PROOF OF CONCEPT

REDOX FLOW BATTERY-POWERED SHORT SEA SHIPPING

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Proof of Concept

Redox flow battery-powered short sea shipping

by

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Preface

Dear reader,

My interest within the maritime world has been sparked at a really young age. Our family has been working in the shipping industry since the early 18th century. My ancestors saw large developments within the industry. Now it is my responsibility to be part of the current developments towards sustainable shipping.

Therefore, it was natural for me doing this research into the feasibility of a new zero-emission ship design. Completion of my thesis has been a challenging learning process in, among others, the vast world of both data analysis and economics of shipping.

First of all, I would like to thank Jan Jaap Nieuwenhuis and Jeroen Pruyn for their support, knowledge and critical feedback during the development of my research. Furthermore, I would like to thank Edwin van Hassel for being part of my graduation committee.

I am grateful for the opportunity, of doing my research at the office of Conoship International, despite the COVID-19 pandemic. In addition, I would like to thank the employees of Conoship International for the interesting conversations I have had with them during the daily 'lunch walks' through the Stadspark, about amongst others my graduation.

Finally, my gratitude goes to my girlfriend Dorieke, family and friends for their encouragement, friendship and help during the past 9 months of research and moving from Delft to Groningen.

Bob Hillen
Groningen, September 2021

Abstract

The international shipping industry is responsible for approximately 3% of worldwide greenhouse gas (GHG) emissions [14]. The World Health Organisation estimates that human-induced climate change will be the cause of death of an estimated 5,000,000 people, between 2030 and 2050 [85]. This shows that GHG emissions need to be reduced for minimisation of the human-induce climate change's harmful effects.

Many 'green' fuels and design concepts have been explored, but no definitive solution has been found yet. This research provides 'proof of concept' for vanadium bromide redox flow battery-powered short sea shipping, henceforward referred to as E-Conoship. It has been determined under which circumstances this 'green' ship type is operational and economical feasible in today's short sea shipping market of North West Europe.

An elaborate analysis of historical voyage data has been carried out to determine operational feasibility. To determine economic feasibility, a cost-comparison model has been constructed, including the capital, operational and voyage related expenses of shipping. Then case study method, including scenario analysis, has been used to determine under which circumstances E-Conoship is cost-competitive with diesel-powered ships.

In conclusion, its operational feasible to operate an E-Conoship with a maximum range of 500 nautical miles. Two options are available: (1) direct replacement of vessels, and (2) acquiring voyages. This research shows that it is economical feasible, provided that more than one of the following factors are addressed: battery system cost reduction, CO_2-tax, lower electricity prices in comparison with marine gas oil, subsidies, increased amount of annual sailing days, and lastly financing at lower interest costs compared to diesel-powered ships.

Contents

Nomenclature

Acronym	**Definition**
BCA	Bromine complexing agents
CAPEX	Capital expenditure
CCM	Cost-comparsion model
CII	Carbon intensity indicator
DWAT	Deadweight all told
DWCC	Deadweight cargo capacity
ECA	Emission control area
E-Conoship	Vanadium bromide redox flow battery-powered ship
EEDI	Energy efficiency design index
EEG	Energy efficiency gap
EEM	Energy efficiency measurement
EEOI	Energy efficiency operational indicator
EEXI	Energy efficiency existing ship index
Eurotrader	Diesel-powered ship
GHG	Greenhouse gasses
GT	Gross tonnage
IMO	International maritime organisation
LCA	Life cycle assessment
LSMGO	Low sulphur marine gas oil
LSW	Lightship weight
MBM	Market-based measures
NECA	Nitrogen emission control area
MEUR	Million euros
MDO	Marine diesel oil
MPP	Multipurpose
NGO	Non-governmental organisation
NW Europe	North denWest Europe
OPEX	Operational expenditure
OPS	Onshore power supply
PEC	Pilotage exemption certificate
redox	reduction-oxidation
RFB	Redox flow battery
SCC	Sea cargo charter
SCR	Selective catalytic reduction
SECA	Sulphur emission control area
SEEMP	Ship energy efficiency management plan
sfc	Specific fuel consumption
SOLAS	Safety of life at sea
SSS	Short sea shipping
TRL	Technology readiness level
TTW	Tank-to-wake
V/Br RFB	Vanadium bromide redox flow battery
VOYEX	Voyage expenditure
VRFB	Vanadium redox flow battery
WACC	Weighted average costs of capital

1

Introduction

The International Maritime Organisation (IMO) is the United Nations specialized agency responsible for prevention of pollution by ships [50]. The IMO has adopted a strategy to significantly reduce greenhouse gas (GHG) emissions from ships, the overall vision being that all GHG should be phased out as soon as possible. The strategy includes the following goal: by 2050, total annual emissions of greenhouse gasses must be reduced by at least 50% compared to 2008. This is an absolute level; given the growth in trade, individual ships must reduce their pollutant emissions by 70-85% on average [49].

The IMO commissioned multiple ways to reduce GHG emissions: the Energy Efficiency Design Index (EEDI), the Energy Efficiency Operational Indicator (EEOI) and the Ship Energy Efficiency Management Plan (SEEMP), which are mitigation measures from an operational perspective. In addition, an Energy Efficiency Existing ship Index (EEXI) and a Carbon Intensity Indicator (CII) come into force at January 1, 2023 [25].

Another way is via market-based measures (MBMs) [59]. These MBMs use a variety of monetary incentives to encourage the shipping industry to reduce pollutant emissions, for example through environmental taxes or the provision of subsidies [58].

In addition, pressure from local and global politics could accelerate the transition to an emission-free shipping sector. An example of this is a statement by Ursula von der Leyden, President of the European Commission, on 17 September 2020 [83]:

> *”We are doing everything in our power to keep the promise that we made to Europeans: make Europe the first climate neutral continent in the world, by 2050. Today marks a major milestone in this journey. With the new target to cut EU greenhouse gas emissions by at least 55% by 2030, we will lead the way to a cleaner planet and a green recovery. Europe will emerge stronger from the coronavirus pandemic by investing in a resource-efficient circular economy, promoting innovation in clean technology and creating green jobs.”*

A paper by Yuen et al. [112] analysed the drivers and outcomes of sustainable shipping practices. Pressure from shipping company stakeholders is found to have a direct impact on the adoption of sustainable practices. According to Linder [61], external pressure, including from local communities about emissions and regulatory threats, are important reasons for shipping companies to reduce emissions.

The above demonstrates that there are various incentives for the shipping industry to reduce its GHG emissions. However, there is still an enormous amount of innovation and adaption needed, before the shipping industry can be called an emission-free sector. This requires, among others a reduction in overall short sea shipping (SSS) GHG emissions.

For SSS the following definition, determined by the Commission of the European Communities in 1999, will be used [26]:

> *"Movement of cargo and passengers by sea between ports situated in geographical Europe or between those ports and ports situated in non-European countries having a coastline on the enclosed sea bordering Europe. Short-range maritime transport covers national and international maritime transport, as well as feeder services, along the coast and from/towards the islands, rivers, and lakes"*

Conoship International B.V. is an innovative ship design and engineering office based in the Netherlands. Conoship has designed a potential solution to reduce pollutant emissions, by means of a zero-emission ship design. One of the applications could be within the SSS market. The energy source of this ship design is a vanadium bromide redox flow battery (V/Br RFB) system. Emission-free operations will be achievable because of this particular battery system. A ship operating fully electric with this system for longer distances is unique [33].

The objective of this research is to deliver a 'proof of concept' for the operational and economical feasibility of V/Br RFB-powered shipping. This is intended to bring the realisation of this new ship type one step closer to fruition, in order to reduce the shipping sectors GHG emission. Furthermore, by doing so inform among others, Conoship, and potential shipowners about the opportunities and barriers of the system, the possibility of operating V/Br RFB-powered vessels and under which circumstances V/Br RFB-powered shipping is economically cost-competitive with a state of the art diesel-powered ship.

For this research, the SSS market of North West (NW) Europe is restricted to the waters between the port of Seville, Spain and the port of Arkhangelsk, Russia. This excludes the maritime transport from and to the hinterland via inland waterways and voyages to and from the Mediterranean. Inland waterways are not included in this study because of the unfavourable weight ratio between V/Br RFB-sytem and the deadweight cargo capacity (DWCC), when applied to 'small' inland vessels.

This research focuses on the technical, economical and operational aspects of a V/Br RFB-battery powered ship, from henceforward reffered to as E-Conoship. In the context of this thesis, infrastructure is left outside of the scope, because section 2.6.2, shows that technical it has already been proven, the remainder barrier left is who should invest in onshore power supply at general cargo terminals. Therefore, it is of greater interest for this research to focus on the limited range, and the economic costs of the E-Conoship. Future market and development scenarios of the V/Br RFB-system are part of this study too. This leads to the following research question to be addressed in the remainder of this thesis:

"Under which circumstances is Conoship's vanadium bromide redox flow battery-powered ship design operational and economical feasible in today's short sea shipping market of North West Europe?"

In order to guide this research and to be able to answer the main research question, it has been divided into the following two sub-questions:

1. *What current shipping routes present potential for vanadium bromide redox flow battery-powered shipping?*
2. *"Under which circumstances is Conoship's vanadium bromide redox flow battery-powered ship design cost-competitive with diesel-powered ships?"*

Within the remainder of this thesis in chapter 2, the theoretical framework in which the background, general approach and the preliminary research question of this thesis will be dealt with. Within chapter 3, the the methodology used to for the remainder of this thesis will be dealt with. In chapter 4 and 5 sub-question one has been answered. The second sub-question will be answered through chapters 6 and 7. Chapter 8, will discuss this research, followed by chapter 9 in which the main research question has been answered. Lastly within chapter 10, recommendations will be given for further research.

2

Theoretical framework

Within this chapter the theoretical framework is dealt with. In the first section the background is given, in the following section literature is researched to determine the general approach. After this in the following sections the preliminary research question: *What are the barriers and opportunities for the introduction of vanadium bromide redox flow battery-powered shipping in the short sea shipping market of North West Europe?* will be dealt with.

2.1. Background

This section addresses the urgency of reducing pollutant emissions and the various incentives to do so. The international shipping industry is responsible for approximately 3% of all GHG emissions worldwide; this will only further increase with the expansion of the industry. In 1997, the Kyoto Protocol defined six gasses as GHG: CO_2, CH_4, N_2O, HFCs, PFCs and SF_6. From these six gasses, CO_2 contributes the most to global warming [14].

According to Satein [88], in addition to GHG emissions, there are also gasses that can be classified as indirect GHG emissions, such as NO_x and to a lesser extent SO_2. That sulphur oxides (SO_x) should be reduced not only for climate reasons is shown in a study on the effects of sulphur oxide (SO_x) emissions on human health [17]. In the report by Corbett et al. [17], "Health Impacts Associated with Delay of Marpol Global Sulphur Standards", it is estimated that postponing the IMO MARPOL Annex VI global sulphur regulation by 5 years (from 2020 to 2025) would contribute to more than 570,000 additional deaths worldwide.

The World Health Organisation estimates that human-induced climate change will be the cause of death of an estimated 5,000,000 people, between 2030 and 2050 [85]. This shows that GHG emissions (indirect and direct) need to be reduced in order to minimise the harmful effect of climate change on human health.

A review by Serra and Fancello [89] shows that besides the ecological awareness there are more incentives to reduce pollutant emissions.It was found that there are three main incentives for the shipping industry to reduce its GHG emissions, namely:

1. Regulatory and institutional pressure
2. Market factors and resource availability issues
3. Social pressure, ecological awareness and responsiveness

In the remainder of this section, the three main incentives mentioned above will be discussed in more detail.

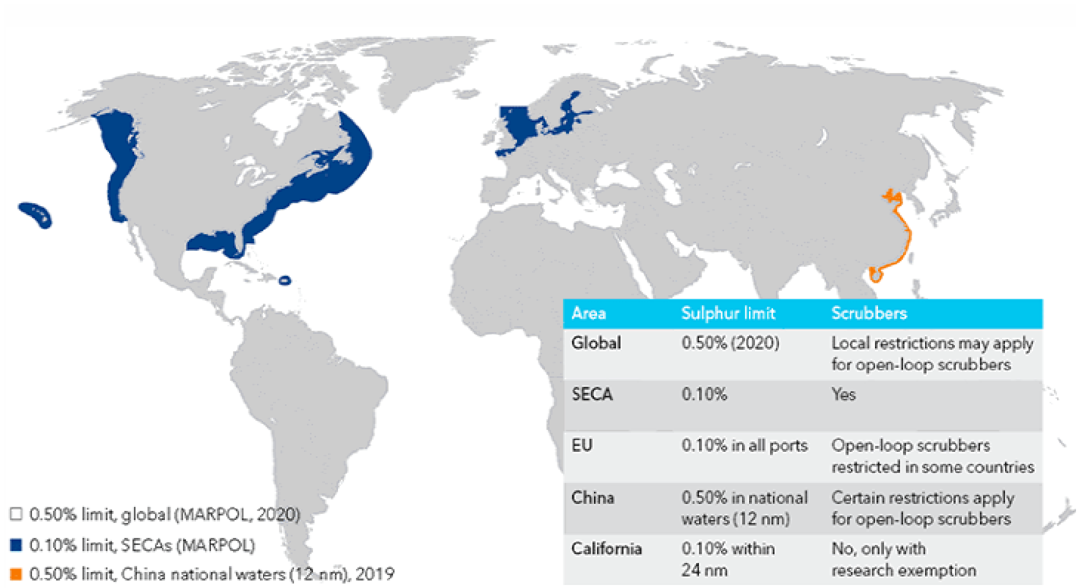
2.1.1. Regulatory and institutional pressure

The first incentive can be illustrated by the IMO's EEDI, which was put in effect in 2011. This regulation entails that all new ships built after 1 January 2013 must have an EEDI. This is ship type and size dependent, and it requires a minimum energy efficiency level expressed in gram-CO_2/tonne-mile. This level is progressively enhanced every 5 years. This to stimulate continuous innovation in order to reduce the harmful emissions produced by ships [66]. Stalmokaitė and Hassler [96] emphasise that one of the goals of the EEDI is to stimulate the building of more energy efficient ships.

As the EEDI only covers ships built after 2013, a one-off certification, the so-called EEXI, is expected to take effect on 1 January 2023. This will apply to all ships above 400GT, irrespective of their date of construction, which fall under MARPOL Annex VI. The EEXI is a technical requirement to reduce carbon emissions. This certification represents a requirement similar to that of EEDI stage 2 or 3 (with some minor modifications) [25].

In addition to these, a new measurement called CII is expected to come into force on 1 January 2023. This CII includes an annual mandatory efficiency ratio [gram CO_2/ dwt-mile] and a rating system whereby all cargo and cruise ships above 5,000GT are rated from A to E each year. A is the highest rating, which means low emissions; moreover, the requirements to reach a certain level will gradually become more demanding towards 2030. This CII is a operational measurement, to reduce carbon emissions [25].

Furthermore, the latest global sulphur (SO_x) limit was put in effect in 2020. Besides this global limit there are areas where stricter regulations apply, the so-called SO_x emission control area's (SECAs), see figure 2.1.



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

Figure 2.1: Sulphur Emission Control Area [24]

Besides the SO_x regulations there are also NO_x emission limits. These are listed in the so called MARPOL Annex VI, NO_x emission limits. Those are applicable to all marine combustion engines with an installed power of 130 kW or more. However, there are exceptions one is for vessels who operate solely in case of emergencies (rescue vessels). The set NO_x limit depends on the engines maximum operation speed (rpm) and the vessels construction date. There are different levels, named; Tier I, Tier II and Tier III. Whereby Tier III regulations only apply for specific NO_x emission controlled area's, so called NECAs, see figure 2.2 [13].

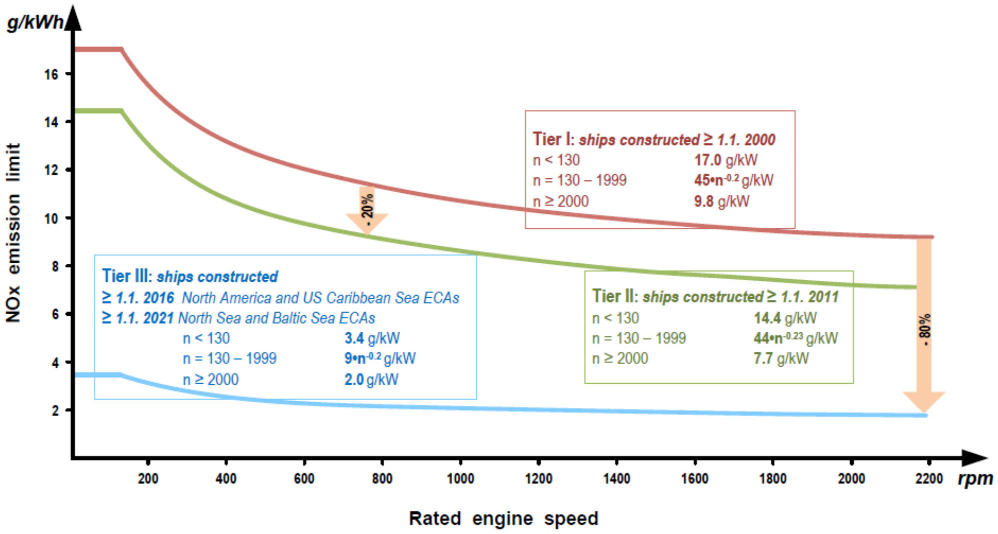


Figure 2.2: Marpol Annex VI regulation limits [13]

2.1.2. Market factors and resource availability

Serra and Fancello [89] state that fuel (energy) account for 50% to 70% of a ship's operating costs. The price fluctuations of fuel are therefore related to the willingness to investigate alternative (sustainable) fuel options, when the prices of conventional fuels rise, there seems to be the tendency to look for other options. The availability of fossil fuels also plays a role: reserves of fossil fuels are finite. Alternative options must be sought to replace the traditional fuels [94]. However, it is expected that the transition to renewable fuels will be completed before fossil fuel reserves are depleted. Illustrated by the following 'popular' quote in the words of Ahmed Zaki Yamani, former Minister of Oil for Saudi Arabia [110]: *"The Stone Age didn't end for lack of stone, and the oil age will end long before the world runs out of oil."*

2.1.3. Social pressure, ecological awareness and responsiveness

The maritime sector's responsiveness and social pressure is shown, for example, by the Sea Cargo Charter (SCC), an initiative signed by 17 of the world's largest charterers and cargo owners. With this, they commit to four principles: climate adaptation assessment, accountability, enforcement and transparency. The SCC provides a framework for assessing and disclosing the climate compatibility of ship chartering activities around the world. It is intended to be a benchmark for a responsible charterer in the maritime sector, and it also sets out how this can be achieved [60].

The Dutch parliament has reacted to the social pressure with an the initiative to invest millions of euros in the development of emission-free shipping [80]. This shows that if a company wants to develop a new technology, there is a clear incentive to do so in the field of sustainable green development.

Besides governmental support for green development, there is social pressure from financiers of the shipping industry, in form of the Poseidon Principles. These principles are in line with the objectives of the IMO, providing a framework for assessing and disclosing the climate compatibility of ship financing portfolios. Furthermore, Michael Parker, Chairman, Global Shipping Logistics & Offshore, stated the following [77]:

> *"As banks, we recognize that our role in the shipping industry enables us to promote responsible environmental stewardship throughout the global maritime value chain. The Poseidon Principles will not only serve our institutions to improve decision-making at a strategic level but will also shape a better future for the shipping industry and our society"*

This shows that the financing world is willing to put social pressure on the shipping industry to develop (new) green shipping solutions. Some of the many banks and financial institutions that have already signed the Poseidon Principles are: ABN AMBRO, Citi, Danish Ship Finance, ING, Nordea, BNP Paribas [78].

Furthermore several non-governmental organisations (NGOs) have launched campaigns to raise awareness of the environmental and social problems in shipping. One example is the cooperation of several NGOs in the Clean Ship Coalition, which draws attention to environmental and social problems in the maritime sector. These include, but are not limited to, protection of marine environment, the safety of shipping operations, the development of sustainable technologies and human health [73].

2.2. Framework

Within the previous section it can be concluded that there are many reasons to reduce pollutant emission within the shipping sector. Conoship International B.V., an innovative ship design an engineering office based in the Netherlands, has designed a vessel that reduces emissions to zero during operation. The systems on board this ship are powered by a V/Br RFB, with a maximum power output of 2.6MW and an effective energy capacity of 45MWh. This makes fully electric sailing over longer distances possible.

The technology of a RFB has been proven in land-based applications, in shipping it is still unknown. To determine whether a V/Br RFB can be applied in the shipping industry, a 'proof of concept' is required. To provide a 'proof of concept', a feasibility study is to be conducted to determine if the proposed solution is achievable. Moreover, it is to be carried out to determine if investing in more expensive full-trials is worthwhile [11],[68].

Research by Morgan et al. [68] has been conducted to determine the added value of a feasibility study to research. The conclusion is that a feasibility study could be useful to optimise the efficiency of research and reduce the risk of financing investments in more expensive full-trials. However, as the feasibility study itself takes time Morgan et al. [68] argues that this could lead to some inefficiency in the existing research pathways. This shows that a feasibility study, if executed carefully, contributes to research.

The terms feasibility study and/or pilot study are often used mutually exclusive in a wide variety of studies. However, according to Eldridge et al. [29], a pilot study is a subset of a feasibility study. It was stated that within a feasibility study the following types of questions are asked: whether something can be done?, should we proceed with it?, and if so, how?. A pilot study contains similar questions, but it also includes a future study, or part of it, carried out on a small scale [29]. Since a pilot study can be seen as part of a feasibility study, literature was searched for both terms to determine the general approach of this research.

On Google Scholar among others, the following search terms related to the maritime industry are examined: *allintitle: "feasibility study" OR "pilot study" shipping*. This resulted in 18 unique studies (n=18), when systematically reading the abstracts three studies remained that were of interest (n=3). In conclusion, when the search term is applied only to words in the title, the search area is small. However, when the same search term is applied to all the words in the articles, n=18900, many of which are not relevant to this thesis.

To summarise, literature research shows that the phrase "feasibility study" functions as an umbrella term. As an illustration, the phrase can be used in any study that seeks to demonstrate the feasibility of a design, method, product or service. Due to the usage of the umbrella term, "feasibility study", there is no uniform approach, method or guideline.

2.2.1. General approach

In order to establish a general approach for this thesis, and to identify the areas to focus on within a feasibility study, the main points raised in papers and other theses are used to establish one approach.

To abstract the required literature to determine the general approach for a feasibility study and this thesis, the so called 'snowball' approach is used. This approach consists of consulting the bibliographies of important documents in order to find other relevant literature.

In the 1990s, Behrens and Hawranek [7] published a manual for the preparation of industrial feasibility studies. According to this manual a feasibility study consist of the following parts: background & history, market analysis and marketing concept, raw materials and supplies, location, site and environment, engineering and technology, organisation and overhead costs, human resources (socio-economic and cultural environment), project implementation schedule, financial and investment appraisal.

A thesis by Dekker [20] conducted a feasibility study on concepts for scalable inland container transport and terminals. This study consist of three main phases: (1) a current market analysis, (2) construction and evaluation of concepts, and lastly (3) research of the economic feasibility.

Another, thesis by Mukhtarov [69] conducted a feasibility study of a container feeder ship as a short sea shipping service in the Caspian Sea. In this thesis, an economic evaluation of a 700TEU container feeder ship was carried out. Furthermore one of the research objectives, among others, was to identify main barriers and opportunities. The main phases of this thesis are: (1) literature review, (2) qualitative analysis (barriers, opportunities and market analysis), and (3) a case study. Furthermore the feasibility studies within table 2.1 have been analysed.

Table 2.1: Feasibility studies used to determine general outline of the thesis

Author	**Subject**	**Focus**
Pratt et al. [76]	Zero-emission hydrogen fuel cell, high-speed passenger ferry	general
Madsen et al. [63]	Coastal research vessel, hydrogen fuel-cell	techno-economic
Molitor et al. [67]	LNG fueled short sea coastal shipping in wider Caribbean region.	general
Abma et al. [2]	Zero-emission, battery-electric powered (lithium-ion) vessel Case study - Gouwenaar II, containership.	techno-economic
Al-Falahi et al. [4]	Battery-powered ferries	techno-economic

From the analysis of the studies in table 2.1, and previously reviewed literature, it is concluded that the main topics to be investigated during the feasibility study should be determined by identifying the main opportunities and barriers of the new technology. In the continuation of this thesis, the main barriers identified will be addressed; once these are known, the remainder of the method for this thesis can be determined, see figure 2.3.[4], [63], [67], [76], [2], [20], [69], [7].

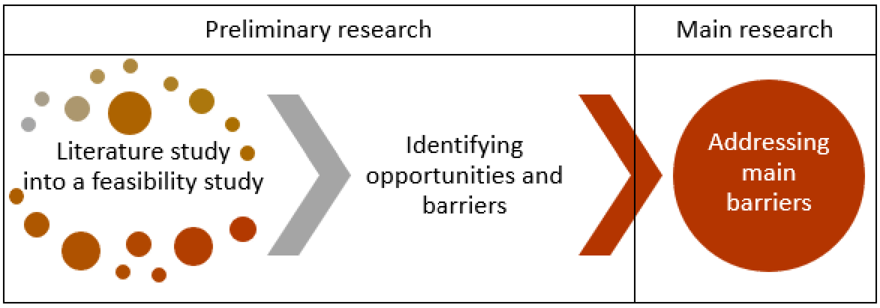


Figure 2.3: General approach feasibility study

Identification of key opportunities and barriers, leads to the following preliminary research questions, which forms a gate before further research can be conducted:

”What are the barriers and opportunities for the introduction of vanadium bromide redox flow battery-powered shipping in the short sea shipping market of North West Europe?”

This preliminary research question will be answered by means of a literature study, in order to determine what to research in the main research phase to obtain a proof of concept for a V/Br RFB-powered ship. To answer this question, first it is required to understand the working principles and development to date of a redox flow battery system. In the next section 2.4 the opportunities of the system will be dealt with. In section 2.5 and 2.6 the barriers are addressed.

2.3. Development and working principles

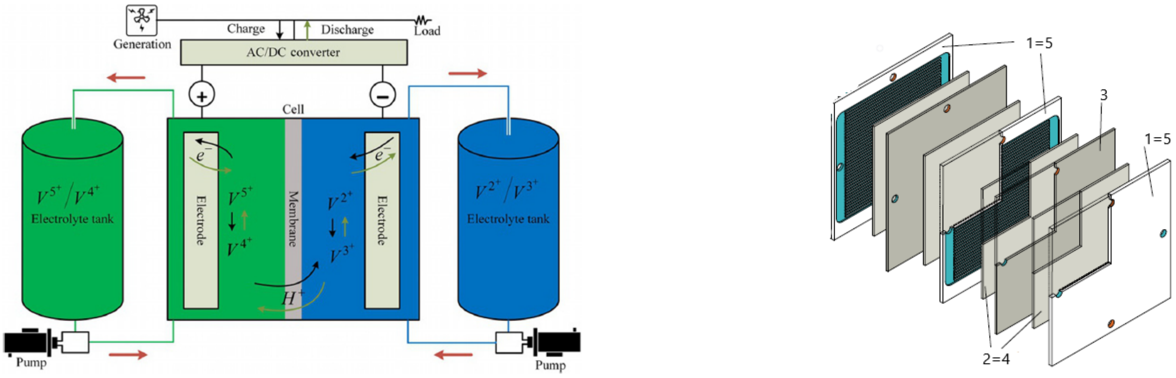
Conoship has designed a short sea ship based on a generation 2 redox flow battery. The development of this generation 2 battery evolved from the first generation of all vanadium redox flow batteries, the basic principle of this battery is to store chemical energy and generate electricity by means of a reduction-oxidation reaction (redox), between vanadium ions dissolved in electrolytes [9],[72].

The first generation battery was developed in the 1980s, by Skyllas-Kazacos et al. [92] at the University of New South Wales, Australia. They developed the first all-vanadium redox flow cell. In this flow cell, the same metal, vanadium, is used on both sides of the cell. Therefore no cross-contamination of solutions due to diffusion of metal cations across the ion exchange membrane is possible [92].

A couple of years later in 1988, a paper written by Rychcik and Skyllas-Kazacos [87], University of New South Wales, Australia, on the characteristic of a new all-vanadium redox flow battery (VRFB) was published. They analysed for this generation 1 VRFB, among others the following issues: battery performance, battery life and its applications. It was concluded that in order to increase the energy storage capacity of the battery while maintaining the same power output, the volume of electrolytes in the tanks must increase.

Further concerning the battery life, Rychcik and Skyllas-Kazacos [87] tested the stability of the charged electrolytes, concluding that with airtight storage an unlimited shelf life can be obtained. Besides, it was concluded that an application for a VRFB system could be electric propulsion, examples of which are industrial trucks and ships [87].

A schematic overview of the working principle of a single cell generation 1 VRFB is shown in figure 2.4a. In this system the electrolyte solutions are pumped through the cell, which is separated by a thin membrane, ion-selective or micro-porous [72]. Then two redox reactions occur simultaneously in the cells to generate electricity (discharge) or to load the battery (charge) [9]. A redox flow battery consist of two main components, see figure 2.4a: electrolyte tanks where the energy is stored, and cell stacks in which the chemical energy is converted into electricity. A cell stack consists of individual cells piled up on top of each other, with a single cell being constructed as follows: (1) a bipolar or end plate, (2) carbon felt (electrode), (3) membrane, (4) carbon felt (electrode), and (5) a bipolar or end plates, see figure 2.4b [9].



(a) Working principle G1 VRFB-system [1].

(b) Stack composed of 2 cells [9]

Figure 2.4: Schematic overview of a vanadium redox flow battery [1],[9]

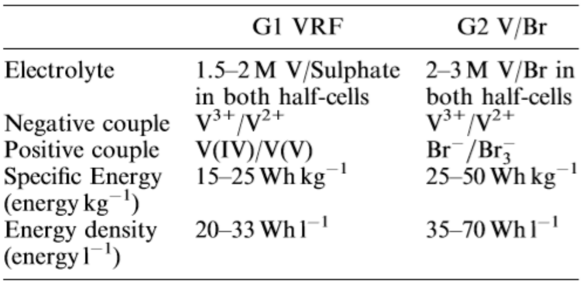
During the redox reactions in a G1 VRFB, vanadium occurs in 4 different oxidation states: V^{2+}, V^{3+}, V^{4+} and V^{5+}, the latter two in fact being vanadium oxide ions, VO^{2+} and VO_2^+ respectively [9]. As the electrolyte solutions are pumped though the stacks, the following two half-cell reactions take place in each cell: one positive side, see equation 2.1, and negative side, see equation 2.2. During the half-cell reactions, ions transport from one electrode to another (anode to cathode) through the membrane, which is impassable to electrons. Therefore, the electrons must pass through the external circuit, producing electricity [1]. The overall result is shown in equation 2.3.

$$\textbf{Positive electrode:}\quad VO^{2+} + H_2O \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftarrows}} VO_2^+ + 2H^+ + e^- \tag{2.1}$$

$$\textbf{Negative electrode:}\quad V^{3+} + e^- \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftarrows}} V^{2+} \tag{2.2}$$

$$\textbf{Overall}\quad VO^{2+} + V^{3+} + H_2O \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftarrows}} V^{2+} + VO_2^+ + 2H^+ \tag{2.3}$$

According to among others: Weber et al. [104], Clemente and Costa-Castelló [16], and Skyllas-Kazacos et al. [91] one of the barriers for large-scale implementation of the generation 1 redox flow battery, is its low energy density (20-33 Wh/l) and low specific energy (15-25 Wh/kg). Therefore, Skyllas-Kazacos et al. [91] developed a second generation redox flow battery: the generation 2 vanadium bromide redox flow battery (G2 V/Br). In this battery the specific energy and energy density are increased by using a vanadium bromide solution instead of a vanadium sulphate solution in both half-cells. For a comparison between both batteries see figure 2.5.



	G1 VRF	G2 V/Br
Electrolyte	1.5–2 M V/Sulphate in both half-cells	2–3 M V/Br in both half-cells
Negative couple	V^{3+}/V^{2+}	V^{3+}/V^{2+}
Positive couple	V(IV)/V(V)	Br^-/Br_3^-
Specific Energy (energy kg^{-1})	15–25 Wh kg^{-1}	25–50 Wh kg^{-1}
Energy density (energy l^{-1})	20–33 Wh l^{-1}	35–70 Wh l^{-1}

Figure 2.5: Comparison: generation 1 and 2 vanadium-based redox flow batteries [91]

The G2 V/Br RFB uses the same working principles as VRFB, except the redox couples are different, see equations 2.4, 2.5 and 2.6. Within this generation 2 battery, a vanadium bromide solution is used in both half-cells, to ensure no cross-contamination problems can occur [103],[91].

$$\textbf{Positive:}\quad V^{3+} + VO^{2+} + H_2O + 2Br^- + Cl^- \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftarrows}} 2VO^{2+} + 2H^+ + ClBr_2^- + 3e^- \tag{2.4}$$

$$\textbf{Negative:}\quad V^{3+} + VO^{2+} + 2H^+ + 3e^- \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftarrows}} 2V^{2+} + H_2O \tag{2.5}$$

$$\textbf{Overall}\quad 2Br^- + Cl^- + 2V^{3+} \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftarrows}} ClBr_2^- + 2V^{2+} \tag{2.6}$$

Skyllas-Kazacos et al. [91] state that a side effect of a V/Br solution is the potential danger of bromine gas formation in the positive half cell during charging. These bromine vapours constitute an immediate danger to human health, since contact with human skin causes immediate tissue damage [109].

A solution for this is the use of bromine complexing agents (BCA) [92],[55]. BCA, bind bromine in a non-miscible phase and can therefore reduce the bromine vapour pressure, limit overflow and result in a greater practical range of electrolyte concentration [55].

2.4. Opportunities

In order to gain insight in the opportunities of the G2 V/Br RFB a literature review is carried out. At present, no large vanadium bromide redox flow battery has been built and, no life cycle assessments (LCA) are available for this generation 2 battery. To gain insight into the possibilities to reduce the environmental impact of shipping, with this type of battery, it is important to know the environmental impact.

Because no LCA of a generation 2 battery is available, and determining the total environmental impact of this new generation battery is beyond the scope of this study, an LCA of a G1 VRFB will be used. An LCA of a generation 1 battery gives a global overview of the most important factors influencing the environmental impact of the battery. Moreover, the operating principle, production, processing and assembly of these batteries largely overlap.

A cradle-to-grave LCA for, among others G1 VRFB was carried out by Hiremath et al. [45]. Cradle-to-grave means the entire life cycle, from resource mining (cradle), usage phase until at last the disposal phase (grave). Hiremath et al. [45] concluded that the use phase of the batteries large determines the environmental impact of the system. In addition, Dassisti et al. [19] conducted a cradle-to-grave LCA for a small-sized G1 VRFB, rated power 0.15kW. The size of the environmental footprint is partly determined due to the life time of a product. So, the longer a product is used, the lower its environmental impact. Since, the material (vanadium) and electrolyte are completely reusable at the end of the life cycle, only a small part goes to landfill. Furthermore, Dassisti et al. [19] concluded that the way a G1 VRFB is charged during its life cycle is an important determinant of its environmental impact. Therefore, to reduce the environmental impact, the energy used to charge the system must come from renewable energy sources.

Another LCA was undertaken by Weber et al. [104], they used a cradle-to-cradle approach for a G1 VRFB with an energy capacity of 8.3MWh and a rated power of 1MW. Cradle-to-cradle means that the first product at the end of its life is recycled into a new one. In this LCA the global warming potential (GWP) expressed in kg CO_{2-eq}/MWh is determined for a lithium-ion battery and a G1 VRFB. Within this LCA an efficiency for 75% for the VRFB and 90% efficiency for the Lithium-ion battery is used.

In this LCA by Weber et al. [104], the GWP for both a lithium-ion (LTO) battery and a VRFB (generation 1) is determined for different sources of electricity used to charge the batteries during the usage phase. These sources are wind, photovoltaic (PV) installation (solar energy) and average German grid mix. The amount of GWP is split into life cycle phases: manufacturing, replacement, use phase (8176 charge-discharge cycles over 20 year life-time) and end-of-life (EoL). Lastly two situation are given one in which no recycled material is used for the batteries and one in which recycled material is used. An overview of the environmental impact per situation can be seen in figure 2.6.

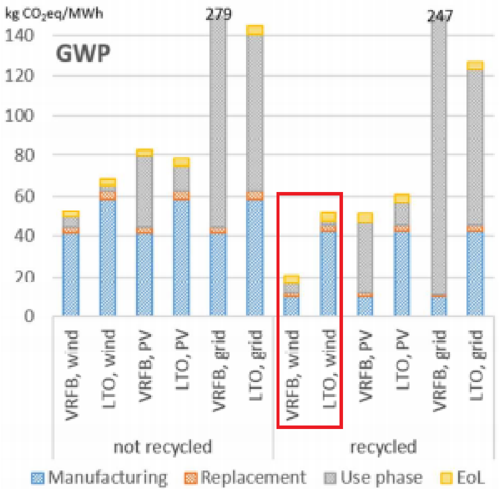


Figure 2.6: Environmental impact per MWh of electricity provided over lifetime [104]

Figure 2.6, shows that one of the opportunities of this battery system is the low environmental impact per MWh compared to lithium-ion, given that the batteries are charged with renewable energy, see red box in figure 2.6. When the battery is charged with energy from the average German grid mix and no recycled materials are used, the GWP increases by a factor of more than 20 compared to a situation where the VRFB uses (a) recycled materials and (b) renewable energy sources to charge the battery over its lifetime.

Another opportunity for V/Br RFB applications is, that the system can be recharged by two different methods conventionally or with mechanical refuelling. In the latter case, the discharged electrolyte fluid can be exchanged for electrically charged fluid [72]. According to Parasuraman et al. [72], this opportunity makes the system attractive for electric vehicle applications, as fast charging is a possibility.

Further, according to Gouveia et al. [35] one of the opportunities of a redox flow battery system is its high degree of modularity. The main reason for this is that power (kW) and energy (kWh) are independent of each other, and therefore the electrolytes can be stored separately from the battery stacks.

Besides this a VRFB system has no cross-contamination problems and a long lifetime (>20 years). In addition the system has a long charge-discharge cycle, low storage losses and high efficiencies of up to 80% can be achieved [35]. Due to the aforementioned properties of a redox flow battery, this system presents opportunities for electrification of the shipping industry and thus for eliminating polluting emissions during operation.

Several studies state the same as that of Gouveia et al. [35], namely that one of the important opportunities of a redox flow system is that power (kW) and capacity (kWh) are independent of each other. This allows each one to be scaled individually, making the system modular and suitable for a wide range of applications. Another opportunity addressed is the fact that the battery can be charged and discharged for more than 15,000 cycles. This equals a lifetime of 20+ years [38],[104],[9],[72].

Clemente and Costa-Castelló [16] have done a literature review on redox flow batteries (RFB), oriented to automatic control. They have concluded that the following points can be considered as the main opportunities of an RFB system: thermally safe, self-discharge is not of concern, long life time, modular, recharge quickly by replacing the electrolyte or reversing the redox reaction and lastly the system can be easily shut down by stopping the flow of electrolytes.

Lastly, Huang and Wang [46] state that the costs of a VRFB system are relatively low as the electrolytes are reusable. Moreover, the system itself is safe as discharging and charging can be done to low and high levels without damaging the system. Moreover, as mentioned previously, the environmental impact of the system is low when it is charged with renewable energy and the batteries are manufactured with recycled materials.

