KTH ROYAL INSTITUTE
OF TECHNOLOGY

This work was presented at the Unit of Heat and Power Technology

Paths forward for Sustainable Maritime Transport
A techno-economic optimization framework for next generation vessels

Master Thesis

By

Julian Ulrich Hausweiler

Student ID 08111962

TRITA-ITM-EX 2023:534

Examiner: Professor Andrew Martin, PhD in Mechanical Engineering, KTH
Internal Supervisor: Mahrokh Samavati, PhD in Process Engineering, KTH

External Supervisor: Vaidehi Gosala, PhD in Electrical Engineering, DLR

Stockholm, 14th of August 2023

# Abstract

Recently, the decarbonization of maritime transport has received increased attention, in order to align with the targets of the Paris Agreement. In 2023, the International Maritime Organization unveiled their revised greenhouse gas strategy with an ambitious target: net-zero emissions by 2050. Addressing this challenge necessitates significant investments in technologies that enable net-zero emissions during vessel operations. While net-zero fuels present an environmental solution, their economic viability remains a challenge under present conditions. This thesis presents a comprehensive techno-economic framework tailored to assess investments in net-zero vessels.

A review of existing literature reveals that investing in vessels involves intricate decisions, often accompanied by high capital costs. Crucially, voyage costs—primarily determined by fuel expenditures—emerge as pivotal in assessing a vessel's financial sustainability. This insight underscores the need for an integrated approach that combines economic considerations with fuel efficient operation. To this end, the study introduces a dual-layer optimization framework: The outer layer optimizes for the vessel's net present value, while the inner layer models the vessel's operational control strategy. The applicability of this framework is then tested using the German container ship sector as a case study. The applied technology consists of a fuel cell electric propulsion system based on hydrogen.

The findings paint a complex picture. Net-zero vessels necessitate considerably higher capital expenditures than their diesel counterparts. The propulsion system contributes to this increase, but the main share of the cost arises from the liquified hydrogen storage system, accounting for 63% of the total costs. Furthermore, frequent replacements exacerbate costs, leading to an increase in capital expenditures of 3 times over the diesel base case. In contrast, the impact on the revenues is expected to be incremental. The cost of lost cargo is estimated at 0.2% of the total carrying capacity. In total, the investment case for the net-zero vessel is positive with an NPV of approximately 120 mil. USD and a payback after 6.48 years, however, still less attractive compared to the diesel base case.

In evaluating future scenarios, the study posits that achieving cost parity between net-zero and conventional vessels is plausible by early 2030. This projection suggests an alignment with currently demanded maritime and environmental regulations within the next decade.

Sammanfattning

Målsättningen av noll koldioxidutsläpp inom sjöfarten har nyligen fått ökat fokus för att vara i linje med Parisavtalets mål. År 2023 presenterade Internationella sjöfartsorganisationen sin reviderade strategi för växthusgaser med ett ambitiöst mål: netto nollutsläpp till 2050. För att möta denna utmaning krävs betydande investeringar i teknologier som möjliggör netto nollutsläpp under fartygsdrift. Även om förnybara bränslen erbjuder en lösning för miljön finns det utmaningar gällande ekonomiska aspekter under rådande förhållanden. Denna avhandling presenterar ett omfattande tekniskt-ekonomiskt ramverk skräddarsytt för att bedöma investeringar i netto nollutsläppsfartyg.

En granskning av befintlig litteratur visar att investeringar i fartyg involverar komplexa beslut, ofta åtföljda av höga kapitalkostnader. Kritiskt nog framstår reskostnader - främst bestämda av bränslekostnader - som centrala för att bedöma ett fartygs ekonomiska hållbarhet. Denna insikt understryker behovet av ett integrerat tillvägagångssätt som kombinerar ekonomiska överväganden med bränsleeffektiv drift. I detta syfte introducerar studien ett två-lagers optimeringsramverk: Det yttre lagret optimerar för fartygets nuvärde, medan det inre lagret modellerar fartygets operativa kontrollstrategi. Ramverkets tillämplighet testas sedan med hjälp av den tyska containerfartygssektorn som fallstudie. Den tillämpade tekniken består av ett bränslecellselektriskt framdrivningssystem baserat på väte.

