Abundo. A review of biohydrogen production technology for application towards hydrogen fuel cells. *Renewable and Sustainable Energy Reviews*, 151:111413, 2021. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2021.111413. URL https://www.sciencedirect.com/science/article/pii/S1364032121006973.

[15] I. Hilverda. Linking energy logistics: Modelling a network of decentralised batteries. Master's thesis, TU Delft, 2019.

[16] International Transport Forum. Decarbonising maritime transport pathways to zero-carbon shipping by 2035., (n.a.). URL https://www.itf-oecd.org/sites/default/files/docs/decarbonising-maritime-transport-2035.pdf.

[17] IRENA . Navigating to a renewable future: Solutions for decarbonising shipping, preliminary findings., international renewable energy agency, abu dhabi, (2019).

[18] W. Jing, I. Kim, and K. An. The Uncapacitated Battery Swapping Facility Location Problem with Localized Charging System Serving Electric Bus Fleet. *Transportation Research Procedia*, 34:227–234, 2018. ISSN 2352-1465. doi: https://doi.org/10.1016/j.trpro.2018.11.036. URL `https://www.sciencedirect.com/science/article/pii/S2352146518303259`.

[19] A. A. Juan, C. A. Mendez, J. Faulin, J. De Armas, and S. E. Grasman. Electric vehicles in logistics and transportation: A survey on emerging environmental, strategic, and operational challenges. *Energies*, 9(2): 86, 2016.

[20] W. Ketter, M. van Oosterhout, B. Ros, K. Schroer, and P. Theile. Modular Energy Concept (White paper report). 2019. URL `https://www.rsm.nl/fileadmin/Images_NEW/ECFEB/pdf/2019_Living_Energy_Conference_RSMEWI__Modular_Energy_Concept_whitepaper_FINAL.pdf`.

[21] A. Konig, L. Nicoletti, D. Schröder, S. Wolff, A. Waclaw, and M. Lienkamp. An Overview of Parameter and Cost for Battery Electric Vehicles. *World Electric Vehicle Journal*, 12(1), 2021. ISSN 2032-6653. doi: 10.3390/wevj12010021. URL `https://www.mdpi.com/2032-6653/12/1/21`.

[22] M. Krikke. Retrofitting ships with new technologies for improved overall environmental footprint. *RETROFIT Project Final Report, Rotterdam: Netherlands Maritime Technology Foundation.* URL `https://cordis.europa.eu/project/id/285420/reporting`.

[23] A. Kunith, R. Mendelevitch, and D. Goehlich. Electrification of a city bus network—an optimization model for cost-effective placing of charging infrastructure and battery sizing of fast-charging electric bus systems. *International Journal of Sustainable Transportation*, 11(10):707–720, 2017.

[24] M. Latarche. Battery and hybrid ships. How do they work and how many are in operation. 2020. URL `https://shipinsight.com/articles/battery-and-hybrid-ships-how-do-they-work-and-how-many-are-in-operation/`.

[25] F. Leng, C. M. Tan, and M. Pecht. Effect of Temperature on the Aging rate of Li Ion Battery Operating above Room Temperature. *Scientific Reports*, 5(1):12967, 2015. ISSN 2045-2322. doi: 10.1038/srep12967. URL `https://doi.org/10.1038/srep12967`.

[26] J. Li, F. Wang, and Y. He. Electric Vehicle Routing Problem with Battery Swapping Considering Energy Consumption and Carbon Emissions. *Sustainability*, 12(24), 2020. ISSN 2071-1050. doi: 10.3390/su122410537. URL `https://www.mdpi.com/2071-1050/12/24/10537`.

[27] W. Li, Y. Li, H. Deng, and L. Bao. Planning of Electric Public Transport System under Battery Swap Mode. *Sustainability*, 10(7), 2018. ISSN 2071-1050. doi: 10.3390/su10072528. URL `https://www.mdpi.com/2071-1050/10/7/2528`.

[28] H. Lindstad, R. Verbeek, M. Blok, S. Zyl, A. Hübscher, H. Kramer, J. Purwanto, O. Ivanova, and H. Boonman. GHG emission reduction potential of EU-related maritime transport and on its impacts. . 2015. URL `https://ec.europa.eu/clima/sites/clima/files/transport/shipping/docs/report_ghg_reduction_potential_en.pdf`.

[29] D. Lyridis, H. Psaraftis, N. Ventikos, P. Zacharioudakis, and K. Dilzas. Cost-Benefit Analysis for Ship Automation Retrofit: The Case of Icebreaker Frej. *Marine Technology*, 42:113–124, 2005. doi: 10.5957/mt1.2005.42.2.113.

[30] S. Ma, M. Jiang, P. Tao, C. Song, J. Wu, J. Wang, T. Deng, and W. Shang. Temperature effect and thermal impact in lithium-ion batteries: A review. *Progress in Natural Science: Materials International*, 28(6):653–666, 2018. ISSN 1002-0071. doi: https://doi.org/10.1016/j.pnsc.2018.11.002. URL `https://www.sciencedirect.com/science/article/pii/S1002007118307536`.

[31] M. Mahmoud, Y. Liu, H. Hartmann, S. Stewart, T. Wagener, D. Semmens, R. Stewart, H. Gupta, D. Dominguez, F. Dominguez, D. Hulse, R. Letcher, B. Rashleigh, C. Smith, R. Street, J. Ticehurst, M. Twery, H. van Delden, R. Waldick, D. White, and L. Winter. A formal framework for scenario development in support of environmental decision-making. *Environmental Modelling Software*, 24(7):798–808, 2009. ISSN 1364-8152. doi: https://doi.org/10.1016/j.envsoft.2008.11.010. URL `https://www.sciencedirect.com/science/article/pii/S1364815208002211`.

[32] G. Mallouppas and E. A. Yfantis. Decarbonization in shipping industry: A review of research, technology development, and innovation proposals. *Journal of Marine Science and Engineering*, 9(4):415, 2021.

[33] C. J. McKinlay, S. R. Turnock, and D. A. Hudson. Route to zero emission shipping: hydrogen, ammonia or methanol? *International Journal of Hydrogen Energy*, 2021.

[34] C. Nuchturee, T. Li, and H. Xia. Energy efficiency of integrated electric propulsion for ships – A review. *Renewable and Sustainable Energy Reviews*, 134:110145, 2020. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2020.110145. URL `https://www.sciencedirect.com/science/article/pii/S1364032120304366`.

[35] S. Robinson, G. Arbez, L. G. Birta, A. Tolk, and G. Wagner. Conceptual modeling: Definition, purpose and benefits. pages 2812–2826, 2015. doi: 10.1109/WSC.2015.7408386.

[36] M. Rogge, S. Wollny, and D. U. Sauer. Fast charging battery buses for the electrification of urban public transport—a feasibility study focusing on charging infrastructure and energy storage requirements. *Energies*, 8(5):4587–4606, 2015.

[37] H. R. Sayarshad and V. Mahmoodian. An intelligent method for dynamic distribution of electric taxi batteries between charging and swapping stations. *Sustainable Cities and Society*, 65:102605, 2021. ISSN 2210-6707. doi: https://doi.org/10.1016/j.scs.2020.102605. URL `https://www.sciencedirect.com/science/article/pii/S2210670720308222`.

[38] P. Serra and G. Fancello. Towards the IMO's GHG goals: A critical overview of the perspectives and challenges of the main options for decarbonizing international shipping. 2020. URL `https://ideas.repec.org/a/gam/jsusta/v12y2020i8p3220-d346282.html`.

[39] K. Sperling, M. Overschie, R. Hekkenberg, and K. Mulder. Technologies in inland navigation – a long term perspective. 2007. URL `https://www.researchgate.net/publication/259842990_Sustainable_Technologies_in_Inland_Navigation_-_A_long_term_perspective`.

[40] B. Taskar and P. Andersen. Benefit of speed reduction for ships in different weather conditions. *Transportation Research Part D: Transport and Environment*, 85:102337, 2020. ISSN 1361-9209. doi: https://doi.org/10.1016/j.trd.2020.102337. URL `https://www.sciencedirect.com/science/article/pii/S1361920919317870`.

[41] UKEssays. Linear Programming: Advantages, Disadvantages and Strategies. 2018. URL `https://www.ukessays.com/essays/management/i-linear-programming.php?vref=1`.

[42] L. van Biert, M. Godjevac, K. Visser, and P. V. Aravind. A review of fuel cell systems for maritime applications. *Journal of Power Sources*, 327:345–364, 2016. ISSN 0378-7753. doi: https://doi.org/10.1016/j.jpowsour.2016.07.007. URL `https://www.sciencedirect.com/science/article/pii/S0378775316308631`.

[43] H. J. Verheij, C. Stolker, and R. Groenveld. *Inland Waterways - Ports, waterways and inland navigation*. VSSD, Delft, 2008.

[44] W. Wei, D. Wu, Q. Ww, M. Shafie-Khah, and J. P. S. Catalao. Interdependence between transportation system and power distribution system: a comprehensive review on models and applications. *Journal of Modern Power Systems and Clean Energy*, 7(3):433–448, 2019. ISSN 2196-5420. doi: 10.1007/s40565-019-0516-7. URL `https://doi.org/10.1007/s40565-019-0516-7`.

[45] H. Xing, C. Stuart, S. Spence, and H. Chen. Fuel Cell Power Systems for Maritime Applications: Progress and Perspectives. *Sustainability*, 13(3), 2021. ISSN 2071-1050. doi: 10.3390/su13031213. URL `https://www.mdpi.com/2071-1050/13/3/1213`.

[46] M. Xylia, S. Leduc, P. Patrizio, F. Kraxner, and S. Silveira. Locating charging infrastructure for electric buses in stockholm. *Transportation Research Part C: Emerging Technologies*, 78:183–200, 2017.

[47] J. Yang and H. Sun. Battery swap station location-routing problem with capacitated electric vehicles. *Computers Operations Research*, 55:217–232, 2015. ISSN 0305-0548. doi: https://doi.org/10.1016/j.cor.2014.07.003. URL `https://www.sciencedirect.com/science/article/pii/S0305054814001841`.

[48] B. Zeng, Y. Luo, C. Zhang, and Y. Liu. Assessing the Impact of an EV Battery Swapping Station on the Reliability of Distribution Systems. *Applied Sciences*, 10(22), 2020. ISSN 2076-3417. doi: 10.3390/app10228023. URL `https://www.mdpi.com/2076-3417/10/22/8023`.

[49] ZES. A system change to power clean corridors [internal document], 2020.

[50] ZES. Master plan [internal document], 2020.

[51] ZES. Business plan [internal document], 2021.

[52] ZES. Strategie besluitvorming zes mbt docking station [internal document], 2021.

[53] S. Zhang, M. Chen, and W. Zhang. A novel location-routing problem in electric vehicle transportation with stochastic demands. *Journal of Cleaner Production*, 221:567–581, 2019. ISSN 0959-6526. doi: https://doi.org/10.1016/j.jclepro.2019.02.167. URL `https://www.sciencedirect.com/science/article/pii/S0959652619305669`.

[54] T. Zhang, X. Chen, Z. Yu, X. Zhu, and D. Shi. A monte carlo simulation approach to evaluate service capacities of ev charging and battery swapping stations. *IEEE Transactions on Industrial Informatics*, 14 (9):3914–3923, 2018.

A Research Paper

Optimal exchangeable battery distribution and docking station location for electric sailing in IWW shipping: The case study of ZES

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Abstract

With the increasing need of more sustainable transportation, the electrification of IWW shipping becomes of great relevance. There are several ways to achieve this, from which the implementation of an exchangeable battery system is discussed in this paper. Several challenges arise from the large-scale implementation of such a system. One of which is the optimal distribution of the batteries and the location of the docking stations to guarantee electric sailing for a certain demand of vessels. By developing a time-discrete mixed-integer linear programming optimisation model the outputs of this research aim at assessing this. The obtained results showed the optimisation opportunities and possible synergies that can be achieved when vessels share the batteries and charging infrastructure. Though, it is not trivial to determine beforehand the optimal result for different inputs, through different scenario analysis, information that can be useful to assist the strategic decision of the system implementation from a logistic perspective can be obtained.

Keywords: IWW shipping, Optimisation, Exchangeable batteries, Electric sailing

1 Introduction

The Netherlands has recently committed to very challenging environmental targets regarding transportation. One of which is to become carbon-neutral by 2050. Nowadays, IWW shipping accounts 5% of the total transportation emissions. This urges the need to achieve long-term full decarbonisation of IWW transport. Many different measures can be applied for this, however, to successfully create an impact on emissions, zero-emission energy concepts (ZEECs) need to be developed.

This research focuses on one of these concepts which is the electrification of IWW transport using exchangeable batteries. This ZEEC was designed by the company Zero Emission Services (ZES), and it consists of three main components, batteries, docking stations and vessels. The exchangeable batteries are designed to fit in 20ft containers and are charged at docking stations. Then, the charged batteries are used to power the vessels. The batteries do not belong to a specific vessel but to the whole system. With this, batteries can power a vessel and once the vessel arrives at a terminal with a docking station it can leave the batteries to charge, load another one, and sail, saving time. The batteries that were left at the terminal can be used by another vessel or for other businesses. Sharing batteries among vessels results in the need for fewer batteries per vessel as vessel demand increases, which becomes an advantage of this system, as battery costs are a major constraint to the system.

The implementation of such a system does not come without several logistic challenges. The problem becomes largely more complex as the three main components of the system interact. So far no research has been done in the field, and exchangeable batteries system were not implemented before in IWW shipping.

The aim of this research is, therefore, to develop an optimisation model to help assess the implementation of an exchangeable batteries system for IWW shipping. For this, the docking station locations from a set of terminals, and the number of batteries and their deployment in the network in order to fulfil the vessels' power requirements, need to be determined. The battery movement through the network needs to match the vessels' routes. To meet these requirements of the system, a time-discrete mixed-integer linear programming optimisation model with deterministic inputs is developed. The network used as input for the model is simplified so as to be easily scalable and flexible to be adapted to other networks.

The model is first applied to a set of fictitious sailing profiles to determine the optimisation potential, and then it is applied to the case study of ZES. Given the computational time constraints, the model runs were limited to a maximum of four vessels and 24 time-steps. The real-life sailing profiles had to be adjusted and simplified so as to fit this constraint.

The remainder of the paper is organised as follows. In Section 2, a general description of the exchangeable battery system to power IWW vessels is given. The system main components are briefly described. In Section 3 the existing related literature regarding models for transport electrification and its applicability to IWW shipping is reviewed. In Section 4 the model is formulated. Firstly, the problem is described and the model requirements, assumptions and simplifications are stated. Then, the mathematical formulation of the problem is given. After which the model is verified and validated. In Section 5, computational experiments are conducted with a set of fictitious sailing profiles to assess the optimisation potential of the model, and then, the model is applied to the real-life sailing profiles of the case study. A brief discussion over the results is given in this section. In Section 6 conclusions and future research recommendations are given.