2.5. Barriers: identification

According to Tran et al. [102] to achieve success in the field of sustainable shipping management, there are some critical factors that play a part in the amount of success one would achieve: stakeholders' focus, intra-firm management, inter-firm collaboration, new technology acceptance, and strategic fit. This illustrates that its not only the technical solution of a new technology that determines if it will be implemented on a large scale

.

In order to determine what the barriers are, one first needs to acquire a clear definition of a barrier:

> *"A **barrier** is anything that prevents or blocks the introduction of a new zero emission technology in the maritime industry; this can be natural or man-made."*

According to Rehmatulla and Smith [82] even if some energy efficiency measures are cost-effective, this does not automatically mean that they will actually be adopted. This difference between optimal and actual implementation is called the 'implementation gap' or 'energy efficiency gap' (EEG) [82].

In other words, EEG is the difference in applied energy efficiency measures that is present against the greater amount of measures that may appear efficient or cost-effective from the perspective of a consumer or company, based on a techno-economic analysis [81]. The EEG exists due to market failures and any barrier to energy efficient measures. Deviations from a perfect market are seen as market failures, an example of this is monopolistic behaviour [6].

A 1994 paper by Jaffe and Stavins [53] explains how the 'gap' differs according to the definition of energy efficiency potential and the perspective that is being considered. According to Jaffe and Stavins [53] there are three perspectives on energy efficiency potential: hypothetical potential, technologist's economic potential and economist's economic potential. Where the hypothetical potential indicates that all technologically available measures are applied, resulting in the utilization of the total energy efficiency potential.

Several studies have been examined to gain understanding of what barriers and/or market failures exist before a new technology is widely implemented. One by Bergsma et al. [8], who conducted a literature review of 'systemic challenges' affecting the maritime energy transition in Europe. Bergsma et al. [8] defines a 'systemic challenge' as the lack or inadequate capacity of the European maritime sector to accomplish one or more of the following four activities: (1) developing strategy and policy, (2) stimulating demand for green innovations, (3) ensuring that the necessary resources are available and mobilised, and finally (4) developing & sharing knowledge. In the context of this thesis, the 'systemic challenges' will henceforth be referred to as barriers.

The barriers related to the above activities depend on the element considered; a distinction is made between: actors, institutions, infrastructure and interaction. Actors are stakeholders in the maritime business, for example; Conoship and research institute such as Maritime Research Institute Netherlands (MARIN). Institutions refer to standards, routines or rules that regulate interactions and relationships; examples include maritime law and conventions, such as MARPOL Annex VI and SOLAS [8].

Followed by infrastructure which is seen as: physical knowledge and financial structures. This can be for example machines, such as advanced 3D printing robots, expertise of strategic information. Finally, there is the interactions element, which relates to the connections of people (networks) within the industry. The barriers associated with these elements have been identified by Bergsma et al. [8], and compiled into one table for clarity, see table 2.2.

Table 2.2: Barriers affecting Europe's maritime energy transition [8]

Barriers related to:	**1. Developing strategy & policy**	**2. Stimulating the demand for green innovations**	**3. Ensure that the necessary resources are available and mobilised**	**4. Development & sharing of knowledge**
Actors	Presence of many unaligned actors	Absence of a business case	Limited access to resources for actors	Presence and quality of knowledge organizations & heterogeneity of the relevant actors
Institutions	Limited capabilities toward regulation formulation & presence of traditional cultural norms	Absence of a level playing field & limited regulatory drivers	Limited standardization	Insufficient alignment & embedding of knowledge
Infrastructure	Insufficient lobbying power	Limited availability of & risk-reducing funds	Limited availability of educated staff & lack of physical infrastructure	Knowledge infrastructure irrespective of economic trends & complexity of knowledge development
Interaction	Insufficient public awareness & negative perception of the sector	Fierce global competition	Limited quality of interaction & with resource providers	Limited (cross-) sectoral interaction

In addition to Bergsma et al. [8], more studies have been conducted, including that of Rehmatulla and Smith [82], who have investigated the opportunities and barriers to a low-carbon shipping industry, with a focus on wind technologies. It has been concluded that barriers can be categorized under the following topics: organisational, behavioural and economic, see figure 2.7.

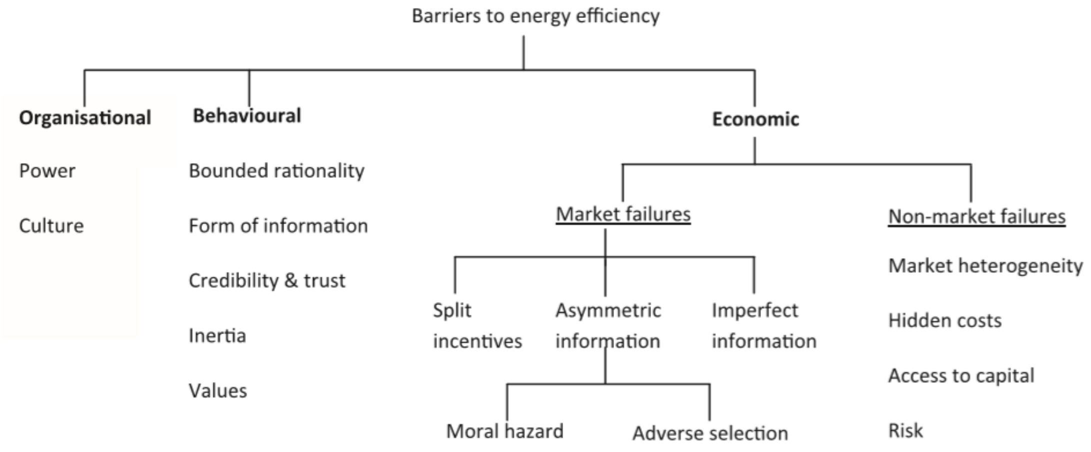


Figure 2.7: Barriers for adoption of energy efficiency measures [82]

Dewan et al. [22] has done a similar study, with the goal to determine barriers for adoption of energy efficiency operational measures in the maritime industry. A qualitative survey was conducted among various stakeholders, which identified to some extent the same barriers as Rehmatulla and Smith [82]. The barriers mentioned were elaborated in detail; all identified barriers can be found in appendix A, table A.1.

Altogether, Bergsma et al. [8], Rehmatulla and Smith [82], and Dewan et al. [22] describe to some extent the same barriers, only the approach or grouping in which they are presented differs. For this thesis, the grouping of all 3 researchers has been combined into one way of presenting the barriers to the adoption of a new technology in short sea shipping, as shown in table 2.3.

Table 2.3: Barriers for adoption of a new technology in short sea shipping

Type of barrier	Barriers for adoption of a V/Br RFB in short sea shipping
Technical	1. Reduced range, 2. Technology readiness level
Infrastructure	Charging facilities
Competition	Other zero emission, or low carbon technologies
Information/knowledge	1. Inadequate, 2. Insufficient, or 3. Incorrect information
Inter- and intra- organisation	1. Reserve attitude, 2. Split incentives, 3. Public opinion, 4. Acceptance 5. Risk perception
Policy	1. IMO 2. Classification societies, e.g. Llyods or Bureau Veritas
Financial	1. More expensive 2. Access to capital 3. Hidden costs

2.6. Barrier: description and analysis

Within this section the barriers as shown in table 2.3 are described in more detail and analysed. The goal of this is to get a better understanding of the individual barriers and determine whether they pose an obstacle to the introduction of V/Br RFB-powered shipping. In the following order, the barriers are described and analysed: technical, infrastructure, competition, information/knowledge, inter- and intra organisational, policy and lastly financial.

2.6.1. Technical barrier

Gray et al. [37], did an analysis into suitable low-carbon fuels for, among others, the maritime industry. It was concluded that one of the barriers to the introduction of battery-powered ships is the lower deadweight cargo capacity (DWCC) and range compared to diesel-powered ships, due to lower specific energy and energy density. As described in section 4.1 one of the barriers of a RFB is its specific energy capacity, although a generation 2 battery has an increase energy capacity there is still a significant difference between the energy capacity of marine diesel oil and that of a G2 V/Br RFB.

This is supported by data about the specific energy and energy density of V/Br [91]. In comparison to a conventional fuel, such as marine diesel oil (MDO) with a lower heating value of 42,700kJ/kg (1Wh = 3.6kJ) and a conversion factor of 0.84kg/l MDO, a difference of more than 200 times is found, see table 2.4.

Table 2.4: Specific energy and energy density: V/Br RFB vs MDO

	V/Br RFB	MDO	Ratio
Specific energy [Wh/kg]	50	11,861	238:1
Energy density [Wh/l]	70	14,120	202:1

So, the specific energy and energy density of MDO, a conventional fuel, are therefore both more than 200 times larger than those of a G2 V/Br redox flow battery. This illustrates that it is crucial to determine how much energy capacity [MWh] is needed to complete merchant voyages. In other words, it is important to know what range is required to operate in a particular shipping market. Furthermore, this illustrates that to obtain the same range as a conventional ship DWCC must be scarified, given that the main dimensions of the vessel remain constant.

The lower energy density therefore limits the range. Due to this lower energy density Conoship's vanadium bromide redox flow battery-powered ship design, henceforward referred to as E-Conoship, has a range of 500 nautical miles (nm) at design speed of 10knots. This could be a barrier as a voyage from, for instance, the port of Bilbao in Spain to the port of Rotterdam in the Netherlands is about 800nm [65], limiting the operational reach of a E-Conoship.

Therefore, limited range could be a major barrier that needs to be dealt with before further research on a 'proof of concept' for an E-Conoship is carried out. To address this, a preliminary market analysis will be carried out in chapter 5 to determine whether it is possible to complete merchant voyages with a limited range.

According to Serra and Fancello [89] a technical barrier for implementing a new technology is the technology readiness level (TRL). This has to do with the maturity of a technology, there are 9 stages of maturity, see figure 2.8, originally developed by NASA in the 1970s.

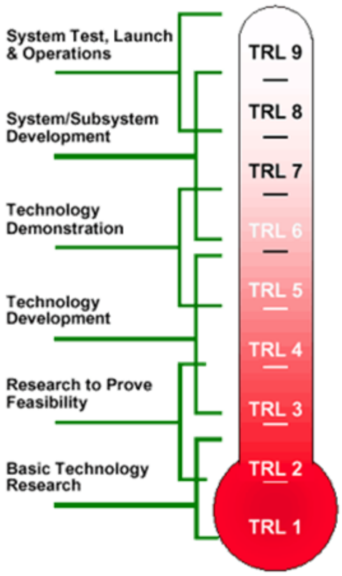


Figure 2.8: Phases of technology readiness level [28]

Within the maritime industry no applications are known of generation 1 or 2 VRFBs. The generation 1 is a proven land based technology with TRL 9. An example of an existing application is a 4MW/6MWh G1 VRFB installed for wind power storage, Tomamae, Hokkaido in Japan [91]. The generation 2, battery is in development by the Fraunhofer Institute, a partner of Conoship. So far, only a V/Br RFB with an energy capacity of a few kilowatt hours has been made and tested.

In conclusion, the technical barriers of low specific energy and energy density could potentially lead to an operational problem. Therefore this thesis is required to determine if it is possible to operate short sea shipping ships with a limited range.

Furthermore, this thesis is required to support research and development of the V/Br RFB. One of the goals of this thesis is to investigate if there is market for an E-Conoship in SSS, this will be researched analytically (TRL 3). This thesis assumes that the development of the V/Br RFB itself does not threaten the feasibility of V/Br RFB-powered shipping. In essence, it is assumed that the specifications specified for this battery in the marine application can be achieved at the required scale of 2MW, 45MWh.

2.6.2. Infrastructure barriers

Halim et al. [40] have written an article outlining, a pathway to decarbonising international maritime transport. Within this article the market barriers and/ or failures that are delaying the introduction of green technologies and fuels are described. One of the barriers identified by Halim et al. [40] is that some CO_2 mitigation measures expect change of infrastructure and enough production capabilities. Examples of mitigation measures which need a larger energy infrastructure are: advanced bio-fuels, hydrogen, ammonia, batteries. One of the barriers is achieving sufficient scale to make the introduction of bunkering (recharging) and energy supply commercially viable. Gray et al. [37] agrees, stating that the current inadequate charging infrastructure is seen as a major obstacle to the introduction of fully electric vessel.

In order to operate an E-Conoship it is necessary that they can be recharged with onshore power supply (OPS). The system on-board of this ship will have an effective energy capacity of 45MWh and a maximum power output of 2.6mW (2x1.3MW). The battery can be charged with a voltage between 6.6kV until 11kV. Moreover, it can be charged with any available alternating current (AC) shore power, as the alternating/direct current (AC/DC) converter is built into the ship's electrical system. In addition, the on-board electrical system detects the maximum available shore power capacity to maximize the charging current while preventing the shore power from being overloaded.

Currently permanent onshore power supply (OPS) is installed in several ports in NW Europe, among others are, Gothenburg (SE), Zeebrugge (BE), Kothka (FI), Antwerp (BE), Rotterdam (NL) and Hamburg (DE). The energy capacity of these installations vary from 0.8MW until 12MW. However, most OPS systems are currently build at terminals for: cruise, roll-on roll-off (RoRo), ROPAX and container ships [57].

This shows that, in order to operate an E-Conoship which is a general cargo vessel, infrastructure must be realised at general cargo terminals. Besides the permanent OPS structure is it also possible to install temporary OPS. An example of this is the Siemens Shirarbor, whereby all electrical equipment is enclosed in a container, it can supply up to 1MW [39].

Kumar et al. [57] identifies an important barrier for OPS systems, namely: who should invest in it? A number of possibilities are: power utility companies, ship owners, (regional/national/international) governments, external investors, port owners, and so on.

In conclusion, technical it is possible to realise the needed infrastructure, but to realise OPS at general cargo terminals the question arises who should invest in it? In the context of this thesis, the remaining barrier related to infrastructure is left outside the scope.

2.6.3. Competition barriers

Nowadays, many researchers are investigating alternative shipping fuels. Researchers are investigating the following alternative marine fuels, among others: LNG, LBG, (renewable) methanol, (renawable) hydrogen, battery-powered, ethanol/butanol, synthetic diesel, LPG, ammonia [95],[41],[86],[97]. This illustrates that there are many possible options for an emission-free industry. Because there is a finite market share for newly built ships, not all the different alternatives can be introduced to the market. This is a barrier to the introduction of any new technology.

Perčić et al. [74] has done an LCA for the costs of alternative marine fuels to reduce carbon emissions in SSS. A case study was carried out for three different ferries in the SSS area of Croatia. It was concluded that a ship powered by electricity (batteries) offers the most environmental friendly energy system and is the most cost-effective. A major difference between a dry cargo vessel and a ferry is that a ferry operates all year round over a short distance, in this case a maximum distance of 30.1nm, between one or more fixed points. This show that there is potential for battery-powered ship, however more research is needed to determine if a V/Br RFB is also an feasible option, for longer distances.

Sopta et al. [93] did a literature review about alternative fuels and technologies for SSS. This includes a DNV-GI forecast up till 2050. What can be learned from this forecast, is that in all scenarios several fuels are used, all aiming at emission reduction; one of the scenarios is shown in figure 2.9. It can be seen that RFBs are currently not included in this future scenario. This is (partly) due to the fact that the technology is still at an early stage of development in terms of maritime applications.

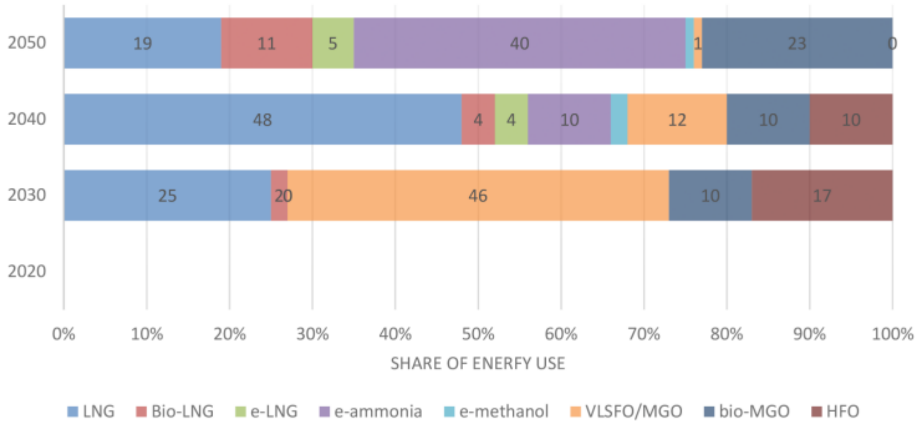


Figure 2.9: Possible future scenario [93]

In conclusion, competition is a barrier, because among others, competing technologies have gained much more attention in the maritime industry than the V/Br RFB. This thesis is needed to demonstrate to Conoship and other stakeholders, whether it is operationally and economically feasible to deploy ships with a vanadium bromide redox flow battery system. Besides this it is important to create awareness to the wider public that an E-Conoship is one of the possibilities to reduce emissions in shipping.

2.6.4. Information/knowledge barriers

As a result of inadequate, insufficient or incorrect information, a company could make large investments in the 'wrong' technology. The lack of detailed information on a technology with a low TRL is an obstacle to the introduction of energy-efficient measurements. This could be a significant barrier, where the financial industry is reluctant to invest in this new design and no company is willing to use the technology as there is no evidence that it is efficient and commercially viable [40],[89].

The presence of inaccurate information can lead to wrong decisions and is considered a barrier to the adoption of new technologies. An example of this is when different parties (e.g. commercial or political) try to influence the choice for a certain technology by spreading information about their own preferences, without this necessarily being the most optimal solution. To decrease the change of inadequate, insufficient or incorrect information, this research is required and besides this, Conoship collaborates with different companies whom are involved with V/Br RFB innovation: VanadiumCorp Resources Inc., Franhofer Institute and ICL Group.

VanadiumCorp is a vanadium mining company, and focuses on the development of clean energy technologies, they want to produce and recycle vanadium electrolytes sustainable, and construct a V/Br RFB-sytem. From the Fraunhofer Institute, the RFB-group is working on the development of the V/Br RFB, and they have a partnership with the University of New South Wales, where, among other things, the generation 1 VRFB was developed. Lastly a collaboration with ICL Group is made, a global manufacturer of products based on unique minerals, which develops bromine-based solutions for energy storage through various technologies.

In conclusion, within this thesis the absence of knowledge, whether it is possible to operate V/Br RFB-ships and whether the system is economically competitive, both could affect the implementation of V/Br RFB in SSS, will be dealt with. Furthermore, collaboration with the above actors could accelerate the rate of development, and inadequate, insufficient or incorrect information could potentially be detected at an early stage. However, the interests of each party must be considered, so that the appropriate decisions can be taken.

2.6.5. Inter- and intra organisational barriers

A barrier addressed by Serra and Fancello [89] is that of time constraints in for example decision-making and an absence of proper planning. Since it takes time to introduce a new technology, an "off-the-shelf" solution gets chosen in many cases. Another barrier listed by several is that of split incentives, this occurs when two people do not have the same priorities and incentives [40],[82],[81],[89]. An example is the difference in incentives between a charterer and a ship owner in a time charter market. In this market, the owner delivers the vessel, but the fuel costs are for the charterer. This indicates that a shipowner is interested in the most affordable ship and not in fuel costs, while the charterer is only interested in low fuel costs. In other words, the ship owner wants the lowest investment costs for the ship, so there is often no reason to buy the most energy-efficient ship [40],[89].

In addition most time-charter contracts are too short (1 year) to invest in green shipping. However, charterers can reward (higher charter rates) owners for investments in sustainable green technologies or hand out long charter (> 15 year) contracts, making it more attractive for a ship owner to invest in energy-efficient ships [40].

Longarela-Ares et al. [62] confirms this, and found that under which contract a vessel operates, plays an important role in investment in energy efficiency measurements (EEMs). It is stated that if a ship has more time charter contracts (TCC) than voyage charter contracts (VCC), the probability of investing in EEMs is lower. With a VCC the shipowner is responsible for the CAPEX, OPEX and VOYEX [98].

Furthermore, it is concluded that a ship operating with TCC is most likely to adopt operational EEMs, such as slow steaming, on the contrary vessels with VCC are more likely to adopt technical EEMs [62].

It must be demonstrated to both shipowners and charterers that investing in V/Br RFB-powered vessels can be financially attractive to both. It is also noted that there is a reserved attitude towards the implementation of green solutions, as there is a fear of investing in the wrong technology. Therefore this thesis aims to determine under which circumstances an E-Conoship can be operational and economical feasible in today's short sea shipping market.

Further an inter- and intra organisational barrier, is that of negative externality in the maritime industry. Halim et al. [40] states that negative externality occurs when a certain party takes an action, but does not have to pay (resolve) the costs (consequences) imposed on a third party. This is the case in the shipping sector, whose polluting emissions have a negative impact on both the economy and the environment in society, without them bearing the costs. The costs caused by polluting ships are never fully paid by the shipping industry itself. The fact that industry is not forced to do so plays a major roles in this, Which creates a barrier. There are hardly any economical reasons to reduce emissions.

Measures are being taken to address this. An example is the Norwegian government, which has imposed an NOx tax on shipping in Norwegian territorial waters since 2007. This turns out to be effective as there is a reduction in NOx emissions. Currently Norway is considering a carbon tax on shipping as well [23]. Furthermore, September 15, 2020 the EU Parliament has voted to extend the carbon market to shipping. Jutta Paules, a Member of the EU Parliament, put is as follows: *"It is high time that the 'polluter pays' principle is applied to shipping"* [44].

Dewan et al. [22] states that a barrier can be found within the management of shipping companies, as the focus is primarily on ensuring safe and profitable shipping operations. Here, energy efficiency is something that has to be done to comply with regulations.

As a first step Conoship established a partnership with Vega Reederei, a German shipping company based in Hamburg and founded in 1919. During the recession of 2007-2009 Vega sold all its ships active in the SSS market. Today they want to re-enter this market, but only with sustainable ships. Vega is interested in the possibility of RFB-powered short sea ships, but wants ”a proof of concept”. In essence, it is about the feasibility of deploying these ships in the short sea shipping market of North West Europe and if they are competitive in cost terms with diesel-powered short sea ships.

In conclusion, inter- and intra organisational barriers need to be addressed and clarification among others is needed with regard to the operational possibilities and economical costs of an E-Conoship.

2.6.6. Policy barriers

The IMO sets rules for the international shipping industry and every (new) ship must comply with these rules. Therefore, it can be considered as a barrier to introduce a new technology. For instance, the International Convention for the Safety of Life at Sea (SOLAS). This deals with safety standards in the equipment, operation or construction of merchant ships [105]. Another example is the IMO's, SO_x and NO_x regulations, which concerns the limitation of pollutant emissions [13],[24].

Furthermore, any (new) technology must meet the requirements of classification societies, such as: Lloyd's Register, Bureau Veritas, and DNV-GL. Before any new technology (ship) may be build a project based approval is required, for this among others potential hazards must be identified and a risk assessment has to be completed. An option but not obligatory is an approval in principle (AiP). In addition in a later stadium when more vessels have been build a type approval is required. Meeting these requirements is seen as a policy barrier to the introduction of a new technology within the maritime industry.

Finally, regarding the policy barrier, Serra and Fancello [89] states that most ship operators are currently waiting for a proven green technology to become available. This is partly due to uncertainties with regard to regulations (policies) as they are still being drafted. Therefore, shipowners wait to see what happens before they decide to invest, this creates a barrier to the introduction of new technologies.

As mentioned previously, before any new technology can be successfully introduced, it must comply with existing regulation. Because a ship with a V/Br RFB will not produce emissions during operation (sailing), it automatically complies with regulations concerning GHG emissions and other pollutant emissions (SO_x, NO_x et cetera).

A RFB system consists of electrolytic tanks in which chemical energy is stored, to be made available via the cell stacks [9]. The result is that a ship equipped with a V/Br RFB must comply with stricter regulations than ships for example using MDO as a main fuel. Those regulation are written in SOLAS Chapter VII - Carriage of dangerous goods and MARPOL Annex II [52]. Besides this any ship must comply with the requirements certified by classification societies such as Lloyd's.

In conclusion, the policy barriers is important to consider and risk assessment, hazards must be identified for an E-Conoship can be build. In addition, regulations with respect to carriage of dangerous goods and compliance with for example Lloyds need to be included in the final design of a ship equipped with V/Br RFB's. For this research compliance with regulation is left outside the scope.

2.6.7. Financial barriers

One of the financial barriers for wide spread adoption of mitigation measures is a restricted access to capital. In addition, most 'green' solutions are more expensive than conventional ones, which increases the payback period and reduces the economic incentive to invest. For fully electric ships, there are also the additional costs of installing charging stations on shore, which cannot be ignored [89].

According to Serra and Fancello [89], these additional costs could ultimately lead to a decrease in the profitability of the maritime sector, which could have negative side effects, such as a shift to road transport instead of shipping.

Another financial barrier is that vessels have a lifespan of around 20-25 years, so the ships sailing today will still be there in 2035. This fleet of older ships represents a huge sunken costs, and in most cases these ships will not be scrapped prematurely. Therefore, it poses a challenge concerning decarbonisation in the short-term [40].

The next barrier relates to shipping operators, as they have traditionally been reluctant to adopt green solutions due to the high CAPEX and the risk of investing in the 'wrong' technology. Three overarching types of risk can be distinguished: business risk, technical risk and external risk. The 1^{st} mainly concerns the financial risk and the 2^{nd} concerns the uncertainty about the reliability and related performance of the new technology. Lastly, external risk is related to the unpredictable economic future, fuel prices, the regulatory environment and finally the policy [89].

Financial barriers include limited access to capital and the fact that most "green" solutions are more expensive. The former is beyond the scope of this thesis. The latter needs further investigation to determine if this is also the case for a V/Br RFB system. Another financial barrier is the financial risk, related to regulations, fuel prices and economic future. Because no V/Br RFB-powered vessel has been built yet and it is currently unknown what the effect is of, for example, regulations, fuel price and economic future on OPEX, CAPEX and VOYEX of an E-Conoship, this must be determined.

The lifespan of a vessel is around 20-25 years, as a ship with V/Br RFB emits no GHG emissions during operations it already complies with IMO 2050 targets and regulations. Therefore the financial risk related to regulatory environment can be taken away. Furthermore, as describe earlier it is expected that a CO_2-tax will be put into effect within the next few years. This can reduce the financial risk, as then ship will be punished if they emit CO_2 resulting in more financial incentives to invest in green shipping.

In conclusion, there is still uncertainty regarding the financial investment required to operate V/Br RFB-powered vessels. Therefore, this barrier needs to be further investigated in order to determine if and to what extent this system is financially competitive with traditional diesel-powered vessels.

2.7. Conclusion

After analysing the opportunities and barriers for vanadium redox flow battery-powered shipping the following preliminary question can be answered: *"What are the barriers and opportunities for the introduction of vanadium bromide redox flow battery-powered shipping in the short sea shipping market of North West Europe?"* At first the following opportunities are identified, based on a literature review, see table 2.5.

Table 2.5

No.	Opportunity	No.	Opportunity
1.	No emissions during operation	5.	Lifetime over 20 years (+15,000 cycles)
2.	Long charge-discharge cycle, self discharge is not of concern	6.	Low total GWP when charged with green energy, compared to Li-ion battery
3.	High degree of modularity, power and energy are independent of each other	7.	Safe to operate, system can be easily shut down in case of emergency
4	No cross contamination-problems	8.	Recharging conventionally or mechanical refuelling

Second, the barriers for the introduction of V/Br RFB-powered shipping in the SSS market of NW-Europe are determined. All barriers previously addressed are put into one table 2.6. Within this table, red colored barriers are the ones which are considered as main barriers and these will be addressed in the remainder of this thesis.

Table 2.6: Barriers for adoption of a new technology in short sea shipping

Type of barrier	Barriers for adoption of a V/Br RFB in short sea shipping
Technical	1. Limited range, 2. Technology readiness level
Infrastructure	Charging facilities
Competition	Other zero emission, or low carbon technologies
Information/knowledge	1. Inadequate, 2. Insufficient, or 3. Incorrect information
Inter- and intra- organisation	1. Reserve attitude, 2. Split incentives, 3. Public opinion, 4. Acceptance 5. Risk perception
Policy	1. IMO 2. Classification societies, e.g. Llyods or Bureau Veritas
Financial	1. More expensive 2. Access to capital 3. Hidden costs

The technical barrier, limited range, could lead to an operational constraint whereby it is not possible to operate V/Br RFB-powered ships within the SSS market of North West Europe due to limited range. Without being able to sail merchant voyages, a V/Br RFB-powered ship cannot be operated, so this barrier needs to be further investigated. It should be determined whether a V/Br RFB-powered ship is operationally feasible in the current SSS market.

The financial barrier, more expensive, could lead to a situation in which nobody wants to invest in a V/Br RFB-powered ship, despite the fact that it emits no GHG during operations. It is currently unknown what the total cost, consisting of fixed and variable costs of this new ship type will be, and under which circumstances this new ship could be economical feasible in today's SSS market of NW Europe. To deliver a proof of concept is therefore required to determine these.

By addressing the above main barriers, at the same time the blue colored 'information/knowledge' and 'Inter- and intra- organisation' type of barriers are dealt with. By researching whether it is possible to complete merchant voyages with a limited range, it removes a certain amount of: inadequate, insufficient and incorrect information. Furthermore, by identifying what are the costs of an V/Br RFB-powered ship, and under which circumstance such a ship is economical feasible in today's SSS market, risk perception and part of reserve attitude could be removed.

3

Research methodology

Within this chapter the objective, scope, research question and the methodology for the remainder of this thesis will be addressed. Within the first section, objective scope and research question will be dealt with. In section 3.2, the methodology used to determine the operational feasibility will be dealt with in the following section the economical feasibility will be elaborated on.

3.1. Objective, scope and research question

The objective of this research is to deliver a 'proof of concept' for operational and economical feasibility of V/Br RFB-powered shipping. This is intended to bring the realisation of this new ship type one step closer to fruition, in order to reduce the shipping sectors GHG emission. Furthermore, by doing so inform among others, Conoship, and potential shipowners about the opportunities and barriers of the system, the possibility of operating V/Br RFB-powered vessels and under which circumstances V/Br RFB-powered shipping is economically cost-competitive with a state of the art diesel-powered ship. Thereby determining if there is market potential for ships equipped with V/Br RFB in the SSS market.

For this research, the short sea shipping market of NW Europe is restricted to the waters between the port of Seville, Spain and the port of Arkhangelsk, Russia. This excludes the maritime transport from and to the hinterland via inland waterway and voyages to and from the Mediterranean. The area of NW Europe has been chosen due to the ECA zones, public opinion and the European climate goals. Inland waterways are not included in this study because of the unfavourable weight ratio between V/Br RFB-sytem and the deadweight cargo capacity (DWCC), when applied to 'small' inland vessels. This research focuses on the technical, economical and operational aspects of a V/Br RFB-battery powered ship. In the context of this thesis, infrastructure is left outside of the scope, because section 2.6.2, shows that technical it has already been proven, the remainder barrier left is who should invest in OPS at general cargo terminals. Therefore, it is of greater interest for this research to focus on the limited range, and the economic costs of the E-Conoship. Future market and development scenarios of the V/Br RFB-system are part of this study too. This leads to the following research question to be addressed in the remainder of this thesis:

"Under which circumstances is Conoship's vanadium bromide redox flow battery-powered ship design operational and economical feasible in today's short sea shipping market of North West Europe?"

In order to guide this research and to be able to answer the main research question, it has been divided into the following 2 sub-questions:

1. *"What current shipping routes present potential for vanadium bromide redox flow battery-powered shipping?"*
2. *"Under which circumstances is Conoship's vanadium bromide redox flow battery-powered ship design cost-competitive with diesel-powered ships?"*

3.2. Operational feasibility

Within the operational phase the first sub-question will be addressed: *What current shipping routes present potential for vanadium bromide redox flow battery powered shipping?*

Previous chapter informs that a limited range could be an impediment to the introduction of V/Br RFB-powered shipping. Therefore, before the first sub-question can be answered, it must be identified if there is any market potential for ships to complete short distance (≤500nm) voyages. At first, the shipping activities of ships operating on the short sea shipping market are required to be defined. This will be done by analysing historical voyage data, see chapter 4.

Once the capability to operate ships with a limited range has been assessed, research can continue to determine the current shipping routes that present the greatest potential for vanadium bromide redox battery-powered shipping. This in order to determine under which circumstances Conoship's vanadium bromide redox battery powered ship design is operationally feasible in today's SSS market.

According to Stopford [98], a market research summarises all relevant fact about the market, examine trends, and draws conclusions about what might happen in the future. A complete market research report consist of six stages: (1) establish terms of reference, (2) analyse past trends, (3) survey competitors plans and opinions of experts, (4) identify influences on future market development, (5) combine information into forecast, and (6) present results. Within this thesis the first two stages of a market research are conducted, in chapter 5, to determine the shipping routes that present potential.

3.3. Economic feasibility

A financial barrier to the introduction of a new technology in SSS, is that the new technology is often more expensive than a conventional one. For a V/Br RFB-powered ship, the total costs, consisting of capital, operational and voyage related costs are unknown. Furthermore, for many of these costs there are uncertainties that affect them. In this thesis, the total costs will be determined and the associated uncertainties will be identified. This in order to answer the second sub-question: *"Under which circumstances is Conoship's vanadium bromide redox flow battery-powered ship cost-competitive with diesel-powered ships?"*. In doing so, a vanadium bromide redox flow battery-powered ship will be referred to as an E-Conoship.

An E-Conoship is considered cost-competitive if, within 20 years the economic lifetime of both vessels, a break-even point is reached after which the total costs are lower compared to a diesel-powered ship. A ship with a diesel engine has been chosen for comparison for several reasons, one of which is that the majority of today's ships operate on diesel engines. In addition, with existing regulations a ship equipped with a diesel engine (compliant among others with IMO tier 3) can still be built today and used for over 20 years.

According to Hunt and Butman [47], certain engineers and managers consider it beneficial to split cost information for comparing project alternatives into two categories, fixed costs (e.g. design, construction) and variable costs (e.g. operation, maintenance, insurance). These costs can then be added up and compared to a revenue or cash flow benefit to find a break-even point on the time scale. A break-even point occurs when both are equal to one another.

This research does not go into the uncertainties related to potentially higher income for a 'green ship'. In advance, within this research DWCC, hold volume and no preference of the cargo owner will be taken into account. Given above statements income for both ships are the same and, are therefore not included within this economical feasibility study.

Result is that a break-even analysis will be done solely based on the fixed and variable costs of the two vessels. According to Stopford [98], the three main cost categories are capital expenditure (CAPEX), operational expenditure (OPEX), and lastly voyages expenditure (VOYEX). Within this thesis a cost-comparison model will be made, taken into account these cost categories over a period of 20 years, for further details see chapter 6.

Several methods can be used to compare different alternatives. A case study method is used by many to compare alternatives, including a thesis by Priyanto [79] that uses this method to determine the economic feasibility of methanol versus marine diesel oil shipping. In addition, two other studies one by Mukhtarov [69] and one by Al-Falahi et al. [4] use a case study methodology to compare economic shipping costs. According to Yazan [111], there are different views on case study methods, but all methods contain the same phases, namely: case definition, data collection, data analysis and data validation, see figure 3.1.

Figure 3.1: Four phases of a case study [111]

The case will be Conoship's general cargo short sea ship design operating fully on a V/Br RFB-system. This design at maximum draught has a deadweight cargo capacity (DWCC) of 4968t. The economic shipping cost of this ship, will be compared to a conventional general cargo ship with similar DWCC, and powered by a diesel 4-stroke engine. The main fuel for this ship is required to be: MDO, IFO or MGO, as more than 90% of the current short sea shipping fleet, 3,000 - 7,500DWAT, of North West Europe runs on these fuel types [64].

A comparison between both vessels will be first made for case 1.0 a voyage between port A and B, later multiple cases and scenarios will be executed. This will be determined based on a market research of the current SSS fleet, which is dealt with in the operational phase of this thesis, chapters four and five. Suitable voyages to sail with an E-Conoship will be used as the basic input for the cost comparison model, in order to determine the economic costs of shipping. Once the economic shipping costs: VOYEX, CAPEX and OPEX are determined for this case 1.0, the first break-even analysis can be made.

The analysis phase of the case study, will be done with scenario analysis. With this it can be determined, under which circumstances an E-Conoship is cost-competitive with diesel-powered ships. Scenario analysis embraces the uncertainty of the future by exploring independent and unrelated futures, while maintaining the analytical precision of existing quantitative tools within each future scenario [101]. Tourki et al. [101] proposed the following methodology for scenario analysis, see figure 3.2. Different scenarios are examined in more detail in chapter 7.

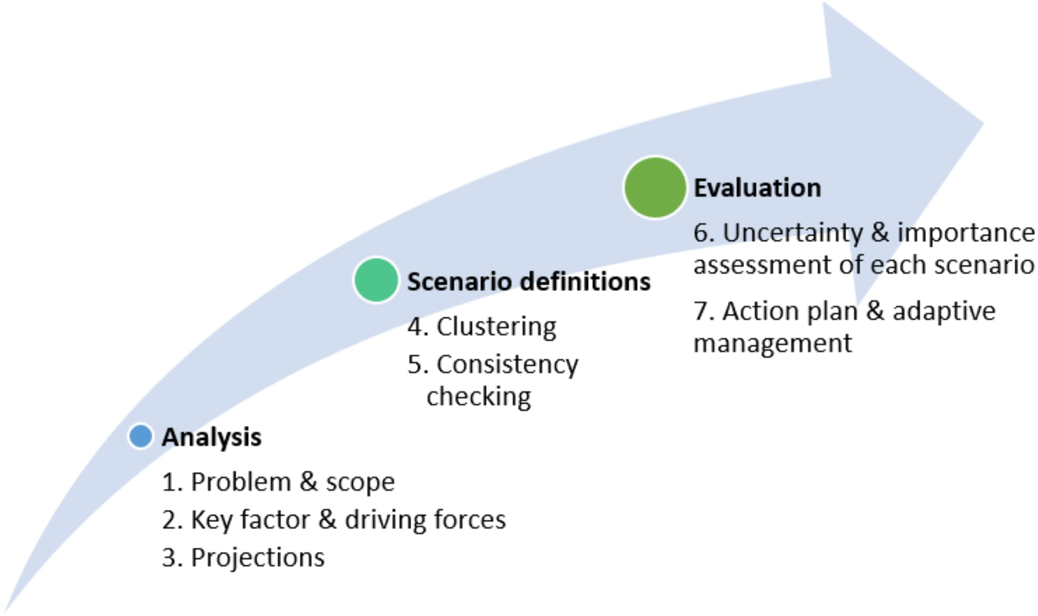


Figure 3.2: Methodology for scenario analysis [101]

3.4. Outline

Within this research, before starting a new phase, the previous research phase has to be completed and a so-called gateway has to be passed. For gate I, the main barriers that need to be addressed in the remainder of the thesis must be determined, this is done in chapter 2. Gate II, is there because, before economic feasibility can be determined, voyage input from the operational phase is needed. The conclusion of this thesis that aims to answers the next research question is twofold:

"Under which circumstances is Conoship's vanadium bromide redox flow battery-powered ship design operational and economical feasible in today's short sea shipping market of North West Europe?"

It is twofold, because on the one hand there is the operational feasibility and on the other hand the economic feasibility, which together form the answer to the main research question. For a general overview of the structure of this thesis, see figure 3.3.