Resultaten ger en komplex bild. Netto nollutsläppsfartyg kräver betydligt högre kapitalutgifter än sina dieselbaserade motsvarigheter. Drivsystemet bidrar till denna ökning, men den största kostnaden kommer från det flytande vätesystemet, vilket står för 63% av de totala kostnaderna. Dessutom orsakar frekventa utbyten höjda kostnader, vilket leder till en ökning av kapitalutgifterna med tre gånger jämfört med dieselfallet. I kontrast förväntas påverkan på intäkterna vara inkrementell. Kostnaden för förlorat gods uppskattas till 0,2% av den totala lastkapaciteten. Sammanlagt är investeringsfallet för netto nollutsläppsfartyget positivt med ett NPV på cirka 120 milj. USD och en återbetalning efter 6,48 år, men fortfarande mindre attraktivt jämfört med dieselfallet.

När man utvärderar framtida scenarier hävdar studien att det är troligt att uppnå kostnadsparitet mellan netto nollutsläpp och konventionella fartyg tidigt 2030. Denna prognos tyder på en anpassning till för närvarande efterfrågade sjöfarts- och miljöregler inom det närmaste decenniet.

Table of contents

List of figures

List of tables

Nomenclature

<u>Regulators and Policies</u>

CII	Carbon Intensity Indicator
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
ETS	European Trading Scheme
EU	European Union
GLOMEEP	Global Maritime Energy Efficiency Project
ICCT	International Council on Clean Transportation
IMO	International Maritime Organization
MEPC	Marine Environment Protection Committee
SEEMP	Ship Energy Efficiency Management Plant

<u>Financial Metrics</u>

DCF	Discounted Cash Flow
DPBP	Discounted Payback Period
IRR	Internal Rate of Return
NPV	Net Present Value
PBP	Payback Period
ROA	Real Option Analysis
ROI	Return On Investment
TCO	Total Cost of Ownership
TEA	Techno Economic Analysis

<u>Optimization Strategies and Algorithms</u>

ECMS	Equivalent Consumption Minimization Strategy
EGO	Energy Grid Optimizer
GA	Genetic Algorithm
GWO	Grey Wolf Optimization
MILP	Mixed Integer Linear Programming
MOGA	Multi Objective Genetic Algorithm
NSGA-II	Non-Dominant Sorting Genetic Algorithm
PSO	Particle Swarm Optimization
RB	Rule Based Strategy

Technical Components and Parameters

AIS	Automatic Identification System
API	Application Programming Interface
CTF	Cycles to Failure
DOC	Depth of Charge
DOD	Depth of Discharge
EMS	Energy Management System
EV	Electric Vehicle
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
ICE	Internal Combustion Engine
PEMFC	Proton Exchange Membran Fuel Cell
PID	Propulsion Improving Devices
SOC	State of Charge
TEU	Twenty Foot Equivalent Unit
WHRS	Waste Heat Recovery System

Fuels and Emissions

GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
HVO	Hydro Vegetable Oil
LH2	Liquified Hydrogen
LNG	Liquified Natural Gas
MDO	Maritime Diesel Oil
MGO	Maritime Gas Oil
ULSFO	Ultra Low Sulphur Fuel Oil
VLSFO	Very Low Sulphur Fuel Oil

1 Introduction

> ‘There is a high human and financial cost to the choice of inaction. It is not a choice we can afford. We have another choice. In our capacities as decision makers we can choose to transform the world into a place that is not just habitable, but an exciting place to live. This choice relies on investment, innovation, and enterprise. Fortunately, some of that is already underway.’ (Figueres, 2013)

Ten years ago, at the United Nations meeting for Climate Change in San Francisco, former Executive Secretary on Climate Change, Christiana Figueres, emphasized the dire consequences of maintaining the status quo. Accepting business as usual is a pathway we cannot afford. Investments, innovations, and entrepreneurship are essential to develop sustainable alternatives and foster transformation in today's economy. In the face of this global challenge, the urgency to address climate change and its far-reaching consequences has never been more evident. The need to decarbonize various sectors is paramount.

The maritime transport sector, responsible for approximately 3% of global greenhouse gas (GHG) emissions, stands at the crossroads of this transformation. Moreover, the maritime sector is projected to witness a 50% increase in CO_2 emissions from 2008 to 2050, further emphasizing the need for intervention (IMO, 2018). Despite its environmental footprint, maritime transport plays a crucial role in the global economy, facilitating up to 80% of global trade volume, including essential cargo such as food, medicine, and energy (UNCTAD, 2022). This dual nature of the sector – being both a significant emitter and the backbone of today’s economy – makes its decarbonization a complex yet indispensable task. Historically, maritime transport has been heavily dependent on fossil fuels, with heavy fuel oil (HFO) and maritime diesel oil (MDO) being its predominant energy source. The advantages of conventional fuels, such as cost-effectiveness and high energy density, have made them the preferred choice for decades (UNCTAD, 2021). Environmental problems from this reliance on fossil fuels are further exacerbated by the aging of the world fleet, with ships averaging 21.9 years by 2022. Uncertainties about future technological developments, the most cost-efficient fuels, evolving regulations, and potential carbon pricing have made investments in newer, more efficient ships a complex slow decision-making process (UNCTAD, 2022).