2 System description

The exchangeable batteries system is composed of batteries, docking stations and vessels, which interact as follows. The batteries are designed to fit in 20ft containers and are charged at docking stations. Then, the charged batteries are used to power the vessels. The batteries do not belong to a specific vessel but to the whole system. With this, batteries can power a vessel and once the vessel arrives at a terminal with a docking station it can leave the batteries to charge, load another one, and sail, saving time. The batteries that were left at the terminal can be used by another vessel. Idle batteries at DS can also be used for other businesses like to provide grid stabilisation and for energy market applications[7] such as Frequency Containment Reserve (FCR). Sharing batteries among vessels results in the need for fewer batteries per vessel as vessel demand increases, which becomes an advantage of this system, as battery costs are a major constraint to the system. This implementation has more logistic challenges when more vessels and larger networks with more routes and terminals are considered. Not only the DS locations needs to be determined, but also the needed batteries, including their routing. The movement of the batteries through the network has to match with the different vessels' routes, as they do not depend on one exclusive vessel.

The attributes, interrelations and challenges of the three components of the system are described below.

Batteries

Battery Capacity

It is one of the main restrictions to the system, as it limits the vessels' autonomy. The main challenge is that maximum usable capacity is not a fix value and depends on several factors such as temperature and charging and discharging regimes. Both battery capacity and charging performance deteriorates at extremely low or high temperatures [3] Lithium-ion batteries are capable of operating over a relatively wide temperature range, however, batteries achieve optimal service life when used at 20°C or slightly lower. [3] Different temperature conditions result in different adverse effects. [12] For example, the effect of temperature is higher during charging than discharging. [3] Also, at higher temperatures, greater performance and increased storage capacity of the battery. A study performed by [10], showed that an increase in temperature from 35°C to 45°C led to a 20% increase in maximum storage capacity. However, there is a side effect to this increased performance, the life cycle of the battery is decreased over time.

Battery power losses & Ageing

There are several sources of power loss in lithium-ion batteries due to their use, the most relevant ones are losses due to heat and losses for DC to AC power transformation. Apart from power losses, batteries deteriorate with time and lose power capacity. Ageing in lithium-ion batteries is a complex issue and depends on several factors like the charging regime and the number of cycles. [1] In general, lithium-ion batteries are more sensitive to fast charging than fast discharging.[4] Another source of increased ageing or life cycle degradation for lithium-ion batteries is the temperature. [10] To evaluate the overall effect of these various degradation mechanisms simultaneously is extremely difficult. [4]

Costs

Another major boundary for the system is the battery cost. Lithium-ion technology development has been primarily driven by consumer electronics and automotive markets. For comparison, the entire maritime market to date comprises less than 1% of the total amount of lithium-ion batteries produced yearly and to some extent, this has driven the higher cost of a comparative marine battery system. [4] It is expected that the battery cost will decrease in time, once the system is implemented on a large scale and benefits from economies of scale can be obtained. Again, how much the price reduction would be or when is uncertain, but a look into car batteries can be done to see the estimated cost decrease for the coming years. As estimated by [3] in his research, the decrease would be around 14% from 2025 to 2030. Still, this is an estimation and for a more well-known market, cars. Therefore, it is difficult to draw direct parallelism for IWW vessels.

Docking Stations

Location

Vessels powered electrically with batteries suffer autonomy reduction due to batteries lower ranges. Meaning that vessels require to stop to charge the batteries more often than to refuel diesel. Therefore, more docking stations locations in the network than diesel refuelling stations are needed. The docking stations will be located at existing container terminals to take advantage of the infrastructure and equipment available. The best locations for the stations will depend on several factors which can be intrinsic or extrinsic. In the first case, DS locations depend on the distance to container terminals quays, the availability of grid connection, as well as the availability of land (space) to build them. These will limit the options of possible terminals where DS can be located. Apart from this, the locations will depend on the number of batteries that are in the system, the battery capacity, the number of docking places at the vessel and the vessel's power requirements. This will establish the docking station demand and, hence, the needed locations

Docking design: docking spots & charging capacities

The design of the docking station refers to the number of needed docking spots and the power that each docking spots supplies to charge the batteries. For each location, the demand profile needs to be determined to decide upon the number of docking places required and the energy contract to have with the energy provider. [19] The docking station investment and operational costs are linked to the location (cost of land, cost of building), as well as to the number and power capacity of docking spots chosen. The docking station operational costs include energy purchase from power supplier, network costs for connection to the grid, logistical costs for the loading, unloading and transportation of the batteries to and from the vessel, and operational costs for maintenance, insurance, among others. [18] The definition of docking stations locations and design, namely size and power, are interconnected.

Vessels

Retrofit costs & loss of profit per container

When installing state-of-the-art or innovative components or systems on board of ships, retrofit is needed. These retrofits can be driven by the need to meet new regulations or emissions standards or by the shipowner interest to upgrade to higher operational standards. [8] In the implementation of exchangeable batteries for fully electric sailing, vessels need to be retrofitted to fit the exchangeable batteries. This signifies a cost for shippers. This cost is composed by [11] the cost for purchasing and installing the connector and convector (ZES) to fit the batteries on board, the potential loss of income during the time off the vessel is being retrofitted, the cost for sailing to the shipyard for retrofitting, and the cost to train the crew for the new operations. The retrofit cost depends on the vessel type, age and dimensions. Apart from the retrofit costs for shippers, there is also a loss of income for carrying less cargo containers to leave place for the batteries.

Vessels' power requirements

An important aspect to consider in the implementation of exchangeable batteries is that the vessels' power consumption depends on several factors like the vessel's speed, climate conditions (wind, waves), the vessel's shape, the vessel's load and whether the vessel is sailing in restricted or unrestricted areas. The vessel's speed is greatly influenced by the resistance encountered while sailing. Factors like the surface of the hull underwater, vessel's cross-section and width and depth of the waterway affect the total resistance. [16] Vessel's speed impact over the power consumption is complex to determine. [15] Moreover, additional fuel consumption for a voyage needs to be considered due to waves, which does not depend on ship speed. [15] and extra power may be required to overcome the effects of wind ad currents. This additional power may amount to 15% of the total power under certain circumstances. [16] Another factor affecting power consumption is the vessel's load. Empty vessels require less propulsion power than loaded vessels. These can be seen in the sailing profiles when looking at round trips, when the vessel carries more load the power requirements are larger than when it carries less load. The sailing profiles are therefore a good way to incorporate this factor in the model. The combination of factors as speed, weather, vessels' hull shape and load on the power requirement is really hard to assess.

Extra times at terminals & sailing times

Apart from the abovementioned challenges, there are other challenges regarding extra times needed at terminals for the operation of loading/ unloading the batteries as well as possible extra stops needed. As the vessel's autonomy decreases when using batteries, given that their power capacity is less than with fuels, this can lead to the need for more stops for the vessels to swap depleted batteries with new ones or change their sailing speed to reduce power consumption. Both options lead to extra sailing times and indirectly to profit loss.

As it can be seen, the different attributes of the three main components of the system have several challenges. To cope with them, assumptions and simplifications were made to represent them in the model. Which will be explained in Section 4.

3 Literature review

As far as this research concerns, there is no specific literature on optimisation models for IWW shipping electrification. A literature review on other modes of transport was performed, then a comparison with IWW was made to determine the applicability and limitations of existing models to IWW shipping. In particular, buses were chosen as the mode of transport to compare. The reasons for this are the availability of literature and the similarity of bus road transport and IWW transport in terms of type of vehicles and operations. Buses are large vehicles with higher power demands if compared to cars and have fixed routes and schedules, like IWW vessels. Trucks could have been another option to compare, as they are also large vehicles with relatively high demands of power, long routes and less stops than buses, similarly to IWW vessels. However, literature on trucks electrification is also limited.

The results of the literature review are structured starting with the challenges that electrifying buses transport have and the models developed to address these challenges for buses. Followed by a discussion on the possible applicability and limitations of these models to IWW vessels.

Logistic challenges of transport electrification & Models developed to address them

In the implementation of buses electrification there are logistic challenges to overcome in order to secure system reliability. The first challenge, regards the number and location of the charging infrastructure. [20][6]

The strategic location of charging stations is key for the system to properly work and for users to trust it. The charging infrastructure will be in place in the network for many years. Therefore, the location decisions will also affect tactical and operational decision for these charging stations.[5] Moreover, the large capital costs involved in installing charging infrastructure, make the decision on number and locations of charging stations not straightforward. [6]

The research performed by [5] addresses this problem and proposes a mixed-integer problem decomposed in two subproblems. The first one aims to solve the uncapacitated fixed charge facility location to find the optimal station location and the demand of each station. Whereas the second one, aims at finding the optimal configuration of the localised charging system, in particular the charger type and battery inventory. The problem is solved for a fleet of battery electric buses and aims at minimising the total investments, by determining the needed number of swapping stations and their locations and the demand assigned to each of them. The buses go to the swapping station from the depot, meaning they do not need a swapping service on during the route. The main limitations of the model are that it is assumed that a battery will be available at a station when a bus arrives, busses will only reach swapping stations from depot, meaning they can finish their whole route without recharging their batteries and swapping stations are assumed uncapacitated, meaning there is no limit of batteries the stations can charge and no charging time. Moreover, the model solves the location of the stations and the demand assigned to each station first, and then determines the number of needed batteries. Therefore, the interrelation between stations number and location and the needed batteries is not modelled. In this same line of research, [17] studied the optimal distribution of charging infrastructure for electric buses. The model they developed is a MILP that aims to assess upscaling the implementation of electric buses by identifying the optimal spatial distribution of charging infrastructure to minimise costs and energy consumption. The model is based on balancing the energy at arrival of a stop as the energy the bus had when leaving the previous stop minus the required energy to travel the distance between stops. The main limitation of the model regards to the location of the charging stations being limited to starting and end stops in the buses routes, meaning that the battery capacity should be enough to do the whole trip.

Apart from the location problem, decisions need to be made on the charging stations capacities and charging regimes. The size or capacity of the recharging stations affects the transportation planning as stations cannot serve more than their installed capacity. [6] Electric buses have higher power demands than electric cars, and they operate under fixed routes and daily schedules, therefore subject to more constraints in relation to where the charging infrastructure can be placed. [17] Moreover, a charging station can be fast or slow charging. Standard charging is performed with a moderate charging power mainly in the bus depot overnight and during longer brakes. [14] Charging schedules can be implemented in buses electrification, for example use overnight charging to avoid the need of fast charging stations. [13] However, this causes a high battery capacity and a high weight of the system, when the bus shall be operated the entire day. Fast charging on the track during operation can reduce the battery capacity and therefore the weight significantly.[14] However, there is a trade-off between charging speed/time and the damage to the battery, making this type of charging to have their own limitations. [21] [6] To overcome this, battery exchange schemes/stations can be implemented. This avoids the bus to be idle while recharging [13] as well as battery deterioration, as battery life can be extended by charging at slower speed. [21] Some drawbacks of battery swap stations include the need of unified battery standards among vehicles and stations. [6] Decisions on the station type will directly affect the charging times and will depend on the buses power demand, size of batteries,[6] the location of the stations, but also on the buses schedules to see if their provide sufficient charging times at certain locations. [14] As it can be seen the charging station design (size, power and type) and location decisions are interrelated, making it not trivial to decide upon the best option.

To tackle the battery charging times challenge for buses electrification, research has focused on vehicle schedules and battery reservation strategies to properly match the power demand from the vehicles with the available resources (batteries). Research in this direction include the one done by [2], in which the authors find the optimal location of the EV charging among the swapping stations available in the network. This is done by scheduling the arrival of the buses at the swapping stations, and by determining the charging priority of the depleted batteries at the stations. The scheduling allows to guarantee that a fully charged battery will be available and ready to deploy when the vehicle arrives at the station. Therefore, there is no waiting time of the bus for charging. The authors developed a time-discrete multi-objective optimisation algorithm to solve the problem.

The second main challenge of bus electrification regards the limited driving-range capabilities of the vehicles which are restricted by the amount of electricity stored in their batteries. [6] This challenge has been address by several authors, as it is a key barrier that reduces the attractiveness of bus electrification [13] and imposes non-trivial additional constraints when designing efficient distribution routes. [6] Maximum battery capacity is linked to technological limitations, but also to size, weight and cost limitations. Batteries can make up to one-third of the total cost of an electric bus. [9] Therefore, a balance between battery capacity and range needs to be made. The restriction in driving range imposed by the batteries to the buses, has also an impact on buses schedules, as additional times and stops might be required to charge the batteries. [6] Again this problem is linked to the charging infrastructure location problem.

A research which looks into both challenges, an efficient layout of the charging infrastructure and an appropriate dimensioning of battery capacity, is the one performed by [9]. The authors propose an advanced mixed-integer linear optimisation model that solves a capacitated set covering problem to determine the number and location of charging stations and the required battery capacity for each bus line, minimizing costs and without altering the original operational schedule. Some key aspects of the model proposed in this research are the network perspective which allows to identify synergies when between the charging infrastructure for several bus lines at once, the incorporation of the trade-off between battery capacity and charging infrastructure and the nodal energy balance. One limit that this model has is that the charging time is limited to the time the bus it at the stop.

Applicability of existing models to electrify the IWW shipping with exchangeable batteries

Despite some parallelisms can be drawn from studied problems on buses electrification and the developed models to solve them, there are some peculiarities of the implementation of an exchangeable batteries system in inland waterways vessels which makes the direct applicability of these models not possible. For example, the extremely high costs of the needed batteries and docking stations for IWW vessels make their optimisation a key aspect for the exchangeable battery concept to be economically feasible and, hence, successful. Therefore, the interrelation between the both need to be considered when finding their optimal number and location, contrary to what is suggested by [5].

Moreover, assuming a fully-charged battery is available at all times to be loaded on a vessel as proposed by [5] is not realistic, as the needed charging times at the docking stations are not being considered. Docking stations also have a limit amount of docking spots and, therefore, a limited charging capacity. [5] This is why the time needed to charge batteries needs to be considered, in order not to overload the stations with batteries that cannot be charged. Apart from this, it is not realistic to limit the charging time as suggested by [9], as the batteries needed to power IWW vessels are very large, and the charging times are not neglectable. Battery level is a key parameter that should be tracked so as to optimise the charging times and number of needed batteries.