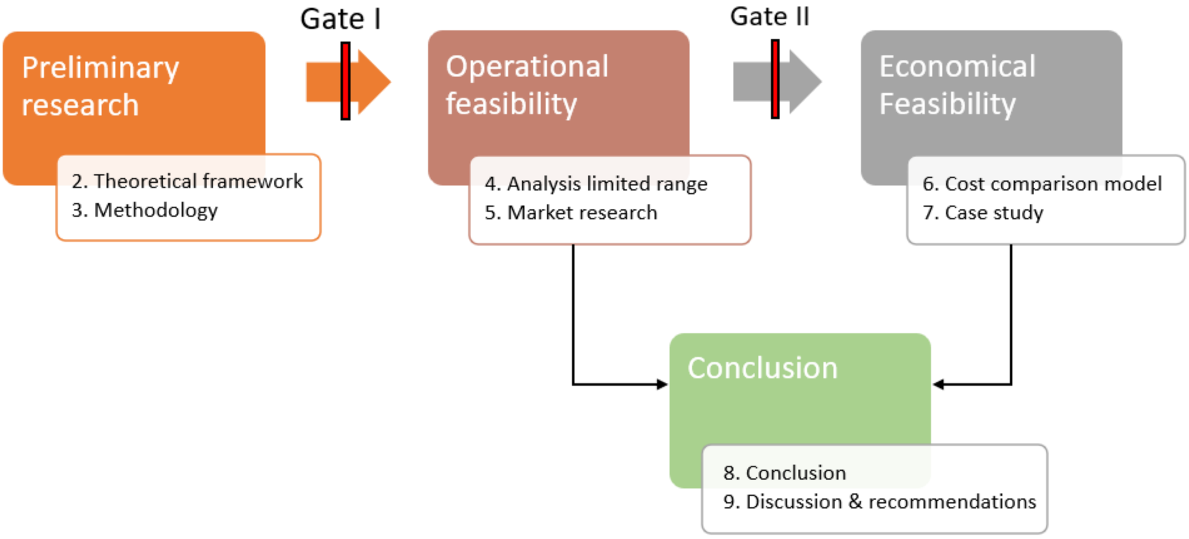


Figure 3.3: Overview of the structure of this thesis

4

Analysis of limited range

The analysis of the barriers in chapter 2 showed that it is important to know whether ships with a limited range can complete merchant voyages. It is essential that this question is answered in order to conduct further research, and it will therefore be dealt with in this chapter.

4.1. Analysis historical voyage data

An analysis of historical voyage data can be used to determine whether limited range is an impediment to the introduction of an E-Conoship. For this analysis competitors for a general cargo E-Conoship destined to operate in the SSS area of North West Europe, will be used. The geographical area extends from the port of Seville in Spain to the port of Arkhangelsk in Russia, including ports in the Baltic Sea. The area of NW Europe has been chosen due to the ECA zones, public opinion and the European climate goals. Inland waterways are not included in this study because of the unfavourable weight ratio between V/Br RFB-sytem and the deadweight cargo capacity (DWCC), when applied to 'small' inland vessels.

This E-Conoship has a proposed sailing range of 500 nautical miles (nm) at design speed of 10 knots fully operating with a V/Br RFB-system. The first step is the identification of shipping activities. Therefore, the route profile of ships operating in the SSS market of NW Europe must be known. For this identification of shipping routes, attention will be paid in the first place to general cargo ships for SSS, which consist of the following ship types: multi-purpose (MPP) ships, general cargo ships, bulk carriers, aggregates carriers, palletised cargo carriers and MPP/Heavy lift cargo ships.

Ships with a gross tonnage (GT) of ≥5,000GT must comply with the EU monitoring, reporting and verification regulations [18]. This means that for those ships it is compulsory to share data about distances travelled time spent at sea, amount of each type of fuel consumed in port/at sea and cargo carried. This reveals the first gap in data collection, as the example ship design has a gross tonnage of approximately 3,815GT, see formula 4.1.

$$GT = K_1 * V = (0.2 + 0.02log_{10}(V)) * V \approx 3,815GT \quad {}^{*}V \approx 13,500m^3 \tag{4.1}$$

As the area of interest for this research is primarily dictated by ships with a gross tonnage ≤5,000GT. The first objective of this research is to fill the gap in literature and determine SSS routes (maritime flow) for these vessels. Then, on the basis of this, determine which merchant voyages can be accomplished with a limited range. Ducruet et al. [27] analysed the global pattern of maritime flow using data of merchant ship movement in 2004 and 2001. The methodology used: (1) data selection (based on ship type and size), (2) macroscopic patterns using 'single linkage analysis methods' to simplify the pattern of flows and identify key structures (geographical levels considered, continents, maritime range, and ports), (3) port hierarchies and nodal regions, (4) Geographic specialisation of maritime forelands. To identify whether reduced range is a 'real' barrier the first two steps as addressed by Ducruet et al. [27] will be used.

4.2. Data selection

The previously mentioned ship types, which are all considered comparable to E-Conoship, must be analysed to determine the SSS market of NW Europe. Moreover, E-Conoship has a deadweight all told (DWAT) of 6,075t, and DWCC of approximately 5,000t. Vessels with DWAT capacities between 3,000t and 7,500t are considered competitors, and are expected to operate short sea.

The data required for analysis will be selected, through Clarksons Research [15]. First, the World Fleet, as registered in December 2020, has been acquired for the earlier mentioned ship types, see figure 4.1. Highlighted light blue in figure 4.1, is the area of interest NW Europe, whereby the area until port of Arkhangelsk in Russia also must be included.

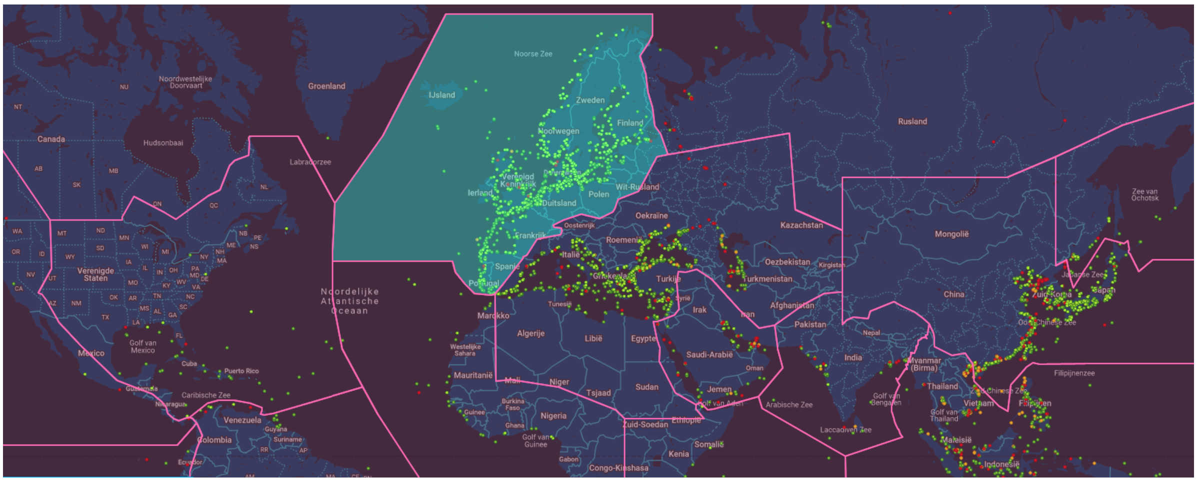


Figure 4.1: Snapshot: general cargo world fleet, December 2020 [3,000 - 7,500 DWAT] [15]

The total world fleet of the above mentioned ships, range 3,000 - 7,500DWAT, contains 4,855 ships. Second, ystematically this fleet is reduced to ships operating in the SSS market of NW Europe. This has been done via the following steps:

1. Select: ships which are currently 'In Service'
2. Select: 'Beta Global Zone Group' (last 12 months) - Europe
3. Select: 'Beta Region' - United Kingdom/Continent (last 12 months), same area as NW Europe
4. Select: ships 'Atlantic' based (last 12 months)
5. Select: 'Operators Nationality' - countries located at continent Europe
6. By hand: Look at 'port Calls' to determine operational area of ship - more than 75% of the time operational in NW Europe over the year, than added to the SSS fleet operating in NW Europe, otherwise ship removed from database [64],[15].

This results in a total SSS fleet operating in NW Europe of 1,047 ships (21.6% of total fleet), 3,000 - 7,500 DWAT, which are considered to be of interest. For all of these 1,047 ships the IMO number, which is an unique number corresponding to a single ship, is known. To determine the SSS routes and associated distances travelled, a sample of the entire fleet must be taken as analysing the entire data-set is to labour intensive. This sample size is assumed to be representative of for the ships operating in the SSS market of NW Europe.

4.2.1. Data pre-processing

The first step to determine is to determine based on a literature research what 'sample size' is needed to perform research. As determining the minimum sample size necessary to achieve the main objective is essential. After all, without a good sample size, the research results are worthless. The required sample size should be selected with means of an appropriate probability sampling technique [10].

The general steps to be taken can be found in figure 4.2 [99]. The first and second step, define target population and determine the sampling frame have been carried out in previous paragraphs. The target population is the SSS vessels operating in NW Europe with deadweight all told capacity between 3,000 DWAT and 7,500 DWAT, this is also the sampling frame.

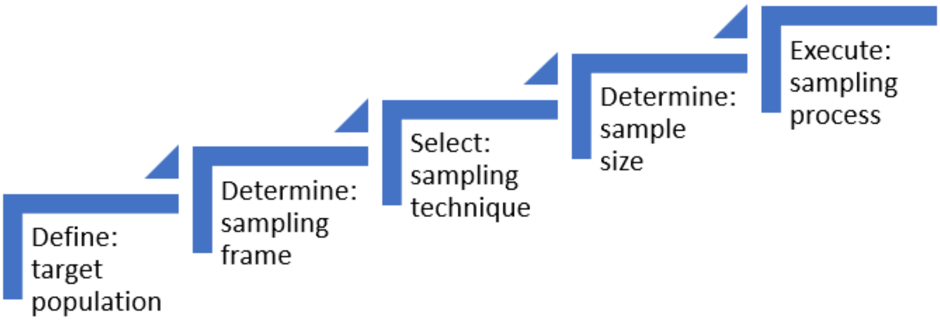


Figure 4.2: General steps in determining sample size [99]

Third step is to choose a sampling technique broadly speaking there are two overarching sampling techniques namely: probability sampling and non-probability sampling. Respectively the first overarching technique, indicates that every vessel in the database has an equal change of being included in the sample. The other overarching sampling technique non probability sampling, is often associated with case study research design and qualitative research. Samples made using this technique are not necessarily representative, or random, but a clear reason is needed to include some operators or vessels instead of others [99].

For this research a non probability sampling technique will be chosen because the sample size must have the same distribution of characteristics as the entire SSS fleet operating in NW Europe. To achieve this a clear rationale is needed to include some vessels instead of others.

There are many non-probability sampling methods a few examples are: quota sampling, snowball sampling, convenience sampling, intentionally or judgemental sampling. For this research there is opted for quota sampling, this is a method at which, in this case particular vessels are chosen based of predefined features. This will be done in such a way that the total sample size has the same distribution as the entire SSS fleet operating in NW Europe deadweight all told range 3,000 - 7,500 DWAT [99].

After the quota sampling method is chosen the following step is to determine the sample size for a finite number of initial vessels, this will be done by means of the following formula 4.2, the meaning and values for the different symbols can be found in table 4.1. It is suggested that researches should use 50% as an estimate of p, as this results in a maximisation of variance and produces a maximum sample size [99].

$$n = \frac{\frac{Z^2 * p(1-p)}{\epsilon^2}}{1 + \frac{Z^2 * p(1-p)}{\epsilon^2 N}} = 281 \tag{4.2}$$

Table 4.1: Data input to determine sample size

Symbol	**Meaning**	**Value**
Z	level of confidence required	95% (0.05; Z=1.96)
ϵ	margin of error	5% (0.05)
N	fleet size	1,047
p	fleet proportion	50% (0.5)

The final step is to execute the sampling process. For this the deadweight all told capacity distribution of the different vessels in the sample size must be similar to that of the target fleet. Therefore, first the distribution of number of ships in the SSS-fleet arranged in deadweight capacity with bins of 500 DWAT is given in figure 4.3. Whereby the average deadweight all told capacity of the entire fleet operating in NW Europe is 4,505 DWAT.

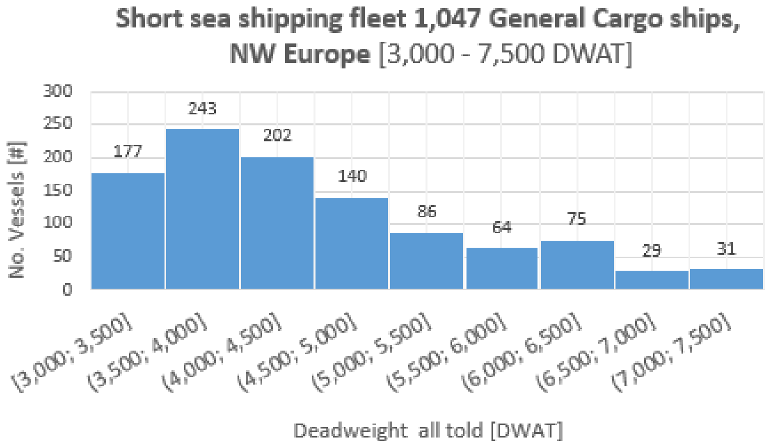


Figure 4.3: General cargo, short sea shipping fleet (1,047 ships), NW Europe [3,000-7,500DWAT]

With a known vessel distribution of number of vessel per deadweight all told capacity, the last step can be performed. This is done by counting the number of vessel of the target fleet per bin each with a width of 500 DWAT. This step is denoted by X_i with i=1,2 ...., 9 whereby, X_1 is No. vessels in bin_1= 3,000 until 3,500 DWAT, X_2 is No. vessels in bin_2= 3,500 until 4,000 DWAT, ... until X_9 is No. vessels in bin_9= 7,000 until 7,500 DWAT is reached.

Then multiplying this X_i with 281, the number of vessels required for the total sample size. Next step is dividing this by 1,047, total number of vessel in the target fleet. This results in the number of vessels required in the sample size per bin, whereby the amount of vessels per bin are rounded to integers. This process is represented by formula 4.3.

$$X_i(\textbf{sample.size}) = \sum_{i=1}^{9} \frac{X_i \cdot 281}{1,047} \tag{4.3}$$

This results in a sample size, see figure 4.4, with a similar distribution of vessels per deadweight all told capacity as the target fleet.

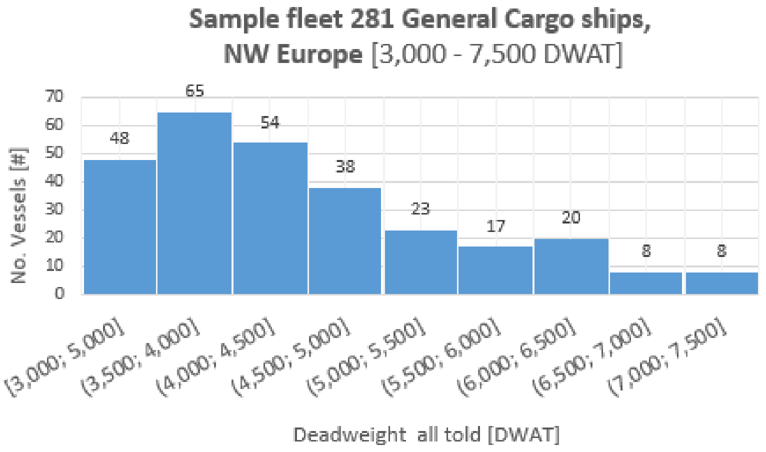


Figure 4.4: General cargo, short sea shipping sample fleet (281 ships), NW Europe

Now that it has been determined how many ships per 500 DWAT bin are needed for the sample size of 281 ships, the next quota can be set. For this quota it is important that the sample size represents the vessel operators in the same ratio as that they are represented in the target fleet.

The top 25 of the 229 SSS operators in NW Europe operate 52.44% of all vessels, see figure 4.5. To derive the number of vessel per operator in NW Europe to be included in the sample size, excluding all operators with less than 2 vessels in the target fleet, the same method as for the number of vessel per bin of 500DWAT is used.

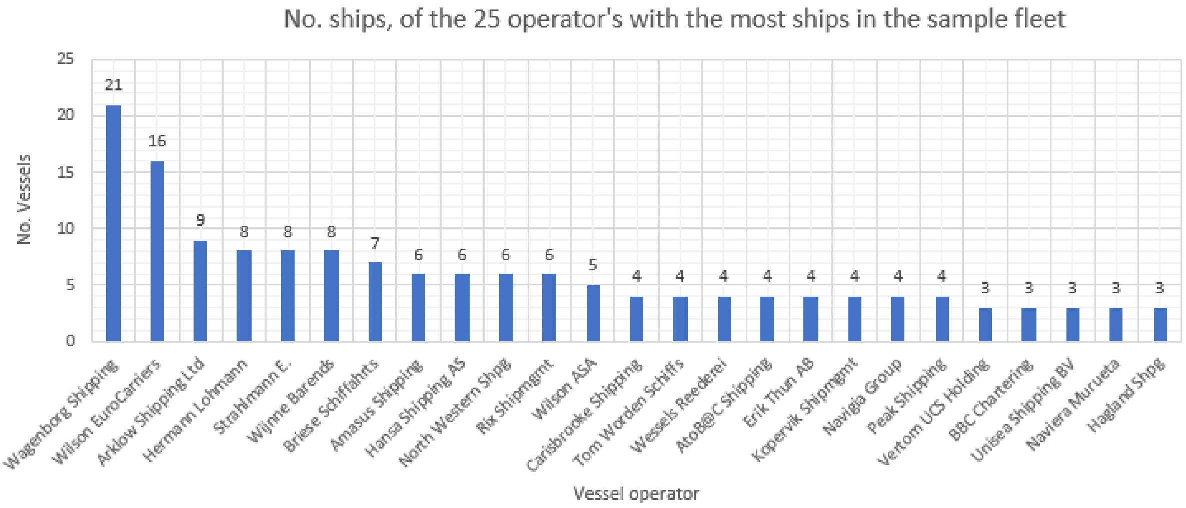
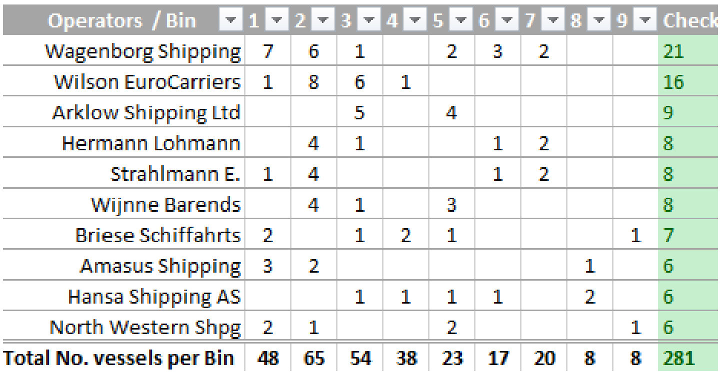


Figure 4.5: No. of ships in sample fleet, top 25 operators, short sea shipping NW Europe

Information is available on the number of vessels required per operator, see figure 4.5, and also the number of vessels per deadweight capacity bin of 500 DWAT is known, see figure 4.4. The problem at hand is that the distribution as presented in figure 4.4 must remain preserved as well the distribution of the amount of vessels each unique operators runs. Both constraints are applicable to determine which vessels to include in the sample size. This means that there is a restriction about how many vessels of each unique operator can be included in the sample size.

A total of 123 out of 229 vessel operators are included in the sample size, the top 25 of operators and there associated number of vessels in the sample size can be found in figure 4.5. From the list of 1,047 ships per bin of 500 DWAT a number of ships have been selected, taking into account the ship operators, with the sum corresponding to the total number of ships required in the sample size, a snapshot of the first 10 operators and the amount of vessel in each bin selected can be seen in figure 4.6.



Operators / Bin	1	2	3	4	5	6	7	8	9	Check
Wagenborg Shipping	7	6	1		2	3	2			21
Wilson EuroCarriers	1	8	6	1						16
Arklow Shipping Ltd			5		4					9
Hermann Lohmann		4	1			1	2			8
Strahlmann E.	1	4				1	2			8
Wijnne Barends		4	1		3					8
Briese Schiffahrts	2		1	2	1				1	7
Amasus Shipping	3	2						1		6
Hansa Shipping AS			1	1	1	1		2		6
North Western Shpg	2	1			2				1	6
Total No. vessels per Bin	**48**	**65**	**54**	**38**	**23**	**17**	**20**	**8**	**8**	**281**

Figure 4.6: No. of ships per operator in the sample fleet, divided into bins of 500DWAT

4.2.2. Data collection

For those 281 vessels, with known IMO number, historical data will be collected to determine the voyages over the following period from 19^{th} of January, 2020 until 19^{th} of January, 2021. From those vessel their port calls will be collected including dates of arrival and departure, how this data is obtained and exported will be dealt with in the next paragraphs. To obtain historical port Calls for the sample fleet, several channels has been investigated, see table 4.2.

Table 4.2: Options for retrieving historical data

Source	Contacted via	Status	Follow-up
Clarkson Research	mail & phone	non-received	Multiple mails, still no reply
Fleet Mon	mail	cost proposal	Concluded to be too expensive
VesselFinder	website	cost proposal	Too expensive & no convenient format
Marine Traffic	mail	apply for Marine Traffic Global	Marine Traffic Global - incl. Credits
VTExplorer	website	cost proposal	Too expensive & no convenient format

For this research it is opted to use Marine Traffic as this one provides the most convenient and affordable data. Within Marine Traffic historical data can be retrieved up to one year in the past [64]. For the identification of shipping activities the maximum retrieval of historical port Calls will be used. Furthermore, before any data is exported from Marine Traffic the following filters are applied:

1. Filter; actual time of arrival/ actual time of departure 19-01-2020 until 19-01-2021
2. Filter; port Call type: Arrival
3. Filter; port Type: port & Marina[1]
4. Filter; in transit port Calls[2]: not in transit

[1] A harbour for small boats

[2] Whether the ship has stopped within the area in question, or has passed through it.

Once this data is filtered it will be exported by means of a comma-separated value (CSV) file. After all port Calls of the entire sample fleet, 281 ships, is obtained the data need to be processed, which will be elaborated on in the next paragraph.

4.3. Data analysing

After 281 individual CSV-files are obtained they are combined in one large CSV-file. This is the first step in data analysis. The number of voyages and associated distance are set in one graph to identify if there is market potential when a ship has as reduced range of 500nm, see figure 5.5.

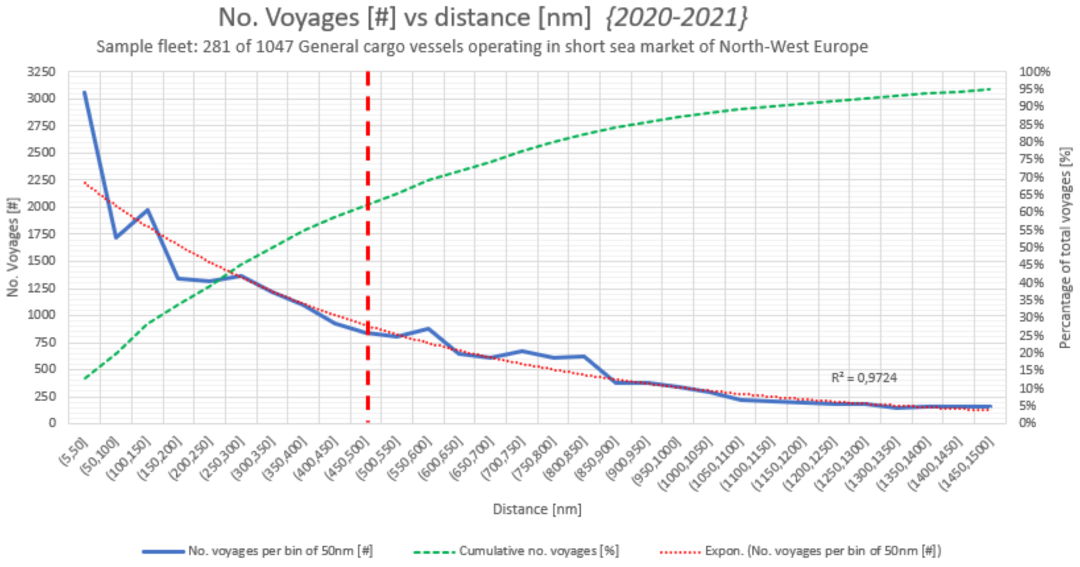


Figure 4.7: Number of voyages [#] within a certain range [nm]

Using figure 4.7, it is possible to determine the percentage of merchant voyages that can be completed with a given range. However, it is not yet known how many ships travel less than a set range (distance) during the majority of their voyages.

To determine what percentage of the ships sail respectively 75% and 85% of all their voyages less than a set distance. Thirteen different scenarios were generated: from 500nm to 1,100nm with steps of 50nm. The first scenario is a set range of 500nm, with this 62% of all voyages over the past year can be completed. Furthermore, 11% (31/281) and 5.7% (16/281) of the ships sail respectively at least 75% and 85% of all their voyages less than the set 500nm range. For an overview of the thirteen different scenarios, see figure 4.8.

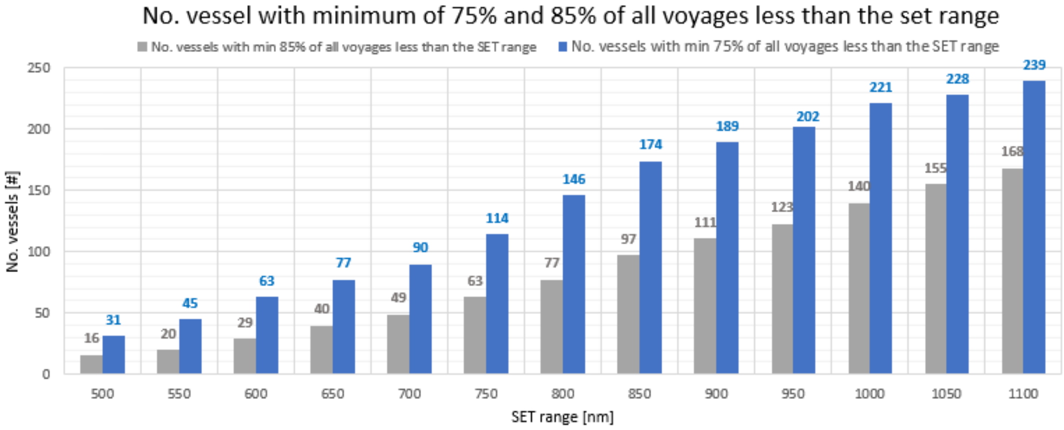


Figure 4.8: Market potential, different scenarios for a given range

4.4. Conclusion: limited range

After analysing almost 25,000 port calls of 281 general cargo vessels (3,000-7,500DWAT) in the NW Europe SSS market over the past year, it becomes clear that with a 500nm range about 62% of all voyages can be completed. Furthermore, about 11% of the vessels sail at least 75% of all their voyages within the 500nm range. The 11% represents 115 vessels operating in NW Europe, as the sample fleet is considered representative of the entire general cargo short sea fleet operating in NW Europe, 3,000-7,500DWAT.

Therefore, this data analysis has shown that with a limited range of 500nm more than half of all voyages over the past year can be completed. In addition, there is potential for replacement of 115 ships, without changing existing trades. However, it is still important to get a better understanding of the SSS market in NW Europe to clearly define what area/ports/routes present the most potential for E-Conoship's, this will be researched in the following chapter.

5

Market research

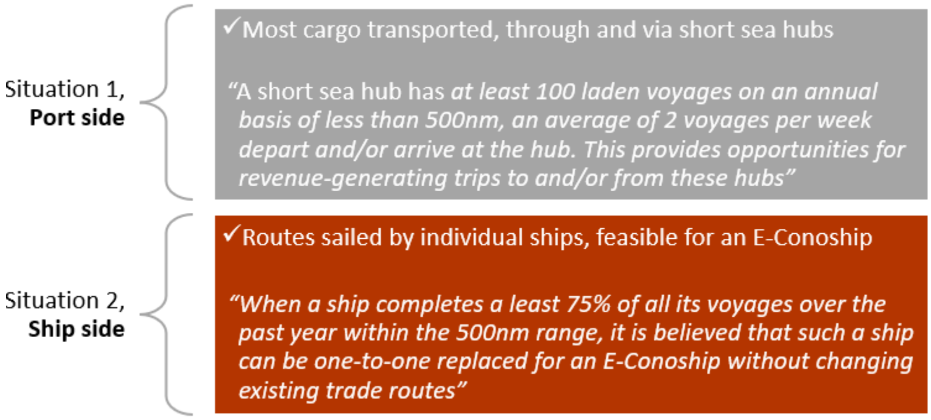
As has been concluded in the previous chapter it is important to get a better understanding of the SSS market in NW Europe. The goal of this chapter is to better understand the SSS market, thereby identifying which current shipping routes present potential for vanadium bromide redox flow battery-powered shipping by analysing past trends.

5.1. Terms of reference

An E-Conoship has a range of 500nm at a design speed of 10 knots. This range includes a 15% sea margin. The range can be increased by ”slow steaming”. To determine the operational feasibility of an E-Conoship, the following sub-question will be answered: *”what current shipping routes present potential for vanadium bromide redox flow battery-powered shipping?”*. To do so the (market) potential for V/Br RFB-powered shipping will be analysed through two different situations. The two situations are analysed using historical voyage data of 281 vessels, which are representative of the entire short sea shipping fleet of 1,047 vessels operating in NW Europe.

Situation one, see figure 5.1, port side, selecting current routes (between ports) that have a high degree of laden voyages under 500nm. With this a fleet manager can divide his ships between short and long distance transport from or via these SSS hubs, or voyages from these SSS hubs can be obtained via spot market.

Situation two, see figure 5.1, shipping side, selecting routes based on individual vessels operating at least 75% of all their voyages within the 500nm range. In this situation, it is expected that a (old) ship can be one-to-one replaced by an E-Conoship without jeopardizing the existing trade routes.



Situation 1,
Port side

✓Most cargo transported, through and via short sea hubs

“A short sea hub has *at least 100 laden voyages on an annual basis of less than 500nm, an average of 2 voyages per week depart and/or arrive at the hub. This provides opportunities for revenue-generating trips to and/or from these hubs”*

Situation 2,
Ship side

✓Routes sailed by individual ships, feasible for an E-Conoship

“When a ship completes a least 75% of all its voyages over the past year within the 500nm range, it is believed that such a ship can be one-to-one replaced for an E-Conoship without changing existing trade routes”

Figure 5.1: Two different situations to analyse the current short sea shipping market

5.2. Analysis past trends

Within this paragraph the different loading conditions of the ships sailing merchant voyages will be analysed, to determine if the average distance travelled per voyages depends on the loading condition. Therefore, almost 25,000 historical port Calls, conducted by 281 ships over the period 19 January 2020 to 19 January 2021 were analysed. The loading conditions of the merchant voyages in this database are divided into three groups: ”in ballast”, ”partially laden” and ”laden”.

Analysis of this shows that about 41% of the merchant voyages are completed ”in ballast”, i.e. sailing empty to other ports to pick up cargo. Furthermore, around 16% and 40% of the trips respectively are ”partially laden” or (fully) ”laden”. For approximately 3% of all trips made in the past year, the loading condition is not known, and therefore defined as ”unknown”, see table 5.1. Table 5.1 shows this and the average distance travelled in nautical miles, by type of loading condition.

Table 5.1: Average distance per voyage per loading condition

Loading condition	In Ballast	Partially Laden	Laden	Unkown	Partially laden and Laden
Average distance per voyage [nm]	335	445	633	539	581
Percentage of total voyages [%]	41.08	15.59	40.41	2.91	56

In table 5.1 it can be seen that the average distance covered per voyage varies depending on the load condition. The average distance covered during a voyage with cargo is twice that of in ballast. However, when only the voyages under 500nm are analysed, the average distance under the different load conditions does not or hardly differ.

In addition, for the purpose of this research, the loading conditions are combined in two groups: ”in ballast” and ”laden”. Laden includes voyages either partially laden or (fully) laden. One reason for this is that a partly laden voyage can potentially generate a higher income than a fully laden voyage. Secondly, a voyage that is not partly laden or laden will be completed ”in ballast” and, compared to a voyage that is completed empty, all cargo carried is considered profitable.

5.2.1. Situation 1: No. laden voyages

To determine what area(s) and/or route(s) present potential for V/Br RFB-powered shipping the short sea shipping hubs will be identified, based on number of inbound and outward laden voyages. Over the past year, the SSS fleet of 281 vessels has moored in 956 unique ports, including several outside NW Europe. This is due to the fact that the vessels sometimes pass ”the border” of the defined area of interest NW Europe, as described in section 4.2.

To analyse vessel movements, and determine merchant voyages, the historical voyage data must be pre-processed. At first voyages with a distance less than 5nm are those (1,062) from a specific terminal within a port area to another terminal in the same area. Which are irrelevant for the determination of the short sea shipping voyages and are therefore excluded of further data-analysis. The remaining 23,862 port calls are analysed to determine the short sea shipping hubs and route(s) whom present potential for V/Br RFB-powered shipping.

Analysis of the data shows that ports which are close to each other and/or have traffic between them, can be seen as one cluster/group of ports. Close to each other is defined as a distance X, between 5nm$\leq$ X $\leq$15nm. Therefore, in the context of this thesis, ports that are in proximity to each other and/or have regular voyages between them are considered to be a cluster.

A hub is defined as a cluster or a single port where a lot of laden voyages arrive and depart, sailed by at least tens of different vessels. For example, there is a lot of traffic to and from the port of Amsterdam, so it can be viewed as a major hub. However, after analysing the historical voyage data of the port of Amsterdam, it becomes clear that most voyages arrive in and/or depart from IJmuiden see table 5.2. The port of Amsterdam and the port of IJmuiden are approximately 8nm apart. For these reasons Amsterdam and IJmuiden are considered a cluster.

Table 5.2: Voyage data clusters I and II

Cluster I	**No. Departures**	**No. Arrivals**	**Cluster II**	**No. Departures**	**No. Arrivals**
Vlissingen (NL)	169	172	Amsterdam (NL)	305	302
Vlissingen stad (NL)	7	9	IJmuiden (NL)	753	749
Ghent (BE)	192	189			
Zelzate (BE)	4	4			
Sluiskil (NL)	4	1			
Terneuzen (NL)	538	542			
	No. Voyages			**No. Voyages**	
Vlissingen - Terneuzen	11		Amsterdam - IJmuiden	296	
Terneuzen - Vlissingen	9		IJmuiden - Amsterdam	301	
Terneuzen - Ghent	185				
Ghent - Terneuzen	190				
Terneuzen - Zelzate	4				
Zelzate - Terneuzen	4				
Ghent - Sluiskil	1				
Sluiskil - Ghent	4				
Vlissingen stad - Terneuzen	1				
Total merchant voyages	510	516	**Total merchant voyages**	461	454

In the end seven clusters are identified in NW Europe, see table 5.3. In table 5.2, merchant voyage data of clusters I and II are given to show the maritime transport between the ports within a cluster. To determine the number of departures or arrivals in and from the defined clusters, the number of voyages within the clusters themselves are excluded, see for illustration table 5.2.

Table 5.3: Clusters in the short sea shipping area of North West Europe

Cluster	**Region**	**Ports**
I	Terneuzen	Vlissingen (Stad) (NL), Terneuzen (NL), Sluiskil (NL), Zelzate (BE) and Ghent (BE)
II	IJmuiden	Amsterdam (NL) and IJmuiden (NL)
III	Rotterdam	Schiedam (NL), Vlaardingen (NL), Rozenburg (NL), Rotterdam,- Waalhaven, Vondeling,Maasvlakte, Europoort, Botlek, Centrum and Delfshaven (NL)
IV	Gdansk	Gdanks (PL) and Gdynia (PL)
V	Hull	Hull (GB), Immingham (GB), New Holland (GB), Barrow Haven (GB), Goole (GB) and Grimsby (GB)
VI	Belfast	Belfast (GB) and Kilroot (GB)
VII	Brunsbuettel	Brunsbuettel (DE) and Ostermoor (DE)

After removing the inter cluster voyages, 22,627 voyages are left to be analysed. With these known seven clusters, the top 25 short sea shipping ports and Clusters in NW Europe, based on number of arrivals and departures is determined. This results in the following top 25 alphabetically ordered in table 5.4. This top 25, is the basis for further determination of the area(s) and route(s) whom present potential for V/Br RFB-powered shipping.

Table 5.4: Top 25, alphabetically ordered, short sea shipping ports in North West Europe

	Port	Country		Port	Country
1	Amsterdam and IJmuiden	NL	**14**	Leixoes	PT
2	Antwerp	BE	**15**	Liepaja	LV
3	Bayonne	FR	**16**	Porsgrunn	NO
4	Belfast and Kilroot	GB	**17**	Portsmouth	GB
5	Bergen	NO	**18**	Riga	LV
6	Bilbao	ES	**19**	Rostock	DE
7	Brake	DE	**20**	Rotterdam region	NL
8	Brunsbuettel and Ostermoor	DE	**21**	Skogn	NO
9	Gdansk and Gdynia	PL	**22**	Sodertalje	SE
10	Ghent (Terneuzen region)	BE & NL	**23**	St Petersbug	RU
11	Hamburg	DE	**24**	Szczecin	PL
12	Hull region	GB	**25**	Wismar	DE
13	Klaipeda	LT			

The top 25 has been analysed, with a cut-off criteria of 100 laden voyages within the 500nm range inbound and outbound combined the short sea shipping hubs are determined. With at least 100 laden voyages on an annual basis of less than 500nm, an average of 2 voyages per week depart and/or arrive at the hub. This provides opportunities for revenue-generating trips to and/or from these hubs.

Most voyages to and/from: Bilbao (ES), Leixoes (PT), and St Petersburg (RU) have a distance of more than 500nm, i.e. beyond what can be completed by E-Conoship. These ports are disregarded for further analysis, as the associated SSS movements do not represent the greatest potential for V/Br RFB-powered shipping in NW Europe.

Bayonne (FR) and Portsmouth (GB) are ports that are in the top 25 SSS ports based on the number of voyages, but these voyages are made by one or a few ships, so these ports are not considered SSS hubs. These ports will return in situation two, where historical voyage data will be analysed from the shipping side. Regarding the German ports: Brake (DE) and Wismar (DE), the number of voyages incoming and outgoing loaded with cargo from these ports are below the cut-off criteria and therefore excluded from further analysis.

The cut-off criteria results in 15 hubs in which each one has at least 100 voyages inbound and outbound within the 500nm range, for number of departure, see appendix B.1. and for number of arrivals, see appendix B.2. The top 5 is: Brunsbuettel region (DE), Rotterdam region (NL), Hull region (GB), Sodertalje (SE) and Klaipeda (LT). This shows that the northern part of NW Europe currently presents the greatest potential for vanadium bromide redox battery-powered shipping. The 15 hubs, present opportunities for short-range merchant voyages.

In-depth hub analysis: Brunsbuettel (DE) and Sodertalje (SE)

Some hub areas must be passed by before among others: ports along the Baltic Sea, ports inside large fjords and other large ports can be reached. These hubs are further analysed to determine if these are indeed large short sea shipping hubs. Two of these are Brunsbuettel region (DE) and Sodertalje (SE).

To determine, if these ports are indeed large short sea shipping hubs, among others voyage data around those hubs will be further analysed. Already within the voyage data, only voyages who have status ”not in transit” are included, see section 4.2.2. Furthermore, the port facilities will be examined. In addition voyages from/and to this port are analysed based on vessel draught upon departure and arrival. When the ship’s draught is the same on arrival and departure, this means that no cargo has been loaded or unloaded during this port call.