However, the tides are changing. In 2023, the UNs regulatory body for maritime transport, the International Maritime Organization (IMO), mandates a transition to net-zero emission by 2050 (IMO, 2023). While interim solutions like low-carbon fuels, energy efficiency measures, and slow steaming offer some respite, they are not enough to achieve carbon neutrality. The future lies in zero-emission fuels like synthetic hydrogen, ammonia, and methanol. Yet, the transition to these fuels is not just a technological challenge but also an economic one. Various decarbonization pathways present distinct benefits and drawbacks, each necessitating unique economic and regulatory support (Smith et al., 2021). As a result, the pivotal research question arises:

When will sustainable maritime transport technologies achieve cost parity with conventional ones?

The aspiration of the thesis is to answer this question by developing a techno-economic optimization framework for next-generation vessels. The proposed framework should be able to size, simulate, and subsequently analyze the chosen net-zero technologies in order to provide a holistic overview of the necessary technical and economic features for the investment decision. Thus, the thesis can serve as an information tool to support investors and regulators concerning the future of sustainable maritime transport.

To start with, Chapter 2 of the thesis provides an overview over decarbonization efforts in the maritime industry. International and regional climate goals and their subsequent strategies are explained. The regulatory context, is then placed within the different technological pathways for decarbonization in order to understand the larger trajectory of the sector. Subsequently, Chapter 3 discusses past work on financial analysis frameworks for maritime applications. Additionally, a diverse set of optimization architectures is presented in order to illustrate the technical and economic relationships behind the investment case. Chapter 4 presents the techno-economic optimization model, the methodology, based on the findings from the literature. The chapter describes the different algorithms, cost and revenue predictions, as well as technical and economic assumptions integrated in the model. Following, Chapter 5 introduces the German container industry as the case study. The results of the case study are subsequently addressed and analyzed in Chapter 6. Besides the technical and economic results, a sensitivity analysis is conducted to find a break-even scenario between net-zero and conventional maritime transport. Lastly, Chapter 7 draws a conclusion regarding the established framework and the outlook of sustainable maritime transport is discussed. Beyond that a recommendation for future work is provided.

2 Context

The current transport system accounts for approximately a quarter of global GHG emissions, coming mainly from road passenger and freight transport, aviation, and shipping. While road transport contributes the largest share of global transport emissions (road passenger 45.1% and road freight 29.4%), projections show a decline of road emissions within the next years due to an increase of electrification and alternative fuel-based solutions. In contrast, aviation and shipping account for 11.6% and 10.6% of transport emissions, resulting in nearly 1 billion tons of carbon emission each year, respectively (Ritchie, 2020). Especially, the maritime transport sector poses a challenge to decarbonization since large transport systems cannot easily be electrified (DNV, 2023c). Maritime forecasts further project an increase in maritime emissions by 50% due to its high fuel dependency, as global transport demand is expected to grow (IMO, 2020). Besides, investments in ship fleets are highly complex processes. Investors need to consider ship market developments, fluctuating freight rates, operational costs, new technologies, and regulatory standards. Furthermore, the shipping industry is one of the most capital-intensive industries defined by high up-front investments, aggravating the importance of concise decisions (Fan and Xie, 2021).

Therefore, the following chapter is dedicated to the creation of a fundamental basis for the understanding of the maritime industry and its development. It is necessary to comprehend the wider climate political context to further understand the necessity behind decarbonization within the shipping industry and its pathways for potential investment scenarios. Hence, the chapter firstly focuses on current regulations and environmental targets on a global and regional level. Secondly, different technological pathways with their respective decarbonization solutions and impacts are discussed.

2.1 Policies and Regulations for Decarbonization in the Maritime Industry

The maritime shipping sector is at a critical juncture as it encounters the pressing need for decarbonization. The industry, which carries over 80% of global trade by volume, is a significant contributor to greenhouse gas emissions (UNCTAD, 2021). The International Maritime Organization and the European Union (EU) have taken the lead in formulating policies to navigate this complex challenge. However, the strategies adopted by these two entities show marked differences, in an effort to achieve rapid decarbonization. While IMO regulations are mandatory for the member states of the United Nations, the European Commission regulates its European member countries. On top of that, there are global financial frameworks focusing on sustainable investments for maritime transport. As a result, the European maritime industry follows a diverse set of complex policy approaches in order to decarbonize its sector.