Allowing the possible vessels to use exchangeable batteries only to those which power requirements are low enough to be fulfilled with the power of batteries on board is a major limitation. [5] [17] The combination of docking stations locations and batteries in the network should allow the fleet of vessels analysed to sail electric regardless of the power requirement. If needed more docking stations should be placed in the system to swap the depleted batteries for fully charged ones. Therefore, all vessels stops at terminals should be considered as a potential docking station to allow possible batteries swapping in the route and not only on end terminals as proposed by [17]. Finally, vessels' routes and schedules are fixed making it not realistic for vessels to choose the docking station at where to load/ unload the batteries according to the possible queue or battery charging schedules as studied by [2]

Despite the abovementioned limitations for the applicability of the assessed models to IWW vessels, there are some concepts developed by the authors that can be applied in the development of a new model for IWW shipping. In particular the cost minimisation perspective suggested by [5], [17] and [9] for the optimisation of the exchangeable battery system is of interest for this research. Apart from this, the time-discrete modelling approach developed by [2] is of relevance for this research. Developing a model with discrete time-steps to represent the power requirements of vessels, their locations and the battery charge level seems reasonable. Moreover, the nodal energy balance concept used by [17] and [9] has potential applicability. The battery charge level needs to be determined at all times, therefore, a energy balance between time steps is needed. Finally, the network perspective to develop a MILP as done by [9] is also of relevance for this research. Finding possible synergies between the charging infrastructure, the needed batteries and the vessels will lead to better results in terms of DS and batteries optimisation.

In this research, the problem aimed at solving, requires to incorporate not only the docking stations optimisation but also the battery optimisation. For which battery location and battery charge level are two parameters that need be tracked at all times. Therefore, this research aims to extend the existing literature and propose an optimisation model for the implementation of exchangeable batteries in IWW shipping in order to minimise costs, by optimising the needed number and locations of docking stations and the number of batteries, so as to satisfy a given demand of vessels, with their specific routes and power requirements. For this, the following concepts of the assessed models will be used: energy balance, synergies possibilities by using a network perspective of the system allowing batteries to be shared by vessels sailing in different routes, time-discrete modelling and cost minimisation approach.

4 Model formulation

4.1 Problem description

In this paper, the optimal combination of batteries and docking stations to successfully provide the required power to a specific vessel demand, in order to implement exchangeable batteries to IWW shipping is studied.

The problem has a defined vessel demand with their routes and power requirements, a network of terminals at which the vessels stop in their routes and which are potential DS locations with defined number of charging spots and capacity, and a fleet of batteries with a defined maximum usable capacity. The batteries need to guarantee that the needed energy for vessels to sail electric is satisfied at all times. The charging infrastructure or the DS must ensure the batteries are charged at the needed time. The batteries movement throughout the network needs to match the vessels' routes. For a battery to be loaded to a vessel it has to be fully charged. Each battery and docking station has an investment cost associated. The problem to solve is to determine the DS location and needed batteries to minimise the total investment cost, while satisfying the vessel demand power requirements.

4.2 Model requirements

The main model requirements are that the duration modelled needs to account for the longest round trip of the fleet of vessels considered. The model should allow to analyse different fleet composition (vessels with different routes and power consumption), different corridors and terminal locations. Moreover, the model should allow easy scalability to more terminals, more vessels and potentially more time steps. Finally, the model needs to easily allow to analyse different input scenarios such as different battery capacity, different docking stations design (charging spots and their power), fixed DS locations, and different docking spots in vessels.

4.3 Model assumptions & Simplifications

The main assumptions made to develop the optimisation model are that all batteries are assumed to be lithium-ion. For the battery capacity, an average value of maximum usable battery capacity is assumed. Given the relevance that battery capacity has as a restriction to the system, battery capacity is modelled as a parameter that will allow to assess scenarios with different battery capacities. Battery ageing and power loses were included in the maximum usable battery capacity, as it is very complex to model this independently. Batteries need to be fully charged before they are placed on a ship and a minimum battery level is set to avoid batteries to fully discharge, and to keep a safety margin to account for unforeseen events that might require larger power consumption from the vessel than those stated in the sailing profiles. Batteries are assumed to be linearly charged/ discharged in time. The batteries supply energy to the vessel alternatively in each time step. Meaning, that if more than one battery is on a vessel, at a time step p only one battery is used to power the vessel.

Apart from this, docking stations can be located only at terminals which are in the route of a vessel. The vessel's speeds and distances sailed are not modelled. Vessels' sailing profiles (sailing times and power consumption) are not changed due to external factors as the weather or currents. These can indirectly be accounted for by altering the energy consumption per time period of the sailing profiles (model input). The time the vessel stops at a terminal is considered to be enough to load or unload a battery. No extra time for swapping batteries at a docking station and no extra stops from the original routes are considered. The only costs considered in the model are the batteries and docking stations Capex. The costs on the shipper's side (retrofit costs and loss of revenue for carrying batteries instead of cargo) are not considered. A service level of 100% is considered, meaning all the vessels' power demands need to be satisfied.

4.4 Mathematical formulation

In this section a mathematical model of this problem is proposed. To clarify the model, the notations that will be used in this paper are listed as follows.

Sets

b∈B {1,2,3,. . . S}	Set of batteries
v∈V {1,2,3,. . . ,M}	Set of vessels
t∈T {1,2,3. . . T}	Set of terminals
p∈P {1,2,3,. . . H}	Set of time periods

Variables

$$\mathrm{n}_b = \begin{cases} 1, & \text{if battery } b \text{ is being used} \\ 0, & \text{otherwise} \end{cases}$$

$$\mathrm{u}_t = \begin{cases} 1, & \text{if terminal } t \text{ is used as docking station} \\ 0, & \text{otherwise} \end{cases}$$

$$\mathrm{x}_{b,t,p} = \begin{cases} 1, & \text{if battery } b \text{ is at terminal } t \text{ at time } p \\ 0, & \text{otherwise} \end{cases}$$

$$\mathrm{y}_{b,v,p} = \begin{cases} 1, & \text{if battery } b \text{ is on vessel } v \text{ at time } p \\ 0, & \text{otherwise} \end{cases}$$

$$\mathrm{k}_{b,t,p} = \begin{cases} 1, & \text{if battery } b \text{ is being charged at terminal } t \text{ at time } p \\ 0, & \text{otherwise} \end{cases}$$

$$\mathrm{m}_{b,v,p} = \begin{cases} 1, & \text{if battery } b \text{ is providing energy to vessel } v \text{ at time } p \\ 0, & \text{otherwise} \end{cases}$$

$l_{b,p}$	Battery level of battery b at time p

Parameters

Terminals

cds_t	Capex for installing a DS in terminal t [€]
chp_t	Number of charging points of a DS installed at terminal t
pw_t	Power of each charging spot [kW]

Batteries

cb_b	Capex of battery b [€]
cap_b	Maximum battery capacity of battery b [kWh]
mlv	Minimum battery level charge required to be used in vessel
mlb	Minimum battery level at all times to avoid batteries to be fully discharged (safety margin)

Vessels

$sp_{v,t,p}$	Sailing route. If vessel v is at terminal t at time step p, then $sp_{v,v,p}$=1, and 0 otherwise.
$pv_{v,p}$	Power consumption of vessel v at time step p [kWh]
chv_v	Number of batteries that can be fitted in vessel v (docking points).

Initial values

$Lb_{b,0}$	Battery level at start of period (p=0)

$$\mathrm{Ut}_{b,t,0} = \begin{cases} 1, & \text{If battery } b \text{ is at terminal } t \text{ at p=0} \\ 0, & \text{otherwise} \end{cases}$$

$$\mathrm{Uv}_{b,v,0} = \begin{cases} 1, & \text{If battery } b \text{ is on vessel } v \text{ at p=0} \\ 0, & \text{otherwise} \end{cases}$$

$$\mathrm{k0}_{b,t,0} = \begin{cases} 1, & \text{If battery } b \text{ is at terminal } t \text{ and is being charged at p=0} \\ 0, & \text{otherwise} \end{cases}$$

$$\mathrm{m0}_{b,v,0} = \begin{cases} 1, & \text{If battery } b \text{ is on vessel } v \text{ and the battery is being used at p=0} \\ 0, & \text{otherwise} \end{cases}$$

Others

M_1	Large number
M_2	Small number

Objective function

The objective is to minimise the total investment cost of the batteries and docking stations.

$$min\left(\sum_{b\in B} n_b.cb_b + \sum_{t\in T} u_t.cds_t\right) \tag{1}$$

The first term of the objective function represent the battery investment costs (Capex) and the second term the docking station the investment costs (Capex).

Constraints

$$n_b.M_1 \geq \sum_{t\in T}\sum_{p\in P/p>0} x_{b,t,p} + \sum_{v\in V}\sum_{p\in P/p>0} y_{b,v,p} \ ; \ \forall b \in B \tag{2}$$

$$u_t.M_1 \geq \sum_{b\in B}\sum_{p\in P/p>0} x_{b,t,p}.n_b \ ; \ \forall t \in T \tag{3}$$

$$1 \geq \sum_{b\in B} m_{b,v,p} \geq pv_{v,p}.M_2 \ ; \ \forall v \in V \ ; \ \forall p \in P \ ; \ \forall p > 0 \tag{4}$$

$$l_{b,p} \leq l_{b,p-1} + \left(\sum_{t\in T} pw_t.k_{b,t,p} - \sum_{v\in V} pv_{v,p}.m_{b,v,p}\right) \ ; \ \forall b \in B \ ; \ \forall p \in P \ ; \ \forall p > 0 \tag{5}$$

$$cap_b.n_b \geq l_{b,p} \geq cap_b.n_b.mbl \ ; \ \forall b \in B \ ; \ \forall p \in P \ ; \ \forall p > 0 \tag{6}$$

$$(y_{b,v,p} - y_{b,v,p-1}).mlv.cap_b \leq l_{b,p} \ ; \ \forall b \in B \ ; \ \forall v \in V \ ; \ \forall p \in P \ ; \ \forall p > 0 \tag{7}$$

$$\sum_{t\in T} x_{b,t,p} + \sum_{v\in V} y_{b,v,p} = n_b \ ; \ \ \forall b\in B \ ; \ \ \forall p\in P \ ; \ \ \forall p>0 \tag{8}$$

$$x_{b,t,p} \leq x_{b,t,p-1} + \sum_{v\in V}(y_{b,v,p-1}.sp_{v,t,p}) \ ; \ \ \forall b\in B \ ; \ \ \forall t\in T \ ; \ \ \forall p\in P \ ; \ \ \forall p>0 \tag{9}$$

$$y_{b,v,p} \leq y_{b,v,p-1} + \sum_{t\in T}(x_{b,t,p-1}.sp_{v,t,p}) \ ; \ \ \forall b\in B \ ; \ \ \forall v\in V \ ; \ \ \forall p\in P \ ; \ \ \forall p>0 \tag{10}$$

$$\sum_{b\in B} x_{b,t,p} \leq cht_t \ ; \ \ \forall t\in T \ ; \ \ \forall p\in P \tag{11}$$

$$\sum_{b\in B} y_{b,v,p} \leq chv_v \ ; \ \ \forall v\in V \ ; \ \ \forall p\in P \tag{12}$$

$$k_{b,t,p} \leq x_{b,t,p} \ ; \ \ \forall b\in B \ ; \ \ \forall t\in T \ ; \ \ \forall p\in P \ ; \ \ \forall p>0 \tag{13}$$

$$m_{b,v,p} \leq y_{b,v,p} \ ; \ \ \forall b\in B \ ; \ \ \forall v\in V \ ; \ \ \forall p\in P \ ; \ \ \forall p>0 \tag{14}$$

$$x_{b,t,0} = Ut_{b,t,0}.n_b \ ; \ \ \forall b\in B \ ; \ \ \forall t\in T \tag{15}$$

$$y_{b,v,0} = Uv_{b,v,0}.n_b \ ; \ \ \forall b\in B \ ; \ \ \forall v\in V \tag{16}$$

$$k_{b,t,0} = k0_{b,t,0}.n_b \ ; \ \ \forall b\in B \ ; \ \ \forall t\in T \tag{17}$$

$$m_{b,v,0} = m0_{b,v,0}.n_b \ ; \ \ \forall b\in B \ ; \ \ \forall v\in V \tag{18}$$

$$l_{b,0} = Lb_0.n_b \ ; \ \ \forall b\in B \tag{19}$$

$$k_{b,t,p} \geq 0 \ ; \ \ \forall b\in B \ ; \ \ \forall t\in T \ ; \ \ \forall p\in P \tag{20}$$

$$m_{b,v,p} \geq 0 \ ; \ \ \forall b\in B \ ; \ \ \forall v\in V \ ; \ \ \forall p\in P \tag{21}$$

$$x_{b,t,p} \in \{0,1\} \ ; \ \ \forall b\in B \ ; \ \ \forall t\in t \ ; \ \ \forall p\in P \tag{22}$$

$$y_{b,v,p} \in \{0,1\} \ ; \ \ \forall b\in B \ ; \ \ \forall v\in V \ ; \ \ \forall p\in P \tag{23}$$

$$n_b \in \{0,1\} \ ; \ \ \forall b\in B \tag{24}$$

$$u_t \in \{0,1\} \ ; \ \ \forall t\in T \tag{25}$$

$$k_{b,t,p} \in \{0,1\} \ ; \ \ \forall b\in B \ ; \ \ \forall t\in t \ ; \ \ \forall p\in P \tag{26}$$

$$m_{b,v,p} \in \{0,1\} \ ; \ \ \forall b\in B \ ; \ \ \forall v\in V \ ; \ \ \forall p\in P \tag{27}$$

Constraints 2 and 3 determine the usage of the batteries and the terminals as docking stations. Constraint 4 limits to one the number of batteries that can supply energy to a vessel at each time step. Constraint 5 determines the battery charge level at every time step. It also guarantees that the power requirement from the vessel at each time step is satisfied. Constraint 6 bounds the battery level between the maximum capacity and a minimum battery level to avoid batteries to fully discharge (safety margin). It also guarantees non-negative values for the battery level. Constraint 7 sets a minimum battery level for the battery to be placed on a vessel. Constraint 8 limits the battery location to either a terminal or on a vessel, whereas constraints 9 and 10 match the vessels' routes to the batteries. Not allowing for a battery to move in the network if it is not on a vessel. Constraints 11 and 12 limit the maximum number of batteries that can be at a docking station and on a vessel according to the number of charging and docking spots respectively. Constraints 13 and 14 force the battery to be at a docking station to be charged and to be on a vessel to provide it with energy respectively. Constraints 15, 16, 17, 18 and 19 set the initial battery location, battery usage and battery charge level values. Finally, constraints 20 and 21 set the variables to be non-negative and constraints 22, 23, 24, 25, 26 and 27 defines the binary variables.

4.5 Model verification

To verify the model, this is to check if the model works correctly, two verification were performed. Starting with a base model, different parameters were modified and the new results compared against the base model to check if they were logical. Due to time limitations in the runs of the model, small scenarios were designed for the verification.

Base Model

The base model consists of a simplified network with seven possible terminals that can be potential docking stations, three vessels, sailing different routes and a fleet of twenty possible batteries. A time period of 24 hours with time steps of 1 hour is modelled. The initial locations of the batteries are two on each ship and two on each of the possible docking stations. All the batteries are fully charged at p=0.