Brunbuettel region (DE) hub analysis

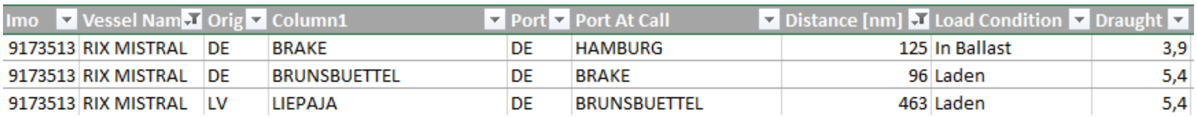
Brunsbuettel (DE) is located at the intersection of the Kiel Canal and the River Elbe. In addition from Brunsbuettel, 11 of the 14 other hubs are within 500nm, further are Bergen (NO) and Sodertalje (SE) at less than 550nm. At last Riga (LV), situated about 610nm from Brunsbuettel, lies within reach of an E-Conoship, if vessel speed is set at 9 knots. Due to its location many other ports within the Baltic Sea and North Sea are also within a range of 500nm.

The facilities in the port Brunsbuettel handles dry and liquid bulk, liquefied petroleum gas, project and breakbulk cargo. Ports of Brunsbuettel operates, Elbehafen (DE), Oilport (DE) and port of Ostermoor (DE) [12]. For several voyages from/and to Brunsbuettel, completed by different vessels the voyage data is analysed, see table 5.5.

Table 5.5: Analysis voyage data SSS Hub Brunsbuettel

IMO	Vessel name	Departure	Arrival	Draught [m]
9331361	Leonie	Kokolla (FI)	Brunsbuettel (DE)	4.7
		Brunsbuettel (DE)	Brest (FR)	4.7
9760380	Lady Alida	Riga (LV)	Brunsbuettel (DE)	4.9
		Brunsbuettel (DE)	Shoreham (GB)	4.9
9138197	Baltic Carrier	Hull (GB)	Brunsbuettel (DE)	5.0
		Brunsbuettel (DE)	Nantes (FR)	5.0
9173513	Rix Mistral	Liepaja (LV)	Brunsbuettel (DE)	5.4
		Brunsbuettel (DE)	Brake (DE)	5.4
9148166	Francisca	Vlissingen (NL)	Brunsbuettel (DE)	4.8
		Brunsbuettel (DE)	Hamburg (DE)	3.2

From table 5.5, it becomes evident that several voyages pass by Brunsbuettel (DE), without loading or unloading cargo, while the retrieved status "not in transit" is noted. Also in table 5.7 the draught of two voyages are colored blue; in these voyages cargo was unloaded at the port of Brunsbuettel (DE) before a voyage in ballast to Hamburg (DE) was conducted. In addition, when one of the voyages of Rix Mistral is further analysed, it can be seen that the voyage started in Liepaja (LV), passes through the port area of Brunsbuettel (DE), i.e. passes the lock at Brunsbuettel, and is unloaded at the port of Brake, see figure 5.2.



Imo	Vessel Nam	Orig	Column1	Port	Port At Call	Distance [nm]	Load Condition	Draught
9173513	RIX MISTRAL	DE	BRAKE	DE	HAMBURG	125	In Ballast	3,9
9173513	RIX MISTRAL	DE	BRUNSBUETTEL	DE	BRAKE	96	Laden	5,4
9173513	RIX MISTRAL	LV	LIEPAJA	DE	BRUNSBUETTEL	463	Laden	5,4

Figure 5.2: Analysis, voyages through port of Brunsbuettel (DE)

Sodertalje (SE) hub analysis

Sodertalje (SE) is located at the entrance of Mälaren, a large lake, vessels arriving from the Baltic Sea, must pass the locks at Sodertalje (SE) to continue further inland. In addition from the port of Sodertalje (SE), 5 of the 14 other hubs are within 500nm, further are Hamburg (DE), Brunsbuettel (DE) at less than 500nm, see table 5.6. In addition, many other ports in the Baltic Sea lie within a range of 500nm.

Table 5.6: Distance from port of Sodertalje (SE) to other ports

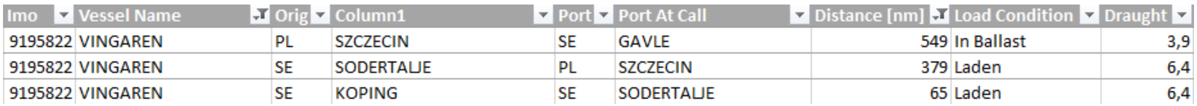
Start port	Distance ≤500nm	Distance ≤550nm	Distance ≤600nm
Sodertalje (SE)	Klaipeda (LT), Rostock (DE) Riga (LV), Gdansk region (PL) and Liepaja (LV)	Hamburg (DE) and Brunsbuettel region (DE)	Porsgunn (NO)

When analysing vessel arrivals and departures in Sodertalje (SE), see table 5.7. The same as with Brunsbuettel becomes evident many voyages are logged as a voyage ”not in transit” while at the same time no actual port activity, loading and unloading is performed. In table 5.7 two draughts of voyages are coloured blue; in these voyages cargo was unloaded at the port of Sodertalje (SE) before a voyage to Riga (LV) was conducted.

Table 5.7: Analysis voyage data SSS Hub Sodertalje

IMO	Vessel name	Departure	Arrival	Draught [m]
9195822	Vingaren	Koping (SE)	Sodertalje (SE)	6.4
		Sodertalje (SE)	Szczecin (PL)	6.4
9101156	Frej	Vasteras (SE)	Sodertalje (SE)	6.0
		Sodertalje (SE)	Hull (GB)	6.0
9534547	Frisian Sea	Buetzfleth (DE)	Sodertalje (SE)	5.1
		Sodertalje (SE)	Vasteras (SE)	5.1
9805427	Ina Lehmann	Szczecin (PL)	Sodertalje (SE)	5.4
		Sodertalje (SE)	Riga (LV)	4.1
		Randers (DK)	Sodertalje (SE)	4.2
		Sodertalje (SE)	Vasteras (SE)	4.2

From table 5.7, it becomes evident that several voyages pass by Sodertalje (SE), without loading or unloading cargo, while the retrieved status ”not in transit” is noted. When one of the voyages of Vingaren is further analysed, it can be seen that the voyage started in Koping (SE), passes by Sodertalje (SE) i.e. passes the lock at Sodertalje, and is unloaded at the port of Szcecin (PL), see figure 5.3.



Imo	Vessel Name	Orig	Column1	Port	Port At Call	Distance [nm]	Load Condition	Draught
9195822	VINGAREN	PL	SZCZECIN	SE	GAVLE	549	In Ballast	3,9
9195822	VINGAREN	SE	SODERTALJE	PL	SZCZECIN	379	Laden	6,4
9195822	VINGAREN	SE	KOPING	SE	SODERTALJE	65	Laden	6,4

Figure 5.3: Analysis, voyages through port of Sodertalje (SE)

Conclusion in-depth hub analysis
From the analysed voyage data, it becomes evident that ships passing through locks in port areas, in this case Brunsbuettel (DE) and Sodertalje (SE), are logged as a voyage ”not in transit”, and have therefore been included in the data. So despite the fact that there are ships loading and unloading in the port of Brunsbuettel (DE) and Sodertalje (SE), a large part of the voyages consist of passing the locks, without actual port activity of loading and/or unloading cargo. In terms of laden voyages Brunsbuettel and Sodertalje are therefore not short sea shipping hubs. However, plenty vessels pass these port area’s and in many cases they have to wait, before they can enter the locks. In addition, from these ports many SSS hubs are within E-Conoship’s sailing range.

This makes both ports suitable locations for fast charging stations, both geographically and in terms of the amount of passing shipping traffic. This leads to table 5.8 in which, the top 15 short sea shipping hubs is given, the purple colored hubs are Brunsbuettel and Sodertalje these are not necessary large hubs with regard to cargo handling. Despite this these ports are of interest for placement of charging station. Further research is needed to determine to what extend these port can serve as charging station. The new top 5 with regard to, no. departures and arrivals laden within the 500nm, whereby cargo is loaded and/or unloaded is:

1. Cluster III (NL), Rotterdam Region
2. Cluster V (GB), Hull region
3. Klaipeda (LT)
4. Rostock (DE)
5. Hamburg (DE)

Table 5.8: Short sea shipping hub, arrival and departure combined

Short sea shipping hub	Total no. departures and arrivals [#]	No. departures and arrivals ≤500nm [#]	Percentage of total no. departures and arrivals laden ≤500nm [#]
Cluster III (NL) Rotterdam region	1,193	344 In ballast **221 Laden**	19%
Cluster V (GB) Hull region	823	223 In ballast **196 Laden**	24%
Klaipeda (LT)	712	225 In ballast **176 Laden**	25%
Rostock (DE)	462	178 In ballast **169 Laden**	37%
Hamburg (DE)	544	201 In ballast **157 Laden**	29%
Cluster II (NL) IJmuiden region	915	279 In ballast 149 Laden	16%
Cluster I (NL/BE) Terneuzen region	1,026	330 In ballast 138 Laden	14%
Bergen (NO)	260	25 In ballast 137 Laden	53%
Riga (LV)	765	223 In ballast 130 Laden	17%
Cluster IV (PL) Gdansk region	532	181 In ballast 109 Laden	20%
Antwerp (BE)	630	212 In ballast 105 Laden	17%
Porsgrunn (NO)	314	64 In ballast 104 Laden	33%
Liepaja (LV)	359	143 In ballast 103 Laden	29%
Cluster VII (DE) **Brunsbuettel region**	481	51 In ballast **239 Laden**	50%
Sodertalje (SE)	474	165 In ballast **186 Laden**	39%
Total:	9,484	2,843 In ballast 2,319 Laden	24.4%

Within figure 5.4, the top 25 hubs in NW Europe can be seen, the intensity of shipping traffic is roughly given, represented with yellow lines. The orange-coloured ports did not meet the criteria to be considered as a short sea shipping hub in terms of laden inbound and outbound voyages within the 500nm range. The purple-coloured ports are those at which many voyages pass by, which present potential for fast charging stations. Lastly for situation 1, the blue-coloured ports remain, these ports are located along the North Sea and the Baltic Sea.

Figure 5.4: Short sea shipping hubs in NW Europe

Conclusion, situation 1
In conclusion through the 15 short sea hubs last year 9,484 merchant voyages were made, see table 5.8. This is equivalent to approximately 43% of all merchant voyages with a distance of ≥5nm completed by the sample fleet of 281 ships in NW Europe. In addition 2,319 voyages of the 9,484 merchant voyages (24.5%) are completed with loading condition, "laden" and a maximum voyage distance ≤500nm. The top five hubs are: Rotterdam (NL) region, Hull (GB) region, Klaipeda (LT), Hamburg (DE) and Rostock (DE). From these hubs, cargo can be transported via the spot market or by a fleet manager who divides his vessel between short-distance and long-distance transport. This demonstrates the potential for short-range merchant shipping and thus that a limited range is not an impediment to the implementation of V/Br RFB-powered shipping.

5.2.2. Situation 2: one-to-one replacement

To determine which vessels completed at least 75% of all their voyages in the past year within the 500nm range, the number of voyages within a given range must first be known. Therefore, all voyages with a distance of 5nm and more completed by the sample fleet of 281 vessels have been divided into bins of 50nm. This results in figure 5.5, where the nodes on the blue line represent the number of voyages per bin. Further, the green square dotted line represents the cumulative number of voyages of the total sample fleet expressed as a percentage of the total number of voyages completed by the sample fleet over the past year. The vertical red dashed dotted line in figure 5.5, represent a maritime range of 500nm. With this, 62% of all merchant voyages over the past year can be completed. When this range is increased to 600nm, 69% of all voyages can be completed. The exponential trend line, which can be seen in figure 5.5, shows that as the distance travelled per voyages increases, the number of voyages decreases.

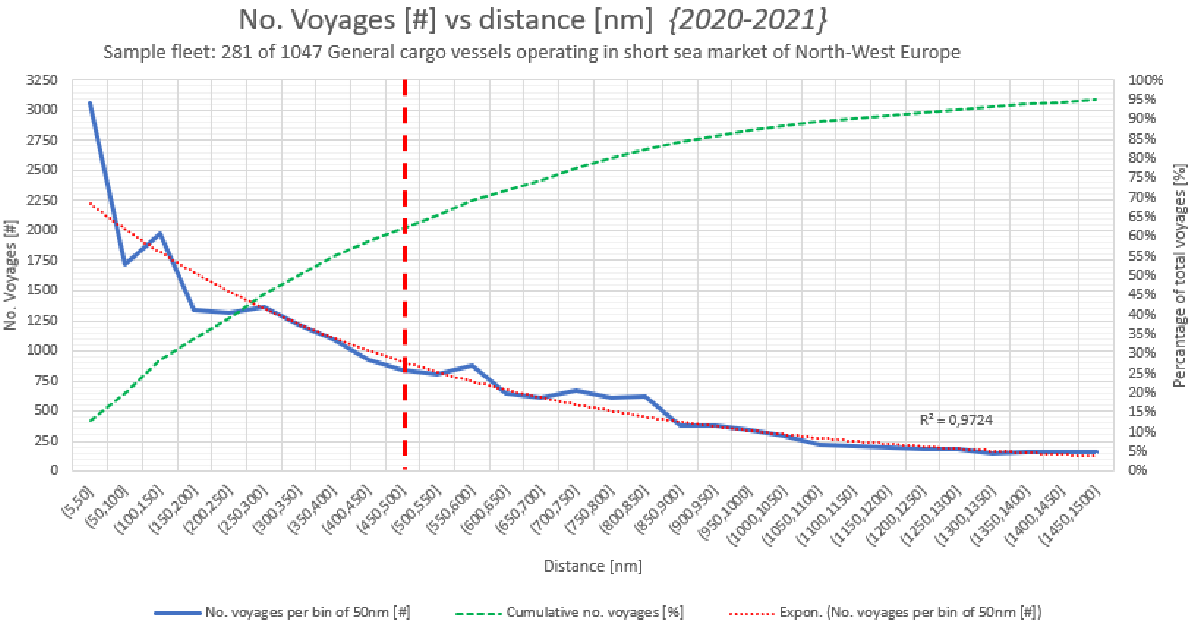


Figure 5.5: Number of voyages [#] within a certain range [nm]

Although figure 5.5 shows the number of voyages within a certain range, it does not provide inside in which vessels completed these voyages. If a ship travels less than 500nm for 50% of its merchant voyages and more than 500nm for the other half, a direct replacement by V/Br RFB-powered ships is not possible. If however the majority of the merchant voyages of a ship is within the 500nm range, replacement is a possibility.

Therefore, the number of ships sailing respectively at least 75% and 85% of all their merchant voyages less than a set distance is determined. Thirteen different scenarios are generated: from 500nm to 1,100nm with steps of 50nm. The first scenario is a set range of 500nm, with this 11% (31/281) and 5.7% (16/281) of the ships sail respectively at least 75% and 85% of all their voyages less than the set 500nm range. If the range is extended to 600nm the amount of vessels sailing 75% and 85% of all their voyages below that range is doubled compared to the 500nm range. For an overview of the thirteen different scenarios, see table 5.9.

Table 5.9: No. vessels sailing ≥75% or ≥85% of all voyages ≤ set range

	Range [nm]	500	550	600	650	700	750	800	850	900	950	1,000	1,050	1,100
No. Vessels sailing ≥ ...% of all voyages ≤ set range	**75%**	31	45	63	77	90	114	146	174	189	202	221	223	239
	85%	16	20	29	40	49	63	77	97	111	123	140	155	168

For the first scenario, 31 ships sail at least 75% of all their voyages within this range. To determine the sailing area of these 31 vessels, the individual voyage data is analysed. The operational area shown in table 5.10 is the area in which these ships complete most voyages. Furthermore, in table 5.10 it can be seen that the 31 ships sailing short sea, ≤500nm, are operated by 26 different operators, which shows that there are many different trades available for short range maritime transport. Rix Shipping (LV) is best represented with 3 ships; Rix Alliance, Rix Mistral and Rix Star. Many ships operate along the Norwegian coastline, blue-coloured area. In addition many ships operate within the Baltic Sea, purple-coloured area. Some ships cross regions on their voyages, in this case mostly ports along the North Sea and Baltic Sea.

Table 5.10: Vessel sailing at least 75% of all voyages within ≤500nm

IMO	DWT	Age	Operator	Vessel name	Percentage of voyages ≤500nm	Operational area
9369514	3850	14.5	Faversham Ships Ltd (GB)	MUSKETIER	100.0%	Portsmouth (GB), St Helier (JE), and Guersney (CG)
9375898	3345	13.6	Ulvan Personal AS (NO)	KRISTIAN WITH	99.1%	**Norway**
8015879	3319	38.9	KTM Shipping (NO)	SCAN FJORD	98.2%	**Norway**
9436276	6798	11.1	Naviera Mureata (ES)	SUA	98.0%	Bayonne (FR) and Coruna (ES)
9196266	3193	20.6	ATR Schiffahrt (DE)	ANOUK	96.5%	**Baltic Sea** and North Sea
9319430	3817	14.9	Peak Shipping (NO)	MILADY	93.6%	Murkan (DE) and Baltisysk (RU)
9301598	7098	14.6	Tom Wörden Schiffs (NO)	FINNLAND	93.2%	**Baltic Sea**
7633387	4418	43.3	Storesletten Rederi (NO)	INGVILD	92.0%	**Norway**
9195822	4748	20.8	Berndtssons Rederi AB (SE)	VINGAREN	89.1%	**Baltic Sea**
9007075	3982	29.1	Arriva Shipping (NO)	NORSUND	89.0%	**Norway**
9173513	3735	22.9	Rix Shipping (LV)	RIX MISTRAL	88.2%	**Baltic Sea** and North Sea
9147459	3246	24.6	Karl Meyer (DE)	ALAND	88.0%	**Baltic Sea**
9128403	3002	25.3	Rix Shipping (LV)	RIX ALLIANCE	87.9%	**Baltic Sea** and North Sea
9142497	3155	23.3	Karl Meyer (DE)	JUTLAND	86.8%	**Baltic Sea** and North Sea
9006356	3710	26.7	Karmoy Skipsconsult (NO)	BUVIK	86.4%	**Norway** and Denmark
9006306	3710	27.9	Berge Rederi (NO)	SULA	85.4%	**Norway**
9454462	3075	13.0	Wagenborg Shipping (NL)	ELISE	82.9%	**Baltic Sea** and North Sea
9020285	4191	29.3	Erik Thun AB (SE)	NAVEN	82.9%	**Baltic Sea**
8505953	3643	34.7	Hagland Shipping (NO)	FALKLAND	82.1%	**Norway** and Denmark
9116008	4228	25.7	Atrica Marine (EE)	GRIFTBOR	81.9%	**Baltic Sea**
9237010	4400	19.5	Tom Wörden Schiffs (NO)	SILVA	81.5%	**Baltic Sea**
9375800	3630	13.6	Siegfried Bojen (DE)	LADY CLARA	80.7%	North Sea and United Kingdom
9143829	4750	23.2	ECL AS. group owner: Wilson ASA (NO)	SAMSKIP COMMANDER	79.9%	**Norway** and Netherlands
9006277	3710	28.9	Rix Shipping (LV)	RIX STAR	79.8%	**Baltic Sea** and North Sea
9769104	4938	4.2	VG-Shipping OY Ltd (FI)	EEVA VG	78.8%	**Baltic Sea**
9247106	5400	19.5	Aasen Shipping (NO)	AASHEIM	78.8%	United Kingdom, North Sea
9196187	3780	20.6	Wagenborg Shipping (NL)	WESTBORG	76.8%	**Baltic Sea** and North Sea
9436238	6795	12.0	Liberty One (DE)	HALLAND	76.7%	**Baltic Sea**
9387310	3850	12.4	Gerdes Schiffahrts (DE)	ROVA STONES	76.6%	**Norway** and Germany
9760380	3700	4.6	Wijne Barends (NL)	LADY ALIDA	76.4%	Netherlands and Germany
9155975	4156	22.9	Klip marine (EE)	LOTTALAND	75.5%	**Baltic Sea**

Detailed analysis shows that some vessels operate within a ”bounded” geographical area, among others are: the Kristian With (IMO 9375898) and the Ingvild (IMO 7633387). Vingaren, Ingvild, Kristian With, Scan Fjord and Aasheim are elaborated in more detail, to illustrate the potential of vessel replacement and the routes whom present potential for V/Br RFB-powered shipping.

Vingaren, IMO 9195822, 4,748DWAT and age 20.8 years operates approximately 90% of all its voyages within the 500nm range, see figure 5.6a. Over the past year this ship completed 125 voyages, whereby in total 64 passage of the port of Sodertalje (SE) to in most cases ports at the lake of Mälaren, among others are Koping and Vasteras. In addition this vessel is operated by Berndtssons Rederi AB, a Swedish company. The oldest vessel operating at least 75% of all its voyages within the 500nm range is Ingvild, IMO 7633387, 4,418DWAT and age 43.3 years, see figure 5.6b. This vessel is operated by Storesletten Rederi AS, a Norwegian shipping company. Ingvild completed 173 of her 188 voyages within the 500nm range. Last year’s voyages were mainly along the Norwegian coastline, as 151 of the 173 voyages were completed by the Ingvild nationally. This ship departed or arrived 19 times laden in the port of Skogn (NO). This port is part of the top 25 SSS ports in NW Europe.

(a) IMO 9195822, Vingaren (20.8 years) [54]

(b) IMO 7633387, Ingvild (43.3 years) [51]

Figure 5.6: Vessels operating at least ≥ 75% of all voyages ≤500nm [54],[51]

Two ships that completed almost 100% of all their merchant voyages within the 500nm range are the Scan Fjord, IMO 8015879 and the Kristian With, IMO 9375898. The Kristian With has a deadweight of 3,345DWAT and an age of 13.7 years. The Scan Fjord has a deadweight of 3,319DWAT and age 38.9 years. Both ships have sailed most of their voyages along the Norwegian coastline for the past year. Kristian With has completed 461 merchant voyages of which 60 departed from or arrived in the port of Bergen (NO). The Scan Fjord has completed 393 merchant voyages of which 34 departed from or arrived in the port of Bergen (NO). Which is one of the top 15 short sea shipping hubs in NW Europe.

Another vessel operating at least ≥ 75% of all voyages ≤500nm, is Aasheim, IMO 9247106. This ship has a deadweight 5,400DWAT and a vessel age of 19.5 years and is operated by Aasen shipping a Norwegian company. This ship completed 132 voyages of which 104 are within the 500nm range. From these voyages, 36 have either departed or arrived in cluster VI, ports Belfast and Kilroot (GB).

Furthermore, detailed analysis shows that some operate on very specific routes, among others: Musketier (IMO 9369514), SUA (IMO 9436276) and the Milady (IMO 9319430), see table 5.11. These ships could be replaced one on one by an E-Conoship. Moreover, some of the ports where these ships call are also among the top 25 ports for short sea shipping.

Table 5.11: Short sea shipping routes ≤500nm

	Departure	**Arrival**	**Distance [nm]**	**No. Voyages**	**Ship**
1	Portsmouth (GB)	Guernsey (CG)	107nm	103	
	Portsmouth (GB	St Helier (JE)	120nm	74	
	St Helier (JE)	Portsmouth (GB)	120nm	33	MPP ship, Muketier 3,850dwt, IMO 9369514
	St Helier (JE)	Guernsey (CG)	26nm	81	operated by Faversham Ships Ltd
	Guernsey (CG)	Portsmouth (GB)	107nm	83	
	Guernsey (CG)	St Helier (JE)	26nm	31	
2	Bayonne (FR)	Coruna (ES)	310nm	64	MPP ship, Sua 6,798dwt, IMO 9436276
	Corunua (ES)	Bayone (FR)	310nm	51	operated by Naviera Murueta
3	Baltisysk (RU)	Mukran (DE)	225nm	47	MPP ship, Milady 3,817dwt, IMO 9319430
	Mukran (DE)	Baltisysk (RU)	225nm	45	operated by Peak Shipping

Conclusion, situation 2

In conclusion, 31 ships (11%) of the SSS sample fleet operates at least 75% of all its voyages within the 500nm range. Converted to the entire SSS-fleet this is equivalent to 115 ships.

These ships are operated by a variety of operators, 4 generalised situations have been found in which these ships, sail 75% of all their voyages within the 500nm. In total 4 generalised situations have been found for the routes and/or operational: 3.2% of the SSS fleet operates mainly within the Baltic Sea area, 3.2% of the SSS fleet operates most of their voyages along the Norwegian coastline, 2.5% is scattered around North Sea and Baltic Sea, and 2.1% of the SSS fleet operates most of their voyages within specif routes, visiting a couple of ports.

5.3. Conclusion

Within this section the following sub-question will be answered: *”what current shipping routes present potential for vanadium bromide redox flow battery-powered shipping?”*

Viewed from situation 1
The area and/or shipping routes with potential in NW Europe is dictated by the SSS hubs located along the Baltic Sea and the North Sea. From each SSS hub at least 100 laden voyages of less than 500nm depart and/or arrive on an annual basis. With this on average 2 voyages per week depart and/or arrive laden at these hubs. Therefore, it is assumed that via spot-market or by a fleet manager that divides its vessel between short distance and long distance transport revenue-generating trips to and/or from these hubs can be realised.

The top 5 SSS hubs are: Rotterdam region (NL), Hull region (GB), Klaipeda (LT), Rostock (DE) and Hamburg (DE). From the ports of Rostock and Hamburg, the other ports of the top five SSS hubs are within 500nm. From the ports of Hull and Rotterdam, a stop-over to reload the battery in ”fast-charge” hub Brunsbuettel is needed to reach Klaipeda, as a distance of 785nm and 710nm respectively must be crossed to reach Klaipeda. Viewed from situation 1, routes between or via these SSS hubs present potential for V/Br RFB-powered shipping in NW-Europe, examples form the data analysis are among others:

1.1 Rotterdam (NL) → Hull (GB) → Hamburg (DE) → Klaipeda (LT) → Sodertalje (SE) → Liepaja (LV), with an average distance of 310nm between these ports
1.2 Hamburg (DE) → Klaipeda (LT) → Porsgrunn (NO) → Szczecin (PL) → Riga (LV) → Rostock (DE), with an average distance of 475nm between these ports

Viewed from situation 2
In total 115 vessels of the SSS fleet operate 75% of all their voyages within the 500nm range. These 115 ships can be directly replaced one-to-one for an E-Conoship, without changing existing routes. In total 4 generalised situations have been found for the routes and/or operational: 3.2% of the SSS fleet operates mainly within the Baltic Sea area, 3.2% of the SSS fleet operates most of their voyages along the Norwegian coastline, 2.5% is scattered around North Sea and Baltic Sea, and 2.1% of the SSS fleet operates most of their voyages within specif routes, visiting a couple of ports. A few examples of routes and area bounded routes sailed by a single ship of the SSS fleet, which can be replaced one-to-one by an E-Conoship are given:

2.1 Bayonne (FR) → Coruna (ES), with an average distance of 310nm between these ports
2.2 Kopervik → Bergen → Alesund → Hogset → Trondheim → Harstad, all ports are located in Norway, with an average distance of 170nm between these ports

5.3.1. Input economical feasibility

The above conclusion is based solely on the operational side of an E-Conoship. In order to obtain a ”proof of concept”, the economic feasibility must also be determined. Therefore, the input from the operational side will be used for the cost-comparison analysis between a ship with a diesel engine and an E-Conoship. The operational area and the voyage distance, determine among other factors the voyage related costs. Within the next chapters, different routes (distances and operational areas) will be used to determine voyages related expenditure. The routes which will be used are those earlier mentioned: 1.1, 1.2, 2.1. and 2.2.

6

Cost-comparison model

This chapter introduces a cost-comparison model (CCM). This model is the basis for being able to answer the following sub-question: *"Under which circumstances is Conoship's vanadium bromide redox flow battery-powered ship design cost-competitive with diesel-powered ships?"*. In doing so, a vanadium bromide redox flow battery-powered ship will be referred to as an E-Conoship. Within this chapter, the first section explains the general outline of the model, followed by a section describing the vessels used for comparison. In the sections 6.3, 6.4 and 6.5, the various cost-components are described in more detail.

6.1. General outline

In this CCM an E-Conoship, will be compared to a diesel-powered ship based on the following economic parameters: capital expenditure (CAPEX), operational expenditure (OPEX) and voyage expenditure (VOYEX). After consultation with Conoship, and conform market practice the economical lifetime of both vessels in the model is set at 20 years. An E-Conoship is considered cost-competitive if, within the economic lifetime of both vessels, a break-even point is reached after which the total costs are lower compared to a diesel-powered ship. Initially, all cost components are calculated for the current situation, then several cases with varying scenarios are carried out to determine under which circumstances an E-Conoship is cost-competitive with diesel-powered ships, within the CCM referred to as Eurotrader.

Capital expenditure

Once a ship is built, the 'physical' operations of the ship have no direct effect on the cost of capital. According to Stopford [98], the CAPEX consists of the initial investment costs and liabilities to pay the shipyard, periodic cash payments to banks or equity investors who contributed the capital for the purchase of the ship. The periodic cash payments within the CCM consist of interest on the average outstanding debt between beginning and end of a period; this is explained in more detail in section 6.2.2. Part of the initial investment costs of E-Conoship are the battery stacks needed for the V/Br RFB.

Operational expenditure

According to Stopford [98], OPEX are the costs related to the daily running of the vessel, excluding fuel costs but including repairs and maintenance. In this model, the costs related to E-Conoship's required electrolyte fluid are included in the OPEX via a lease construction, see section 6.4 for further explanation. The OPEX increases each year by an inflation rate of 2%.

Voyages expenditure

VOYEX are variable costs and depend on the voyages undertaken, the voyages used within the model are based on research conducted in chapter 4 and 5. Within this model the voyage related costs, among others consists of fuel costs, for the E-Conoship this is the costs related to recharging the electrolyte fluid. Furthermore part of VOYEX are port costs and pilotage dues [98], which will be dealt with in section 6.5. The voyages related costs increase each year by an inflation rate of 2%.

Cargo handling costs

This cost comparison model does not take into account the costs of cargo handling, i.e. the costs related to loading and unloading cargo. The reason for this is that only the costs that differ between the two ships are important for the comparison, and in this model it is assumed that the costs of cargo handling are the same for both ships. These are assumed to be the similar because the volume of the cargo holds, the deadweight cargo capacity (DWCC), and the length between perpendiculars (L_{pp}) of both ships are the same.

6.1.1. Break-even analysis

To determine if an E-Conoship is cost-competitive, a break-even analysis will be conducted, as shown in figure 6.1. In this analysis, the initial investment is depicted by *c*. Furthermore, costs accumulated over time (x in years), OPEX and VOYEX, represented by *a* and *b* respectively, are considered. These costs become more expensive over time due to inflation. Lastly, the interest costs on the initial investment are considered, depicted by *d*.

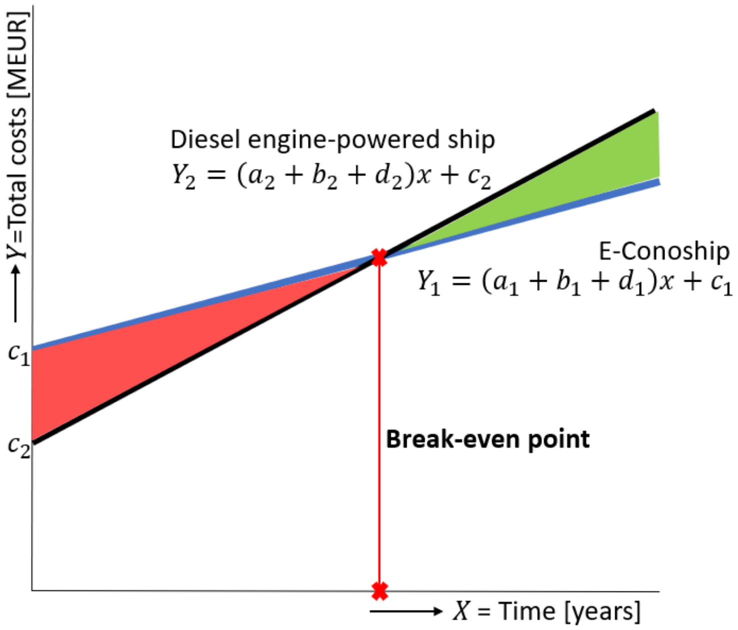


Figure 6.1: Break-even analysis; E-Conoship and diesel-powered ship

The input to make this break-even analysis, consist of the different cost-components CAPEX, OPEX and VOYEX. The parameters/variables that determine the final values of these components can be seen in the breakdown structure, see table 6.1.

Table 6.1: Model input; breakdown of cost components

Capital expenditure (CAPEX)	Operational expenditure (OPEX) (1)	Voyage expenditure (VOYEX) (2)
1. Initial investment:	1. Crew costs	**1. Fuel costs**
1. General	2. Stores and Consumables	- required (engine) power * duration
2. Hull and Superstructure	3. Maintenance and repairs	- route dependent
3. Propulsion and Manoeuvring system	4. Insurance	- energy price
4. Electrical Installation, incl. battery stacks	5. General costs	
5. Primary ship system	6. Exclusively for E-Conoship:	**2. Port costs**
6. Deck Machinery, lifesaving and fire protection	Electrolyte fluid leasing costs	- vessel type, discount percentage
7. Accommodation, wheelhouse		- GT-size; GT-tariff
8. Nautical, navigational and communication equipment		- cargo type; cargo tariff
9. Special equipment		
		3. Pilotage dues
		- starting tariff; actual ship draught
2. Interest		- route tariff; area bounded
- interest rate and duration		
- current liability	(1)Increases due to inflation	(2)Increases due to inflation

Model input, variable changes
When the first break-even analysis has been completed, the cost-components will be analysed in chapter 7.3 analysis cost-components.. They are analysed to determine where the largest differences are and whether they can be influenced by adjusting various variables in the model.

Within the model, the input variables can be changed on the basis of various reasons, as shown in table 6.2. This is done to determine under which circumstances an E-Conoship is cost-competitive compared to a diesel-powered ship. The variables that have a significant influence on one or more of the following main cost-components: CAPEX, OPEX or VOYEX, and which can be adjusted, will be examined in different scenarios within chapter 7.

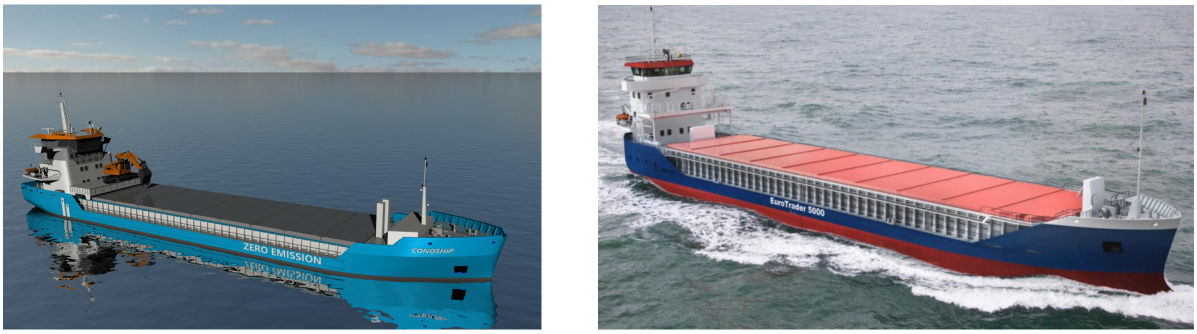
Table 6.2: Reasons for changes in economic parameters

Reason	**Example**	**Affected by among others**
Technological developments	Higher specific energy	V/Br RFB development; science
Market effect	Energy price fluctuations (electricity and LSMGO)	Supply and demand
Operational effect	Efficient planning; more annual sailing days	Shipping company and terminal facilities
Political driven	Subsidies	National governments and Lobbying
Regulatory	CO_2-tax	EU and IMO

6.2. Vessel selection

For the break-even analysis of E-Conoship and a diesel-powered vessel, the loading capacities must be as close as possible, in this case study a maximum of 1% difference will be used. Both the DWCC and the volume of the cargo hold must comply with this requirement.

E-Conoship, see figure 6.2a, will be compared with Eurotrader a general cargo ship, see figure 6.2b. This is a diesel-powered vessel that runs on low sulphur marine gas oil (LSMGO). Eurotrader has been selected for comparison because DWCC and hold volume are close to that of E-Conoship. Furthermore, equipment specification and speed-power calculations are internally available within Conoship International.



(a) E-Conoship, DWAT 6,075t

(b) Eurotrader, DWAT 4,980t

Figure 6.2: Case study vessels for economic comparison

At present the difference in DWCC and hold volume between the two ships does not meet the requirement, see table 6.3. In order to obtain a compatible DWCC, the depth of Eurotrader will be increased. Subsequently, the height of E-Conoship's hatch coaming will be increased to obtain the required hold volume.

Table 6.3: E-Conoship and Eurotrader loading capacities

	E-Conoship	Eurotrader	Difference [%]
DWCC [t]	4,980	4,693	-5.7
Hold volume [m^3]	6,250	6,350	+1.6

Within table 6.4 the main vessel dimensions of E-Conoship and Eurotrader are given.

Table 6.4: Main vessel dimensions: E-Conoship and Eurotrader

Type	**Symbol**	**E-Conoship**	**Eurotrader**
Length over all	L_{oa} [m]	88.52	89.52
Length perpendicular	L_{pp} [m]	84.98	84.99
Breadth moulded	$B_{moulded}$ [m]	16.30	14.72
Depth	D [m]	8.30	6.60
Design draught	T_{design} [m]	6.50	5.00
Max draught	T_{max} [m]	6.65	5.75
Block coefficient @Tmax	C_b [-]	0.822	0.845
Appendage factor	App.factor [-]	1.0075	1.0075
Hold volume	V_{hold} [m3]	6,250	6,350

To increase the DWCC of Eurotrader, the depth is increased while the height of freeboard remains the same. Deepening the ship requires more steel weight, which increases the light ship weight (LSW). Eurotrader's stability booklet shows that at maximum draught (T_{max}=5.75m) the immersion is 11.85t/cm. To increase the DWCC by 287t, factoring in the additional weight of the steel due to deepening (≈15t), the ship needs to be deepened by 26m.

This results in a new maximum draught of 6.01m, with a block coefficient of 0.847. Then with equation 6.1, the new displacement in tonnage (Δ) can be calculated. Whereby the appendage factor is based on previous ships designed at Conoship International, with a similar hull shape, and has a value of 1.0075 [-].

$$\Delta_{T=6.01m} = L_{pp} * B_{moulded} * T_{max,new} * C_{b,T=6.01m} * \rho_{sea,water} * App.Factor = 6,577t \tag{6.1}$$

With a known increase of the LSW to 1,315t, the DWCC at a draught of 6.01m can be calculated see equation 6.2.

$$DWCC_{T=6.01m} = \Delta_{T=6.01m} - LSW - consumables = 4,975t \tag{6.2}$$

Due to increased depth of Eurotrader the hold volume increasses with 195m^3 to a new hold volume of 6,545m^3. The result is that the DWCC of both vessels is closer to each other while the difference in hold volume is increased, see table 6.5.

Table 6.5: E-Conoship and Eurotrader with increased depth, loading capacities

	E-Conoship	Eurotrader	Difference [%]
DWCC [t]	4,980	4,975	-0.10
Hold volume [m^3]	6,250	6,545	+4.72

To increase the hold volume of E-Conoship, the height of the hatch coaming will be enlarged. The cargo hold is 51.7m long and 13.3m wide. With these dimensions the hatch coaming must be enlarged with 0.429m to increase the hold volume with 295m^3. Due to enlargement of the hatch coaming the steel weight and thereby the LSW will increase. Input parameters are: steel weight per cubic meter is 8t/m^3, +35% steel weight due to stiffeners, thickness of steel plates is 20mm, area of enlargement is 55.77m^2. Equation 6.3 is used to determine the additional steel weight resulting from the enlargement of the hatch coaming. Due to extra steel weight the LSW increases, this results in a new DWCC for E-Conoship of 4,968t.

$$m_{steel} = 8 * 1.35 * 55.77 * 0.02 = 12.05t \tag{6.3}$$

After deepening Eurotrader and increasing the hatch coaming height of E-Conoship both DWCC and hold volume are within the requirement of maximum 1% difference see table 6.6

Table 6.6: loading capacities: E-Conoship with enlarged hatch coaming and Eurotrader with increased depth

	E-Conoship	Eurotrader	Difference [%]
DWCC [t]	4,968	4,975	+0.14
Hold volume [m^3]	6,545	6,545	~

6.3. Capital expenditure

Within this section the capital expenditures are determined. In the first subsection the investment/purchase costs of E-Conoship will be dealt with in the following subsection the capital costs will be elaborated on.

6.3.1. Investment costs

To determine the investment/purchase costs of E-Conoship and Eurotrader, current market prices are used and it is assumed that E-Conoship is a first-off build and Eurotrader a one-off build. Discount for series building will not be taken into account. Furthermore both vessels have the same Class Notation as defined by Bureau Veritas see table 6.7. In addition, the hull of both vessels is to be made of the same material namely: mild steel grade A with class certificates.

The crew of E-Conoship consists of 6 members and Eurotrader has 7 crew members. In addition, the equipment on board of both ships is largely the same, one which differs is the propulsion equipment.

The E-Conoship does not need any ballast tanks or a ballast water treatment system, as it has approximately 1,000 tonnes of electrolyte fluid permanent on board, which ensures that the ship can be ”ballast free”. Due to this, costs can be saved with regard to a ballast water treatment system. Unlike E-Conoship, Eurotrader needs ballast water to ensure safe operations.

Table 6.7: Class Notation Bureau Veritas

Type	Hull	Machinery	Additional notations
Class Notation	I*Hull	*Mach	*AUT-UMS, Unrestricted Navigation, General Cargo Ship Ice Class 1C, Strenghtbottom, Heavy cargo 120kN/m^2

The initial investment cost calculation is made with an internally used method (document) by the Marketing and Sales Engineering department of Conoship International. Due to classified information the costs are normalised, relative to the costs of Eurotrader. Only the total amount of the investment costs is given. Within this Conoship method, different costs related to the investment costs are subdivided into ten different chapters, as shown in table 6.8. Within this table the total costs per chapter depicted by a code 000 till 900 are given. There is no ’special’ equipment on board of both vessels therefore this cost item is zero, depicted with a [-] sign. The difference in initial investment, excluding the cost of electrolyte fluid, amounts to 3.1MEUR, of which almost 2.1MEUR is accounted for by the battery stacks. The entire spread sheet with detailed information of the division of costs can be found in the classified Appendix C.

Table 6.8: Investment costs of E-Conoship and Eurotrader

Code	**Title**	**E-Conoship**	**EuroTrader**
000	General	127%	100%
100	Hull and Superstructure	118%	100%
200	Propulsion and Manoeuvring system	57%	100%
300	Primary ship systems	71%	100%
400	Electrical installation	550%$^{(1)}$	100%
500	Deck machinery, lifesaving and fire protection	93%	100%
600	Secondary Ship’s system	100%	100%
700	Accommodation, wheelhouse	100%	100%
800	Nautical, Navigational and Communication Equipment	100%	100%
900	Special Equipment	-	-
	Initial investment costs	€12,669,580	€9,548,640

(1) Incl. battery stack costs 2.08MEUR (800€/kW obtained via VanadiumCorp, a partner of Conoship)

Residual value

The residual value of both ships depends on the light displacement tonnage, this is the weight of the vessel excluding cargo, water, ballast stores, passengers and crew. In essence this is the same as the LSW. In addition, the amount of the residual value depends on the scrap price, at the moment this is 462€/t per LSW [34]. The LSW of E-Conoship is 1,757t and that of Eurotrader is 1,315t. The result is that the scrap price of E-Conoship is currently €811,734 and that of Eurotrader is €607,530. In this situation, no additional residual value is assigned to the E-Conoship, due to the uncertainty about the residual value of the battery stacks in the future.

The residual value of both ships are not directly included in the CCM, since the purpose of this model is to determine when and under which circumstances the variable costs have compensated for the difference in initial investment. Moreover, the residual value can only be released when the ship is sold or scrapped. This means that when the residual value is taken into account in the model, an E-Conoship would not become cost-competitive earlier in time. Indirectly, the higher end-of-life value of an E-Conoship will be taken into account by the financing of both ships.

6.3.2. Capital costs

Capital costs are dealt with in this section, they consist of interest costs which decline each year. These costs are taken into account as initial investment for E-Conoship is significantly higher, about three million euros, compared to Eurotrader, which results in higher costs.

Interest

The initial investment of E-Conoship is financed through 100% bank equity against a 4% interest rate (r). Percentage for interest are chosen based on market practice and intern sources of Conoship International B.V. In addition a diesel-powered ship, such as Eurotrader can be financed with 70% bank equity against 4% interest and 30% debt via external investors against a 8% interest rate, then the weighted average cost of capital (WACC) is 5.2% for Eurotrader, as determined with equation 6.4, where MV in this equation stands for the percentage of the market value of the total amount financed. The E-Conoship is more favourably financed as it is a ”green” ship with a higher expected residual value at the end of its life.

$$WACC_{Eurotrader} = \frac{\sum_{i=1}^{n} r_i * MV_i}{\sum_{i=1}^{n} *MV_i} = \frac{4 * 0.7 + 8 * 0.3}{1} = 5.2\% \tag{6.4}$$

Those values can be varied within the model, because in reality, capital structure and interest rate may vary both in value and from ship to ship on the basis of different risk profiles. A fixed interest for now is chosen to give an indication of the effect of interest cost to be paid for both E-Conoship and Eurotrader.

The amount of debt used to calculate annual interest, is equal to average amount of outstanding debt of the loan between the beginning (D$_i$) and the end (D$_{i+1}$) of each period (i = one year), see figure 6.3. In addition the amount of debt will be fully repaid in 15 years on a straight-line basis, which is in line with the current market practice.

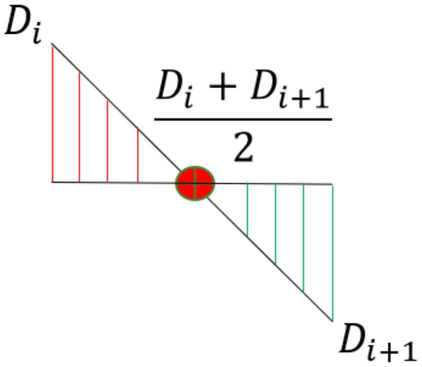


Figure 6.3: Debt used to calculate annual interest

With known debt in year zero (=initial investment), the amount of interest each period to be paid over the average amount of outstanding debt can be determined by the equations presented in 6.5.

$$C_{r(i)} = \frac{D_i + D_{i+1}}{2} * WACC_i \quad with \quad D_i = D_0 - D_0(\frac{i}{n}) \quad [€] \tag{6.5}$$

In this equations:

C$_{r(i)}$ = annual interest cost i=1,2,3..n	[€]
D$_i$ = outstanding debt end of year i=1,2,3...n	[€]
D$_0$ = outstanding debt year zero (=initial investment)	[€]
n = period of repayment 15 years	[year]
WACC$_i$ = weighted average cost of capital	[%]

6.4. Operational expenditure

According to Stopford [98] the operational expenditure of a vessel can be divided into overarching groups namely: crew costs, stores & lubricants, maintenance & repairs, insurances and lastly general costs. This division of OPEX costs will be used for this case study as well, however for the E-Conoship one additional item is considered namely the leasing costs of the electrolyte fluid.

The OPEX is determined using data from one of Conoship's partners, Vega Reederei, a German shipping and ship management company founded in 1991 and based in Hamburg. The crew costs are based on a crew of 6 for E-Conoship of the following ranks: captain (master), chief officer, electrician, 2x able seaman and a cook. The crew costs of Eurotrader are based on a crew of 7 with the following ranks: captain (master), chief officer, chief engineer, 2^{nd} engineer, 2x able seaman and a cook.

Stores & consumables and maintenance & repairs are based on the equipment and crew of both vessels. The majority of the maintenance & repair costs are with regard to propulsion related equipment, V/Br RFB-system for E-Conoship and a Wärtislä 20 diesel engine IMO tier III complaint in Eurotrader. The insurance costs for E-Conoship has been determined by Vega Reederei. The insurance costs for Eurotrader are determined by scaling the insurance costs linearly to the intial investment costs of both ships, see equation 6.6.

$$Insurance_{Eurotrader} = \frac{Insurance_{E-Conoship} * Investment_{Eurotrader}}{Investment_{E-Conoship}} \quad [€/day] \tag{6.6}$$

The general costs are related to: costs of registry of flag state, marine radio, nautical charts, inspection/certificates, outlay ship operating costs inspection certificates. Lastly, the leasing costs for electrolyte fluid needed onboard of E-Conoship. The leasing costs consist of depreciation and interest expenses. The value of the electrolyte is depreciated linearly over a period of 20 years to a residual value equal to half of the initial investment. The initial investment is 175€/kWh effective energy, price obtained via VanadiumCorp Inc, a partner of Conoship, this adds up to 7.88MEUR as the required effective energy storage output of the V/Br RFB is 45,000kWh. The leasing company assumes an annual return on investment of 3.5%, this value is determined among others a risk profile. This leads to a day rate of 1,295€/day for the electrolyte fluid, see table 6.9.

Table 6.9: Electrolyte fluid leasing costs for a period of 20 years

Leasing costs	value
Depreciation [€/year]	196,875
Interest costs [€/year]	275,625
Total leasing costs [€/year]	472,500
Day rate [€/day]	1,295

The different components of the OPEX can be seen in table 6.10. Every year the OPEX costs increase, by an annual inflation rate of 2%. The same method as described in 6.3.2 is used to determine the amount of inflation to be paid over the year.

Table 6.10: Division of OPEX E-Conoship and Eurotrader

Type	E-Conoship	Eurotrader
Crew costs	73%	100%
Stores & consumables	87%	100%
Maintenance & repairs	95%	100%
Insurance	133%	100%
General Costs	99%	100%
Lease electrolyte fluid	100%	-
OPEX, year 0 to 1 [€/day]	3,444	2,409

6.5. Voyage expenditure

Voyage expenditure (VOYEX) are variable costs and depend on the voyages undertaken. The main items considered are fuel costs (FC), port dues (PD), canal dues (CD), tugs and pilotage (TP). The summation of these individual costs lead to the total voyage costs (VC), see equation 6.7 [98]. Within this section the different components of VC will be addressed in the same order as in equation 6.7. In addition, every year the VOYEX increases, by an annual inflation rate of 2%. The same method as described in 6.3.2 is used to determine the amount of inflation to be paid over the year.

$$VC_i = FC_i + PD_i + TP_i + CD_i \tag{6.7}$$

6.5.1. Energy/fuel costs

A large part of the voyages costs are fuel costs [98]. To determine these cost: the fuel/energy consumption and prices need to be known for both E-Conoship (electricity in MWh) and Eurotrader (low sulphur marine gas oil (LSMGO) in ton). The fuel costs are determined with today's fuel prices of LSMGO and electricity prices. LSMGO costs approximately 500€/t [90]. The electricity price consist of a baseload electricity price, grid tariff, and taxes. The baseload electricity prices for 13 NW Europe countries can be found in table 6.11 [32].

Table 6.11: Baseload electricity prices 4^{th} quarter 2020 [32]

Country	Electricity price [€/MWh]	Country	Electricity price [€/MWh]	Country	Electricity price [€/MWh]
Norway	11.8	Lativia	41.2	Ireland	51.0
Sweden	22.5	Estonia	41.4	United kingdom	52.6
Denmark	30.5	Lithuania	41.6	Poland	54.2
Finland	32.7	Belgium	42.3	Average electricity price	
Germany	38.8	Netherlands	42.4	38.69 €/MWh	

The average and median baseload electricity price of the 13 countries are respectively 38.69€/MWh and €41.4/MWh. Moreover, on average 45% of the electricity bill is baseload price, 25% is taxes and 30% of the bill is grid tariff [100]. Considering the median price for baseload electricity, the total price including taxes and grid tariff would be 92€/MWh.

Transported cargo and time spent in port

The transported cargo on the voyages within the CCM will be grain, a dry bulk cargo. Furthermore, manoeuvring time to enter and exit the port is assumed to be 2 hours (1 hour inwards, 1 hour outwards). In addition, three different grain quantities will be included in the model to determine voyage costs. These three loading conditions are chosen because data with regard to vessel draught is available. Moreover, the rate of loading and unloading of grain in the different ports is initially set at 200t/h, this rate includes idle time in port. The density of grain is 790kg/m^3 [5], with this the utilisation rate of grain transport in terms of ratio weight vs. DWCC and volume vs. hold volume is determined, see table 6.12.

Table 6.12: Utilisation rate, with grain transport

Weight [t]	Volume [m^3]	Weight / DWCC [-]	Volume / hold volume [-]
3,840	4,861	0.77	0.74
4,067	5,148	0.82	0.79
4,693	5,941	0.94	0.91

Energy/fuel consumption

The energy/fuel consumption for vessels sailing in ballast is less than that required for sailing in laden condition at the same vessel speed. Therefore, the engine brake power required in ballast will be the power normally used to sail one knot slower. In essence the engine brake power required to sail an average of 10kn in ballast is equivalent to a laden voyage with an average speed of 9kn. Furthermore if the vessel is being unloaded at the quay a hotel load of 50kW is required. In the following paragraphs it will be described how the fuel consumption of both Eurotrader and E-Conoship are determined.

Eurotrader

To determine how much ton of LSMGO Eurotrader (m_f) uses on voyages, the fuel consumption in ton per hour is multiplied by the duration of a certain required fuel consumption. For a combustion engine with a certain required engine brake power, the following equation can be used 6.8 [56]. A situation (i) represents a different voyage (i=1,2,3..n), with certain average speed of the ship and the corresponding required power, delivered by the main engine or by a separate diesel generator.

$$m_{f;Eurotrader} = \sum_{i=1}^{i=n} \dot{m}_f(i) * t(i) = \sum_{i=1}^{i=n} \frac{sfc(i)}{10^6} * P(i) * t(i) \quad [t] \tag{6.8}$$

In this equation:

$\dot{m}_f(i)$ =	Fuel consumption per situation	[t/h]
$sfc(i)$ =	Specific fuel consumption per situation	[g/kWh]
$P(i)$ =	Required engine brake power or hotel load per situation	[kW]
$t(i)$ =	Duration of a given situation (i) in hours	[h]

The specific fuel consumption for the main engine in g/kWh is given by the engine manufacture in this case Wärtislä. The main engine of Eurotrader is a Wärtislä 20 6L20 1200kW @1000rpm with a selective catalytic reduction (SCR) system which complies with IMO tier III regulations. The sfc of this engine at 100% load is 195.3g/kWh in accordance with ISO regulation a 5% margin is allowed, therefore the actual sfc is 5% higher than specified, see table 6.13 [108].

Table 6.13: Engine technical information Wärtislä 6L20 1200kW @1000rpm [108]

Mode; percentage of full load	100%	85%	75%	50%
Pb [kW]	1,200	1,020	900	600
sfc [g/kWh]	195.3	192.0	191.3	195.1
sfc (incl. 5% margin) [g/kWh]	205.1	201.6	200.9	204.9

When Eurotrader is being unloaded or loaded alongside a quay the main eninge is shut off and a Sisu diesel generator with a rated power of 220kW is used to provide the required hotel load. The sfc of this generator can be found in table 6.14.

Table 6.14: Sisu diesel generator technical information

Mode; percentage of full load	100%	75%	50%	25%
$P_{generator}$ (measured) [kW]	217	165	110	55
sfc (measured) [g/kWh]	218.0	226.4	224.2	213.4

With a known sfc, the engine brake power ($P_b(i)$) for the different situations need to be known. To determine $P_b(i)$ of the enlarged Eurotrader, speed-power calculations with T=5.75m are scaled to new the situation with a draught of 6.01m, with means of the so called ”Admiralty constant”. The ”Admiralty constant” (C_{adm}) can be used to estimate the required engine brake power for the enlarged Eurotrader, see equation 6.9. For general cargo/ MPP vessels, C has a value between 400 and 600. On the basis that this value remains the same after vessel enlargement, the only difference between both vessels for calculation of the engine brake power is the displacement [56].

$$P_b = \frac{\Delta^{\frac{2}{3}} * V_s^3}{C_{adm}} \quad [kW] \tag{6.9}$$

To determine the required engine brake power in the situation with an enlarged displacement, equation 6.10 can be used. For the engine brake power in service the following items are included, Beaufort 2 (BF2) plus a 15% SM, and lastly a 50kW hotel load. For an overview of the required engine brake power at different ship speeds and draughts, see table 6.15.

$$P_{b,service.T=6.01m} = \frac{\Delta_{(T=6.01m)}}{\Delta_{(T=5.75m)}}^{\frac{2}{3}} * P_{b,service.T=5.75m} = 1.0312 * P_{b,service.T=5.75m} \quad [kW] \tag{6.10}$$

Table 6.15: Speed-power with QDESP, Eurotrader, T=5.75m and T=6.01m

V_s [kn]		9.0	10.0	11.0	12.0
T=5.75m	$P_{b,trial}$ [kW]	548	690	922	1,453
T=5.75m	$P_{b,service}$ [kW]	680	844	1,110	1,721
T=6.01m	$P_{b,service}$ [kW]	701	870	1,145	1,775

E-Conoship

To determine the energy consumption (electricity) on voyages, first the required engine brake power and the hotel load must be known at different voyage speeds. To determine the required engine brake power for E-Conoship speed-power calculations are done with QDESP. This is an internally used speed-power prediction program, based on the Holtrop & Mennen method with a B-Series propeller design. The speed-power calculations are performed at a design draught of 6.5m. The coefficient used to calculate the shaft power can be found in table 6.16.

Table 6.16: Coefficients calculated with QDESP

Coefficient	c1	c2	c3	c4	b
Value	-1607.42833	304.06667	-25.16667	0.83333	3223.19125

To calculate the shaft power (P_s) in kilowatt at different sailing speeds the following formula 6.11 is used, whereby x represents the ship speed in knots.

$$P_s = (c_4 * x^4) + (c_3 * x^3) + (c_2 * x^2) + (c_1 * x) + b \quad [kW] \tag{6.11}$$

With a known shaft power the engine brake power in service ($P_{b,service}$) is calculated. For this the following items are considered: 97% gearbox efficiency (η_{GB}), Beaufort 2 (BF2) plus a 15% sea margin (SM), and lastly a 50kW hotel load. This results in the following formula to determine the engine brake power in service, see formula 6.12 and table 6.17.

$$P_{b,service} = \frac{P_s}{\eta_{GB}} * SM + 50 \quad [kW] \tag{6.12}$$

Table 6.17: Engine brake power in service of E-Conoship at T=6.5m

V_s [kn]	8.0	9.0	10.0	11.0
P_s [kW]	352	507	722	1,038
$P_{b,service}$ [kW]	467	651	906	1,281

The last step to determine the energy consumption (electricity), depends on the effective energy (η_e), i.e. the losses between required brake power (P_b) and the delivered electricity by an onshore power connection. For E-Conoship this are an E-motor (Marelli Motori, rated power 2x600kW), AC/DC converters, switchboard and the V/Br RFB, see table 6.18.

Table 6.18: Efficiency of different components onboard of E-Conoship

	E-motor	AC/DC converter	Switchboard	V/Br RFB	η_e
η	0.95	0.95	0.98	0.82	0.73

With known losses in the different components the required amount of electricity (kWh) to charge the V/Br RFB can be determined, see equation 6.13. A situation (i) represents a different voyage (i=1,2,3..n), with certain average speed of the ship and the corresponding required power.

$$m_{f;E-Conoship} = \sum_{i=1}^{i=n} \frac{P_b(i) * t(i)}{\eta_e} \quad [kWh] \tag{6.13}$$

Difference Eurotrader vs. E-Conoship

Eurotrader has a lower displacement than E-Conoship and therefore the resistance of Eurotrader is lower than that of E-Conoship. However, the required engine brake power (P_b) for E-Conoship is lower than for Eurotrader at the same ’lower’ vessel speed, which is partly due to the fact that propulsive efficiency (η_D) of E-Conoship is higher than that of Eurotrader.

The total propulsive efficiency depends on the hull efficiency (η_H), open water propeller efficiency (η_O) and relative rotative efficiency (η_R) [56]. E-Conoship has a propeller diameter that is 900mm larger than that of Eurotrader. Furthermore, due to the electrical installation, E-Conoship has a fixed pitch propeller (FPP) instead of a controllable pitch propeller (CPP) on Eurotrader, an FPP has a higher open water efficiency than a CPP. The electrical installation allows the propeller to be designed more critically, as an electric motor is capable of turning a propeller even at low revs.

Besides this, Eurotrader is designed with a CPP at constant rpm and design speed V=11.3kn with an ideal pitch angle. When the vessels speed is lower than design speed a lot of efficiency losses occur. The results that only in case when the vessel is close to it is design speed the engine brake power is lower than that of E-Conoship.

6.5.2. Port dues

The port dues (PD) consist of cost items related to gross tonnage (GT) size, which needs to be paid independent of the vessels loading condition (laden or ballast). Second, costs related to the type of vessel and cargo transported. In this CCM no cargo will be transshipped and therefore these costs will not be taken into account. Furthermore, the tariffs differ per port, but for this CCM the port tariffs have been set equal for each port. The different tariffs are based on available data of the ports; Rotterdam and Amsterdam [43], [42]. With equation 6.14 the total port dues are determined. In addition, the different tariff components and values used to determine port dues are listed below.

$$PD = (GT_{size} * GT_{tariff}) + (GT_{size} * Cargo_{tariff} * discount_{percentage}) \qquad (6.14)$$

In this equation:

GT_{size} = gross tonnage of E-Conoship and Eurotrader [GT]
GT_{tariff} = 0.20 [€/GT]
$Cargo_{tariff}$ = 0.40 grain (dry bulk) [€/GT]
Discount percentage = 50.8% general cargo shortsea/feeder service

To determine the PD, first the GT of both ships is calculated according to the International Convention on Tonnage Measurement of Ships (1969) with equation 6.15 [48] . The input with regard to the ship’s total volume of all enclosed spaces of E-Conoship and Eurotrader can respectively be found in table 6.19 and table 6.20. Inserting the enclosed volumes of both ships into equation 6.15, provides a: 3,818GT for E-Conoship and 3,080GT for E-Conoship.

$$GT = K_1 * V = (0.2 + 0.02 * log_{10}(V)) * V \qquad (6.15)$$

In this equation:

V = Ship’s total volume of all enclosed spaces [m^3]
K_1 = Multiplier based on ships enclosed volume

Table 6.19: Enclosed volumes of E-Conoship

Item	Volume [m^3]	Item	Volume [m^3]
Hull incl hatchcovers	12,313.00	Deckhouse and ventilation fore	82.74
Poopdeck and boatdeck	494.00	**Volumes open to sea**	
Captainsdeck and bridgedeck	345.80	Coolerbins	-12.35
Hatch coaming (+42.9cm)	295	Bowproptube	-7.48

Total enclosed volume: 13,510.71m^3

Table 6.20: Enclosed volumes of the enlarged Eurotrader

Item	Volume [m3]	Item	Volume [m3]
Hull incl hatchcovers	10,160.77	Depth enlargement (+26cm)	277
Accomodations + wheelhouse	514.75	**Volumes open to sea**	
Funnel, headbox, appendage	7.00	Coolerbins	-11.50
Ventilation hold aft and fore	16.4	Bowproptube	-3.30

Total enclosed volume: 10,966.97m3

6.5.3. Tugs, Pilotage and Canal costs

Within this sub-section the remaining part of the VOYEX costs will be dealt with namely: tugs, pilotage and canal costs.

To start with costs related to tugs. Both E-Conoship and Eurotrader do not require tugs for assistance in berthing at cargo terminals. Therefore the cost of tugs will be not be part of the total voyage costs. Canal costs depend on the canal that has to be passed, for example the Kiel canal in Germany between Brunsbuettel and Kiel. In this CCM, canal costs are not included as the voyages do not pass through a canal for which separate canal costs have to be paid.

Pilots are needed to provide safe passage to specific ports or water areas. The way in which the pilotage costs are charged varies from port to port. For small seagoing vessels, it is possible to apply for a Pilotage Exemption Certificate (PEC) within the Port of Rotterdam, this applies to vessels with length overall (LOA) of up to 115 m, distance from keel to highest fixed point on the vessel up to 18 m, and finally the vessel must sail within 200nm of the coastline. Both E-Conoship and Eurotrader do not fulfil these requirements, as the distance from the keel to the highest fixed point of both ships exceeds 18m [75].

It is therefore possible to apply for a different PEC type B, this applies to vessels with the following requirement; 75m< L$_{oa}$ ≤115m, no height restrictions. To apply for this the master (captain) or first officer of the vessel has to complete multiple theoretical and practical examinations. This includes among others, a language test in both English and Dutch. Furthermore, the applicant must demonstrate a number of successful voyages on the route to which the application applies. When the PEC type B is obtained, the certificate must be validated by a frequency requirement of 6 calls per year. If this is not complied with, the certificate will be revoked [75].

Pilotage cost in case study model

Not for all cases within the CCM a PEC will be taken into account and, therefore both ships have to pay pilotage costs. These are based on available data of pilotage area's: 'region Rotterdam-Rijnmond' and 'region Amsterdam-IJmond'. Both are located within the Netherlands, where there is one tariff-structure for pilotage costs (PC). First a starting tariff (s), to get a pilot on board dependent on ship's deepest actual draught T$_{act}$ has to be paid. Then a route-dependent tariff (t), full distance from 'pilot aboard' to the quay at the cargo-terminal. Lastly surcharges & discounts (d), for now the surcharges & discount will not be taken into account, see equation 6.16 [71], [70].

$$PC = s(T_{act}) + t(area, T_{act}) \quad [€] \tag{6.16}$$

The route-dependent tariff (t) is divided into several areas, each with its own tariff areas labelled with the letters of the alphabet. If the area is more inland, the route dependent tariff becomes more expensive. For the model, the route dependent tariff will be based on the tariff for area C and D of 'region Rotterdam-Rijnmond' and area B of 'region Amsterdam-IJmond'. Area B is located close to the sea, while area C,D are both located more inland. The average costs of these areas will be used as input for the pilotage costs [71],[70].

To determine the start tariff and route dependent tariff the actual deepest draught must be known. The actual deepest vessel draught upon departure or arrival is in the case of E-Conoship and Eurotrader, the aft draught as both vessels have a stern trim.

In addition, with long distance voyages there could be a significant difference in vessel draught upon arrival in comparison with the departure, due to among others fuel consumed. In this case the voyages are short distance (less than 500nm), and the actual total fuel consumption on such voyages for Eurotrader is insignificant on ships draught. As well for E-Conoship, there is no noticeable difference between the draught upon arrival and departure, because the electrolyte fluid is used but not consumed. Therefore, the draught will be assumed constant over the complete voyage.

The design booklet of both vessels provided by Conoship gives various loading conditions in terms of tonnes of transported cargo and the corresponding ship's draught. However, the different loading conditions are not the same for both ships. Therefore, the actual draught for the required transported cargo is determined using the immersion in tonnes per centimetre and known draught at a reference amount of cargo in ton, see table 6.21.

Table 6.21: Actual draught at required cargo [t] transported E-Conoship

Required amount of cargo [t]	Reference cargo [t]	Δ Cargo [t]	Immersion [t/cm]	T [dm] at reference cargo [t]	ΔT [dm]
3840	3948	-108	13.02	61.22	-0.83
4067	3948	119	13.02	61.22	+0.91
4693	4813	-120	13.23	65.71	-0.91

With this data in table 6.21 and equation 6.17 the actual deepest ship draught at the required amount of tonnes of cargo transported can be determined.

$$T_{@required.cargo} = T_{@reference.cargo} + \Delta T \quad [dm] \tag{6.17}$$

With known actual deepest vessel draught the pilotage costs for E-Conoship and Eurotrader is determined. The average pilotage tariffs of 'region Rotterdam-Rijnmond' and 'region Amterdam-IJmond' results in pilotage costs which can be seen in table 6.22. The majority (≈83%) of the pilotage costs are for getting the pilot onboard (start tariff), the rest of the costs are route-dependent [71],[70].

Table 6.22: Pilotage costs Eurotrader and E-Conoship at different amount of cargo transported [71],[70]

Transported Cargo [t]	**Eurotrader** draught [dm]	Start tariff [€]	Route tariff [€]	Total Pilotage costs [€]	**E-Conoship** draught [dm]	Start tariff [€]	Route tariff [€]	Total Pilotage costs [€]
0	43	524.5	101.5	626.0	36	352.5	70.5	423.0
3,840	58	1,225.5	239.0	1,464.5	60	1,353.5	263.0	1,616.5
4,067	59	1,287.5	251.5	1,539.0	62	1,482.0	288.0	1,770.0
4,693	63	1,548.0	301.0	1,849.0	65	1,676.5	325.5	2,002.0

7

Case Study

Within this chapter the goal is to answer the following sub question: *"Under which circumstances is Conoship's vanadium bromide redox flow battery-powered ship design cost-competitive with diesel-powered ships?"* In the first section, the cases to be addressed will be elaborated on. In the following section, case 1.0 will be analysed to determine which variable leads to the largest cost difference between the two ships and can be varied. In the last sections the evaluation and conclusion of this chapter, and the answer to the sub-question will be given.

7.1. Define

Within the previous chapter the CCM has been described in detail, within this chapter the CCM will be used for different cases and scenarios to determine under which circumstances an E-Conoship is cost-competitive with Eurotrader.

The voyages used as input for the case study, are the ones as addressed within the operational phase of this research, more specifically section 5.3.1. For the first case, a voyage is used based upon the ship Sua (IMO9436276). Sua, has completed 185 sailing days in the past year, 2020 to 2021, most of them between Bayonne (FR) and Coruna (ES) over a distance of 310nm. The Sua, has as average vessel speed in ballast over the past year 10.2kn, and 9.6kn in laden condition. With some adjustment in planning it is assumed in this case that the amount of annual sailing days could be 200.

For all other cases, the same average voyage speed and annual sailing days have been chosen, in order to be able to assess the effect of the distance covered per voyage on the total cost. The different voyages that will be used in this case study are shown in table 7.1.

Table 7.1: Case study, voyage input

No.	**Case: 1.0** **Avg. distance 310nm**	**Case: 2.0** **Avg. distance 475nm**	**Case: 3.0** **Avg. distance 310nm**	**Case: 4.0** **Avg. distance 170nm**
I	Bayonne (ES) - Coruna (ES)	Hamburg (DE) - Klaipeda (LT)	Rotterdam (NL) - Hull (GB)	Kopervik (NO) - Bergen (NO)
II	Coruna (ES) - Bayonne (FR)	Klaipeda (LT) - Porsgrunn (NO)	Hull (GB) - Hamburg (DE)	Bergen (NO) - Alesund (NO)
III	Bayonne (FR) - Coruna (ES)	Porsgrunn (NO) - Szczecin (PL)	Hamburg (DE) - Klaipeda (LT)	Alesund (NO) - Hogset (NO)
IV	Coruna (ES) - Bayonne (FR)	Szczecin (PL) - Riga (LV)	Klaipeda (LT) - Sodertalje (SE)	Hogset (NO) - Trondheim (NO)
V	Bayonne (FR) - Coruna (ES)	Riga (LV) - Rostock (DE)	Sodertalje (SE) - Liepaja (LV)	Trondheim (NO) - Harstad (NO)

The distance between two adjacent ports of the voyages used can be found in table 7.2. For all cases the amount of annual sailing days will be initially set at 200, later this could be varied if considered necessary, by adjusting cargo unloading and loading speed which includes idle time in port.

Table 7.2: Distance between two ports for each case [65]

Case	**1.0**	**2.0**	**3.0**	**4.0**
I, distance [nm]	310	494	200	80
II, distance [nm]	310	544	410	175
III, distance [nm]	310	384	490	75
IV, distance [nm]	310	469	250	100
V, distance [nm]	310	485	200	420
Average distance [nm]	310	475	310	170

Furthermore, for each of the above cases the following values are used for the starting variables in the model: (1) WACC, E-Conoship 4% and Eurotrader 5.2%, (2) fuel/energy price, E-Conoship 92€/MWh, and Eurotrader 500€/t and (3) inflation rate of 2% for both vessels.

7.2. Data collection: case 1.0

With the CCM model, above data and a known fuel consumption dependent on among others vessel speed, the fuel costs are determined, see table 7.3. Within table 7.3, port A is Bayonne (FR) and port B is Coruna (ES). The total duration of the voyage is 11.96 days, of which 6.56 days are sailing and 5.41 days are spent in port. Of this time spent in port, 8 hours are sailing from sea to terminal or vice versa. This combined results in 200 annual sailing days per year.

Table 7.3: Case 1.0, required energy/fuel for E-Conoship and Eurotrader

Voyage between port A and B 310nm	Condition and cargo [t]	Avg. speed [kn]	Eurotrader Pb,service [kW]	E-conoship Pb,service [kW]	Time at sea [h]	Time at port [h]	Required LSMGO [t]	Required Electricity [MWh]
A to B Loading at A Discharge at B	**Laden** 3,840	9.6	805	793	32.3	39.1	5.94	40.05
B to A	**Ballast** 0	10.1	721	673	30.7	1.0	4.68	29.41
A to B Loading at A Discharge at B	**Laden** 4,067	9.9	851	876	31.3	41.2	6.11	42.95
B to A	**Ballast** 0	10.3	758	718	30.1	1.0	4.83	30.79
A to B Loading at A Discharge at B	**Laden** 4,693	9.4	775	742	33.0	47.4	6.04	38.91
Average voyage speed [kn]		9.86	Total time [days]		6.56	5.41		
				Required LSMGO [t/day]			2.31	
					Required electricity [MWh/day]			15.22

With data of table 7.3, the daily fuel/energy costs over the entire voyage is determined this includes time at sea and at port. In addition, with a known specific energy of 11.86MWh/t for LSMGO the fuel consumption in ton is converted to energy consumption in MWh and energy price €/MWh, see table 7.4

Table 7.4: Daily fuel/energy costs E-Conoship and Eurotrader, case 1.0

Vessel	Energy type	Fuel/energy consumption	Energy prices	Daily costs [€/day]
E-Conoship	Electricity	15.22MWh/day	92€/MWh	1,400
Eurotrader	LSMGO	2.31t/day (27.37MWh/day)	500€/t (42.15€/MWh)	1,154

In addition, all different components of the voyage related costs for E-Conoship and Eurotrader for case 1.0 in year 0 are known. Also, average VOYEX over year 0 to 1 is given, taken into account an inflation rate of 2%, see table 7.5.

Table 7.5: Case 1.0: voyage related costs

Type	E-Conoship	Eurotrader
Fuel costs [€/day]	1,400	1,154
Port dues [€/day]	1,027	829
Pilotage costs [€/day]	1.042	1,021
VOYEX in year 0 [€/day]	3,470	€3,003
VOYEX year 0 to 1 [€/day]	3,505	€3,033

In table 7.6 the differences in initial investment between E-Conoship and Eurotrader are shown in absolute figures. In addition, the variable costs, interest, OPEX and VOYEX [€/day] are given for year zero to one. The amount of variable costs to be paid differs each year. The OPEX and VOYEX, become each year more expensive due to an inflation rate of 2%, however the relative difference between both vessel, respectively 43% and 16%, remain constant. Furthermore the amount of interest to be paid declines each year, but the relative difference between both vessel remains 2%.

Table 7.6: Initial investment year 0 and variable costs year 0 until 1, E-Conoship and Eurotrader, case 1.0

	E-Conoship	**Eurotrader**	*Difference*
Initial investment [€]	12,669,580	9,548,640	+3,120,940
Interest [€/day]	1,342	1,315	+2%
OPEX [€/day]	3,444	2,409	+43%
VOYEX [€/day]	3,505	3,033	+16%
Total daily costs [€/day]	8,291	6,757	

With this data the break-even analysis can be made, see figure 7.1. Under the given circumstances, the lines for the total costs of both ships diverge and no break-even point will be reached. Based on the assumptions made, the E-Conoship is therefore not cost-competitive with Eurotrader.

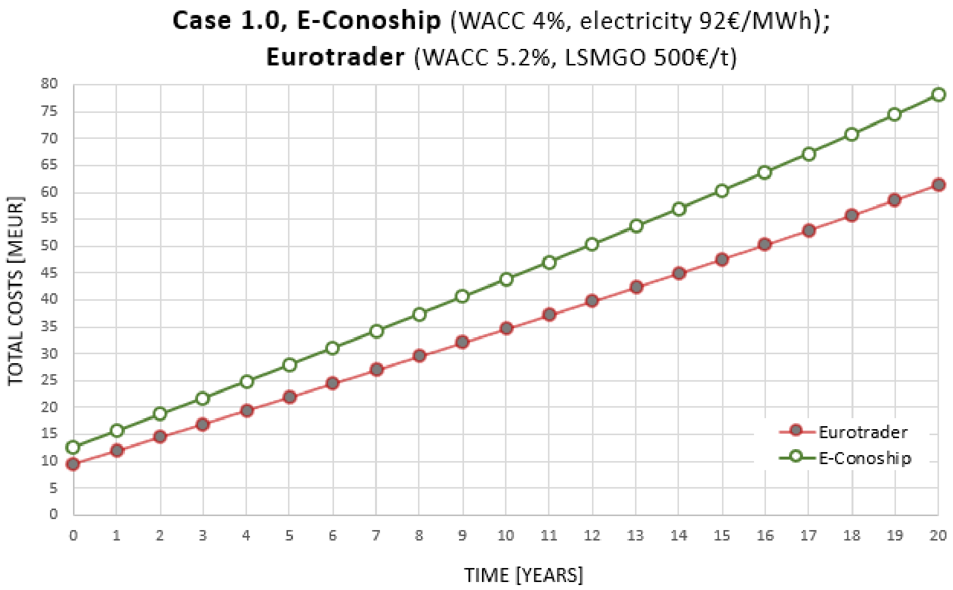


Figure 7.1: Break-even analysis; case 1.0, E-Conoship vs. Eurotrader

7.2.1. Analysis cost-components

In this section, the cost-components of case 1.0 in the CCM are analysed to determine which variables contribute to the difference in costs and to what extent they can be changed. First the difference in CAPEX will be analysed, followed by OPEX and lastly VOYEX difference.

Analysis difference in CAPEX

As described in the previous chapter the CAPEX consist of initial investment and interest costs. The investment costs of a first-off build E-Conoship are approximately 3.12 million euros higher than that of Eurotrader. To get a better understanding of the difference in CAPEX the components and explanation why they differ are presented in table 7.7.