Verification 1: increase in the batteries capacities

Increasing battery capacity will lead to the need of fewer batteries in the system as the vessel's autonomy increases. Moreover, it should lead to the need of less docking stations. If the capacity increases so as to cover the whole 24 hours modelled with one battery, the output of the model should be that only one battery is used for each of the vessels and no docking stations to recharge the batteries are needed. To run the first verification, only the battery capacity was altered. It was increased from 2.000kW to 8.600kW.

Verification 2: increase in the number of docking spots in the vessels

If more docking spots are available on the vessels, it means that the vessels can carry more batteries and, therefore, have larger autonomy. For this verification the number of docking spots was increased to four. Then, twelve batteries were modelled, initially located on the vessels fully charged, plus fourteen batteries located at the terminals (two in each terminal). As the battery Capex is lower than the DS Capex, it is expected to have an output with more batteries and less or even no DS used.

Verification outputs

For the base case, six batteries and six docking stations were needed. As for the first verification, only three batteries and no docking stations were needed. Whereas for the second verification nine batteries and three docking stations were required. Therefore, the obtained values match the expected ones.

4.6 Model validation

The Proof of Concept (PoC) of the ZEEC implementation is used to validate the model, this is to check the model is an accurate representation of the reality. The PoC was carried out with the Alphenaar vessel which has a sailing route in the Zoeterwoude - Alpherium - Moerdijk corridor between the CCT harbor in Alpherium and Moedijk. The trip is about 60km and takes approximately 6 hours.

The company is aware that with the current sailing profile, the Alphenaar cannot sail fully electric the round trip abovementioned if it only carries two batteries with useful capacity of 2MWh on average. It is, therefore, expected that the output of the model in the validation will be infeasible for only one docking station, while a possible solution should be to have two docking stations.

For the validation it was assumed that two batteries were available at time p=0 in the vessel, and two batteries were at each of the terminals at which the vessel Alphenaar stops at in its route. All the batteries were assumed to be fully charged at the initiation of the model run. The modelled time was 48 hs in 2-hour time steps.

The outputs obtained were the need of two batteries and two docking stations placed in Alphen aan der Rijn and Moerdijk. As explained before the expected output of the model is to have two docking stations that will allow the vessel to complete each one-way trip with the power of two batteries. Then the batteries are recharged while the ship is at the terminal.

5 Computational experiments

5.1 Model implementation

There are many programs in which the MILP can be developed and implemented. For this research, Python was the language used for the programming and Spyder the program to run the code. The optimiser Gurobi was chosen as the solver for the optimisation problem.

Given the amount of binary variables that the model has, computational time is an issue when solving the optimisation problem. Though Gurobi has very fast solvers as it first reduces the size of the problem using a pre-solver, the running times proved to be an issue for the modelled problem when more than four vessels and 24 time steps were modelled. For this reason, analysing the whole fleet of vessels of the first scale-up phase was not directly possible.

Therefore, it was decided to firstly analyse numerical experiments with fictitious sailing profiles with which to prove the main opportunities that the optimisation model can bring to the system. For this, three key performance indicators (KPIs) were defined: number of batteries per vessel, DS per vessel and investment cost per vessel. The sailing profiles are designed so as to show the possible gains that can be obtained in each case. Though the profiles are not real they attempt to be as realistic as possible. For this, a consistent network of locations and connections was considered with vessels sailing closed-loop routes. Moreover, the sailing and docking times tried to resemble the case data.

The idea is to analyse how increases in the demand for zero emission vessels affect the different KPIs for two scenarios, the same corridor and multiple corridors. Moreover, impact of battery capacity variations, docking stations design (number of charging spots and power of each charging spot) and number of docking spots on the vessels, will also be assessed. Secondly, experiments will be run with the real sailing profiles simplified and adapted to fit in 24 hours to see to what extend the KPIs changed in real-life cases. For this the ZES case study will be presented in this subsection.

5.2 Numerical experiments

The fictitious sailing profiles were build in order to show the potential that the model can have in terms of battery and docking station number and location optimisation. Though fictitious, these profiles tried to resemble a logical sailing profile of a real vessel of the case study. Meaning that the following considerations were made when building them:

- 24/7 operation: not allowing a vessel to use the batteries during the day and another during the night. This is the sort of operation the case study container barges have.
- Sailing times larger than times at terminals
- Total power consumption per trip between terminals similar to real sailing profiles
- Closed-loop routes
- Round trips shorter than the 24 hours modelled so as to guarantee that the battery at the end of the time period is enough to start a new trip.

A network of five terminals and vessels with four different routes were considered as it can be seen in the figure below.

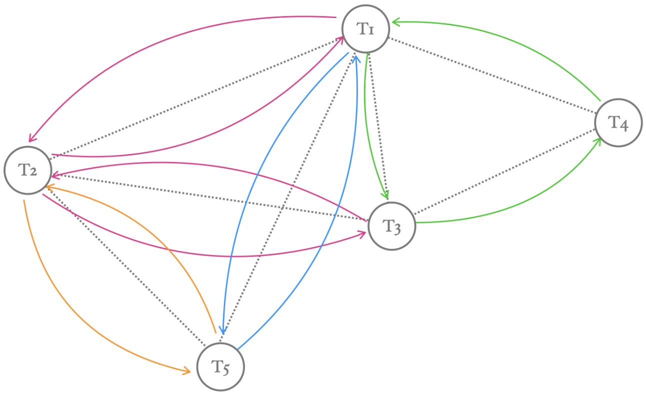


Figure 1: Fictitious routes

- Route A (red): T1 - T2 - T3 -T2 -T1
- Route B (green): T1 - T3 - T4 - T1
- Route C (orange): T2 - T5 - T2
- Route D (blue): T1 - T5 – T1

With the abovementioned considerations and network the following profiles were designed.

Table 1: Fictitious sailing profiles

	Sailing profile A		Sailing profile B		Sailing profile C		Sailing profile D	
Time [hs]	**Location**	**Power [kW]**	**Location**	**Power [kW]**	**Location**	**Power [kW]**	**Location**	**Power [kW]**
1	T1	0	Sailing	700	T5	0	Sailing	600
2	Sailing	800	Sailing	700	T5	0	Sailing	600
3	Sailing	800	T1	0	T5	0	T1	0
4	T2	0	T1	0	Sailing	550	Sailing	600
5	T2	0	Sailing	700	Sailing	550	Sailing	600
6	Sailing	800	Sailing	700	Sailing	550	T5	0
7	Sailing	800	Sailing	700	Sailing	550	Sailing	600
8	Sailing	800	T3	0	Sailing	550	Sailing	600
9	Sailing	800	T3	0	Sailing	550	T1	0
10	T3	0	Sailing	700	T2	0	Sailing	600
11	T3	0	Sailing	700	T2	0	Sailing	600
12	Sailing	800	Sailing	700	T2	0	T5	0
13	Sailing	800	T4	0	Sailing	550	Sailing	600
14	Sailing	800	T4	0	Sailing	550	Sailing	600
15	Sailing	800	Sailing	700	Sailing	550	T1	0
16	T2	0	Sailing	700	Sailing	550	Sailing	600
17	T2	0	Sailing	700	Sailing	550	Sailing	600
18	Sailing	800	T1	0	Sailing	550	T5	0
19	Sailing	800	T1	0	T5	0	Sailing	600
20	Sailing	800	Sailing	700	T5	0	Sailing	600
21	Sailing	800	Sailing	700	T5	0	T1	0
22	T1	0	Sailing	700	Sailing	550	Sailing	600
23	T1	0	T3	0	Sailing	550	Sailing	600
24	Sailing	800	T3	0	Sailing	550	T5	0

Base Case

The aim of the base case is to have reference values to which to compare the outputs of the different scenarios. For each vessel a base case is modelled. The following assumptions and considerations were made for the base case inputs:

- All vessels will be modelled considering the same time horizon of 24 hours
- The time step is 1 hour
- Fully charged batteries are available on the vessels and on the terminals of the vessel's routes at the beginning of the first time period (p=0)
- Every terminal of the route of the vessel is a possible docking station with 2 charging spots that provide 1.000kW each
- Battery capacity: 2.000kWh/battery
- Battery capex: 955.500€/battery
- Docking station capex: 1.350.000€/DS
- The minimum battery level to be place on a vessel is 90% and batteries should have at least a 10% of battery level at all times.

Scenario 1: increase in number of vessels

In the first scenario the vessels' demands will be modified. Firstly, one single route will be considered. The model will be run for one up to four vessels of the same characteristics and sailing profiles. The sailing profile chosen for this test is the sailing profile A. This sailing was selected because it visits three terminals and also has the largest power consumption per sailing period. This led to the best results in terms of battery per vessel and cost per vessel reduction with vessel demand increase, compared to sailing profiles B, C and D. To simulate the added demand (more vessels with the same profile) the profiles are offset one of the other every six hours. The second scenario considers all routes. In this case, four vessels with different routes and sailing profiles were modelled, one per corridor. All the other parameters will be kept as explained for the Base Case. The idea of this scenario is to show the reduction of batteries per vessel and docking station per vessel when vessel demand increases. Therefore, to show the benefit in terms of Capex, of having shared batteries between vessels instead of assigned batteries to each vessel.

Scenario 2: capacity variations of batteries
For the second scenario variations in battery capacity are implemented for the whole battery fleet for a vessel demand of three vessels, sailing the profile D (see table 1). It is expected that battery capacity will increase over time, leading to larger sailing ranges. Therefore, it is very relevant to analyse how battery capacity increases might affect the model outputs. An increase in the battery capacity will have an impact on the needed number of batteries but also can affect the possible docking station locations, as the larger the power the batteries can supply the larger the vessel autonomy and the less docking stations are needed. On the other hand smaller batteries are cheaper, therefore, it might be of interest to have more smaller batteries if vessels do not require so much power. For different battery capacity, different Capex are associated, which were provided by the company. All the other parameters will be kept as explained for the Base Case.

Scenario 3: number & capacities of charging spots in Docking Stations
The base case is run assuming all docking stations to be equal as the one being built for the Proof of Concept at Alphen aan der Rijn. However, depending on the actual demand of charging spots and power, the DS could be larger or smaller. Therefore, several scenarios varying the number of charging spots and power per spot are analysed. The different DS designs will also imply different Capex. This scenario can be useful to assess possible trade-offs between number and size of the docking stations. The different docking stations designs analysed have different Capex. A demand of three vessels sailing the profiles A, B and C was considered. All the other parameters will be kept as explained for the Base Case.

Scenario 4: number of docking spots on board of vessels
The vessels' retrofit costs and revenue loss for carrying batteries instead of cargo are not considered in the model. To analyse the total system costs of implementing the exchangeable batteries system these costs need to be accounted for. Therefore, different scenarios with different number of docking spots on vessels will be analysed. All the other parameters will be kept as explained for the Base Case. The idea is to determine the optimal number of batteries and docking stations to have the least total costs, including the vessels retrofit costs and profit loss for carrying batteries instead of cargo, which are determined by the number of docking spots. Cases with two and three vessels sailing the profile D will be compared. A fully charged battery will be placed per docking spot in the vessel at p=0.

5.2.1 Results

Base Case

Table 2: Base Case results for the fictitious sailing profiles

	Scenarios			
Number of vessels	1	1	1	1
Sailing profile type	A	B	C	D
Number of batteries required	5	2	2	3
Number of docking stations	3	3	2	1
Locations	T1, T2, T3	T1, T3, T4	T2, T5	T5
Total Capex [€]	8.827.500	5.961.000	4.611.000	4.216.500

Scenario 1: increase in number of vessels
The obtained results for this scenario are shown in the tables below for both cases, same route and different routes. In the second table the results are presented as follows. For each vessel demand, the first column are the summed results of the independent sailing profiles (as in the base case). The second column shows the results of the combined case.

Table 3: Results of Scenario 1: increase in demand in the same route for the fictitious sailing profiles

	Scenarios			
Number of vessels	1	2	3	4
Sailing profile type	A	A	A	A
Number of batteries required	5	7	9	11
Number of docking stations	3	3	3	3
Locations	T1, T2, T3	T1, T2, T3	T1, T2, T3	T1, T2, T3
Total Capex [€]	8.827.500	10.738.500	12.649.500	14.560.500
Batteries per vessel	5,0	3,5	3,0	2,8
DS per vessel	3,0	1,5	1,0	0,8
Shared batteries	0	3	8	8
	---	3 by 2 vessels	8 by 2 vessels	6 by 2 vessels 2 by 3 vessels
Cost per vessel [€/vessel]	8.827.500	5.369.250	4.216.500	3.640.125

Table 4: Results of Scenario 1: increase in demand in different routes for the fictitious sailing profiles

	Scenarios					
Number of vessels	2		3		4	
Sailing profile type	A+B	A, B	A+B+C	A, B, C	A+B+C+D	A, B,C, D
Number of batteries required	7	5	9	7	12	11
Number of docking stations	4	4	5	5	5	4
Locations	T1, T2, T3, T4	T1, T2, T3, T4	T1, T2, T3, T4, T5	T1, T2, T3, T4, T5	T1, T2, T3, T4, T5	T1, T2, T3, T5
Total Capex [€]	12.088.500	10.177.500	15.349.500	13.438.500	18.216.000	15.910.500
Batteries per vessel	3,5	2,5	3,0	2,3	3,0	2,8
DS per vessel	2,0	2,0	1,7	1,7	1,3	1,0
Shared batteries	0	2	0	4	0	5
	---	2 by 2 vessels	---	4 by 2 vessels	---	5 by 2 vessels
Cost per vessel [€/vessel]	6.044.250	5.088.750	5.116.500	4.479.500	4.554.000	3.977.625

In both cases, an increase in demand in the same corridor and in different corridors, a decrease of needed batteries and docking stations per vessel can be seen. This is due to sharing of batteries and infrastructure. In the case of the same corridor, the need for batteries for only one vessel is very high, but as soon as more vessels of the same type sail the same route, battery sharing occurs, reducing the needed number of battery per vessel significantly. Every time a new vessel is added to the route, the battery per vessel requirement decreases steadily. For different routes, a decrease of batteries per vessel can be seen when comparing to the sum of the sailing profiles independently (as in the base case). The decrease depends on the routes that have been shared. The decrease is also not constant, as the different routes combinations do not allow the sharing in all terminals. Regarding the DS per vessel only for the combined case of profiles type A, B, C and D, a decrease in needed DS is seen compared to the scenario of summing the independent profiles. As for the investment cost in batteries and DS per vessel a decrease is seen in both cases as demand increases. Showing that a better scenario in terms of Capex can be obtained if more vessels use the installed infrastructure, as benefits from synergies between the routes can be reached.

Scenario 2: capacity variations of batteries
The obtained results for this scenario are shown in the tables below for the same route.

Table 5: Results of Scenario 2: battery capacity variations in the same route for the fictitious sailing profiles

	Scenarios			
Number of vessels	3	3	3	3
Sailing profile type	D	D	D	D
Battery capacity [kWh]	1.500	2.000	2.500	3.000
Battery cost [€]	817.000	955.500	1.107.000	1.252.000
Number of batteries required	8	7	7	7
Number of docking stations	2	2	2	1
Locations	T1, T5	T1, T5	T1, T5	T5
Total Capex [€]	9.236.000	9.388.500	10.449.000	10.114.000
Batteries per vessel	2,7	2,3	2,3	2,3
DS per vessel	0,7	0,7	0,7	0,3
Shared batteries	8	7	6	6
	4 by 2 vessels 4 by 3 vessels	6 by 2 vessels 1 by 3 vessels	5 by 2 vessels 1 by 3 vessels	2 by 2 vessels 4 by 3 vessels
Cost per vessel [€/vessel]	3.078.667	3.129.500	3.483.000	3.371.333

It can be expected that an increase in battery capacity will lead to a reduction on the total number of needed batteries per vessel. However, this depends on the case as larger battery capacity can lead to less docking stations, maintaining the number of batteries. This is the case for a fleet of batteries with 3.000kWh the same number of batteries but less docking stations than with 2.000kWh is needed. This reduction however, does not lead to a benefit in terms of costs per vessel, as the increase in battery cost per unit does not compensate the reduction in docking stations costs. Despite the above, a scenario like this can be of interest as one less docking station will also mean less operational costs (which are not included in the model, but need to be assessed) and more income to that one station, as all batteries need to be charged there. For the case of a battery capacity decrease, one more battery is needed but the same docking stations. Given the cost reduction of the smaller battery, this scenario is better than the original in terms of costs. Regarding the shared batteries not a significant difference is seen between the scenarios.

Scenario 3: number & capacities of charging spots in Docking Stations
The obtained results for this scenario are shown in the tables below for the different routes.

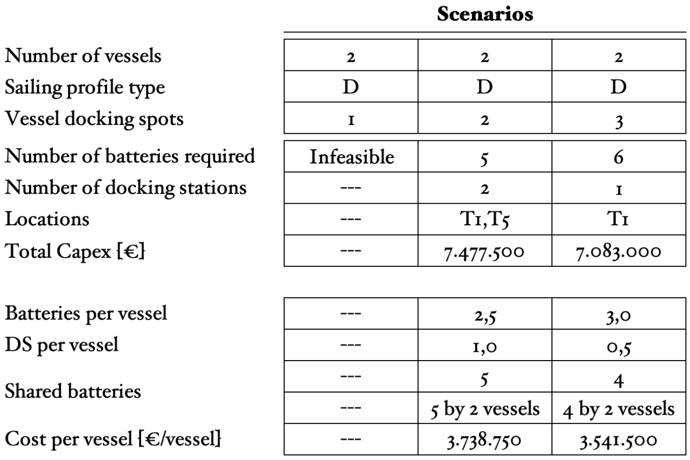
Table 6: Results of Scenario 3: docking stations design variations in different routes for the fictitious sailing profiles

	Scenarios							
Number of vessels	3	3	3	3	3		3	
Sailing profile type	A, B, C	A, B, C	A, B, C	A, B, C	A, B, C		A, B, C	
DS spots	2	2	1	1	2	2	2	1
Power per docking spot [kW]	1.000	500	750	1.000	1.000	500	1.000	750
DS Capex [€]	1.350.000	1.080.000	840.000	950.000	1.350.000	1.080.000	1.350.000	840.000
Number of batteries required	7	Infeasible	Infeasible	Infeasible	10		9	
Number of docking stations	5	---	---	---	3	2	3	2
Locations	T1, T2, T3, T4, T5	---	---	---	T2, T3, T5	T1, T4	T2, T3, T5	T1, T4
Total Capex [€]	13.438.500	---	---	---	15.765.000		14.329.500	
Batteries per vessel	2,3	---	---	---	3,3		3,0	
DS per vessel	1,7	---	---	---	1,7		1,7	
Shared batteries	4	---	---	---	4		4	
	4 by 2 vessels	---	---	---	4 by 4 vessels		4 by 4 vessels	
Cost per vessel [€/vessel]	4.479.500	---	---	---	5.255.000		4.776.500	

It can be seen that when changing all the docking stations types for two charging spots of 1000kW, one charging spot of 750kW and one charging spot of 1.000kW, no result is feasible. Meaning that the charging infrastructure considered cannot satisfy the charging demand of the battery fleet. The charging demand required number of stations of the first scenario (two charging spots of 1.000kW) was determined and two of them were significantly less demanded than the other three (stations in T1 and T4). Then, these two stations were set with a smaller design. The results obtained do not show an improvement in both cases in terms of cost per vessel, batteries per vessel or docking stations per vessel. However, it can be of relevance to determine the demand of each docking station, as having idle capacity can be useful if an increase in demand is expected, but less profitable if this is not so.

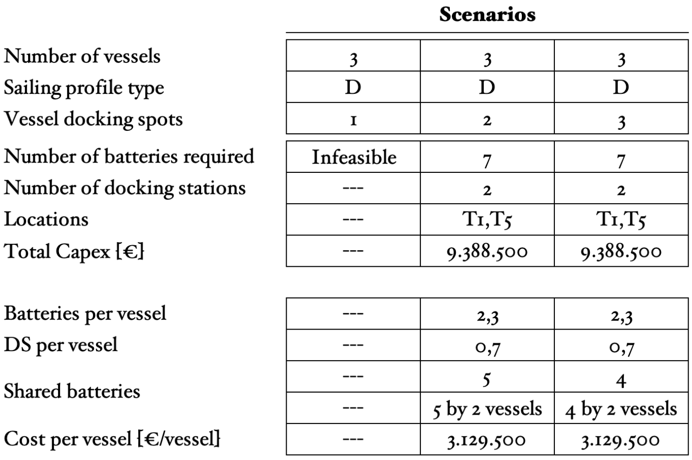
Scenario 4: number of docking spots on board of vessels
The obtained results for this scenario are shown in the tables below for the same route for two and three vessels.

Table 7: Results of Scenario 4: number of docking spots on board variations for two vessels sailing same fictitious route



	Scenarios		
Number of vessels	2	2	2
Sailing profile type	D	D	D
Vessel docking spots	1	2	3
Number of batteries required	Infeasible	5	6
Number of docking stations	---	2	1
Locations	---	T1,T5	T1
Total Capex [€]	---	7.477.500	7.083.000
Batteries per vessel	---	2,5	3,0
DS per vessel	---	1,0	0,5
Shared batteries	---	5	4
	---	5 by 2 vessels	4 by 2 vessels
Cost per vessel [€/vessel]	---	3.738.750	3.541.500

Table 8: Results of Scenario 4: number of docking spots on board variations for three vessels sailing same fictitious route



	Scenarios		
Number of vessels	3	3	3
Sailing profile type	D	D	D
Vessel docking spots	1	2	3
Number of batteries required	Infeasible	7	7
Number of docking stations	---	2	2
Locations	---	T1,T5	T1,T5
Total Capex [€]	---	9.388.500	9.388.500
Batteries per vessel	---	2,3	2,3
DS per vessel	---	0,7	0,7
Shared batteries	---	5	4
	---	5 by 2 vessels	4 by 2 vessels
Cost per vessel [€/vessel]	---	3.129.500	3.129.500

The results of the fourth scenario show that no significant improvements are obtained when adding more docking spots on board. In the case of a two vessel demand on the same corridor adding one more docking spot on board of the vessels leads to a trade-off of less DS but more batteries, that leads to a reduction of the total investment cost per vessel. However, more docking spots on board mean larger retrofit costs and more profit loss for carrying batteries instead of cargo containers. Therefore, the improvement found needs to be compared against this cost increase on shippers side. Very likely it will not compensate the retrofit and profit loss costs. In the case of three vessels on the same corridor no benefit is observed when increasing the number of batteries on board as this does not compensate the need for the investment in 2 DS. For both cases, a reduction in docking spots on board made the model not feasible, meaning that there is no possible combination of charging infrastructure and battery fleet that to guarantee electric sailing for the vessels.

5.3 ZES study case

The vessel demand used for the study case is the one identified by ZES for their first scale up phase and it consists of seven vessels sailing in four corridors, namely, the Groene, Oost Brabant, Noord Nederland and Maas corridor. The terminals involved in the vessel's routes and their representation for the model are shown below.

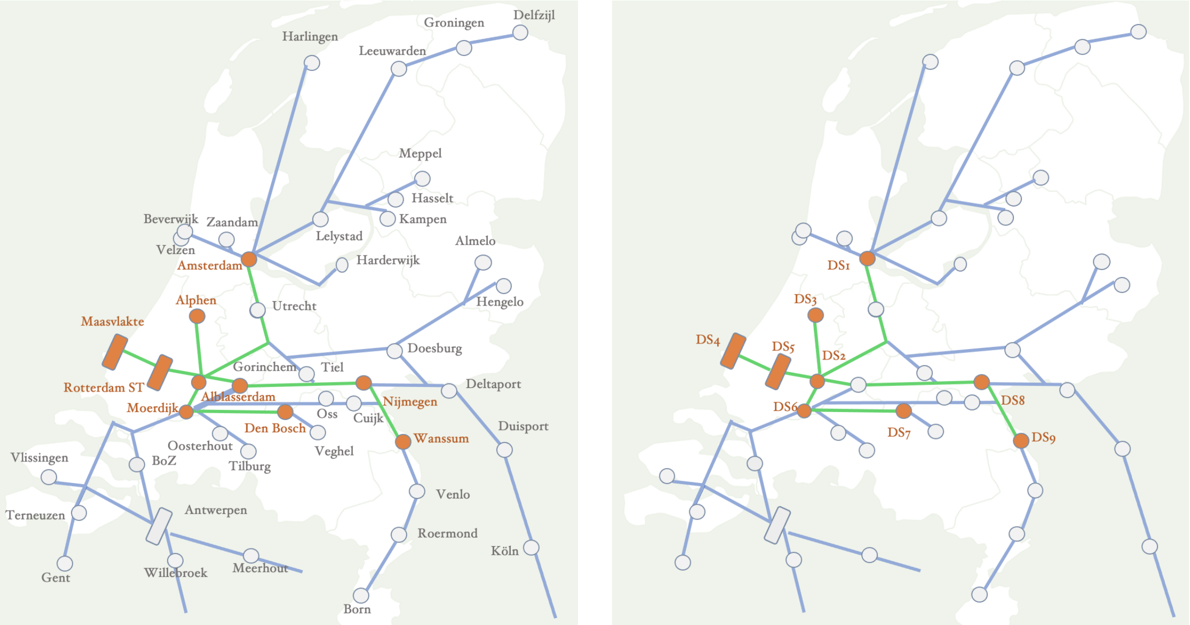


Figure 2: Study case network representation

In these locations ZES determined the feasibility of placing docking stations. It is expected to have different space availability, accessibility to the electric grid and distance to the mooring docks for each terminal, hence, different Capex and Opex will be modelled for each docking station. The same logic than for the fictitious sailing profiles was used to analyse the real-life profiles of the case study. The fleet was simplified to four vessels, the Alphennar, the Gouwenaar, the Den Bosch Max Blauw and the Den Bosch Max Groene and the four scenarios, as with the fictitious sailing profiles, were run.

5.3.1 Results

Base case:

The table below shows the results obtained for the individual vessels.

Table 9: Results of the Base Case for the study case

	Scenarios				
Number of vessels	1	1	1	1	1
Sailing profile type	Alphenaar	Gouwenar	DB Max	Nijmegen	Sendo
Number of batteries required	2	2	2	2	2
Number of docking stations	2	2	3	4	2
Locations	DS3, DS6	DS3, DS6	DS2, DS5, DS7	DS2, DS4, DS8, DS9	DS1, DS5
Total Capex [€]	4.611.000	4.611.000	5.961.000	7.311.000	4.611.000

Scenario 1: increase in number of vessels

The table below shows the results obtained for vessel demand variations for the same sailing profile and for a combination of profiles. For the second table, the first column shows the summed results of the independent sailing profiles (as in the base case), whereas the second column shows the results of the combined profiles.

Table 10: Results of Scenario 1: increase in demand for the same sailing profile for the case study

	Scenarios			
Number of vessels	1	2	3	4
Sailing profile type	DB Max	DB Max	DB Max	DB Max
Number of batteries required	2	5	6	7
Number of docking stations	3	2	3	3
Locations	DS2, DS5, DS7	DS2, DS5	DS2, DS5, DS7	DS2, DS5, DS7
Total Capex [€]	5.961.000	7.477.500	9.783.000	10.738.500
Batteries per vessel	2,0	2,5	2,0	1,8
DS per vessel	3,0	1,0	1,0	0,8
Shared batteries	0,0	3,0	3,0	4,0
	---	3 by 2 vessels	3 by 2 vessels	4 by 2 vessels
Cost per vessel [€/vessel]	5.961.000	3.738.750	3.261.000	2.684.625

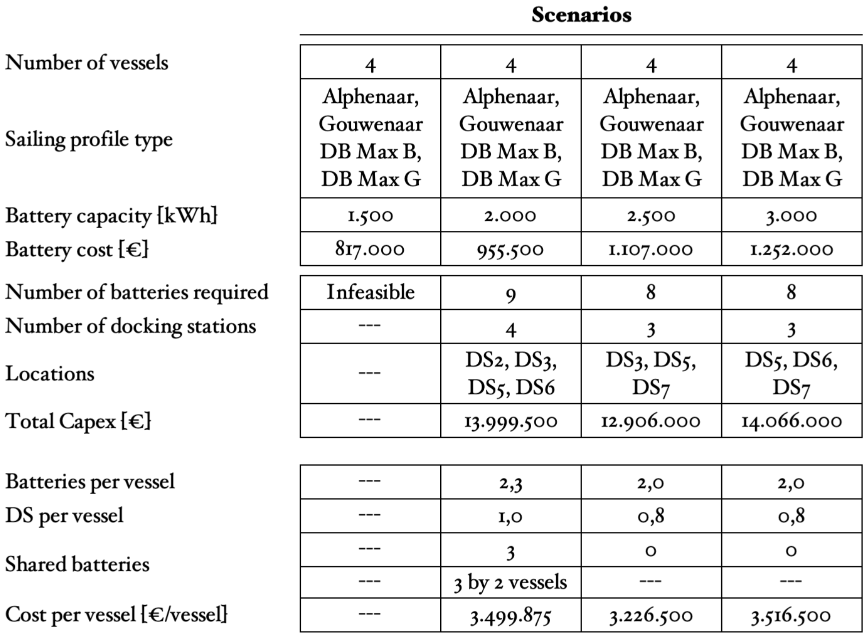
Table 11: Results of Scenario 1: increase in demand for the different sailing profile for the case study

	Scenarios	
Number of vessels	4	4
	Alphenaar + Gouwenaar + DB Max B +DB Max G	Alphenaar, Gouwenaar DB Max B, DB Max G
Number of batteries required	8	9
Number of docking stations	5	4
Locations	DS2, DS3, DS5, DS6, DS7	DS2, DS3, DS5, DS6
Total Capex [€]	14.394.000	13.999.500
Batteries per vessel	2,0	2,3
DS per vessel	1,3	1,0
Shared batteries	0,0	3,0
	---	3 by 2 vessels
Cost per vessel [€/vessel]	3.598.500	3.499.875

As it can be seen in table 10 a reduction of costs per vessel is gained as demand increases for the DB Max vessel. Deploying a second DB Max vessel (column 2) results in an increase in batteries per vessel but in a reduction in DS per vessel. This can be of interest as for a first stage might be more convenient to invest in one DS and more batteries and then expand to one more DS to once more demand is guaranteed. From two to four vessels the increase in demand represented a reduction of both, batteries and DS per vessel. In the case of combining the sailing profiles of the four vessels, a total cost reduction per vessel was observed if compared to the sum of the individual vessels. Also a reduction in needed DS per vessel is seen, though one more battery is needed in the system.