Table 7.7: Explanation in costs difference components CAPEX, E-Conoship and Eurotrader

Code	Title	Costs normalised in relation to Eurotrader	Rationale for cost differences
030	Classification	+30%	New technology
043	Sea trials(s) fuel, tugs, pilots etc.	+49%	5 vs. 2 days sea trials, new technology
053	Failure Mode and Effect Analysis (FMEA)	+100%	New technology, needs approval
073	Basic & Plan approval design/engineering	+67%	New technology, more time consuming
100; 101	Hull and Superstructure, Material Package (Steel) Stock Material, Welding Material (material package)	+18%	E-Conoship +18% steelweight
112	Manholes	-70%	Less tanks, no ballast tanks (12 vs. 40)
140; 141	Outfitting material, welding material (outfitting), welding material (Stainless steel)	+10%	E-Conoship +18% steelweight
160	Painting (applicator)	+25%	25% larger surface to paint
211	Main engine	-100%	No main engine
212	Reverse reduction gearbox	+16%	More complicated reduction gearbox
212	flexible coupling	+100%	2 electrical motors, so 2x flexible coupling
214	Fixed Pitch Propeller (FPP) vs. Controllable Pitch Propeller (CPP)	-59%	Fully electrical so no CPP needed
300; 301	Engine room installations, piping valves, fittings etc.	-13%	No ballast water system
312	Ballast water treatment unit	-100%	No ballast water treatment unit needed
353	De-aeration caps	-67%	Due to electrical engine
380	Exhaust gas silencer for main engine and generator set	-100%	No main engine and generator sets
381	SCR system main engine and generator set	-100%	Not required; system complies with emission regulations
400; 402	Electrical installation (propulsion system) E-Motor in Bow thruster	+100%	2x600kW electrical motors, costs of Bow thruster are included in 400
411; 412	Generator set, Shaft generator	-100%	No need for generator set and shaft generator already part of the electrical installation
415	Stacks of the battery system (costs 800 €/kW)	+100%	Output capacity; battery stack is 2x1300kW
531	Cargohold hatchcover system	-10%	Smaller cargohold

Out of 10 different categories/chapters: the general cost (+27%), the hull and superstructure (+18%) and finally the electrical installation (+550) are more expensive than those of Eurotrader. The other categories of costs are either less expensive or equal in comparison to Eurotrader.

The first category is general costs, where the main difference in costs is caused by the fact that E-Conoship will be the very first vessel (first-off) with this technology, which requires more time for design and engineering. In addition, certifying bodies require more time and resources to approve this new technology.

Regarding the Hull & Superstructure, E-Conoship requires 18% more steel than Eurotrader to achieve the same amount of DWCC and hold volume, result is that E-Conoship is more expensive. This is directly related to the fact that both the specific energy and the energy density of V/Br RFB are 200 times smaller than that of LSMGO, result a larger ship is required.

Within the electrical installation costs the largest expenses are the battery stacks with a total cost of 2.08 million euros. This is determined based on a cost-price of 800 €/kW, provided by VanadiumCorp, times 2,600kW which is the maximum output of the double stack set up.

Furthermore, the capital costs in form of interest is 2% higher than that of Eurotrader. This is due to the fact that required loan on initial investment for E-Conoship is more than 3 million euros higher compared to Eurotrader. The relative difference is less than the relative difference in initial investment, because within the CCM it is assumed that a ’green’ ship, such as E-Conoship can be financed at lower interest costs. Lower interest costs are assumed, because the risk profile of a ’green’s ship is lower compared to Eurotrader.

Analysis differences in OPEX
The operational costs of E-Conoship are 43% higher than that of Eurotrader. The OPEX consist of 6 groups, whereby the insurance of E-Conoship (+33%) more expensive than Eurotrader, the higher insurance costs are due to the fact that the vessel to be insured is more expensive to purchase resulting in higher insurance costs. The largest difference in operational expenditure is due to the lease costs of electrolyte fluid, 1,295€/day, which account for 38% of the OPEX of E-Conoship.

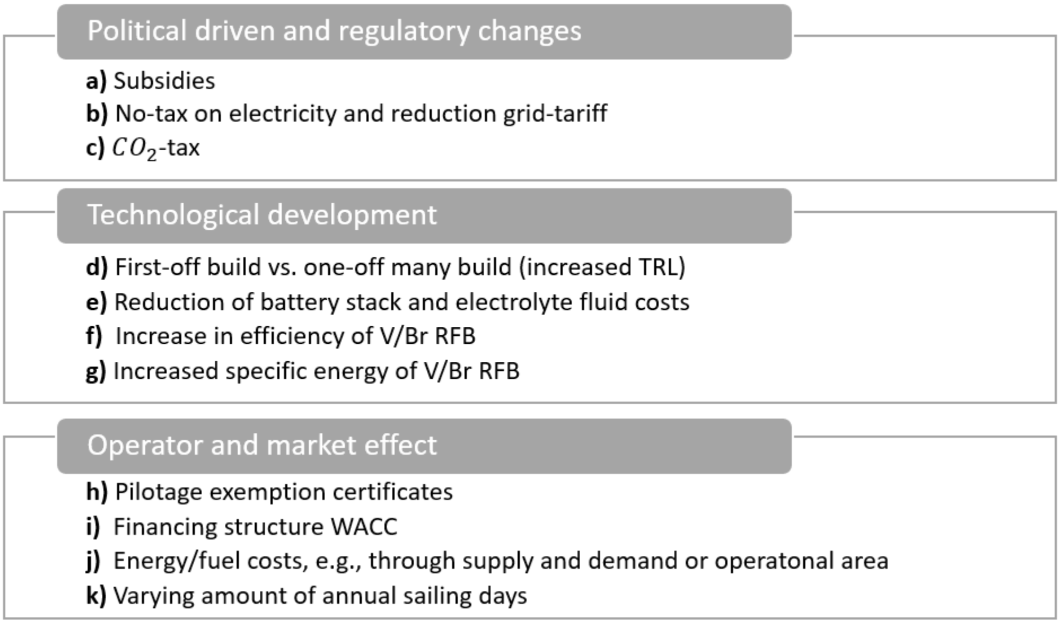
Analysis differences in VOYEX
Voyages related costs are +16% higher than those of Eurotrader. All components of the VOYEX costs are more expensive. The port dues are more expensive as E-Conoship has a larger GT-size than Eurotrader, 3,818GT vs. 3,080GT.

Furthermore pilotage costs are higher for E-Conoship as the actual deepest vessel draught in loaded condition is higher than that for Eurotrader. Pilotage dues could be avoided by applying for a pilotage exemption certificate (PEC). This is not included in case 1.0, but it could be taken into account to reduce overall VOYEX.

The energy/fuel costs of E-Conoship are 21% higher than that of Eurotrader, this is partly due to the fact that the V/Br RFB itself has a efficiency of 82%, which results in an increase of 18% in required electricity to charge the battery. Furthermore, in today’s shipping market there are no penalties (taxes) for vessels who pollute CO_2, which results that with current electricity and LSMGO prices E-Conoship’s total energy/fuel costs are higher than that of Eurotrader.

7.3. Scenario definitions

Several variables cannot be changed, among others is the additional cost related to the fact that E-Conoship needs approximately 18% more steel weight than Eurotrader to obtain similar hold volume and DWCC. On the other hand, some cost items depend on how the future will look in terms of regulations or technological breakthroughs. There are different driving forces that can cause the variables in the model to change. In the scenario definitions, the variables will be divided into clusters by whom/what they are influenced, see figure 7.2.



Political driven and regulatory changes

a) Subsidies
b) No-tax on electricity and reduction grid-tariff
c) CO_2-tax

Technological development

d) First-off build vs. one-off many build (increased TRL)
e) Reduction of battery stack and electrolyte fluid costs
f) Increase in efficiency of V/Br RFB
g) Increased specific energy of V/Br RFB

Operator and market effect

h) Pilotage exemption certificates
i) Financing structure WACC
j) Energy/fuel costs, e.g., through supply and demand or operatonal area
k) Varying amount of annual sailing days

Figure 7.2: Different scenarios grouped in clusters that have an influence on the total costs

7.3.1. Political and regulatory changes

Within this section the options of possible subsidies, lower taxes on electricity prices and a CO_2-tax are dealt with. This is to find out the effect on the total costs of both ships, and to determine under which circumstances E-Conoship is cost-competitive with Eurotrader.

a) Subsidy

The total costs of E-Conoship could be reduced by means of 'green' subsidies. Within the Netherlands the government rewards subsidy to sustainable shipbuilding. A budget of 2.3MEUR is available per tender, with a maximum of 1.25MEUR per applicant. The subsidy is granted on the basis of the following assessment criteria: innovation, sustainability, economic perspective and lastly the quality of the application [84]. In the United Kingdom (UK) the Government invest around 23.5MEUR for development of innovative zero-emission ships and infrastructure in port. This fund is meant for the development of prototype ships and port infrastructure which can can be scaled up to bring the shipping-sector towards net-zero [36].

When subsidies finance the initial purchase/investment costs of the battery stacks (2.08MEUR) and an additional subsidy on leasing costs of the electrolyte fluid, equal to day rate, both OPEX and CAPEX will decrease. This results in a reduction of OPEX with 38%. In addition, the initial investment costs will decline by 2.08MEUR. The cost of capital in form of interest will also decrease. With subsidies alone, E-Conoship is not cost-competitive under the given circumstances.

b) No-tax on electricity and reduction grid-tariff

When governments decide to reduce or eliminate taxes on electricity to support the use of electricity in the shipping sector. Electricity prices could be reduced to for example €50/MWh,lowering the overall VOYEX. With only this variation, E-Conoship is not cost-competitive under the given circumstances.

c) CO_2-tax

In the current shipping market the polluter does not pay for it's pollution. A CO_2-tax on tank to wake (TTW) emissions could solve this and will lead to higher voyage related costs for polluting vessels. In this situation the VOYEX of Eurotader will increase if a CO_2-tax were to come into force. In the shipping industry, however, there is still no clarity on the amount of tax and when it should come into force.

Trafigura is a large Swiss commodity trading company in base metals and energy, among others oil and refined petroleum products. This company states that it wants a CO_2-levy on marine fuels of $250 to $300 (€210 to €252) per ton [107]. In addition major shipping companies are pushing for this kind of tax too. One of them is Maersk, a Danish world leader in container transport. In early June 2021, Maersk stated that it wants a CO_2-tax of $150 (€126 ”$/€=0.84”) per ton of carbon emitted [106]. Besides shipping companies, the flag states of the Marshall Islands and Solomon Islands have submitted a proposal to the IMO to impose a levy of $100 (€84) per tonne of CO_2 emitted by vessels. Furthermore, tax must be increased every five years thereafter [3].

The amount of tax paid per day depends on the operational profile of the vessel and its emissions during operations, the TTW emissions. To determine CO_2 emitted during operations a conversion factor (C_f) between fuel consumption and CO_2 emission is needed. For a diesel/gas oil powered ship the conversion factor is 3.206 t-CO_2/t-fuel [21].

With the conversion factor and a known average fuel consumption per day ($\dot{m}_{fLSMGO}$) over the entire voyage of Eurotrader the amount of CO_2 tonnes emitted per day is known. When this is multiplied with a CO_2-tax in euros per ton emitted carbon dioxide, see equation 7.1, the average daily costs (C_{CO_2}) to be paid for the pollution of CO_2 is known.

$$C_{CO_2} = C_f * \dot{m}_{fLSMGO} * CO_2.tax \quad [€/day] \tag{7.1}$$

With only a CO_2-tax, E-Conoship is under these circumstances not cost-competitive within its economical lifetime of 20 years.

7.3.2. Technological developments

Technological developments can lead to various cost reductions, the first to be discussed is: if more E-Conoships were to be built, then the possibility of a reduction in battery stack and electrolyte fluid costs. Followed by the efficiency of the V/Br RFB and then increased specific energy of the V/Br RFB. The latter with two different scenarios: (1) increase range and (2) similar range.

d) First-off vs. one-off

Currently no E-Conoship has ever been build, first-off, in contrast with a diesel-engine powered ship of whom many have been build over the past decades, one-off. Because E-Conoship will be the first ever build, within the initial investment costs of this vessel costs are included, which do not need to be taken into account as more ships have been build. When more E-Conoship's have been build the TRL will increase and a vanadium bromide redox flow battery becomes a proven technology on board of vessels. Therefore costs with regard to classification, sea trial(s), failure mode and effects analysis, basic & plan approval design/engineering will decline. This adds up to a reduction in CAPEX costs of €224,060, which alone is not enough to result in a cost-competitive E-Conoship.

e) Reduction of battery stack and electrolyte fluid costs

Technological development, availability of materials, economies of scale in production, competition, supply and demand are all factors that can lower the initial purchase cost of the battery stacks and electrolyte fluid. In the current situation, the price of the battery stack is 800€/kW and the price of the electrolyte fluid is 175€/kWh effective energy capacity, both values are provided by VanadiumCorp, a partner of Conoship. If these prices are reduced by 50% over the next few years, the initial investment price of the battery stacks will be 1.08MEUR, reducing the ship's investment costs and the cost of capital in the form of interest. When the price of the electrolyte falls, the leasing costs will fall, given same rate of interest and depreciation to half of the residual value, the new leasing costs will be 647€/day. With only these conditions, E-Conoship is not cost-competitive with Eurotrader.

f) Efficiency of V/Br RFB

Currently the efficiency of the V/Br RFB is 82%, which means that to charge the battery 18% extra electricity is required in other words to charge a 45MWh form empty to full 55MWh is required. When the efficiency of the V/Br RFB is increased due to technology development from 82% to 90%, less electricity needs to be purchased at the quayside to charge the RFB. Under these circumstances the average daily electricity/fuel costs will decline, however with an increase in efficiency of the V/Br RFB alone E-Conoship is not cost-competitive with Eurotrader.

g) Increased specif energy V/Br RFB

When the initial specif energy of (45Wh/kg) of the V/Br RFB increases due to technological development to 90Wh/kg, the range of E-Conoship can either be extended from 500nm to 1000nm at design speed, with the same amount of fluid or remain similar with less fluid onboard. In the next paragraphs first the option of increased range and then option with similar range is described.

g1) Increased range

In this situation with effective energy of 90MWh to obtain the 1,000nm range, the output of the battery stack must also be increased. This is because, the maximum power of the stacks determines the maximum charge capacity. In the current situation, with a maximum power and therefore charge capacity of 2.6MW, it takes 21.3 hours (given $\eta_{V/Br.RFB} = 0.82$) to charge a 45MWh battery fully. When the energy capacity is increased at the same power level, it takes 42.2 hours to charge a 90MWh battery. In this situation the battery cannot be fully charged during one port call, loading and unloading of cargo.

Therefore, if the energy capacity increases it is also necessary to increase the maximum power output of the battery stacks. In this scenario, the maximum power of the stacks is doubled for equal weight of the total stacks, result is that the costs for the V/Br RFB system will also double, assumed that the price for the battery stack and electrolyte fluid remain constant. With this scenario, E-Conoship is not cost-competitive with Eurotrader.

g2) Similar range

In this scenario the specific energy of the V/Br RFB is doubled, result is that half the weight of electrolyte fluid is needed to maintain a range of 500nm. With a reduction of 500 tonnes of electrolyte fluid, E-Conoship can no longer be designed ”ballast free”. Therefore E-Conoship needs ballast tanks and a ballast water treatment system. The additional amount of piping and the weight of the ballast water treatment system adds up to 13 tonnes of steel. When the ship sails in loaded condition, 477t of additional cargo can be transported at maximum draught. In order to make a comparison between the two ships, both ships must have the same DWCC and hold volume.

To obtain similar DWCC and hold volume, the depth of E-Conoship will be reduced, while the height of the freeboard remains constant. This results in a reduced draught, reducing cargo hold volume by approximately 260m^3. To compensate for this loss of cargo hold volume, the length of the cargo hold will be increased by 2.4m. An overview of the above mentioned changes can be found in table 7.8.

Table 7.8: Increased energy density V/Br RFB, 500nm range E-Conoship

Current situation	**New situation, 500t electrolyte fluid**
No ballast system	+13t steel weight due to ballast water treatment system and piping
DWCC: 4,968t	DWCC: +477t DWCC: -477t by decreasing depth with 38cm
Hold volume: 6,545m^3	Hold volume: -260m^3, due to decreasing depth Hold volume: +260m^3, by increasing cargo hold length with 2.4m (4 frames of frame spacing 600mm)

An E-Conoship with less tonnes of electrolyte fluid on board will be henceforward referred to as E-Conoship2. This E-Conoship2 requires less steel to be build, approximately a reduction of 30t in steel weight. A ballast water treatment system, tanks and additional piping is needed for this ship. This leads to the following initial investment costs see table 7.9.

Table 7.9: Initial investment of E-Conoship, E-Conoship2 and Eurotrader

Code	**Title**	**E-Conoship**	**E-Conoship2**	**EuroTrader**
000	General	127%	127%	100%
100	Hull and Superstructure	118%	115%	100%
200	Propulsion and Manoeuvring system	57%	57 %	100%
300	Primary ship systems	71%	84%	100%
400	Electrical installation	550%	550%	100%
500	Deck machinery, lifesaving and fire protection	93%	93%	100%
600	Secondary Ship's system	100%	100%	100%
700	Accommodation, wheelhouse	100%	100%	100%
800	Nautical, Navigational and Communication Equipment	100%	100%	100%
900	Special Equipment	-	-	-
	Initial investment	€12,669,580	€12,675,212	€9,548,640

Due to reduction of tonnes electrolyte fluid on board of E-Conoship2 and decrease in depth the amount of enclosed volume of E-Conoship2 decreases with approximately 300m^3 compared to E-Conoship. Result is that E-Conoship has a gross tonnage of 3,731GT. A reduction in the GT by 2.3% compared to E-Conoship (3,818GT), results in the same amount of port cost reduction. In addition, the pilotage dues of E-Conoship2 will be reduced because the maximum draught is reduced by 0.38m. This reduces the draught of the E-Conoship when sailing with cargo on board, this results in reduction of port costs of 15%. The combined effect of this scenario, leads to a decrease in total costs compared to E-Conoship. However, this is not enough to be cost-competitive with Eurotrader.

7.3.3. Operator and market effect

With this subsection the variable which can be effected through the operator and market effects will be varied. Within the first, possibility of a pilotage exemption certificate will be discussed. Followed by the financing structure, then variation of electricity/fuel prices, and lastly a change of annual sailing days.

h) Pilotage exemption certificate

An operator has the possibility to apply for this certificate when the ship regularly visits the same port. When operators of both ships apply for this certificate, the relative difference in VOYEX does not change much, as the relative difference in pilotage costs is about 2% and the absolute difference is 23€/day. However, the total voyage related cost of both ships will decrease, as the pilotage costs are 1,104€/day for E-Conoship and 1,081€/day for Eurotrader in year 0.

i) Financing structure

In the current situation the relative costs of capital for E-Conoship are 2% higher than that of Eurotrader, despite the more favourable financing structure, WACC 4% vs. WACC 5.2%, see section 6.3.2. When financing an Eurotrader becomes even more unfavourable compared to Eurotrader, for example 60% bank equity against 4% interest and 40% debt via external investors against 10% interest, then the new WACC is 6.4%. The result is that interest costs are more expensive than E-Conoship, see table 7.10. With only a favourable financing structure for E-Conoship with Eurotrader, cost competitiveness cannot be achieved.

Table 7.10: Difference in interest costs E-Conoship compared to Eurotrader

Difference	**Value**
Relative [%]	-17
Absolute [€], year 0-1	-100,852

j) Energy/fuel costs

Development with regard to energy/fuel prices effects the VOYEX costs of both ships. For now it is assumed that energy/fuel prices are fixed during the life-time of both vessels at 500€/t for LSMGO and electricity prices are initial set at the median price level of 13NW countries which is 92€/MWh for electricity charges, grid tariffs and taxes included [32]. In reality energy/fuel prices are not fixed and fluctuate over time. Variation of energy/fuel costs, can be due to different factors, among others are market based (price fluctuation) and the operational areas. The market forces of supply and demand can cause the prices of both to fall or rise over time.

An example is that of the LSMGO bunker prices in the port of Rotterdam as shown in figure 7.3. It can be seen that bunker prices during the peak of COVID-19 where around 200$/mt (≈168€/mt) in 2020, and that at the end of June, 2021 LSMGO prices are increased by a factor 3 to approximately 600$/mt (≈504€/mt).

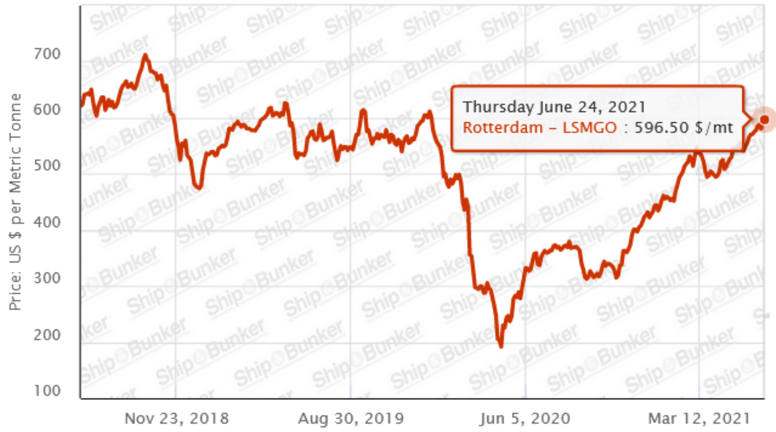


Figure 7.3: Rotterdam Bunker prices LSMGO [$/mt] over the past 3 years [90]

Within this parameter variation, the difference in fuel prices are varied. The initial prices are 92€/MWh for electricity and 500€/t for LSMGO [90],[32]. The conversion of this 500€/t LSMGO into a price per MWh depends on the specific fuel consumption, which is linked to the (engine) power required during operations. For case 1, 500€/t LSMGO is the equivalent of 42.15€/MWh. Under these circumstances, the cost of LSMGO, converted to a price per MWh, is 54% lower than the price of electricity. Therefore, despite the fact that the average energy consumption (MWh/day) of E-Conoship on this voyage is almost two times lower than that of Eurotrader the energy/fuel costs of E-Conoship compared to Eurotrader are higher.

Within the energy/fuel price fluctuations: the median electricity price 92€/MWh, the electricity price in the most expensive country Poland 120€/MWh, and that of most affordable country Norway 26€/MWh will be used. In addition to today's LSMGO of 500€/t, an increase in the energy/fuel price to 600€/t and finally a reduction in the fuel price to 400€/t will be applied. This to determine the effect of energy/fuel price fluctuation on the difference in total VOYEX between E-Conoship and Eurotrader. This parameter variation is done for case 1, see table 7.11.

Table 7.11: Variation of energy/fuel prices and effect on case 1

Variation	0	1	2	3	4	5	6	7	8
Electricity [€/MWh]	92	92	92	120	120	120	26	26	26
LSMGO [€/MWh]	42	51	34	42	51	34	42	51	34
LSMGO [€/t]	500	600	400	500	600	400	500	600	400
VOYEX difference [€/day]	+247	+16	+478	+673	+442	+904	-758	-989	-527

k) Amount of annual sailing days
In the current situation, 200 voyage days per year are assumed. This can be increased by spending less time in port or when more distance in nautical miles is covered per voyage. When this increases, the energy/fuel costs will be a larger part of the voyages related costs. In the current situation with higher energy/fuel costs for E-Conoship compared to Eurotrader this will further increase when more annual sailings are realised. Thus, in the current situation more annual sailings have a negative effect on E-Conoship's cost competitiveness compared to Eurotrader.

7.4. Evaluation of individual scenarios

The scenario definitions have shown that a single one does not result in E-Conoship being cost-competitive with Eurotrader. Furthermore, per scenario it differs how large the impact is on the cost-difference between both ships. In addition, not all scenarios can be influenced by Conoship or a shipping company.

For each scenario the impact on the cost difference, and the influence which Conoship or a shipping company has on a specific scenario are ranked, from 1 until 5. With one meaning small impact or influence, and five meaning a large impact or influence on the total cost difference between E-Conoship and Eurotrader, see table 7.12.

The impact multiplied by the influence leads to a ranking, whereby subsidy, annual sailing days and financing structure form the top 3. To determine under which circumstance E-Conoship is cost-competitive with Eurotrader, the scenarios which have the largest impact on the total costs will be combined. These are: subsidy, CO_2-tax, reduction in costs: battery stack and electrolyte fluid, variation of energy/fuel costs, annual sailing days, and lastly financing structure.

Table 7.12: Scenarios, their impact and influence

Scenario	**Impact**	**Influence**	*Impact x influence*
a) Subsidy	5	4	20
b) No-tax on electricity and/or reduction grid tariff	4	2	8
c) CO_2-tax	5	3	15
d) First off vs. one-off	2	4	8
e) Reduction in costs: battery stack and electrolyte fluid	5	3	15
f) Efficiency of V/Br RFB	2	4	8
g) Increased specif energy	3	2	6
h) Pilotage exemption certificate	2	5	10
i) Energy/fuel costs through: supply/demand or operational area	5	3	15
j) Annual sailing days	5	4	20
k) Financing structure (WACC)	5	4	20

Explanation
Within the next paragraphs the scenarios with the largest impact are further explained. The impact of a subsidy is large as, it could reduce CAPEX, OPEX or VOYEX significantly, see section 7.2. In addition the quality of the subsidy proposal and the level of (green) innovation determine whether the subsidy can be acquired, this is something at which the applicant has a large influence on. However, the maximum amount of subsidy rewarded per applicant cannot be influenced by Conoship or a shipping company, as this is in most cases pre determined [84].

The impact of a CO_2-tax is large, as with this tax the VOYEX of Eurotrader will increase while the VOYEX of an E-Conoship will remain similar. In addition, this amount of tax to be paid increases with more annual sailing days. The introduction of a possible tax could be influenced by lobbying or by showing among others governments, IMO, that there is a viable alternative to pollution ships when a CO_2 tax is applied.

A reduction in costs of both battery stack and the leasing of electrolyte fluid have a large impact on the total costs of E-Conoship, see section 7.1.1 and 7.2.2. When both are reduced the CAPEX and OPEX decreases, with the result that E-Conoship becomes less expensive. Conoship or a shipping company could influence this by asking for price quotes from different companies and contracting the most affordable supplier. In addition costs could be reduced by optimising the required amount of electrolyte fluid an battery stack for a certain trade, for example a range of 300nm instead of 500nm.

Low electricity prices and high LSMGO prices leads to large difference in fuel costs, with as result that VOYEX of E-Conoship becomes less expensive compared to Eurotrader, see section 7.2.2. Influence on fuel prices can be influenced by an operator by operating E-Conoship's in areas with low electrical energy prices and high LSMGO prices. In addition the amount of annual sailing days influences the fuel costs, when more annual sailing days are obtained these costs will increase.

For an E-Conoship to be cost-competitive compared to Eurotrader, besides high annual sailing days a requirement is that the fuel costs in comparison with Eurotrader must be lower, otherwise the negative difference in costs will only increase. The amount of annual sailing days can be influenced by an operator optimizing the voyages, such that minimum time is lost in port, and average voyage distance is as close as possible to the maximum range of the ship.

The last scenario which has a large impact is the financing structure. According to Stopford [98] there are multiple ways to finance a ship. In accordance section 7.2.2 has shown that when an Eurotrader is financed with a higher WACC, the interest costs of E-Conoship could less than that of E-Conoship. This despite the fact that the initial investment of E-Conoship in the current situation is more than 3MEUR higher than that of Eurotrader.

7.4.1. Combination scenarios

The above sub-sections have shown that the likelihood of an E-Conoship being cost-competitive relative to Eurotrader increases when multiple variables are changed. Therefore, a more extensive combination of scenarios will be examined in this section. Within these scenarios, different aspects of both: political and regulation driven, technological developments, as well as operator and market effect are selected.

In total ten different combination scenarios are implemented, all have a lower electricity price than the current median electricity price of 92 €/MWh, see table 7.13. This is because the voyage related costs have to compensate for the initial cost difference between Eurotrader and E-Conoship. Even with a reduction in the cost of the battery stacks, electrolyte fluid, and with subsidy, E-Conoship's initial investment and OPEX are higher than that of Eurotrader.

With combination scenarios x.1 and x.2 the effect of a more favourable financing structure can be seen. Furthermore between scenario x.2 and x.3 the effect of a reduction in battery stack and electrolyte fluid cost can be seen.

Between scenario x.4 and x.5 the effect of a subisdy on the break-even analysis can be seen. Between scenarios x.6 and x.7 the effect of an increase in CO_2-tax can be seen.

Scenario x.8 compared to x.9 shows the effect of annual sailing days. Lastly scenario x.10 with all six scenarios combined shows the effect of favourable financing structure compared to x.9.

Table 7.13: Combination scenarios

Combination scenario	**x.1**	**x.2**	**x.3**	**x.4**	**x.5**	**x.6**	**x.7**	**x.8**	**x.9**	**x.10**
a) Subsidy [MEUR]	1.25	1.25	1.25	1.25	-	-	-	1.25	1.25	1.25
c) CO_2-tax [€/tCO_2]	150	150	150	150	150	150	200	100	100	100
e) Reduction of battery stack and electrolyte fluid costs [%]	-	-	25	25	25	-	-	10	10	10
i) Financing structure, WACC [%]	-	4; 6.4	4; 6.4	4; 6.4	4; 6.4	-	-	-	-	4; 6.4
j) Energy/fuel costs [€/MWh ; €/t]	26; 500	26; 500	26; 500	50; 500	50; 500	50; 600	50; 600	50; 600	50; 600	50; 600
k) Amount of annual sailing days	-	-	-	250	250	-	-	-	220	220

For these combination scenarios, the break-even point is determined in each case, after which E-Conoship is cost-competitive with Eurotrader, see table 7.14. Within table 7.14 a [-] sign means that no break-even point is reached within the economical lifetime of both vessels given the circumstances of that specific case. Case 2.3 results in a break-even point the most earlier in time, namely after 2yr and 29wks, blue colored in table 7.14.

Table 7.14: Break-even points for different cases and subsequent combination scenarios

Case	**Break-even point**	**Case**	**Break-even point**	**Case**	**Break-even point**	**Case**	**Break-even point**
1.0	-	2.0	-	3.0	-	4.0	-
1.1	6yr and 43wks	2.1	6yr and 26wks	3.1	6yr and 44wks	4.1	8yr and 14wks
1.2	5yr and 5wks	2.2	4yr and 46wks	3.2	5yr and 5wks	4.2	5yr and 47wks
1.3	2yr and 33wks	2.3	2yr and 29wks	3.3	2yr and 33wks	4.3	2yr and 47wks
1.4	2yr and 42wks	2.4	2yr and 35wks	3.4	2yr and 43wks	4.4	3yr and 11wks
1.5	6yr and 1wk	2.5	5yr and 35wks	3.5	6yr and 1wk	4.5	7yr and 1wk
1.6	15yr and 19wks	2.6	14yr and 12wks	3.6	15yr ad 24wks	4.6	19yr and 32wks
1.7	9yr and 14wks	2.7	8yr and 47wks	3.7	9yr and 16wks	4.7	10yr and 29wks
1.8	12yr and 40wks	2.8	10yr and 46wks	3.8	12yr and 48wks	4.8	-
1.9	9yr and 38wks	2.9	8yr and 30wks	3.9	9yr and 39wks	4.9	15yr and 6wks
1.10	6yr and 18wks	2.10	5yr and 42wks	3.10	6yr and 19wks	4.10	8yr and 23wks

Effect of reduction of battery stack and electrolyte fluid costs + financing structure
From table 7.14, it follows that for case 1.1 with: a subsidy of 1.25MEUR for E-Conoship, a 150€/tCO_2 tax, electricity prices 26€/MWh and LSMGO price of 500€/t, break-even is obtained after 6yr and 43wks, see figure 7.4.

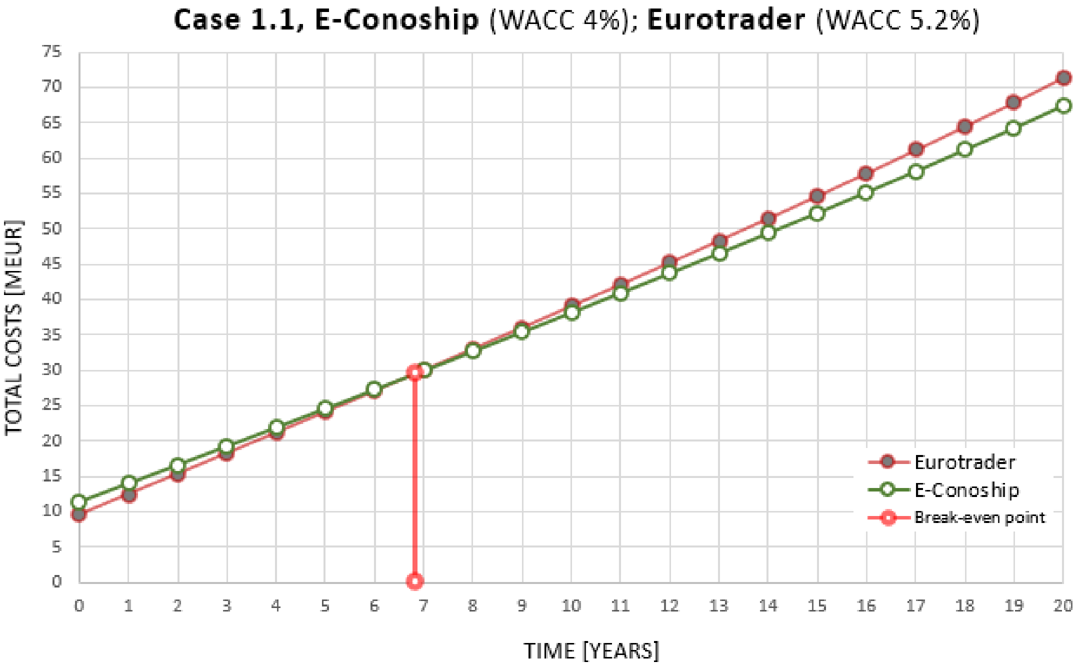


Figure 7.4: Break-even analysis; case 1.1, E-Conoship vs. Eurotrader

When additional to case 1.1: a 25% reduction in the cost of the battery stacks and electrolyte fluid, and Eurotrader WACC increases from 5.2% to 6.4%, time until break-even reduces by more than half, see case 1.3 within figure 7.5.

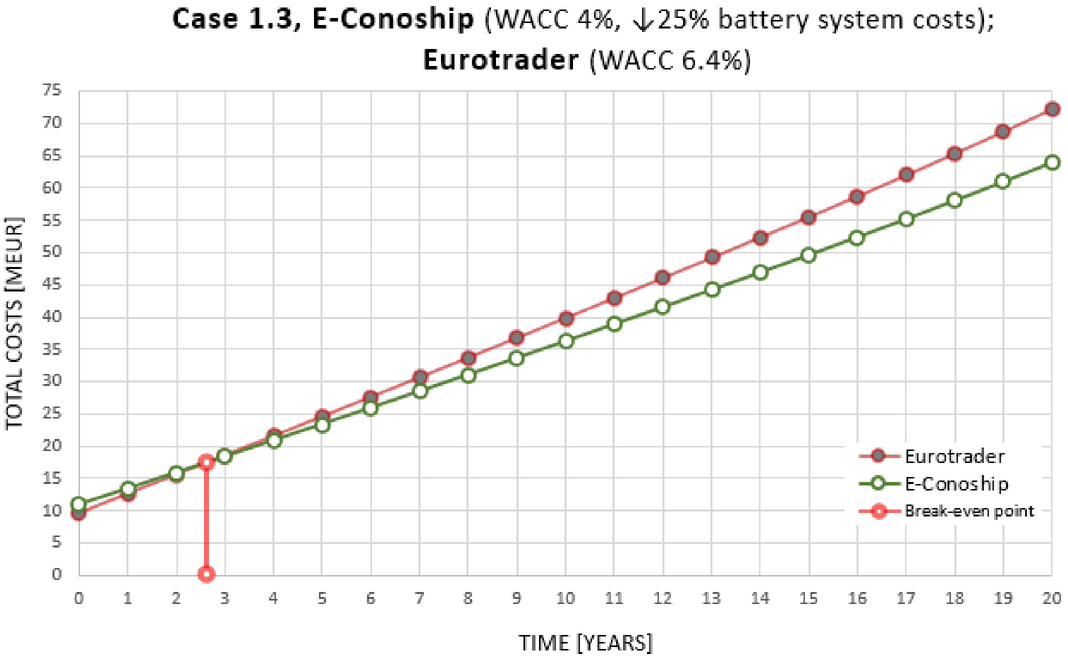


Figure 7.5: Break-even analysis; case 1.3, E-Conoship vs. Eurotrader

Effect of subsidy
From table 7.14, it follows that for case 1.4 with: a subsidy of 1.25MEUR for E-Conoship, a 150€/tCO_2 tax, electricity prices 50€/MWh and LSMGO price of 500€/t, 250 annual sailing days, E-Conoship WACC 4% and Eurotrader WACC 6.4%), break-even is obtained after 2yr and 42wks, see figure 7.6.

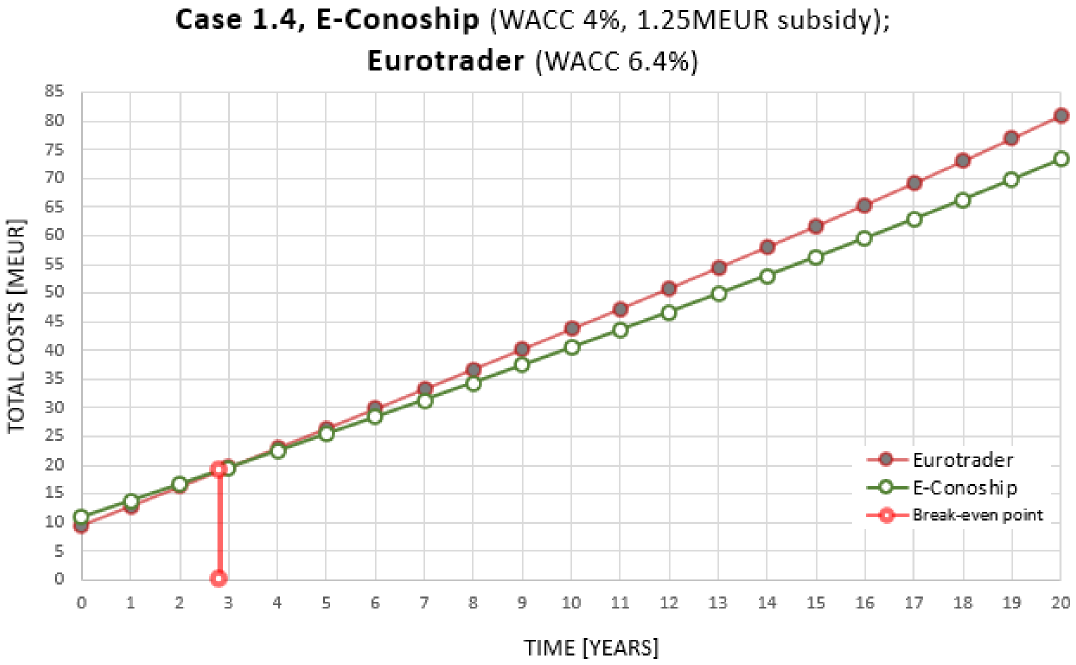


Figure 7.6: Break-even analysis; case 1.4, E-Conoship vs. Eurotrader

When compared to case 1.4, the subsidy of 1.25MEUR is no longer obtained for an E-Conoship, time until break-even increases by more than two, see case 1.5 within figure 7.7.

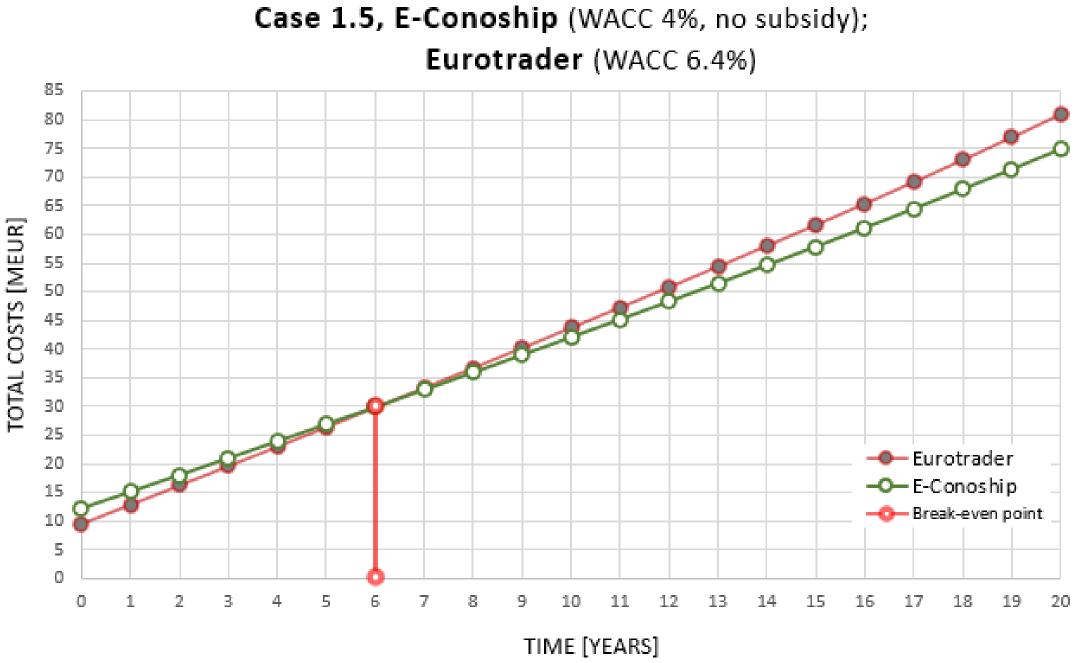


Figure 7.7: Break-even analysis; case 1.5, E-Conoship vs. Eurotrader

Effect of CO_2-tax

The effect of a CO_2-tax, given that energy/fuel costs are lower compared to Eurotrader shows that a raise of tax with 50€/tCO_2, from 150€/tCO_2 to 200€/tCO_2, results in a break-even point which is almost 6 years earlier in time for case 2.6 vs. 2.7, see figures 7.8 and 7.9. When a CO_2-tax of 100€/tCO_2 is applied no break-even point within the economical lifetime of E-Conoship and Eurotrader will be obtained.

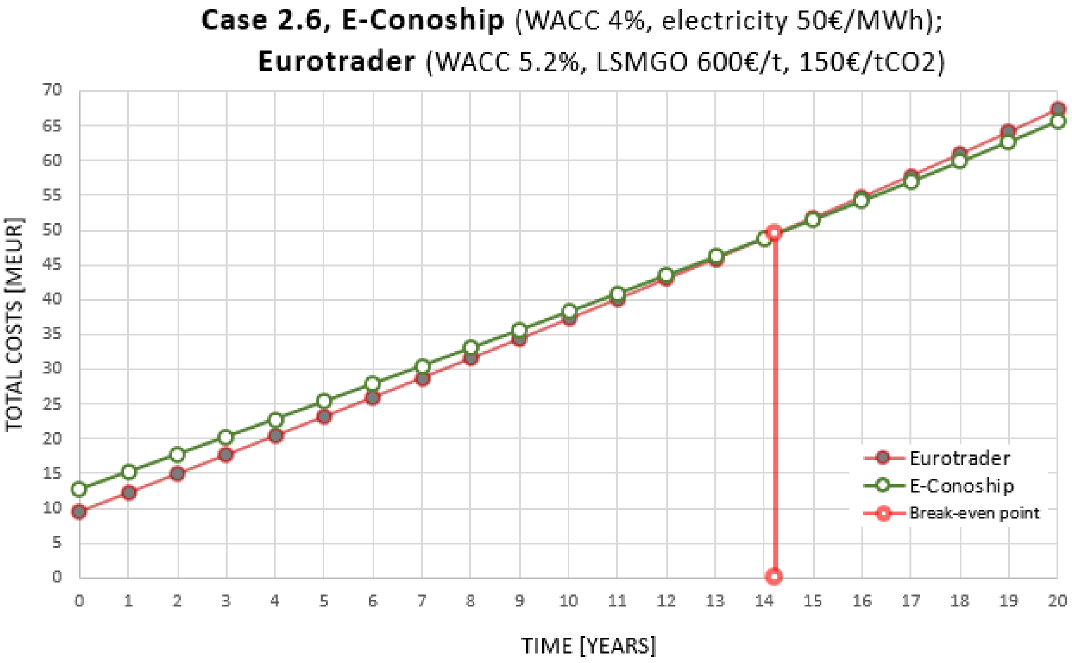


Figure 7.8: Break-even analysis; case 2.6, E-Conoship vs. Eurotrader

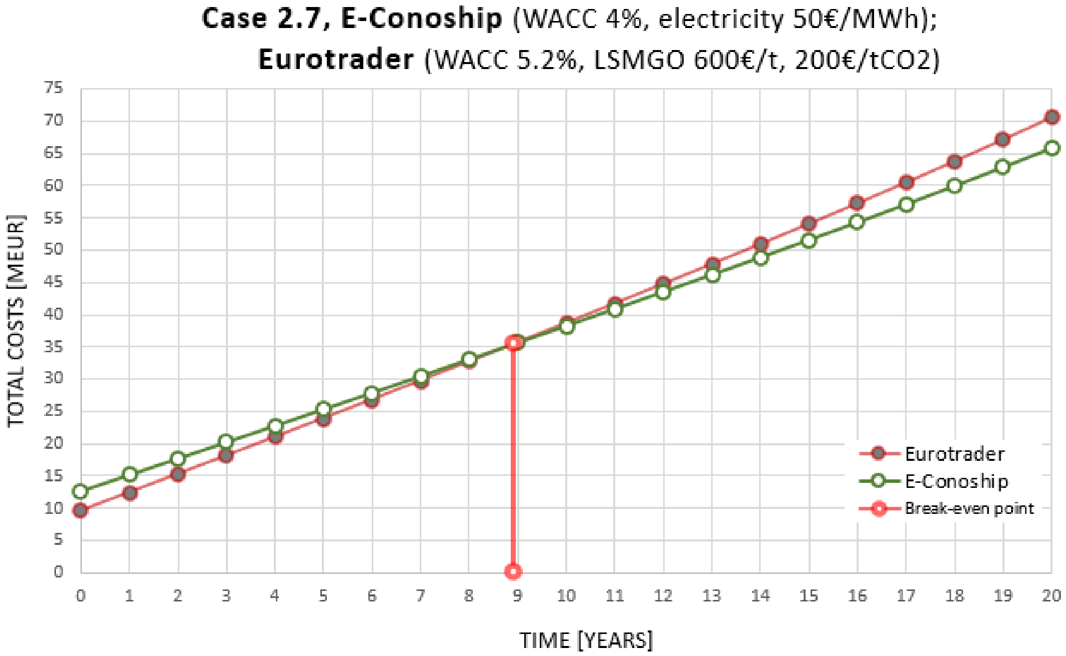


Figure 7.9: Break-even analysis; case 2.7, E-Conoship vs. Eurotrader

Effect of annual sailing days + financing structure
The difference between 1.8 and 1.10 in break-even point, shows that due to 10% more annual sailing days and a more favourable financing structure of E-Conoship compared to Eurotrader, the time after which E-Conoship is cost-competitive with Eurotrader decreases by half, see figure 7.10 and 7.11.

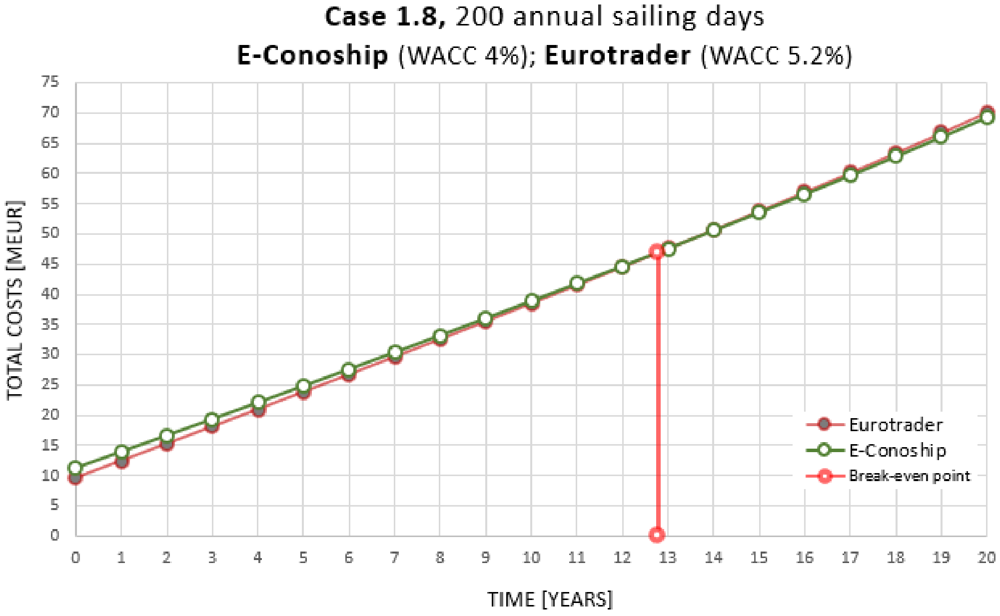


Figure 7.10: Break-even analysis; case 1.8, E-Conoship vs. Eurotrader

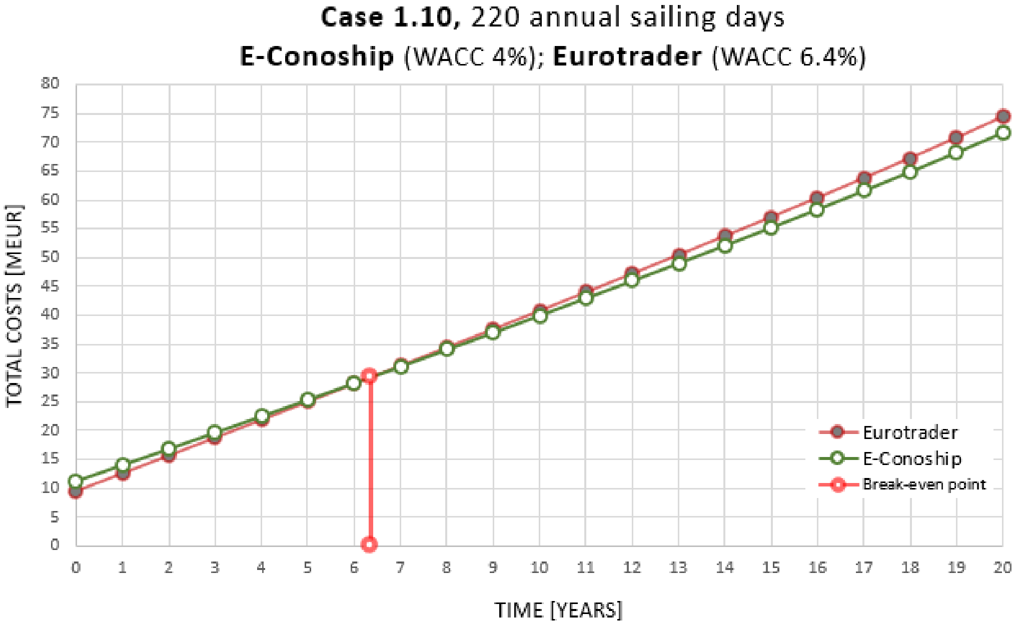


Figure 7.11: Break-even analysis; case 1.10 , E-Conoship vs. Eurotrader

Difference in break-even points between cases: 1.x, 2.x, 3.x and 4.x
From table 7.14, it can be seen that the break-even point shift to earlier in time when more distance is covered per voyages, given the same annual sailing days. This is illustrated by the difference between case 1.4 and 4.5, whereby the break-even point is one year later in case 4.5. This is mainly due to the fact that the amount of the CO_2-tax depends on the fuel consumption and the corresponding emissions, which are highest when sailing.

Furthermore, under the present circumstances, the break-even point in cases 1.x and 3.x are more or less the same, which shows that when the average voyage distance is the similar for two different cases, the total cost does not differ much.

Additional option, from the previously analysis, it becomes evident that reduction of battery and electrolyte costs, results in significant costs reduction. To obtain this, given the current prices of a V/Br RFB-system it could be more advantageous to design a new vessel, which operates with a shorter range, not 500nm but for example instead 200-300nm. This ship should be designed for a specific route or between hubs mentioned in chapter 5. An example mentioned in chapter 5 is a ship with IMO 9369514, Musketier which sails between the ports of Portsmouth (GB), St Helier (JE) and Guernsey (CG), where a full round trip is about 250nm. Another example is a route approached from the port side (situation 1 in chapter 5) between the SSS hubs IJmuiden region (NL), Rotterdam region (NL) and Hull region (GB), these ports are within approximately 200nm of each other. Sailing these short routes requires an entirely new ship design, which will leads to cost reduction compared to E-Conoship, see table 7.15.

Table 7.15: E-Conoship, with a limited range of 200-300nm

E-Conoship with 200-300 range [nm]	*Reduction effect on costs of*
Less power output of battery stack and less energy capacity	Battery stack (CAPEX) and electrolyte fluid (OPEX)
Main dimensions of vessel decrease given same DWCC, result reduction GT and draught	Port costs (VOYEX) and pilotage costs (VOYEX)
Reduction of required steel, needs ballast water-treatment system	requires further investigation, but has an effect on CAPEX

7.5. Conclusion

With the case study and different scenarios carried out by means of the CCM, the following sub question can be answered: *"Under which circumstances is Conoship's vanadium bromide redox flow battery-powered ship design cost-competitive with diesel-powered ships?"*

E-Conoship is cost-competitive if the total costs are less than or equal to that of a ship operating with diesel engines within 20 years. In today's market E-Conoship is under the given circumstances not cost-competitive with a diesel-powered ship, such as the Eurotrader. For E-Conoship to be cost-competitive with Eurotrader, multiple variables has to be changed due to different driving forces. The largest difference between both ship is due to costs for the battery stacks 2.08MEUR and electrolyte fluid leasing costs of 1,295€/day increasing each year with 2% due to inflation.

To acquire a cost-competitive E-Conoship, a reduction in the cost for battery stack and electrolyte fluid is preferable, besides this at least lower VOYEX then Eurotrader's is required. Therefore, a CO_2-tax is required, dependent on the other variables the height of the required tax can be determined. One of which is that energy/fuel costs, must be low for electricity in comparison with LSMGO prices. Examples are, electricity prices, such as currently present in Norway, or reduction of electricity price due to a discount on taxes. Furthermore, subsidies are required, to close the gap in initial investment between both ships. In addition the break-even point shifts to earlier in time by increasing the amount of annual sailing days. Furthermore, the average voyage distance given the same amount of annual sailing days, has a positive effect on the break-even point, the more distance is covered the earlier in time an E-Conoship becomes costs-competitive with an Eurotrader. When the finance structure (WACC) for E-Conoship's initial investment results in lower interest costs compared to Eurotrader, the ship is more likely to be cost-competitive.

Another option for an E-Conoship to be cost-competitive with a diesel-powered vessel is to design a new E-Conoship with a shorter range around 200-300nm. This would decrease among others, battery stack and electrolyte fluid costs. Combined with a CO_2 tax plus a reduction in electricity prices, such an E-Conoship could be cost-competitive with a diesel-powered ship at an early stage.

8

Discussion

This chapter discusses the findings and their significance by reviewing all the research questions addressed and placing them in their context. First of all, this research started with a **preliminary research question** to determine what determinants of feasibility this thesis should focus on, this question was as follows:

What are the barriers and opportunities for the introduction of vanadium bromide redox flow battery-powered shipping in the short sea shipping market of North West Europe?

The main opportunity of this system in shipping is that a V/Br RFB-powered vessel will not produce any polluting emissions during operation (sailing). In this context, its important that the system is charged with renewable energy, e.g. solar or wind power, so that the emissions of the system are as low as possible not only during operation, but also over its entire life cycle. Otherwise it is not an ethical and sustainable solution for the reduction of GHG emissions, then it is merely a relocation of pollutant emissions.

In addition to the opportunities, the barriers, which pose the greatest challenges, are the ones which were dealt with in the remainder of this thesis, these are firstly, the technical barrier, limited range of 500nm (due to low specific energy and energy density), which could potentially lead to not enough short distance trades being available for an E-Conoship to be operational feasible.

Secondly, the financial barrier, that a ’green’ solution is often more expensive than a traditional solution [89]. This could lead to an economical problem, where nobody is willing to invest in V/Br RFB-powered ships, despite the fact that the emissions during operation are reduced to zero.

In view of the barriers, it should taken into account that within this thesis it is a precondition that the development of the V/BR RFr itself does not pose any threat to the feasibility of V/Br RFB-powered shipping. In essence, the specifications given for this new battery are feasible at the required scale, 2MW/45MWh. In reality, the given specification needs to be proven and verified on the required scale before a vessel can be built.

With the answer of the preliminary research question, the **main research question** has been formulated as follows:

”Under which circumstances is Conoship’s vanadium bromide redox flow battery-powered ship design operational and economical feasible in today’s short sea shipping market of North West Europe?”

To give direction to this research and to be able to answer the main question, it has been divided into two sub-questions, which will be discussed in the following paragraphs.

The first sub-question: *”what current shipping routes present potential for vanadium bromide redox flow battery-powered shipping?”*, will be discussed next.

An E-Conoship has a range of 500nm. For this reason, research has been carried out into the possibilities of completing short-distance voyages. To date, this has not been carried out, because for diesel-powered ships, a greater range is no problem at all. Thereby, this research contributes to increasing scientific knowledge of the operational possibilities of limited range sailing for the general cargo short sea shipping market.

Therefore, historical voyage data of 281 general cargo vessels operating in North West Europe over the period 2020-2021 has been analysed. Those vessels are considered representative of the entire SSS fleet of 1,047 vessels, general cargo 3,000 until 7,500DWAT. For this data the maximum period over which data could be acquired has been used. The historical data collected covered the period in the mids of the COVID-19 pandemic. A report by the European Maritime Safety Agency showed that COVID-19 had a negative impact on the amount of shipping traffic [31]. This suggests that there could be more operational opportunities for E-Conoships within the short sea shipping market of North West Europe once the shipping intensity increases back to its normal levels.

For now within the researched data, 11% of the SSS sample fleet sails at least 75% of al its voyages less than 500nm, which is the current maximum range at the design speed of an E-Conoship. This converted to the entire short sea shipping fleets adds up to 115 ships. The sub-question has been answered for a 500nm range, if the range of an E-Conoship is extended to 600nm as a result of ’slow steaming’, more than double the number of ships would travel at least 75% less than 600nm. This would mean that 235 (22%) of the 1,047 of the SSS general cargo ships could potentially be replaced by an E-Conoship on a one-to-one basis.

Moreover, the conclusions drawn are based on existing routes; potentially more routes, ships are available if a longer voyage is split in two, so that an E-Conoship could be recharged halfway. The analysed data has shown that approxiametly 79% of the SSS sample fleet sails at least 75% of all its voyages below the 1000nm range, converted to the entire fleet this adds up to 823 ships. When thus a voyage is split in half 823 ships could potentially be replaced for E-Conoship’s.

The second sub-question: *”Under which circumstances is Conoship’s vanadium bromide redox flow battery-powered ship design cost-competitive with diesel-powered ships?”*

To determine under which circumstances Conoship’s vanadium bromide redox flow battery-powered ship is cost-competitive with diesel-powered ships, a CCM has been build. In the initial situation Conoship’s vanadium bromide redox flow battery-powered ship is not cost-competitive with a diesel-powered ship. This is inline with previous studies about the fact that most ’green’ solution are initially often more expensive[89].

With the CCM in this research it has been shown that an E-Conoship can be cost-competitive with a diesel-powered ship. With the evaluation of different scenarios it has been determined that a combination of the following scenarios have a large effect on the cost-competitive of an E-Conoship: subsidy, CO_2-tax, reduction of battery stack and electrolyte fluid costs, financing structure (WACC), energy/fuel costs, and amount of annual sailing days.

The strength of this research into the economical feasibility, with means of the CCM model is that: the variables in the model can be changed to determine for different (circumstances) scenarios when E-Conoship is cost competitive with Eurotrader. In total four different cases have been carried out, this results in 40 different scenarios of which 87.5% results in a cost competitive E-Conoship within the economical lifetime of 20years. The factors identified in this study provide guidance for practice and serve as a basis for further research to implement vanadium bromide redox flow battery-powered ships in the future.

Within the CCM, the costs of the charging infrastructure were not taken into account. If these costs are paid by the ports, this assumption is valid. When this is not the case, additional costs will have to be taken into account and it will take more effort before an E-Conoship is cost-competitive with a diesel-powered ship.

Contradiction, between operational and economical feasibility there is a discrepancy, for the operational feasibility the longer the range the more voyages, ships are available to replaced by E-Conoships. For an E-Conoship to be economical feasible, cost-competitive with diesel-powered ships, the electrolyte fluid and battery stack costs must significantly decrease. By increasing the range these costs will increase, which results in E-Conoship not being cost-competitive with a diesel-powered ship, see figure 8.1.

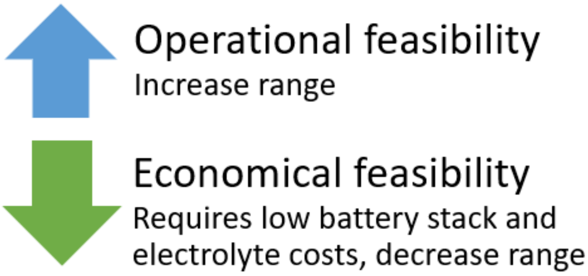


Figure 8.1: Contradiction between operational- and economical feasibility

This discrepancy, in figure 8.1, is due to the fact that the largest difference in cost between the two ships is due to the cost of the battery stacks (2.08MEUR) and electrolyte fluid leasing costs of 1,295€/day which also increases each year with 2% due to inflation.

Within the CCM an E-Conoship is used with a range of 500nm, due to the high costs of the battery stack and electrolyte fluid, economically it is more advantageous to design a ship with a range of 200-300nm. The historical data analysis has shown that is also possibilities to complete merchant voyages below 300nm. Such an E-Conoship could reduce the overall cost, making an E-Conoship earlier in time cost-competitive with a diesel-powered ship.

9

Conclusion

In order to reduce pollutant emissions within the shipping sector, a potential solution could be Conoship's vanadium bromide redox flow battery-powered ship, hereafter reffered to as E-Conoship. Within this research it has been determined if E-Conoship is operational and economical feasible. This in order to deliver a 'proof of concept' for E-Conoship within the short sea shipping market of North West Europe. This has been researched by addressing the following main research question:

"Under which circumstances is Conoship's vanadium bromide redox flow battery-powered ship design operational and economical feasible in today's short sea shipping market of North West Europe?"

Operational:
In terms of operational feasibility, there are two situations in which an E-Conoship may be operationally feasible. The first, is when E-Conoship can be deployed via and through short sea shipping hubs. From a short sea shipping hub at least two laden voyages per week depart and/or arrive with a maximum voyage distance of 500nm. With this a fleet manager can divide his ships between short and long distance transport from or via these SSS hubs, or voyages from these SSS hubs can be obtained via spot market. Secondly, it is operationally feasible when routes sailed by individual ships can be replaced one-on-one by an E-Conoship. This can be achieved when a single ship completes at least 75% of all its voyages within the 500nm range.

Regarding situation one, an E-Conoship is operational feasible, when one is deployed starting in one of the SSS hubs within the Baltic sea and/or North Sea. From each SSS hub at least 100 laden voyages of less than 500nm depart and/or arrive on an annual basis.

The top 5 SSS hubs are: Rotterdam region (NL), Hull region (GB), Klaipeda (LT), Rostock (DE) and Hamburg (DE). From the ports of Rostock and Hamburg, the other ports in the top five SSS hubs are within 500nm. From the ports of Hull and Rotterdam, a stop-over to reload the battery in "fast-charge" hub Brunsbuettel is needed to reach Klaipeda, as a distance of 785nm and 710nm respectively must be crossed to reach Klaipeda.

Regarding situation two, in total 115 ships out of the 1,047 (11%) sail at least 75% of all their voyages within the 500nm range, these ships can be replaced one-to-one for an E-Conoship. From these 115 ships four different options have been found through analysing their historical voyage data.

1 Thirty-three ships of the SSS fleet (3.2%) in NW-Europe whom operate at least 75% of all its voyages within 500nm, have as main operational area the Baltic Sea. Some which overlap, with the following SSS hubs whom are located in this area: Klaipeda (LT), Rostock (DE), Riga (LV), Gdansk region (PL), Liepaja (LV), Sodertalje (SE). Routes between or via these ports present operational opportunities for an E-Conoship.

2 An E-Conoship is operational feasible when E-Conoships are deployed on routes along the Norwegian coastline. This as data analysis of the SSS fleet in chapters 4 and 5 has shown that approximately 33 ships (3.2%) of the entire SSS fleet in NW Europe completes the majority (≥75%) of its voyages ≤500nm along the Norwegian coastline.

3 Twenty-six ships (2.5%) of the SSS fleet cross regions on their voyages; within the analysed data, the ports of calls are spread along the North Sea and Baltic Sea.

4 Data analysis shows that there are certain ships that operate specific routes between two or three ports all within 500nm, whom could be replaced one-to-one by an E-Conoship in total this are about 19 ships of the SSS fleet (2.1%). Examples of such routes are: a voyage Portsmouth (GB), St Helier (JE) and Guersney (CG), and a voyage between Bayonne (FR) and Coruna (ES).

Economical:
Economically feasible is when an E-Conoship is cost-competitive with a diesel-powered ship within its economic life time of 20 years. Cost-competitive is achieved at break-even point, after which the total costs consisting of CAPEX, OPEX and VOYEX are lower compared to a diesel-powered ship. An E-Conoship with a maximum range of 500nm is economical feasible in today's short sea shipping market of North West Europe under the circumstances which will be described in the following paragraphs.

In today's market an E-Conoship is under the given circumstances not cost-competitive with diesel-powered ships, such as the Eurotrader. For an E-Conoship to be cost-competitive with an Eurotrader, multiple variables have to be changed due to different driving forces. The largest financial difference between both ships is due to costs of battery stacks (2.08MEUR) and electrolyte fluid leasing (1,295€/day) increasing each year with 2% due to inflation.

At least the VOYEX of E-Conoship must be lower than that of Eurotrader's, furthermore, a preferable step towards a cost-competitive E-Conoship is a cost reduction of battery stack and electrolyte fluid. To obtain lower VOYEX for E-Conoship compared to Eurotrader, a CO_2-tax is required, dependent on the other variables the height of the required tax can be determined. One these is that energy/fuel costs, must be low for electricity in comparison with LSMGO prices. This can be due to supply/demand, operational area or a reduction of electricity price through discount on taxes or grid-tariffs. An example of a convenient operational area is Norway, where the electricity price is currently 26€/MWh, which compared to the current LSMGO prices of 500€/t is beneficial.

Furthermore subsidies are required, to close the gap in initial investment between both ships. In addition the break-even point shifts to earlier in time by increasing the annual sailing days. Furthermore, the average voyage distance given the same amount of annual sailing days, acquired by adjusting the waiting time in port, has an effect on break-even point. The more distance is covered the earlier in time an E-Conoship becomes costs competitive with an Eurotrader. When the finance structure (WACC) for E-Conoship's initial investment results in lower interest costs compared to Eurotrader, the ship is more likely to be cost-competitive.

An additional option for an E-Conoship to be cost-competitive with diesel-powered ships, is to design a new E-Conoship with a shorter range around 200-300nm. The analysis of historical voyage data has shown, that there are operational opportunities for this short distance trades. This would decrease among others, battery stack and electrolyte fluid costs. Combined with a CO_2 tax plus a reduction in electricity prices, such an E-Conoship could be cost-competitive with a diesel-powered ship at an early stage.

10

Recommendations

First of all, this research has shown that there is potential for V/Br RFB-powered shipping within the SSS market of NW Europe. For further research into operational possibilities one could look within (possible) ECA's zones, applying the same method of analysing historical voyage data as has been used within chapters 4 and 5, examples are: the Mediterranean Sea, Sea of Japan, see figure 10.1.

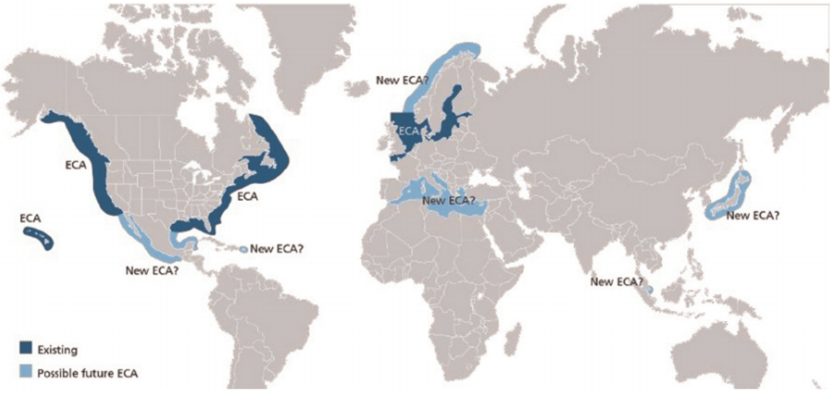


Figure 10.1: Possible future emission control areas [30]

Within section 7.4 'Evaluation of individual scenarios', the 11 scenarios are ranked, based on impact on total costs-difference and the influence which Conoship or a shipping company has on a specific scenario. Within further research to determine the influence more accurate, one could use the design tool Quality function Deployment. With this design tool one can prioritize the customers wishes, and thereby this is a tool whereby the process itself can be documented very well. With this tool the design will keep the focus on the customer and not on personal preferences.

Within this research the barrier, of infrastructure has not been further investigated. However in order to realise E-Conoship's, it's important to investigate the possibilities of charging the battery both, conventionally or via mechanical refuelling. This research shows in which area's the most operational potential can be found for V/Br RFB-powered shipping. In future research, the locations of charging stations should be investigated, in order to serve as many possible E-Conoships.

Furthermore, this research has established that the cost of both the battery stacks and the electrolyte fluid are two major cost components. Additionally, this research proofs hat it is operationally possible to deploy an E-Conoship with a limited range of 200-300nm on specific routes. In order to reduce the costs of the battery stacks and the electrolyte fluid, it should therefore be investigated if it is possible to realise an E-Conoship with a VRFB. This first generation battery has been proven in land-based applications, and the costs are potentially lower than the V/Br RFB.

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A

Barriers for Implementation

A.1. Barriers for implementation of energy efficiency measures in maritime industry

Table A.1: Barriers for implementation of energy efficiency measures in the maritime industry [22]

	Information	**Intra-organisational**	**Financial**	**Technological**	**Policy**	**Geographical**
1	lack of information	organisational culture	limited acces to capital	incompatibility between technologies and ship types	policy information barriers	piracy area
2	overload of information	inertia	external risk	immatureness technical risk	implementation barriers	route dependency
3	new-building contract not including information technologies	bounded rationality	business risk	interference with main process	lack of reviewing and amendment of policy	wind or tidal effect
4	not using information	lack of power	hidden costs	the complexity of measures	conflicting policy regulations	
5	not maintainig information	lack of trust in the organisation	heterogeneity	improvement likeliness		
6	inaccurancy of information	lack of time	imperfect budgeting	incompatibility between technologies and operations		
7	improper form of information	communication problems	unrealistic basis for cost-benefit analysis			
8	cultural difference regarding required information	the lack of trust in technologies				
9	adverse selection	split incentives				
10	moral hazard and principal-agent relationships	the ownership of vessel				
11	lack of credibility and trust in the source of information	difference in risk perception				
12	variations in circumstances					

B

Operational tables

B.1. Short sea shipping hub, departures

Table B.1: Short sea shipping hub, departures, ≤500nm

Short sea shipping hub	Total no. departures [#]	No. departures ≤500nm [#] in ballast;laden	Percentage of total no departures laden ≤500nm
Cluster VII (DE), Brunsbuettel region	241	23; **134**	56%
Klaipeda (LT)	351	75; **121**	34%
Rostock (DE)	230	62; **112**	49%
Cluster III (NL), Rotterdam region	599	181; 110	18%
Hamburg (DE)	274	42; 107	39%
Sodertalje (SE)	237	100; 103	43%
Liepaja (LV)	177	40; 83	47%
Bergen (NO)	130	18; 80	62%
Cluster II (NL), IJmuiden region	461	123; 80	17%
Cluster V (GB), Hull region	418	154; 77	18%
Riga (LV)	383	79; 76	20%
Cluster I (NL/BE), Terneuzen region	510	141; 72	14%
Cluster IV (PL), Gdansk region	266	83; 71	27%
Antwerp (BE)	314	75; 66	21%
Cluster VI (GB), Belfast region	222	48; 58	26%
Porsgrunn (NO)	155	32; 50	60%
Skogn (NO)	124	30; 36	29%
Szcecin (PL)	279	121; 36	13%

B.2. Short sea shipping hub, arrivals

Table B.2: Short sea shipping hub, arrivals, ≤500nm

Short sea shipping hub	Total no. arrivals [#]	No.arrivals ≤500nm [#] in ballast; laden	Percentage of total no. arrivals laden ≤500nm
Cluster V (GB), Hull region	405	69; **119**	29%
Cluster III (NL), Rotterdam region	594	163; **111**	19%
Cluster VII (DE), Brunsbuettel region	240	28; **105**	44%
Sodertalje (SE)	237	65; 83	35%
Cluster II (NL), IJmuiden region	454	156; 69	15%
Cluster I (NL/BE), Terneuzen region	516	189; 66	13%
Szcecin (PL)	284	40; 60	21%
Bergen (NO)	130	7; 57	44%
Rostock (DE)	232	116; 57	25%
Klaipeda (LT)	361	150; 55	15%
Porsgrunn (NO)	159	32; 54	34%
Riga (LV)	382	144; 54	14%
Hamburg (DE)	270	159; 50	19%
Skogn (NO)	124	10; 41	33%
Antwerp (BE)	316	137; 39	12%
Cluster VI (GB), Belfast region	223	91; 35	16%
Cluster IV (PL), Gdansk region	266	98; 35	13%
Liepaja (LV)	182	103; 20	11%

C

Investment costs

This section of the appendix is withheld form the repository due to confidentiality.

D

Research paper

Proof of Concept

Redox flow battery-powered short sea shipping

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Abstract: This paper provides a 'proof of concept' for a vanadium bromide redox flow battery-powered ship (E-Conoship) in the short sea shipping market of North West Europe. An elaborate analysis of historical voyage data has been carried out to determine operational feasibility. To determine economic feasibility, a cost-comparison model has been constructed, including the capital, operational and voyage related expenses of shipping. Case study method, including scenario analysis, has been used to determine under which circumstances E-Conoship is cost-competitive with diesel-powered ships. In conclusion, its operational feasible to operate an E-Conoship with a maximum range of 500 nautical miles. Two options are available: (1) direct replacement of vessels, and (2) acquiring voyages. It is economical feasible, provided that more than one of the following factors are addressed: battery system cost reduction, CO_2-tax, lower electricity prices in comparison with marine gas oil, subsidies, increased amount of annual sailing days, and lastly financing at lower interest costs compared to diesel-powered ships.

Keywords: Short sea shipping - vanadium bromide redox flow battery - feasibility study - zero emission

1 Introduction

The International Maritime Organisation (IMO) is the United Nations specialized agency responsible for prevention of pollution by ships (IMO, 2021). The IMO has adopted a strategy including the following goal: by 2050, total annual emissions of greenhouse gasses must be reduced by at least 50% compared to 2008. This is an absolute level; given the growth in trade, individual ships must reduce their pollutant emissions by 70-85% on average (IMO, 2018).

To reduce GHG emissions, within the maritime industry, Conoship International B.V. an innovative ship design and engineering office based in the Netherlands, has designed a potential solution to reduce pollutant emissions, by means of a zero-emission ship design. One of the applications could be within the short sea shipping (SSS) market. The energy source of this ship design is a vanadium bromide redox flow battery (V/Br RFB) system. Emission-free operations will be achievable because of this particular battery system. A ship operating fully electric with this system for longer distances is unique (Flaherty, 2020).

Besides this, one of the opportunities of this battery system is that it can be recharged by two different methods conventionally or with mechanical refuelling (Parasuraman, Lim, Menictas, & Skyllas-Kazacos, 2013), making the system attractive for electric ship applications. Furthermore, a V/Br RFB system has no cross-contamination problems and a long lifetime over 15,000 cycles (>20 years). In addition the system has a long charge-discharge cycle, low storage losses and efficiencies of up to 80% (Gouveia et al., 2020),(Guarnieri, Mattavelli, Petrone, & Spagnuolo, 2016),(Blanc & Rufer, 2010),(Weber, Peters, Baumann, & Weil, 2018).

2 Preliminary research

The technology of redox flow battery has been proven in land-based applications, in shipping it is still unknown (Skyllas-Kazacos, Kazacos, Poon, & Verseema, 2010). To determine whether a V/Br RFB can be applied in the shipping industry, a 'proof of concept' is required. To provide a 'proof of concept', a feasibility study is to be conducted to determine if the proposed solution is achievable. Moreover, it is to be carried out to determine if investing in more expensive full-trials is worthwhile (Brockman, 2008),(Morgan, Hejdenberg, Hinrichs-Krapels, & Armstrong, 2018). A feasibility study is useful to optimise the efficiency of research and reduce the risk of financing investments in more expensive full-trials (Morgan et al., 2018).

Analysis of different feasibility studies and theses show that it is important to first determine on which of the barriers research should focus (Al-Falahi et al., 2018), (Madsen et al., 2020), (Molitor, Bakosch, & Forsman, 2012), (Pratt, Klebanoff, et al., 2016), (Abma, Atli-Veltin, Verbeek, & van der Groep, 2019), (Dekker, 2018), (Mukhtarov, 2018), (Behrens & Hawranek, 1991). This can be done by analysing the barriers to market introduction of a new technology within the shipping industry.

2.1 Barriers

According to (Tran, Yuen, Li, Balci, & Ma, 2020) the critical factors that will lead to success in the field of sustainable shipping management are: stakeholders' focus, intra-firm management, inter-firm collaboration, new technology acceptance, and strategic fit. This illustrates that its not only the technical solution of a new technology that determines if it will be implemented on a large scale. In order to determine what the barriers are, one first needs to acquire a clear definition of a barrier:

> *"A **barrier** is anything that prevents or blocks the introduction of a new zero emission technology in the maritime industry; this can be natural or man-made."*

Several studies have been examined to gain understanding of what barriers need to be addressed before a new technology can be implemented. The results of research done by: (Bergsma, Pruyn, & van de Kaa, 2021), (Rehmatulla & Smith, 2015), and (Dewan, Yaakob, & Suzana, 2018), is combined in table 1. These researches address the barriers of introduction of new maritime technologies.

Table 1: Barriers identified$^{(1)}$

Type	Identified
Technical	1. Limited range, 2. Technology readiness level
Infrastructure	Charging facilities
Information/ knowledge	1. Inadequate, 2. Insufficient 3 Incorrect info.
Inter- and intra organisation	1. Reserve attitude, 2. Split incentive 3. Public opinion, 4. Acceptance 5. Risk perception
Policy	1. IMO regulation, 2. Classification
Finacial	1. More expensive 2. Acces to capital 3. Hidden costs

$^{(1)}$ red-coloured barriers will be further explained

(Gray, McDonagh, O'Shea, Smyth, & Murphy, 2021), have done an analysis of suitable low-carbon fuels for, among others, the maritime industry. I has been concluded among others, that one of the barriers to the introduction of battery-powered ships is limited range compared to diesel-powered ships.

The limited range for an E-Conoship, is due to the fact that, the specific energy of a V/Br RFB is 50Wh/kg, which is 200 times lower than that of marine diesel oil (Skyllas-Kazacos et al., 2010).

Due to this lower energy density Conoship's vanadium bromide redox flow battery-powered ship design, henceforward referred to as E-Conoship, has a range of 500nm at design speed. This could lead to an operational constraint whereby it is not possible to operate an E-Conoship within the SSS market of NW Europe. Without being able to sail merchant voyages, an E-Conoship cannot be operated, so this barrier needs to be further investigated.