Scenario 2: capacity variations of batteries
The table below shows the results obtained for battery capacity variations for a combination of profiles.

Table 12: Results of Scenario 2: capacity variations for the case study

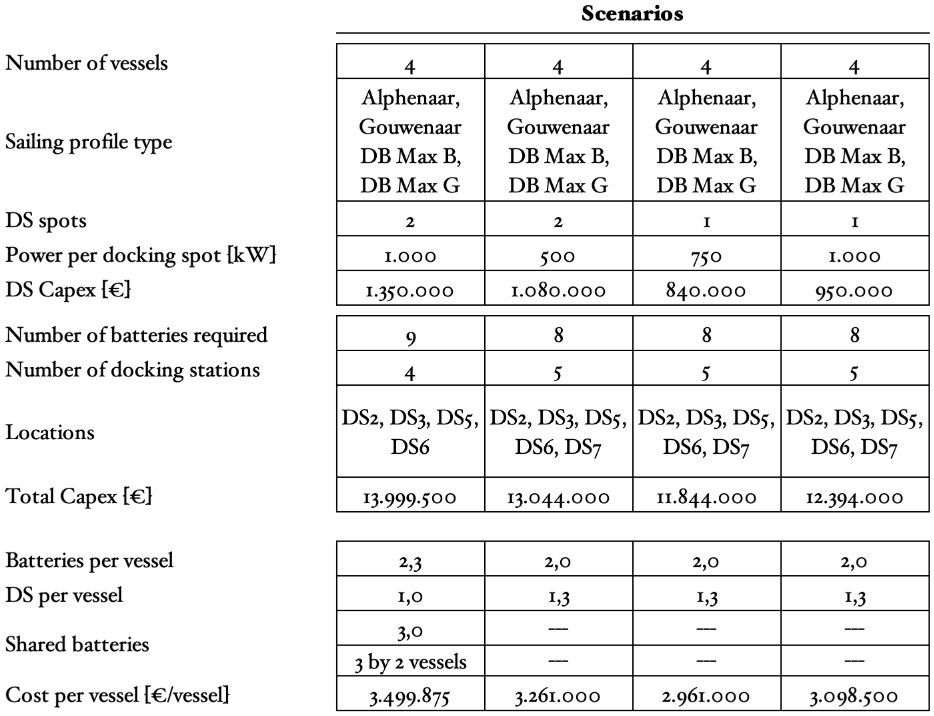


	Scenarios			
Number of vessels	4	4	4	4
Sailing profile type	Alphenaar, Gouwenaar DB Max B, DB Max G	Alphenaar, Gouwenaar DB Max B, DB Max G	Alphenaar, Gouwenaar DB Max B, DB Max G	Alphenaar, Gouwenaar DB Max B, DB Max G
Battery capacity [kWh]	1.500	2.000	2.500	3.000
Battery cost [€]	817.000	955.500	1.107.000	1.252.000
Number of batteries required	Infeasible	9	8	8
Number of docking stations	---	4	3	3
Locations	---	DS2, DS3, DS5, DS6	DS3, DS5, DS7	DS5, DS6, DS7
Total Capex [€]	---	13.999.500	12.906.000	14.066.000
Batteries per vessel	---	2,3	2,0	2,0
DS per vessel	---	1,0	0,8	0,8
Shared batteries	---	3	0	0
	---	3 by 2 vessels	---	---
Cost per vessel [€/vessel]	---	3.499.875	3.226.500	3.516.500

A reduction in battery capacity proved to be unfeasible for the combination of vessels. Both capacity increases, to 2.500kWh and 3.000kWh, proved to require less batteries and less docking stations than the base case. However, for an increase of 3.000kWh the cost per vessel is slightly larger. These results should be further analysed to determine the strategic investment decisions, as reducing one docking station signifies less operational costs.

Scenario 3: number & capacities of charging spots in Docking Stations
The table below shows the results obtained for different DS designs for a combination of profiles.

Table 13: Results of Scenario 3: DS designs variations for the case study



	Scenarios			
Number of vessels	4	4	4	4
Sailing profile type	Alphenaar, Gouwenaar DB Max B, DB Max G	Alphenaar, Gouwenaar DB Max B, DB Max G	Alphenaar, Gouwenaar DB Max B, DB Max G	Alphenaar, Gouwenaar DB Max B, DB Max G
DS spots	2	2	1	1
Power per docking spot [kW]	1.000	500	750	1.000
DS Capex [€]	1.350.000	1.080.000	840.000	950.000
Number of batteries required	9	8	8	8
Number of docking stations	4	5	5	5
Locations	DS2, DS3, DS5, DS6	DS2, DS3, DS5, DS6, DS7	DS2, DS3, DS5, DS6, DS7	DS2, DS3, DS5, DS6, DS7
Total Capex [€]	13.999.500	13.044.000	11.844.000	12.394.000
Batteries per vessel	2,3	2,0	2,0	2,0
DS per vessel	1,0	1,3	1,3	1,3
Shared batteries	3,0	—	—	—
	3 by 2 vessels	—	—	—
Cost per vessel [€/vessel]	3.499.875	3.261.000	2.961.000	3.098.500

For all the assessed DS designs one less battery but one more DS were needed compared to the base case.

From costs perspective the DS design with one charging point of 750kW of capacity is the most optimal. However, it is important to consider possible further vessel demand increase or expansion to other routes to decide which option is the most suitable, as charging infrastructure will remain in place for many years.

Scenario 4: number of docking spots on board

Table 14: Results of Scenario 4: number of docking spots on board variations for the case study

	Scenarios		
Number of vessels	4	4	4
Sailing profile type	Alphenaar, Gouwenaar DB Max B, DB Max G	Alphenaar, Gouwenaar DB Max B, DB Max G	Alphenaar, Gouwenaar DB Max B, DB Max G
Vessel docking spots	1	2	3
Number of batteries required	Infeasible	9	9
Number of docking stations	---	4	2
Locations	---	DS2, DS3, DS5, DS6	DS2, DS3
Total Capex [€]	---	15.972.000	14.061.000
Batteries per vessel	---	2,3	2,3
DS per vessel	---	1,0	0,5
Shared batteries	---	3	3
	---	3 by 2 vessels	3 by 2 vessels
Cost per vessel [€/vessel]	---	3.993.000	3.515.250

Finally, regarding variations in docking spots on board of the vessels, an unfeasible model is obtained when a reduction to one docking spot is modelled (first column of table 14). If more docking spots are available, the results show an improvement in terms of DS per vessel. This is an expected result, as DS Capex is larger than battery Capex. When more docking spots are available on the vessel the more battery capacity can be carried and less stops at DS are required. Again, it is relevant to mention that more docking spots on the vessels mean higher retrofit costs and revenue losses on the shippers' side. Therefore, these results need to be further analysed to determined the optimal solution for the whole system.

5.4 Results discussion

After running the model for the fictitious and real-life sailing profiles, the obtained results showed the optimisation opportunities and possible synergies that can be achieved when vessels share the batteries and charging infrastructure. It is not trivial to determine beforehand the optimal result for different inputs. Four different scenarios and three KPI's were evaluated and the main results are stated below.

- Scenario 1: demand increase
  A demand increase with the same sailing profile showed the highest battery per vessel reductions. When combining routes, the results become more unpredictable and they largely depend on which terminals are shared by the vessels routes, as these are the battery exchange points.
- Scenario 2: battery capacity variations
  Battery capacity variations did not show great improvements for the need of batteries per vessel and only a small improvement in DS per vessel for batteries of 3.000kW. Despite this, larger batteries are also more expensive. Then, the trade-off of less DS is not compensated leading to larger investment costs per vessel.
- Scenario 3: DS design
  The combination of DS designs did not prove to have better results than the base case, regarding the above-mentioned KPIs. Only smaller designs for the case study proved to have a reduction in Capex per vessel.
- Scenario 4: variation in docking spots on vessels
  Adding docking spots on board of the vessels led to less DS. However, further analysis on the shipper's costs side is needed to determine if the gain is relevant for all stakeholders.

In general, better results in terms of batteries reduction per vessel were found with the fictitious sailing profiles than with the real study case ones. This can be expected as the former were built in order to show most of the model potential while remaining as realistic as possible. In real life, it can be expected to have fewer synergies.

6 Conclusions & Recommendations

The proposed optimisation model developed in this research integrates the complexities of the three main components of the exchangeable batteries system to power IWW vessels and allows to analyse different scenarios. The obtained results showed the optimisation opportunities and possible synergies that can be achieved when vessels share the batteries and charging infrastructure. Multiple iterations might be required to obtain the input combination that leads to the most optimal results, as the interactions among the components of the system are complex.

It is important to notice, that the results highly depend on the sailing profiles, which for the case study were provided by shippers based on average consumption of diesel. Changes in speed or weather conditions can alter the power consumption and trip duration, which may affect the results. Prior to run the model, proper analysis of the sailing profiles is needed, and scenario analysis should be performed for the worse, average and best cases in order to assess the impact of these variations and adjust the safety margin if needed, to avoid the risk of running out of battery power while sailing. Moreover, it is worth it to mention, that the results were obtained for a reduced sample of vessels routes and sailing profiles combinations, with a limited time horizon. All the considered vessels are container barges with relatively similar characteristics in terms of power consumption and sailing times and time at terminals. It can be expected to obtain different results if other vessels are analysed. Whether these results are better or worse, in terms of battery sharing and infrastructure requirement, will depend on the sailing profiles, power consumption and terminals at which the vessels stop.

As it was mentioned in the literature review section, no research has been done so far regarding the implementation of an exchangeable battery system to IWW shipping. This research can be considered as the first step to investigate the implementation of this promising zero-emission concept, as it contributes to help assisting the strategic decision of the system implementation from a logistics perspective. Though the outputs of the model do not answer directly this question, through the analysis of different scenarios with different input parameters, information that can be useful to asses this can be obtained.

Several assumptions and simplifications were made when developing the model which limit this research. First, the model aims at minimising the investment costs for the batteries and docking stations, leaving outside the operational costs and other costs like vessel's retrofit. Moreover, the battery capacity was modelled in a simplistic way. A fixed number of maximum available capacity was used per battery and a linear charge/ discharge was considered. In a real-life setting, the available capacity can be lower than the one modelled. Apart from this, the vessels' power consumption were assumed fixed per time step using an average consumption. This is also not realistic, as weather conditions, waves, wind, among other factors modify the power requirement from the vessel.

Regarding the model limitations, they will require further research. It is particularly recommended to perform further research in terms of model improvement (optimisation of running times), incorporation of operational costs and shipper's costs (vessel retrofit and loss of revenue for carrying batteries instead of cargo), incorporation of vessel speed, model non-linear batteries charge/ discharge, charge regimes and battery ageing. Another recommendation regards the possible use of vessels to reallocate batteries in the system and adding possible extra stops to the vessels' routes to exchange batteries.

References

[1] *Lithium-ion battery aging*, (2020). URL https://www.wattalps.com/lithium-ion-battery-aging/.

[2] S. S. Amiri, S. Jadid, and H. Saboori. Multi-objective optimum charging management of electric vehicles through battery swapping stations. *Energy*, 165:549–562, 2018. ISSN 0360-5442. doi: https://doi.org/10.1016/j.energy.2018.09.167. URL https://www.sciencedirect.com/science/article/pii/S036054421831939X.

[3] C.-k. Chang. Factors Affecting Capacity Design of Lithium-Ion Stationary Batteries. *Batteries*, 5(3), 2019. ISSN 2313-0105. doi: 10.3390/batteries5030058. URL https://www.mdpi.com/2313-0105/5/3/58.

[4] EMSA European Maritime Safety Agency. Emsa maritime battery study - electrical energy storage for ships., (2020). URL http://www.emsa.europa.eu/publications/item/3895-study-on-electrical-energy-storage-for-ships.html.

[5] W. Jing, I. Kim, and K. An. The Uncapacitated Battery Swapping Facility Location Problem with Localized Charging System Serving Electric Bus Fleet. *Transportation Research Procedia*, 34:227–

234, 2018. ISSN 2352-1465. doi: https://doi.org/10.1016/j.trpro.2018.11.036. URL `https://www.sciencedirect.com/science/article/pii/S2352146518303259`.

[6] A. A. Juan, C. A. Mendez, J. Faulin, J. De Armas, and S. E. Grasman. Electric vehicles in logistics and transportation: A survey on emerging environmental, strategic, and operational challenges. *Energies*, 9(2):86, 2016.

[7] W. Ketter, M. van Oosterhout, B. Ros, K. Schroer, and P. Theile. Modular Energy Concept (White paper report). 2019. URL `https://www.rsm.nl/fileadmin/Images_NEW/ECFEB/pdf/2019_Living_Energy_Conference_RSMEWI__Modular_Energy_Concept_whitepaper_FINAL.pdf`.

[8] M. Krikke. Retrofitting ships with new technologies for improved overall environmental footprint. *RETROFIT Project Final Report, Rotterdam: Netherlands Maritime Technology Foundation*. URL `https://cordis.europa.eu/project/id/285420/reporting`.

[9] A. Kunith, R. Mendelevitch, and D. Goehlich. Electrification of a city bus network—an optimization model for cost-effective placing of charging infrastructure and battery sizing of fast-charging electric bus systems. *International Journal of Sustainable Transportation*, 11(10):707–720, 2017.

[10] F. Leng, C. M. Tan, and M. Pecht. Effect of Temperature on the Aging rate of Li Ion Battery Operating above Room Temperature. *Scientific Reports*, 5(1):12967, 2015. ISSN 2045-2322. doi: 10.1038/srep12967. URL `https://doi.org/10.1038/srep12967`.

[11] D. Lyridis, H. Psaraftis, N. Ventikos, P. Zacharioudakis, and K. Dilzas. Cost-Benefit Analysis for Ship Automation Retrofit: The Case of Icebreaker Frej. *Marine Technology*, 42:113–124, 2005. doi: 10.5957/mt1.2005.42.2.113.