'Green' solutions are often more expensive than conventional ones, which increases the payback period and reduces the economic incentive to invest (Serra & Fancello, 2020). The 'most' common response to the financial barrier, more expensive is that very few actors want to invest. It is currently unknown what the total costs, consisting of fixed and variable costs of this ship type will be, and under which circumstances this ship could be economical feasible in today's SSS market of NW Europe. To deliver a proof of concept is therefore required to determine these.

The objective of this research is to deliver a 'proof of concept' for the operational and economical feasibility of V/Br RFB-powered shipping. This, to bring the realisation of this ship type one step closer to fruition, in order to reduce the shipping sectors GHG emission. Furthermore, by doing so inform among others, Conoship, and potential shipowners about the opportunities and barriers of the system, the possibility of operating V/Br RFB-powered vessels and under which circumstances V/Br RFB-powered shipping is economically cost-competitive with a state of the art diesel-powered ship. The main research question addressed within this research is as follows:

"Under which circumstances is Conoship's vanadium bromide redox flow battery-powered ship design operational and economical feasible in today's short sea shipping market of North West Europe?"

The paper continues with the research methodology. After which the the operational feasibility is discussed, in chapter 4. The economical feasibility is dealt with in chapter 5. The last chapter addresses the main research question.

3 Research methodology

Within this section the research methodology regarding the operational and economical feasibility of an E-Conoship is dealt with. In the first part the methodology used to determine the operational feasibility will be dealt with in the following part the economical feasibility will be elaborated on.

Operational feasibility

A limited range could be an impediment to the introduction of an E-Conoship. It must first be identified if there is any market potential for ships to complete short distance (≤500nm) voyages. Activities of ships operating on the SSS market are required to be defined. This has been done by analysing historical voyage data, chapter 4.

Once the capability to operate ships with a limited range have been assessed, research can continue to determine the current shipping routes that present the greatest potential for an E-Conoship. This in order to determine under which circumstances an E-Conoship is operationally feasible in today's SSS market. In doing so, the first two phases: establish terms of reference and analyse past trends, of market research will be carried out (Stopford, 2008).

Economic feasibility

A (financial) barrier of the introduction of a new technology in SSS, is that the new technology is often more expensive than a conventional one. For an E-Conoship, the total costs, consisting of capital, operational and voyage related expenditures are unknown. Furthermore, for many of these costs there are uncertainties that affect them. In order to determine the economical feasibility of an E-Conoship, these will be determined.

An E-Conoship is considered cost-competitive if, within 20 years the economic lifetime of both vessels, a break-even point is reached after which the total costs are lower compared to a diesel engine-powered ship. A diesel-powered ship has been chosen for comparison for several reasons, one of which is that the majority of today's ships operate on diesel engines. In addition, with existing regulations a ship equipped with a diesel engine (compliant among others with IMO tier 3) can still be built today and used for over 20 years.

This research does not go into the uncertainties related to potentially higher income for a 'green ship'. Within this research deadweight cargo capacity (DWCC), hold volume and no preference of the cargo owner will be taken into account. Given above statements income for both ships are the same and, are therefore not included within this economical feasibility study. Result is that a break-even analysis has been done solely based on the fixed and variable costs of the two vessels.

Several methods can be used to compare different alternatives. A case study method is used by many to compare alternatives, including a thesis by (Priyanto, 2017) that uses this method to determine the economic feasibility of methanol versus marine diesel oil shipping. In addition, two other studies one by (Mukhtarov, 2018) and one by (Al-Falahi et al., 2018) use a case study methodology to compare economic shipping costs. According to (Yazan, 2015), there are different views on case study methods, but all methods contain the same phases, namely: case definition, data collection, data analysis and data validation, see figure 1.

Figure 1: Four phases of a case study (Yazan, 2015)

Once the economic shipping costs: VOYEX, CAPEX and OPEX are determined for a base case (case 1.0), the first break-even analysis is made. Then, the third phase of a case study can be carried out with scenario analysis.

With scenario analysis it can be determined, under which circumstances an E-Conoship is cost-competitive with to a diesel-powered ship. Scenario analysis embraces the uncertainty of the future by exploring independent and unrelated futures, while maintaining the analytical precision of existing quantitative tools within each future scenario (Tourki, Keisler, & Linkov, 2013). (Tourki et al., 2013) proposed the following methodology for scenario analysis, see figure 2.

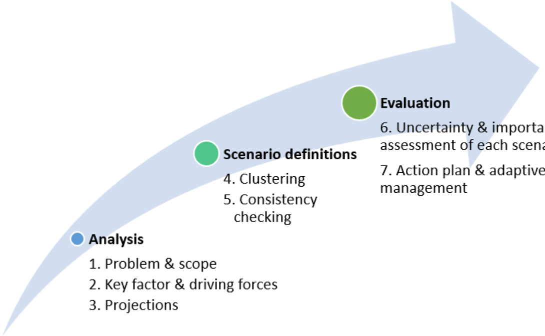


Figure 2: Methodology for scenario analysis (Tourki et al., 2013)

4 Operational

From the preliminary research in chapter 2, it is evident that it is important to know if ships with a limited range can complete merchant voyages. It is essential that this question is answered in order to conduct further research, and it is therefore dealt with in this chapter.

4.1 Analysis historical voyage data

An analysis of historical voyage data can be used to determine if a limited range is an impediment to the introduction of an E-Conoship. For this analysis competitors for a general cargo E-Conoship destined to operate in the SSS area of NW Europe, have been used. The geographical area extends from the port of Seville, Spain to the port of Arkhangelsk, Russia, including ports in the Baltic Sea. The area of NW Europe has been chosen due to the ECA zones, public opinion and the European climate goals. Inland waterways are not included in this study because of the unfavourable weight ratio between V/Br RFB-sytem and the DWCC, when applied to 'small' inland vessels.

Ships included in the analyse data are general cargo ships for SSS between deadweight all told (DWAT): 3,000DWAT and 7,500DWAT, which consists of the following ship types: multi-purpose (MPP) ships, general cargo ships, bulk carriers, aggregates carriers, palletised cargo carriers and MPP/Heavy lift cargo ships. At first, through Clarksons Research (Clarkson Research, 2021), the World Fleet, as registered in December 2020, has been acquired for the earlier mentioned ship types, see figure 3.

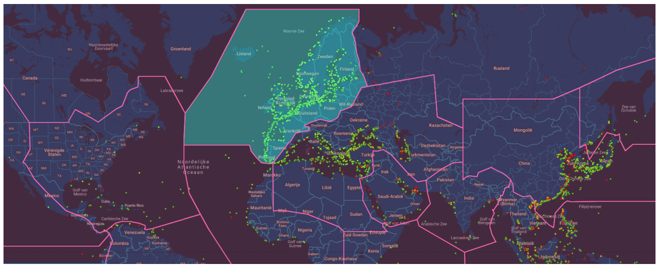


Figure 3: Snapshot: general cargo world fleet, December 2020 [3,000 - 7,500 DWAT] (Clarkson Research, 2021)

The total world fleet of the above mentioned ships, contains 4,855 ships. Systematically this fleet has been reduced to ships operating in the SSS market of NW Europe. This results in a total SSS fleet operating in NW Europe of 1,047 ships (21.6% of total fleet), which are considered to be of interest. To determine the SSS routes and associated distances travelled, a representative sample of the entire fleet has been taken.

First the sample size for a finite number of initial vessels has been determined, this has been done using the sample size formula for a finite population with the following input: 50% as an estimate of the population proportion, level of confidence 95% and margin of error of 5% to maximise the sample size (Taherdoost, 2016).

The result is that the sample should contain 281 ships. Then with quota sampling a non-probability technique the sample is constructed, this is a method at which, in this case particular ships are chosen based on predefined features (Taherdoost, 2016).

For this research the following two quotas are set:
1. DWAT distribution of the different vessels in the sample must be similar to that of the entire SSS-fleet.
2. No. vessels per operators must be in the same ratio as that they are represented in the entire SSS-fleet

The result of the application of the first quota is shown in figure 4, a similar distribution of vessels per DWAT as the whole SSS fleet. As for the second quota, from the list of 1,047 vessels per bin of 500 DWAT, a number of vessels were selected taking into account quotas 1 and 2.

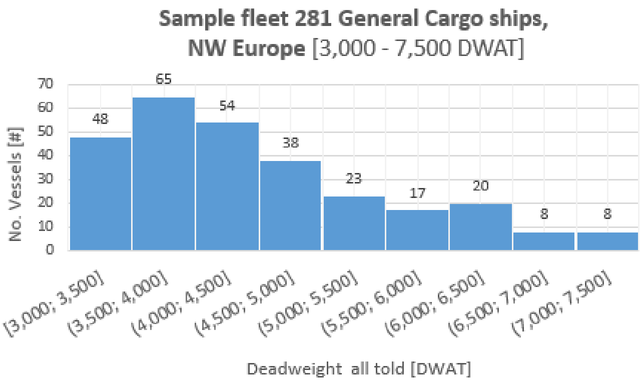


Figure 4: General cargo, short sea shipping sample fleet, 281 ships, NW Europe [3,000-7,500DWAT]

For those 281 vessels, with known IMO number, historical data has been collected to determine the voyages over the following period from the 19th of January, 2020 up to the 19th of January, 2021(Marine Traffic, 2021).

Results and conclusion

After the individual voyage data of each vessel has been collected, the number of voyages and associated distance are analysed. After analysing almost 25,000 port calls of 281 general cargo vessels in the NW Europe SSS market over the past year, it becomes clear that with a 500nm range about 62% of all voyages can be completed. Furthermore, about 11% of the vessels sail at least 75% of all their voyages within the 500nm range. The 11% represents 115 vessels operating in NW Europe.

Historical voyage data shows that with a limited range of 500nm more than half of all voyages over the past year can be completed. In addition, there is potential for replacement of 115 ships, without changing existing trades. However, it is still important to get a better understanding of the SSS market in NW Europe to clearly define what area/ports/routes present potential for E-Conoship's.

4.2 Market research

The goal of this chapter is to better understand the SSS market, thereby identifying which current shipping routes present the most potential for vanadium bromide redox flow battery-powered shipping by analysing past trends.

4.2.1 Terms of reference

E-Conoship provides a range of 500nm at a design speed of 10 knots. This range includes a 15% sea margin. To determine the operational feasibility of an E-Conoship (market) potential, will be analysed through two different situations. The two situations are analysed using historical voyage data of 281 vessels, which are representative of the entire short sea shipping fleet of 1,047 vessels operating in NW Europe.

Situation one, port side, selecting routes between or via SSS hubs that have a high degree of laden voyages. From each SSS hub at least 100 laden voyages of less than 500nm depart and/or arrive on an annual basis. With this on average 2 voyages per week depart and/or arrive laden at these hubs. Therefore, it is assumed that via spot-market or by a fleet manager that divides its vessel between short distance and long distance transport revenue-generating trips to and/or from these hubs can be realised.

Situation two, shipping side, selecting routes based on individual vessels operating at least 75% of all their voyages within the 500nm range. In this situation, it is expected that a (old) ship can be one-to-one replaced by an E-Conoship without jeopardizing the existing trade routes.

4.2.2 Analysis past trends

Within this section the historical voyage data will be analysed according to the two situation as described above. Furthermore, within this research, ship loading conditions are combined in two groups: ”in ballast” and ”laden”. Laden includes voyages either partially laden or (fully) laden. One reason for this is that a partly laden voyage can potentially generate a higher income than a fully laden voyage. Secondly, a voyage that is not partly laden or laden will be completed ”in ballast” and, compared to a voyage that is completed empty, all cargo carried is considered profitable.

Situation 1: No. laden voyages
To determine what area(s) and/or route(s) present potential for V/Br RFB-powered shipping the short sea shipping hubs will be identified, based on number of inbound and outward laden voyages. Over the past year, the SSS fleet of 281 vessels has moored in 956 unique ports, including several outside NW Europe. This is due to the fact that the vessels sometimes pass ”the border” of the defined area of interest NW Europe.

To analyse vessel movements, and determine merchant voyages, the historical voyage data must be preprocessed. At first voyages with a distance less than 5nm are those (1,062) from a specific terminal within a port area to another terminal in the same area. Which are irrelevant for the determination of the short sea shipping voyages and are therefore excluded of further data-analysis. In addition analysis of the data shows that ports which are close to each other and/or have traffic between them, can be seen as one cluster of ports. Close to each other is defined as a distance X, between 5nm≤ X ≤15nm. Therefore, in the context of this thesis, ports that are in proximity to each other and/or have regular voyages between them are considered to be a cluster. In the end seven clusters are identified in NW Europe, see table 2.

Table 2: Clusters in the SSS area of NW-Europe

Cluster; Region	**Ports within each cluster**
I; Terneuzen	Vlissingen (Stad) (NL), Terneuzen (NL), Sluiskil (NL), Zelzate (BE) and Ghent (BE)
II; IJmuiden	Amsterdam (NL) and IJmuiden (NL)
III; Rotterdam	Schiedam (NL), Vlaardingen (NL), Rozenburg (NL), Rotterdam,- Waalhaven, Vondeling, Maasvlakte, Europoort, Botlek, Centrum and Delfshaven (NL)
IV Gdansk	Gdanks (PL) and Gdynia (PL)
V; Hull	Hull (GB), Immingham (GB), New Holland (GB), Barrow Haven (GB), Goole (GB) and Grimsby (GB)
VI; Belfast	Belfast (GB) and Kilroot (GB)
VII; Brunsbuettel	Brunsbuettel (DE) and Ostermoor (DE)

After removing the inter cluster voyages, 22,627 voyages are left to be analysed. With these known seven clusters, the top 25 short sea shipping ports and Clusters in NW Europe, based on number of arrivals and departures is determined. This top 25, is further analysed to determine the SSS hubs. Determined, with cut-off criteria of 100 laden voyages within the 500nm range inbound and outbound combined at each cluster or port. With at least 100 laden voyages on an annual basis of less than 500nm, an average of 2 voyages per week depart and/or arrive at the hub. This provides opportunities for revenue-generating trips to and/or from these hubs.

Some ports or cluster areas must be passed by before among others: ports along the Baltic Sea, ports inside large fjords and other large ports can be reached. These are ’special’, because in terms of laden voyages they are not SSS hubs. However, plenty vessels pass these port area’s and in many cases they have to wait, before they can enter the locks. In addition, from these ports many SSS hubs are within E-Conoship’s sailing range. This makes such ports suitable locations for fast charging stations, both geographically and in terms of the amount of passing shipping traffic. The two 'special' ones are Brunsbuettel region (DE) and Sodertalje (SE). Further research is needed to determine to what extend these ports can serve as charging stations. The top 5 SSS hubs, with regard to, No. departures and arrivals laden within the 500nm, whereby cargo is loaded and/or unloaded is:

1. Rotterdam Region, 2. Hull region, 3. Klaipeda (LT), 4. Rostock (DE) and 5. Hamburg (DE)

Situation 2: one-to-one replacement

11% (31/281) of the SSS sample fleet sails at least 75% of all their voyages less than the 500nm range. To determine the sailing area of these 31 vessels, individual voyage data has been analysed. These ships sailing short sea, ≤500nm, are operated by 26 different operators, which shows that there are many different trades available for short range maritime transport. Rix Shipping (LV) is best represented with 3 ships; Rix Alliance, Rix Mistral and Rix Star.

Detailed analysis shows that some vessels operate within a "bounded" geographical area, among others are: Ingvild, and Vingaren, see figure 5a and 5b.

(a) IMO 9195822, Vingaren (Kanalratte, 2020)

(b) IMO 7633387, Ingvild (Insil, 2010)

Figure 5: Vessels operating at least ≥ 75% of all voyages ≤500nm

Vingaren, IMO 9195822 with 4,748DWAT and age 20.8 years operates approximately 90% of all its voyages within the 500nm range. Over the past year this ship completed most of its voyages within the Baltic Sea area. The oldest vessel operating at least 75% of all its voyages within the 500nm range is Ingvild, IMO 7633387, with 4,418DWAT and age 43.3 years. Last year's voyages were mainly along the Norwegian coastline.

Scan Fjord, IMO 8015879 and Kristian With, IMO 9375898, are elaborated in more detail, to illustrate the potential of vessel replacement and the routes that present potential for E-Conoship's. Those two ships have completed almost 100% of their merchant voyages within the 500nm range. The Kristian With has a deadweight of 3,345DWAT and an age of 13.7 years. The Scan Fjord has a deadweight of 3,319DWAT and age 38.9 years. Both ships sailed most of their voyages along the Norwegian coastline during the past year.

Furthermore, detailed analysis shows that some operate on very specific routes, among others: 1. Musketier, IMO 9369514, 2. SUA, IMO 9436276 and 3. Milady, IMO 9319430, see table 3. These ships could be replaced one on one by an E-Conoship.

Table 3: Short sea shipping routes ≤500nm

Ship	Departure	Arrival	Distance	No. Voyages
1	Portsmouth (GB)	Guernsey (CG)	107nm	103
	Portsmouth (GB	St Helier (JE)	120nm	74
	St Helier (JE)	Portsmouth (GB)	120nm	33
	St Helier (JE)	Guernsey (CG)	26nm	81
	Guernsey (CG)	Portsmouth (GB)	107nm	83
	Guernsey (CG)	St Helier (JE)	26nm	31
2	Bayonne (FR)	Coruna (ES)	310nm	64
	Corunua (ES)	Bayone (FR)	310nm	51
3	Baltisysk (RU)	Mukran (DE)	225nm	47
	Mukran (DE)	Baltisysk (RU)	225nm	45

Within figure 6, the SSS hubs in NW Europe in terms of short sea shipping (≤500nm) can be seen. The intensity of shipping traffic is roughly given, represented with green colours in addition the yellow lines are the main shipping lanes for all cargo shipping. The purple-coloured ports are those 'special' ones at which many voyages pass by, which present potential for fast charging stations. Lastly for situation 1, the blue-coloured ports are the SSS hubs, this ports are located along the North Sea and the Baltic Sea. Fixed routes are sailed between the green-coloured ports.

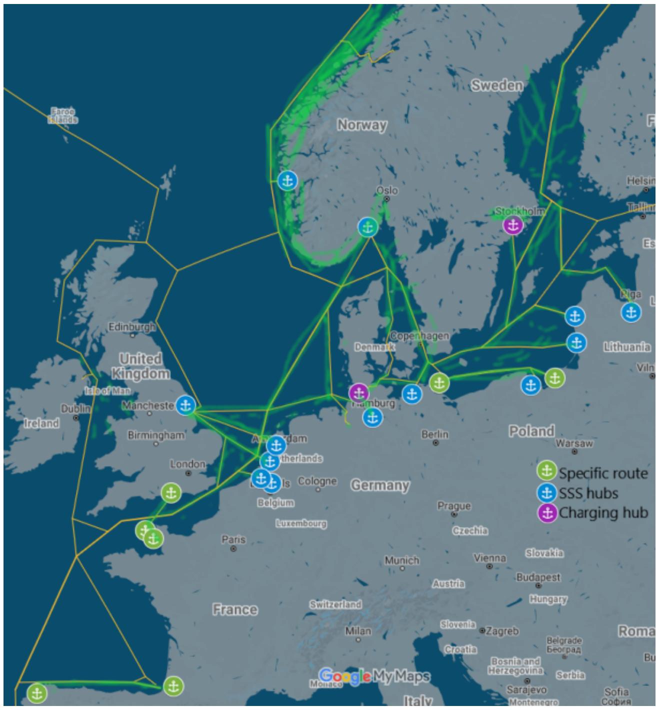


Figure 6: SSS hubs and specific routes, NW Europe

5 Economical

Within this economical chapter first the cost-comparison model will be described in the following section with scenario analysis the different circumstances will be determined under which and E-Conoship is cost-competitive compared to a diesel-powered ship.

5.1 Cost-comparison model

Determining under which circumstances the E-Conoship design is cost-competitive with a diesel ship, is the purpose of this chapter and has been done by means of a cost-comparison model (CCM).

General outline

In this cost-comparison model (CCM) an E-Conoship will be compared to Eurotrader, a diesel-powered ship, based on the following economic parameters: CAPEX, OPEX and VOYEX. Within the model the economical lifetime of both vessels is set at 20 years. An E-Conoship is considered cost-competitive if, within the economic lifetime of both vessels, a break-even point is reached after which the total costs are lower compared to a diesel-powered ship. Initially, all cost components are calculated for the current situation. Then, various scenarios are carried out to determine under which circumstances an E-Conoship is cost-competitive compared to a diesel-powered vessel.

CAPEX, consists of the initial investment and periodic cash payments in form of interest on the average outstanding debt between beginning and end of a period. Part of the initial investment costs of E-Conoship are the battery stacks needed for the vanadium bromide redox flow battery.

OPEX, are the costs related to the daily running of the vessel, excluding fuel costs but including repairs and maintenance. In this model, the costs related to E-Conoship's required electrolyte fluid are included in the OPEX via a lease construction. The OPEX increases each year by an inflation rate of 2%.

VOYEX, consists of port, pilotage and fuel costs, for the E-Conoship the latter are the costs related to recharging the electrolyte fluid. In addition, the voyages related costs increase each year by an inflation rate of 2%.

Cargo handling costs, are not considered within the CCM, because only costs that differ are important. It is assumed that these costs are the same for both ships, due to similar: DWCC, volume of cargo hold, and vessel length between perpendiculars (L_{pp}).

Break-even analysis

To determine if an E-Conoship is cost-competitive, a break-even analysis will be conducted, as shown in figure 7. In this analysis, the initial investment is depicted by c. Furthermore, costs accumulated over time (x in years), OPEX and VOYEX, represented by a and b respectively, are considered. These costs become more expensive over time due to inflation. Lastly, the interest costs are considered, depicted by d.

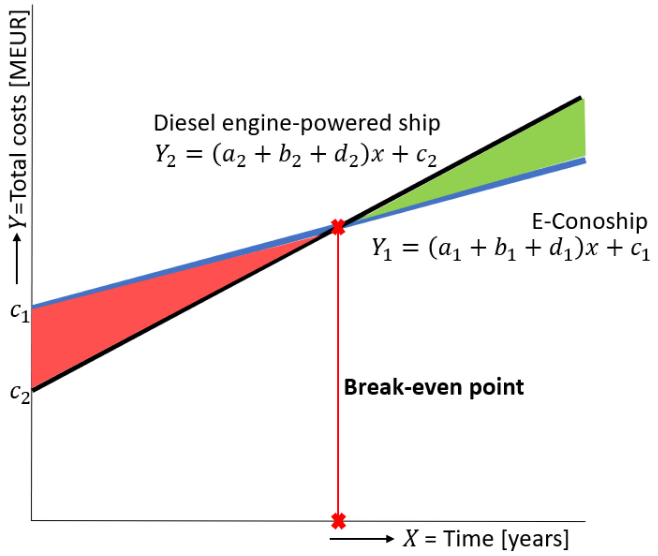


Figure 7: Break-even analysis; E-Conoship and diesel-powered ship

Voyage input, break-even analysis

The first voyage, case 1.0 used in the break-even analysis is based on the analysis of historical voyage data analysis, where one of the conclusions is that several ships sail (almost) fixed routes, one among others is the ship Sua (IMO9436276). Sua, has completed 185 sailing days in the past year, 2020 to 2021, most of them between Bayonne (FR) and Coruna (ES) over a distance of 310nm. In the model it is assumed that with more efficient planning 200 annual sailing days per year could be possible this lead to case 1.0 within table 4. Within the remainder of this research also a second voyage, case 2.0, will be dealt with this is a voyage between SSS hubs, see table 4.

Table 4: Voyages input for the CCM

Condition	**Case 1.0, avg 310nm**	**Case 2.0, avg 474nm**
Laden	Bayonne (FR) - Coruna (ES)	Hamburg DE) - Klaipeda (LT)
Ballast	Coruna (ES) - Bayonne (FR)	Klaipeda (LT) - Porsgrunn (NO)
Laden	Bayonne (FR) - Coruna (ES)	Porsgrunn (NO) - Szczecin (PL)
Ballast	Coruna (ES) - Bayonne (FR)	Szczecin (PL) - Riga (LV)
Laden	Bayonne (FR) - Coruna (ES)	Riga (LV) - Rostock (DE)

5.2 Scenario analysis

In the previous section 5.1 the CCM is described. Within this section the total cost for case 1.0 are analysed to determine what the key factors are which influence the total costs. In table 5 the differences between E-Conoship and Eurotrader are given in absolute figures. Whereby the variable costs, interest, OPEX and VOYEX [€/day] are given for year zero to one. The amount of variable costs to be paid differs each year. The OPEX and VOYEX, become each year more expensive due to an inflation rate of 2%, however the relative difference between both vessel, respectively 43% and 16%, remain constant. Furthermore the amount of interest to be paid over the outstanding debt declines each year, but the relative difference between both vessel remains 2%.

Table 5: Case 1.0, cost components

Cost type	**E-Conoship**	**Eurotrader**	E-Conoship vs. Eurotrader
Initial investment [€]	12,669,580	9,548,640	+3,120,940
Interest [€/day]	1,342	1,315	+2%
OPEX [€/day]	3,444	2,409	+43%
VOYEX [€/day]	3,505	3,033	+16%
Total daily costs, year [0,1) [€/day]	8,291	6,757	

With this data the break-even analysis can be made, see figure 8. Under given circumstances, the lines for the total costs of both ships diverge and no break-even point will be reached. Based on the assumptions made, the E-Conoship is therefore not cost-competitive compared to Eurotrader.

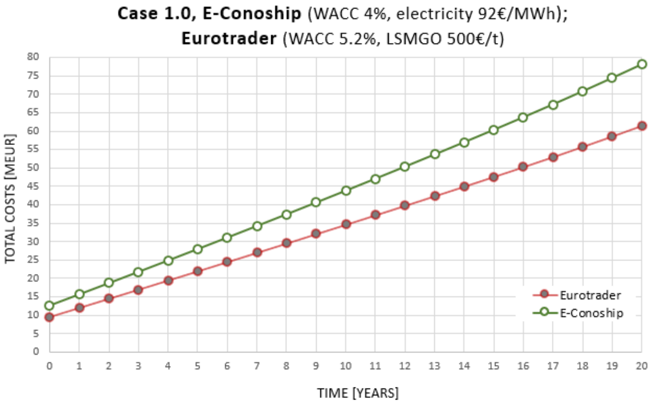


Figure 8: Break-even analysis case 1.0

Analysis cost-components

In this section, the cost-components of case 1.0 in the CCM are analysed to determine which variables contribute to the difference in costs and to what extent they can be changed. First the difference in CAPEX will be analysed, followed by OPEX and lastly VOYEX difference.

Analysis difference in CAPEX

The investment costs of a first-off build E-Conoship are approximately 3.12 million euros (MEUR) higher than that of Eurotrader. The general cost (+27%), the hull and superstructure (+18%) and finally the electrical installation (+550) are more expensive than that of Eurotrader.

Within general costs, the main difference in costs is caused by the fact that E-Conoship will be the very first vessel (first-off) with this technology, which requires more time for design and engineering. In addition, certifying bodies require more time and resources to approve this new technology. Regarding the Hull & Superstructure, E-Conoship requires 18% more steel than Eurotrader to achieve the same amount of DWCC and hold volume, result is that E-Conoship is more expensive. This is directly related to the fact that both the specific energy and the energy density of V/Br RFB are 200 times smaller than that of low sulphur marine gas oil (LSMGO), result a larger ship is required. Within the electrical installation costs the largest expenses are the battery stacks with a total cost of 2.08MEUR This is determined based on a cost-price of 800 €/kW, provided by VanadiumCorp, times 2,600kW which is the maximum output of the double stack set up.

Furthermore, the capital costs in form of interest are 2% higher than that of Eurotrader. This is due to the fact that required loan on initial investment for E-Conoship is more than 3MEUR higher compared to Eurotrader. The relative difference is less than the relative difference in initial investment, because within the CCM it is assumed that a 'green' ship, such as E-Conoship can be financed with lower weighted average capital costs (WACC) in form of interest. Lower WACC has been taken, because the risk profile of a 'green's ship is lower compared to Eurotrader.

Analysis differences in OPEX

The operational costs of E-Conoship are 43% higher than that of Eurotrader. The OPEX consist of 6 groups, whereby the insurance of E-Conoship (+33%) is more expensive than Eurotrader, the higher insurance costs are due to the fact that the vessel to be insured is more expensive to purchase resulting in higher insurance costs. The largest difference in operational expenditure is due to the lease costs of electrolyte fluid, 1,295€/day, which account for 38% of the OPEX of E-Conoship.

Analysis differences in VOYEX

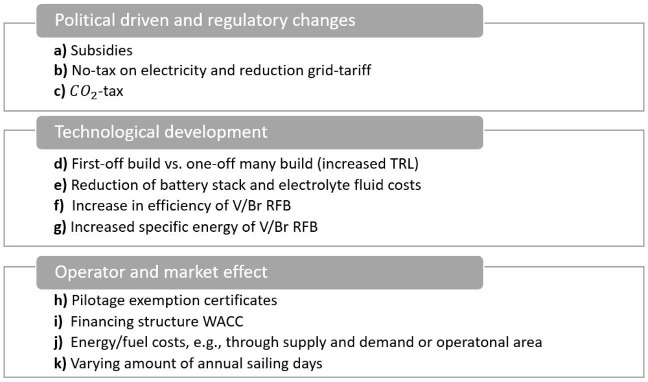
Voyages related costs are +16% higher than those of Eurotrader. All components are more expensive. The port dues are more expensive as E-Conoship has a larger GT-size than Eurotrader, 3,818GT vs. 3,080GT.

Furthermore pilotage costs are higher for E-Conoship as the actual deepest vessel draught in loaded condition is higher than that for Eurotrader. Pilotage dues could be avoided by applying for a pilotage exemption certificate (PEC). This is not included in case 1, but it could be taken into account to reduce overall VOYEX.

The energy/fuel costs of E-Conoship are 21% higher than that of Eurotrader, this is partly due to the fact that the V/Br RFB itself has a efficiency of 82%, which results in an increase of 18% in required electricity to charge the battery. Furthermore, in today's shipping market there are no penalties (taxes) for vessels who pollute CO_2, which results that with current electricity and LSMGO prices E-Conoship's total energy/fuel costs are higher than that of Eurotrader.

Scenario definitions

Within the model the cost-component which can be changed, due to among other how the future will look in terms of regulations or technological breakthroughs, will be varied. There are different driving forces that can cause the variables in the model to change. In total 11 different scenarios are determined, see figure 9.



Political driven and regulatory changes

a) Subsidies
b) No-tax on electricity and reduction grid-tariff
c) CO_2-tax

Technological development

d) First-off build vs. one-off many build (increased TRL)
e) Reduction of battery stack and electrolyte fluid costs
f) Increase in efficiency of V/Br RFB
g) Increased specific energy of V/Br RFB

Operator and market effect

h) Pilotage exemption certificates
i) Financing structure WACC
j) Energy/fuel costs, e.g., through supply and demand or operatonal area
k) Varying amount of annual sailing days

Figure 9: Break-even analysis case 1.0

For an E-Conoship to be cost-competitive compared to Eurotrader, different of the above scenarios have to be put into effect. In addition, not all different scenarios have the same impact on the cost-difference. Some, scenarios cannot be influenced by Conoship or a shipping company.

To determine under which circumstance E-Conoship is cost-competitive compared to Eurotrader, the scenarios which have the largest impact on the total costs will be combined. These are: subsidy, CO_2-tax, reduction in costs: battery stack and electrolyte fluid, variation of energy/fuel costs, annual sailing days, and lastly financing structure. Within the next paragraphs the scenarios with the largest impact are further explained.

Explanation

Impact of a subsidy is large as, it could reduce CAPEX, OPEX or VOYEX significantly. In addition the quality of the subsidy proposal and the level of (green) innovation determine whether the subsidy can be acquired, this is something at which the applicant has a large influence on. However, the maximum amount of subsidy rewarded per applicant cannot be influenced by Conoship or a shipping company, as this is in most cases pre determined (Rijksdienst voor Ondernemend Nederland, 2021).

The impact of a CO_2-tax is large, as with this tax the VOYEX of Eurotrader will increase while the VOYEX of an E-Conoship will remain similar. In addition, this amount of tax to be paid increases with more annual sailing days. The introduction of a possible tax could be influenced by lobbying or by showing among others governments, IMO, that there is a viable alternative to pollution ships when a CO_2 tax is applied.

A reduction in costs of both battery stack and the leasing of electrolyte fluid have a large impact on the total costs of E-Conoship. When both are reduced the CAPEX and OPEX decreases, with the result that E-Conoship becomes less expensive. Conoship or a shipping company could influence this by asking for price quotes from different companies and contracting the most affordable supplier. In addition costs could be reduced by optimising the required amount of electrolyte fluid an battery stack for a certain trade, for example a range of 300nm instead of 500nm.

Low electricity prices and high LSMGO prices leads to large difference in fuel costs, with as result that VOYEX of E-Conoship becomes less expensive compared to Eurotrader. Influence on fuel prices can be influenced by an operator, by operating E-Conoship's in areas with low electrical energy prices and high LSMGO prices. In addition the amount of annual sailing days influences the fuel costs, when more annual sailing days are obtained these costs will increase. For an E-Conoship to be cost-competitive with Eurotrader, besides high annual sailing days a requirement is that the fuel costs in must be lower than Eurotrader's. The amount of annual sailing days can be influenced by an operator optimizing the voyages, such that minimum time is lost in port, and average voyage distance is as close as possible to the maximum range of the ship.

The last scenario which has a large impact is the financing structure. With a WACC of 6.4% for Eurotrader and a WACC of 4% for E-Conoship, the interest costs of E-Conoship are less than that of Eurotrader. This despite the fact that the initial investment of E-Conoship in the current situation is more than 3MEUR higher than that of Eurotrader.

Combination scenarios

In total 4 combination scenarios are implemented, with lower electricity prices than in case 1.0. This is because VOYEX has to compensate for the the higher initial costs and OPEX of E-Conoship compared to Eurotrader.

Table 6: Combination scenarios

Combination scenario	x.1	x.2	x.3	x.4
a) Subsidy [MEUR]	1.25	1.25	1.25	1.25
c) CO_2-tax [€/tCO_2]	150	150	150	150
e) Reduction of battery stack and electrolyte fluid costs [%]	-	-	25	25
i) Financing structure, WACC [%]	-	4; 6.4	4; 6.4	4; 6.4
j) Energy/fuel costs [€/MWh ; €/t]	26; 500	26; 500	26; 500	26; 500
k) Amount of annual sailing days	-	-	-	220

For these combination scenarios, the break-even point is determined in each case, after which E-Conoship is cost-competitive with Eurotrader, see table 7. Within table 7 a [-] sign, means that no break-even point is reached within the economical lifetime of both vessels given the circumstances of that specific case.

Table 7: Break-even point for different cases

Case	Break-even point	Case	Break-even point
1.0	-	2.0	-
1.1	6yr and 43wks	2.1	6yr and 26wks
1.2	5yr and 5wks	2.2	4yr and 46wk
1.3	2yr and 33wks	2.3	2yr and 29wks
1.4	2yr and 20wks	2.4	2yr and 16wks

From table 7, it can be seen what the effect is of increasing the amount of scenarios, starting with case 1.0, where no break-even point is obtained, until case 1.4 at which a break-even point is obtained after 2year and 20weeks. When the voyage distance increases, as in cases 2.x, the break-even point will be earlier in time.

A subsidy of 1.25MEUR for E-Conoship, 150€/tCO_2 tax, electricity 26€/MWh and LSMGO 500€/t, results in break-even after 6yr and 43wks, see figure 10.

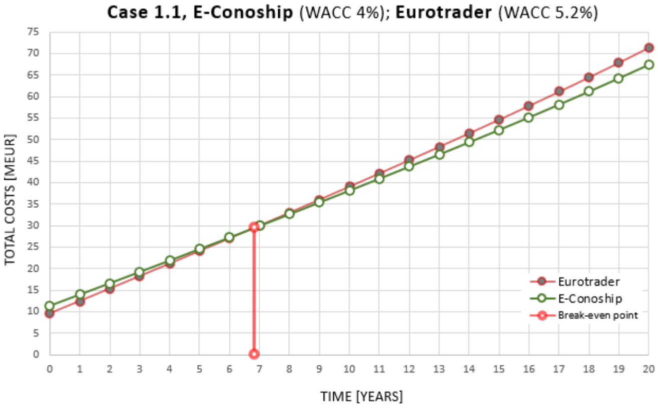


Figure 10: Break-even analysis, case 1.1

When additional to case 1.1: a 25% reduction in the cost of the battery stacks and electrolyte fluid, and Eurotrader WACC increases from 5.2% to 6.4%, amount of annual sailing days increases with 10% to 220, the time until break-even reduces by almost three times, see case 1.3 within figure 11.

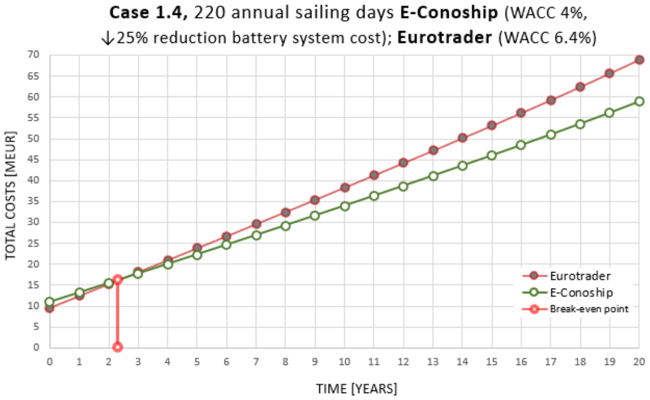


Figure 11: Break-even analysis, case 1.4

6 Conclusion and discussion

In order to reduce pollutant emissions within the shipping sector, a potential solution could be an E-Conoship. The operational and economical feasibility of the E-Conoship has been researched. This has been researched by addressing the following main research question:

"Under which circumstances is Conoship's vanadium bromide redox flow battery-powered ship design operational and economical feasible in today's short sea shipping market of North West Europe?"

It is operational feasible because, there is an opportunity to replace a total of 115 ships out of 1,047 (11%), as those sail at least 75% of all their voyages within the 500nm range. These 115, ships operate divided over 4 areas: along the Norwegian coastline, specific routes, Baltic Sea, and lastly between North Sea and Baltic Sea. Furthermore, an E-Conoship is operational feasible, when one is deployed starting in one of the SSS hubs within the Baltic sea and/or North Sea. From each SSS hub at least 100 laden voyages of less than 500nm depart and/or arrive on an annual basis. These voyages can be acquired, when a fleet manager divide his ships between short and long distance transport, or voyages are obtained via the spot market. It is economical feasible, provided that more than one of the following factors are addressed: battery system cost reduction, CO_2-tax, lower electricity prices in comparison with marine gas oil, subsidies, increased amount of annual sailing days, and lastly financing at lower interest costs compared to diesel-powered ships.

Discussion

The main opportunity of this system in shipping is that an E-Conoship will not produce any polluting emissions during operation (sailing). In this context, its important that the system is charged with renewable energy, e.g. solar or wind power, so that the emissions of the system are as low as possible not only during operation, but also over its entire life cycle. Otherwise it is not an ethical and sustainable solution for the reduction of GHG emissions, then it is merely a relocation of pollutant emissions.

An E-Conoship has a range of 500nm, for this reason research has been carried out into the possibilities of completing short-distance voyages. To date, this has not been carried out, because for diesel-powered ships, a greater range is no problem at all. Thereby, this research contributes to increasing scientific knowledge of the operational possibilities of limited range sailing for the general cargo SSS market. The strength of this research into the economical feasibility, with means of the CCM model is that: the variables in the model can be changed to determine for different (circumstances) scenarios when E-Conoship is cost-competitive with Eurotrader.

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