[12] S. Ma, M. Jiang, P. Tao, C. Song, J. Wu, J. Wang, T. Deng, and W. Shang. Temperature effect and thermal impact in lithium-ion batteries: A review. *Progress in Natural Science: Materials International*, 28(6):653–666, 2018. ISSN 1002-0071. doi: https://doi.org/10.1016/j.pnsc.2018.11.002. URL `https://www.sciencedirect.com/science/article/pii/S1002007118307536`.

[13] M. Mahmoud, Y. Liu, H. Hartmann, S. Stewart, T. Wagener, D. Semmens, R. Stewart, H. Gupta, D. Dominguez, F. Dominguez, D. Hulse, R. Letcher, B. Rashleigh, C. Smith, R. Street, J. Ticehurst, M. Twery, H. van Delden, R. Waldick, D. White, and L. Winter. A formal framework for scenario development in support of environmental decision-making. *Environmental Modelling Software*, 24 (7):798–808, 2009. ISSN 1364-8152. doi: https://doi.org/10.1016/j.envsoft.2008.11.010. URL `https://www.sciencedirect.com/science/article/pii/S1364815208002211`.

[14] M. Rogge, S. Wollny, and D. U. Sauer. Fast charging battery buses for the electrification of urban public transport—a feasibility study focusing on charging infrastructure and energy storage requirements. *Energies*, 8(5):4587–4606, 2015.

[15] B. Taskar and P. Andersen. Benefit of speed reduction for ships in different weather conditions. *Transportation Research Part D: Transport and Environment*, 85:102337, 2020. ISSN 1361-9209. doi: https://doi.org/10.1016/j.trd.2020.102337. URL `https://www.sciencedirect.com/science/article/pii/S1361920919317870`.

[16] H. J. Verheij, C. Stolker, and R. Groenveld. *Inland Waterways - Ports, waterways and inland navigation*. VSSD, Delft, 2008.

[17] M. Xylia, S. Leduc, P. Patrizio, F. Kraxner, and S. Silveira. Locating charging infrastructure for electric buses in stockholm. *Transportation Research Part C: Emerging Technologies*, 78:183–200, 2017.

[18] ZES. A system change to power clean corridors [internal document], 2020.

[19] ZES. Business plan [internal document], 2021.

[20] S. Zhang, M. Chen, and W. Zhang. A novel location-routing problem in electric vehicle transportation with stochastic demands. *Journal of Cleaner Production*, 221:567–581, 2019. ISSN 0959-6526. doi: https://doi.org/10.1016/j.jclepro.2019.02.167. URL `https://www.sciencedirect.com/science/article/pii/S0959652619305669`.

[21] T. Zhang, X. Chen, Z. Yu, X. Zhu, and D. Shi. A monte carlo simulation approach to evaluate service capacities of ev charging and battery swapping stations. *IEEE Transactions on Industrial Informatics*, 14(9):3914–3923, 2018.

B Case study vessels' sailing profiles

In this Appendix the real-life sailing profiles of the case study that were used to run the model in this research are shown. It is important to notice that the original diesel profiles were simplified and adapted to time-steps of 2 hours.

Table 21: Case study vessel's sailing profiles

p: Time step	Alphenaar		Gouwenaar		DB Max Groene		DB Max Blauw		Nijmegen Max		Sendo Nave		Sendo Mare	
	spv: Vessel location	**pv:** Power requreiment [kW]	**spv:** Vessel location	**pv:** Power requreiment [kW]	**spv:** Vessel location	**pv:** Power requreiment [kW]	**spv:** Vessel location	**pv:** Power requreiment [kW]	**spv:** Vessel location	**pv:** Power requreiment [kW]	**spv:** Vessel location	**pv:** Power requreiment [kW]	**spv:** Vessel location	**pv:** Power requreiment [kW]
0	0	801	0	591	2	0	7	0	9	0	0	656	5	0
1	0	801	0	591	0	667	7	0	9	0	0	656	0	215
2	6	0	0	591	0	667	7	0	0	650	0	656	0	215
3	6	0	3	0	0	667	7	0	0	650	0	656	0	215
4	0	591	3	0	5	0	0	800	8	0	0	656	0	215
5	0	591	3	0	5	0	0	800	8	0	5	0	0	215
6	0	591	3	0	5	0	2	0	8	0	0	825	5	0
7	3	0	0	814	0	667	0	667	0	533	4	0	0	825
8	3	0	0	814	0	667	0	667	0	533	0	159	4	0
9	3	0	0	814	0	667	0	667	0	533	0	159	0	111
10	3	0	6	0	2	0	5	0	2	0	0	159	0	111
11	0	814	6	0	0	800	5	0	2	0	0	159	0	111
12	0	814	0	583	0	800	5	0	0	1.000	4	0	0	111
13	0	814	0	583	7	0	0	667	0	1.000	0	825	0	111
14	6	0	0	583	7	0	0	667	4	0	5	0	0	111
15	6	0	3	0	7	0	0	667	4	0	0	576	0	111
16	0	583	3	0	7	0	2	0	4	0	0	576	0	111
17	0	583	3	0	0	800	0	800	4	0	0	576	0	111
18	0	583	3	0	0	800	0	800	4	0	1	0	0	111
19	3	0	0	801	2	0	7	0	0	1.050	0	656	4	0
20	3	0	0	801	0	667	7	0	0	1.050	0	656	0	513
21	3	0	0	801	0	667	7	0	2	0	0	656	5	0
22	3	0	6	0	0	667	7	0	2	0	0	656	0	161
23	0	801	6	0	5	0	0	800	0	1.050	0	656	0	161

C Model code

In this section, the Python code, as well as, examples of the inputs file and the model outputs are given. At the end of this appendix some general comments on the code and the outputs are stated. This Appendix will function as guide on how the model works and will help future research on improvements to the model to take place with ease.

C.1 Input file

The input file is an Excel file with four sheets in which the main attributes of the three system components and the vessels' sailing profiles are given. In the following tables examples of each sheet are provided for the fictitious sailing profiles. 18 batteries (two in each terminal and two in each vessel at p=0), 5 terminals and 4 vessels are used. The parameters are written in blue.

Sheet 1: Batteries
The information given in this sheet is for each battery of the initial fleet: the Capex, the maximum usable capacity and the initial values (at p=0) for battery capacity, location (at a terminal or on a vessel) and usage (charging at a DS or being used by a vessel). For the initial location and usage, the number shows the terminal number or vessel number at which the battery is. The last column works as a check box for the initial location. Every battery needs to be either at a terminal or on a vessel at p=0.

Table 22: Model code: battery inputs

b: Number of battery	**cb:** Battery cost [€]	**cap:** Battery capacity [kWh]	Initial values					
			Lbo: Battery capacity [kWh]	**Uto:** Battery located at terminal	**Uvo:** Battery located on vessel	**ko:** Battery charging at terminal	**mo:** Battery used on vessel	Location Check
1	955.000	2.500	2.500	1	0	1	0	OK
2	955.000	2.500	2.500	1	0	0	0	OK
3	955.000	2.500	2.500	2	0	2	0	OK
4	955.000	2.500	2.500	2	0	0	0	OK
5	955.000	2.500	2.500	3	0	3	0	OK
6	955.000	2.500	2.500	3	0	0	0	OK
7	955.000	2.500	2.500	4	0	4	0	OK
8	955.000	2.500	2.500	4	0	0	0	OK
9	955.000	2.500	2.500	5	0	5	0	OK
10	955.000	2.500	2.500	5	0	0	0	OK
11	955.000	2.500	2.500	0	1	0	1	OK
12	955.000	2.500	2.500	0	1	0	0	OK
13	955.000	2.500	2.500	0	2	0	2	OK
14	955.000	2.500	2.500	0	2	0	0	OK
15	955.000	2.500	2.500	0	3	0	3	OK
16	955.000	2.500	2.500	0	3	0	0	OK
17	955.000	2.500	2.500	0	4	0	4	OK
18	955.000	2.500	2.500	0	4	0	0	OK

Sheet 2: Docking stations
The information shown in this sheet regards the terminals that can be docking stations in the model. Starting with the terminal number, followed by DS Capex, number of charging points and the power of each charging point. The last column is not used by the model but works to have a reference of the name of the terminal.

Table 23: Model code: DS inputs

t: Number of DS	**cds:** DS cost [€]	**cht:** DS charging points	**pw:** Power of each chp [kW]	Terminal name
1	1.490.000	2	1.000	T1
2	1.490.000	2	1.000	T2
3	1.490.000	2	1.000	T3
4	1.490.000	2	1.000	T4
5	1.490.000	2	1.000	T5

Sheet 3: Vessels

In this sheet the information of the number of docking spots on board of each vessel is given. As in the previous case, the last column is used to have a reference of the vessel's name.

Table 24: Model code: vessel inputs

v: Vessel number	**chv:** Docking points	Vessel name
1	2	A
2	2	B
3	2	C
4	2	D

Sheet 4: Sailing profiles

In this last sheet, the information of the sailing profiles is given. The first column correspond to the time steps considered. Then for each vessel the location and power requirement at each time step is given. Location 0 refers to sailing

Table 25: Model code: vessel sailing profiles

p: Time step	Vessel: A		Vessel: B		Vessel: C		Vessel: D	
	spv: Vessel location	**pv:** Power requreiment [kW]	**spv:** Vessel location	**pv:** Power requreiment [kW]	**spv:** Vessel location	**pv:** Power requreiment [kW]	**spv:** Vessel location	**pv:** Power requreiment [kW]
0	1	0	0	700	5	0	0	600
1	0	800	0	700	5	0	0	600
2	0	800	1	0	5	0	1	0
3	2	0	1	0	0	550	0	600
4	2	0	0	700	0	550	0	600
5	0	800	0	700	0	550	5	0
6	0	800	0	700	0	550	0	600
7	0	800	3	0	0	550	0	600
8	0	800	3	0	0	550	1	0
9	3	0	0	700	2	0	0	600
10	3	0	0	700	2	0	0	600
11	0	800	0	700	2	0	5	0
12	0	800	4	0	0	550	0	600
13	0	800	4	0	0	550	0	600
14	0	800	0	700	0	550	1	0
15	2	0	0	700	0	550	0	600
16	2	0	0	700	0	550	0	600
17	0	800	1	0	0	550	5	0
18	0	800	1	0	5	0	0	600
19	0	800	0	700	5	0	0	600
20	0	800	0	700	5	0	1	0
21	1	0	0	700	0	550	0	600
22	1	0	3	0	0	550	0	600
23	0	800	3	0	0	550	5	0

C.2 Pyhton code

```
from gurobipy import *
from openpyxl import load_workbook
from tabulate import tabulate
import numpy as np
import csv
import pandas as pd
np.set_printoptions(threshold=np.inf) # to see all extension when printing


#-----------Create model-------------------------------------------------------
BM = Model ('Basic_Model')


#-----------Import data--------------------------------------------------------
wb = load_workbook('Inputs.xls')
ws = wb.active


#-----------Sets---------------------------------------------------------------
B = np.array([i[0].value for i in wb.worksheets[0]['A3':'A20']])    # set of batteries
V = np.array([i[0].value for i in wb.worksheets[2]['A2':'A5']])     # set of vessels
T = np.array([i[0].value for i in wb.worksheets[1]['A2':'A6']])     # set of terminals
P = np.array([i[0].value for i in wb.worksheets[3]['A3':'A26']])    # set of time periods


#-----------Parameters---------------------------------------------------------

## Batteries
cb = np.array([i[0].value for i in wb.worksheets[0]['B3':'B20']])          # Investment cost [Euro]
cap = np.array([i[0].value for i in wb.worksheets[0]['C3':'C20']])         # Capacity [kW]
mbl = 0.1                                                                  # Min battery level at all times
Lb0 = np.array([i[0].value for i in wb.worksheets[0]['D3':'D20']])         # Initial values: battery level [kW]

ut_aux = np.array([i[0].value for i in wb.worksheets[0]['E3':'E20']])      # Initial values: battery location at terminal
Ut0 = np.zeros((len(B),len(T)))
for b in range(len(B)):
    if ut_aux[b]>0:
        Ut0[b,ut_aux[b]-1]=1

uv_aux = np.array([i[0].value for i in wb.worksheets[0]['F3':'F20']])      # Initial values: battery location on vessel
Uv0 = np.zeros((len(B),len(V)))
for b in range(len(B)):
    if uv_aux[b]>0:
        Uv0[b,uv_aux[b]-1]=1

k_aux = np.array([i[0].value for i in wb.worksheets[0]['G3':'G20']])       # Initial values: battery usage on terminal
k0 = np.zeros((len(B),len(T)))
for b in range(len(B)):
    if k_aux[b]>0:
        k0[b,k_aux[b]-1]=1

m_aux = np.array([i[0].value for i in wb.worksheets[0]['H3':'H20']])       # Initial values: battery usage on vessel
m0 = np.zeros((len(B),len(V)))
for b in range(len(B)):
    if m_aux[b]>0:
        m0[b,m_aux[b]-1]=1

## Vessels
chv = np.array([i[0].value for i in wb.worksheets[2]['B2':'B5']])          # Total number of charging points in vessel

sp_aux = [np.array([i[0].value for i in wb.worksheets[3]['B3':'B26']]),  # Sailing profile of vessels
    np.array([i[0].value for i in wb.worksheets[3]['D3':'D26']]),
```

```
    np.array([i[0].value for i in wb.worksheets[3][’F3’:’F26’]]),
     np.array([i[0].value for i in wb.worksheets[3][’H3’:’H26’]])]

sp_aux = np.array(sp_aux)

sp = np.zeros((len(V),len(T),len(P)))
for v in range(len(V)):
    for p in range (len(P)):
        if sp_aux[v,p]>0:
            sp[v,sp_aux[v,p]-1,p]=1

pv_aux = [np.array([i[0].value for i in wb.worksheets[3][’C3’:’C26’]], dtype=float), # Power requirement per time step
    np.array([i[0].value for i in wb.worksheets[3][’E3’:’E26’]], dtype=float),
    np.array([i[0].value for i in wb.worksheets[3][’G3’:’G26’]], dtype=float),
     np.array([i[0].value for i in wb.worksheets[3][’I3’:’I26’]], dtype=float)]

pv = np.array(pv_aux)

mlv = 1    # Min battery level to be placed on vessel

## Docking Stations
cds = np.array([i[0].value for i in wb.worksheets[1][’B2’:’B6’]])  # Investment cost [Euro]
cht = np.array([i[0].value for i in wb.worksheets[1][’C2’:’C6’]])  # Total number of charging points at terminal
pw = np.array([i[0].value for i in wb.worksheets[1][’D2’:’D6’]])   # Power grids provide the DS [kWh]

## Others
M1 = 2*len(P)      # Large number
M2 = 0.0001        # Small number


#-----------Variables---------------------------------------------------------

# x[b,t,p]: Binary variable if battery is at ds
x = {}
for b in range(len(B)):
    for t in range(len(T)):
        for p in range(len(P)):
            x[b,t,p]=BM.addVar (lb=0, vtype=GRB.BINARY, name="x["+str(b)+","+str(t)+","+str(p)+"]")

# y[b,v,p]: Binary variable if battery is at a vessel
y = {}
for b in range(len(B)):
    for v in range(len(V)):
        for p in range(len(P)):
            y[b,v,p]=BM.addVar (lb=0, vtype=GRB.BINARY, name="y["+str(b)+","+str(v)+","+str(p)+"]")

# n[b]: Binary variable if a battery is used
n = {}
for b in range(len(B)):
    n[b]=BM.addVar (lb=0, vtype=GRB.BINARY, name="n["+str(b)+"]")

# u[t]: Binary variable if a terminal is used as DS
u = {}
for t in range(len(T)):
    u[t]=BM.addVar (lb=0, vtype=GRB.BINARY, name="u["+str(t)+"]")

# l[b,p]: Continuous variable for battery level
l = {}
for b in range(len(B)):
    for p in range(len(P)):
        l[b,p]=BM.addVar (lb=0, vtype=GRB.CONTINUOUS, name="l["+str(b)+","+str(p)+"]")

# m[b,v,p]: Binary variable if battery being used on a vessel
m = {}
for b in range(len(B)):
    for v in range(len(V)):
        for p in range(len(P)):
            m[b,v,p]=BM.addVar (lb=0, vtype=GRB.BINARY, name="m["+str(b)+","+str(v)+","+str(p)
```

```
    +"]")

# k[b,t,p]: Binary variable if battery being charged at a terminal
k = {}
for b in range(len(B)):
    for t in range(len(T)):
        for p in range(len(P)):
            k[b,t,p]=BM.addVar (lb=0, vtype=GRB.BINARY, name="k["+str(b)+","+str(t)+","+str(p)+"]")


BM.update()


#-----------Objective--------------------------------------------------------

obj = quicksum(u[t]*cds[t]  for t in range(len(T))) + quicksum(n[b]*cb[b] for b in range(len(B)))

BM.setObjective(obj, GRB.MINIMIZE)
BM.update()


#------------Constraints-----------------------------------------------------

#Constraint 1 - Used batteries
con1 = {}
for b in range(len(B)):
    BM.addConstr(n[b]*M1, GRB.GREATER_EQUAL, quicksum(quicksum(x[b,t,p] for t in range(len(T)))  for p in range(1,len(P))) + quicksum(quicksum(y[b,v,p] for v in range(len(V)))  for p in range(1,len(P))))

#Constraint 2 - Used terminals
con2 = {}
for t in range(len(T)):
    BM.addConstr(u[t]*M1, GRB.GREATER_EQUAL, quicksum(quicksum(x[b,t,p]*n[b] for b in range(len(B))) for p in range(len(P))))

#Constraint 3 -  Maximum number of used batteries in vessel
con3a = {}
for v in range(len(V)):
    for p in range(1,len(P)):
        BM.addConstr(quicksum(m[b,v,p] for b in range(len(B))), GRB.LESS_EQUAL, 1)

con3b = {}
for v in range(len(V)):
    for p in range(1,len(P)):
        BM.addConstr(quicksum(m[b,v,p] for b in range(len(B))), GRB.GREATER_EQUAL, pv[v,p]*M2)

#Constraint 4 - Battery level
con4 = {}
for b in range(len(B)):
    for p in range(1,len(P)):
        BM.addConstr(l[b,p], GRB.LESS_EQUAL, l[b,p-1]+(quicksum(pw[t]*k[b,t,p] for t in range(len(T)))
        -quicksum(m[b,v,p]*pv[v,p] for v in range(len(V)))))

#Constraint 5 - Maximum & minimum battery level
con5a = {}
for b in range(len(B)):
    for p in range(1,len(P)):
        BM.addConstr(l[b,p], GRB.LESS_EQUAL, cap[b]*n[b])

con5b = {}
for b in range(len(B)):
    for p in range(1,len(P)):
        BM.addConstr(l[b,p], GRB.GREATER_EQUAL, cap[b]*mbl*n[b])

#Constraint 6 - Minimum battery level to be placed on a ship
con6 = {}
for b in range(len(B)):
    for v in range(len(V)):
        for p in range(1,len(P)):
```

```
            BM.addConstr((y[b,v,p]-y[b,v,p-1])*mlv*cap[b], GRB.LESS_EQUAL, l[b,p])

#Constraint 7 - Battery location
con7 = {}
for b in range(len(B)):
    for p in range(1,len(P)):
        BM.addConstr(quicksum(y[b,v,p] for v in range(len(V))) + quicksum(x[b,t,p] for t in range(len(T))), GRB.EQUAL, n[b])

#Constraint 8 - Batteries & vessels routes
con8a = {}
for b in range(len(B)):
    for t in range(len(T)):
        for p in range(1,len(P)):
            BM.addConstr(x[b,t,p], GRB.LESS_EQUAL, x[b,t,p-1]+quicksum(y[b,v,p-1]*sp[v,t,p] for v in range(len(V))))

con8b = {}
for b in range(len(B)):
    for v in range(len(V)):
        for p in range(1,len(P)):
            BM.addConstr(y[b,v,p], GRB.LESS_EQUAL, y[b,v,p-1]+quicksum(x[b,t,p-1]*sp[v,t,p-1] for t in range(len(T))))

#Constraint 9 -  Maximum number of batteries at DS
con9 = {}
for t in range(len(T)):
    for p in range(1,len(P)):
        BM.addConstr(quicksum(x[b,t,p] for b in range(len(B))), GRB.LESS_EQUAL, cht[t])

#Constraint 10 -  Maximum number of batteries on vessel
con10 = {}
for t in range(len(T)):
    for p in range(1,len(P)):
        BM.addConstr(quicksum(y[b,v,p] for b in range(len(B))), GRB.LESS_EQUAL, chv[v])

#Constraint 11 - Battery charging at DS only if it is at DS
con11 = {}
for b in range(len(B)):
    for t in range(len(T)):
        for p in range(1,len(P)):
            BM.addConstr(k[b,t,p], GRB.LESS_EQUAL, x[b,t,p])

#Constraint 12 - Battery used in vessel only if it is on vessel
con12 = {}
for b in range(len(B)):
    for v in range(len(V)):
        for p in range(1,len(P)):
            BM.addConstr(m[b,v,p], GRB.LESS_EQUAL, y[b,v,p])

#Constraint 13 - Initial battery location & battery ussage (on vessel and terminal)
con13a = {}
for b in range(len(B)):
    for t in range(len(T)):
        BM.addConstr(x[b,t,0], GRB.EQUAL, Ut0[b,t])

con13b = {}
for b in range(len(B)):
    for v in range(len(V)):
        BM.addConstr(y[b,v,0], GRB.EQUAL, Uv0[b,v])

con13c = {}
for b in range(len(B)):
    for t in range(len(T)):
        BM.addConstr(k[b,t,0], GRB.EQUAL, k0[b,t])

con13d = {}
for b in range(len(B)):
    for v in range(len(V)):
        BM.addConstr(m[b,v,0], GRB.EQUAL, m0[b,v])

#Constraint 14 - Initial battery levels
con14 = {}
```

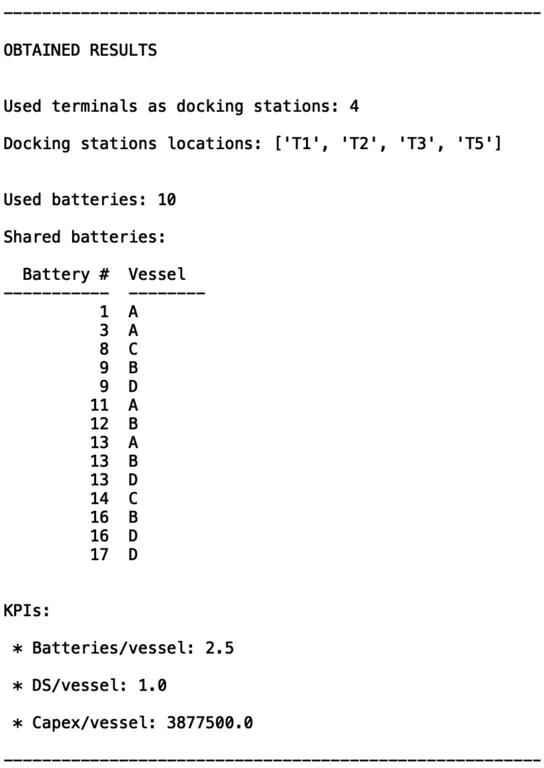
```
for b in range(len(B)):
    BM.addConstr(l[b,0], GRB.EQUAL, Lb0[b])

#Constraint 15 (optional) - Fix battery or DS
con15a = {}
BM.addConstr(n[1], GRB.EQUAL, 1)    # Example fixing battery 2 of the input file to be part of
     the output fleet

con15b = {}
BM.addConstr(u[1], GRB.EQUAL, 1)    # Example fixing terminal 2 of the input file as DS

#-----------Solve--------------------------------------------------------------
BM.setParam ('OutputFlag', True)   # show the gurobi output
BM.setParam ('MIPGap', 0);         # find the optimal solution
BM.write ("output.lp")             # print the model in .lp format file

BM.optimize ()


#-----------Print--------------------------------------------------------------
## Batteries
batteries =0
for i0 in n.values():
    if i0.X > 0:
        batteries = batteries +1

v_names = np.array([i[0].value for i in wb.worksheets[2]['C2':'C5']])
batt_vessel = []
for b in range(len(B)):
    for v in range(len(V)):
        usage=  sum(m[b,v,p].X for p in range(1,len(P)))
        if usage>0:
            batt_vessel.append([b,v_names[v]])

## Docking stations
ds_names = np.array([i[0].value for i in wb.worksheets[1]['E2':'E6']])
DS = 0
uL = []
Aux1 = []
for i2 in u.values():
    if i2.X > 0:
        DS= DS +1
        Aux1.append(1)
    else:
        Aux1.append(0)

for i3 in range(len(Aux1)):
    if Aux1[i3] > 0:
        uL.append(ds_names[i3])

## KPIs
Aux2 = 0
for i3 in n.values():
    if i3.X>0:
        Aux2=Aux2+1
bv = Aux2/len(V)

Aux3 = 0
for i4 in u.values():
    if i4.X>0:
        Aux3=Aux3+1
dsv = Aux3/len(V)

Aux4 = []
for i5 in n.values():
    if i5.X>0:
        Aux4.append(1)
    else:
        Aux4.append(0)
Aux5 = []
for i6 in u.values():
    if i6.X>0:
        Aux5.append(1)
```

```
    else:
        Aux5.append(0)
cxv = (sum(Aux4*cb) + sum(Aux5*cds))/len(V)

print (’\n--------------------------------------------------------------------\n’)
print (’OBTAINED RESULTS\n’)
print (’’)
print (’Used terminals as docking stations:’,DS)
print (’’)
print (’Docking stations locations:’,uL)
print (’’)
print (’’)
print (’Used batteries:’,batteries)
print (’’)
print (’Shared batteries:\n’)
print(tabulate(batt_vessel, headers=["Battery #","Vessel"]))
print (’’)
print (’’)
print (’KPIs:\n’)
print (’ * Batteries/vessel:’,bv)
print (’’)
print (’ * DS/vessel:’,dsv)
print (’’)
print (’ * Capex/vessel:’,cxv)
print (’\n--------------------------------------------------------------------\n’)

#-----------Save outputs in Excel file----------------------------------------
nInfo = []
for a1 in n.values():
    if a1.X > 0:
        nInfo.append(a1.varName)
uInfo = []
for a2 in u.values():
    if a2.X > 0:
        uInfo.append(a2.varName)
xInfo = []
for a3 in x.values():
    if a3.X > 0:
        xInfo.append(a3.varName)
yInfo = []
for a4 in y.values():
    if a4.X > 0:
        yInfo.append(a4.varName)
lName = []
lValue = []
for a5 in l.values():
    if a5.X > 0:
        lName.append(a5.varName)
        lValue.append(a5.X)
kInfo = []
for a6 in k.values():
    if a6.X > 0:
        kInfo.append(a6.varName)
mInfo = []
for a7 in m.values():
    if a7.X > 0:
        mInfo.append(a7.varName)

# Create dataframes for each variable
df1 = pd.DataFrame({’n[b]’: nInfo})
df2 = pd.DataFrame({’u[t]’: uInfo})
df3 = pd.DataFrame({’x[b,t,p]’: xInfo})
df4 = pd.DataFrame({’y[b,v,p]’: yInfo})
df5 = pd.DataFrame({’l[b,p]’: lName,’Level’: lValue})
df6 = pd.DataFrame({’k[b,t,p]’: kInfo})
df7 = pd.DataFrame({’m[b,v,p]’: mInfo})
writer = pd.ExcelWriter(’Output.xlsx’, engine=’xlsxwriter’)

# Write each dataframe to a different worksheet
df1.to_excel(writer, sheet_name=’Batteries n(b)’)
df2.to_excel(writer, sheet_name=’Docking stations u(t)’)
df3.to_excel(writer, sheet_name=’Batt. loc. terminal x(b,t,p)’)
df4.to_excel(writer, sheet_name=’Batt. loc. vessel y(b,v,p)’)
```

```
df5.to_excel(writer, sheet_name='Batt. level (b,p)')
df6.to_excel(writer, sheet_name='Batt. ch. terminal k(b,t,p)')
df7.to_excel(writer, sheet_name='Batt. used vessel m(b,v,p)')
writer.save()
```

C.3 Outputs

After running the code a brief summary of the results is given in the console. The printed outputs are the number of needed DS and their locations, total number of needed batteries, the shared batteries, and the KPIs results (the batteries per vessel, the DS per vessel and the Capex per vessel). Below, and example of the printed outputs is shown.



```
----------------------------------------------------------

OBTAINED RESULTS


Used terminals as docking stations: 4

Docking stations locations: ['T1', 'T2', 'T3', 'T5']


Used batteries: 10

Shared batteries:

  Battery #  Vessel
-----------  --------
          1  A
          3  A
          8  C
          9  B
          9  D
         11  A
         12  B
         13  A
         13  B
         13  D
         14  C
         16  B
         16  D
         17  D


KPIs:

 * Batteries/vessel: 2.5

 * DS/vessel: 1.0

 * Capex/vessel: 3877500.0

----------------------------------------------------------
```

Figure 19: Model code printed output example

Apart from this, an Excel file with all the variables values is generated after each run. This file has seven sheets, one for each variable output.

C.4 Comments

Constraint 15 is an optional constraint that can be used to fix either a specific battery or a DS of the input file. If more than one battery or DS needs to be fixed this constraint can be copied as many times as needed. The model will then find the rest of the needed batteries and DS to solve the problem. In the code an example for fixing the battery 2 and terminal 2 as DS from the input file is given.

Regarding the Excel output file, is importance to notice that in Python the first number considered for variables numbering is 0, then when looking at the battery, DS or vessel results, this needs to be considered.