<u>International Policies and Standards: The Role of the IMO</u>
The International Maritime Organization - a specialized agency of the United Nations - has been at the forefront of implementing regulations and standards for environmental protection in the global shipping industry. One of its key committees, the Marine Environment Protection Committee (MEPC), is dedicated to the prevention and control of pollution from ships. The

MEPC has been instrumental in promoting the adoption and enforcement of new protocols, annexes, and amendments to existing conventions aimed at reducing emissions from shipping. Among the most significant measures adopted by the MEPC is the Initial IMO Strategy on Reduction of GHG Emissions from Ships, which was adopted in 2018. This strategy outlines a vision to phase out GHG emissions from shipping within this century. It sets specific levels of ambition, in order to achieve a 50% reduction by 2050, compared to 2008 levels, while also pursuing efforts towards phasing them out entirely. In a revised strategy, these goals have been strongly increased in 2023 (Ricardo, 2022). The 2023 IMO GHG Strategy enhances the ambitions of the maritime sectors to align with the Paris Agreement as well as the United Nations 2030 Agenda for Sustainable Development. Under this new agenda, total annual GHG emissions are expected to decrease by 30% in 2030 and 80% in 2040 in order to achieve net-zero emissions by 2050 (IMO, 2023). The increased ambitions of the revised IMO regulations can be seen in Figure 1.

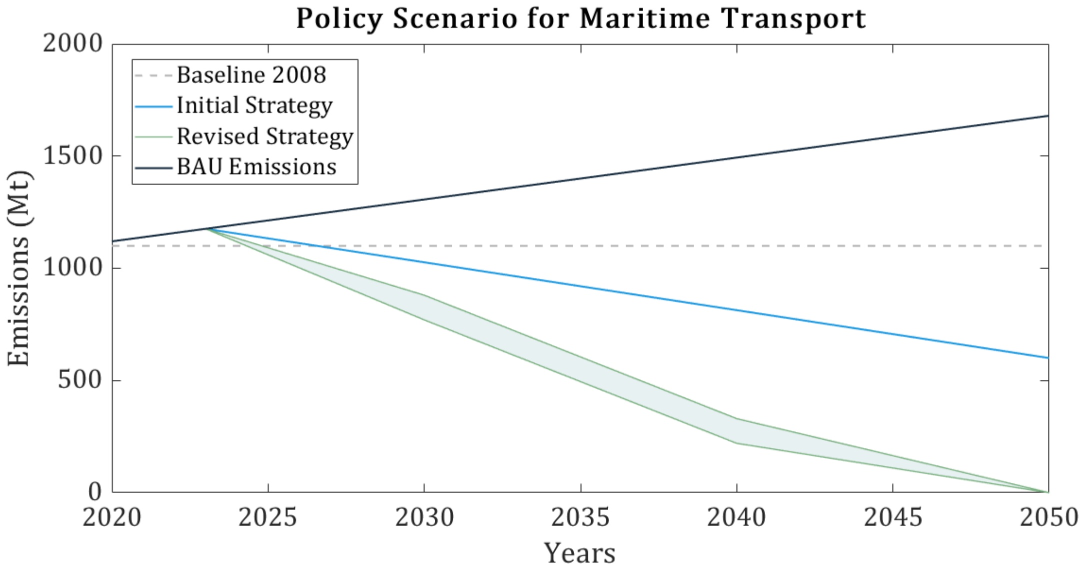

Figure 1: Policy scenarios for the maritime transport sector. Data has been obtained from ICCT (2023).

Two key measures put forth by the IMO to achieve these ambitious targets are the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP). The EEDI, introduced in 2011, sets a specific minimum energy efficiency level per capacity mile (for example, ton-mile) for different ship types and sizes. The EEDI framework has been progressively tightened over time, with the aim to make new ships built from 2025 onwards 30% more energy efficient than those built between 2014 and 2019 (Joung et al., 2020). Despite its effectiveness in reducing emissions from new ships, the EEDI alone is insufficient to achieve the IMO's ambitious targets, highlighting the need for comprehensive and multi-pronged strategies. The SEEMP, on the other hand, is an operational measure that encourages best practices for fuel-efficient ship operation. Each ship is required to have a SEEMP, which provides a possible approach for monitoring ship and fleet efficiency performance over time. While the SEEMP does not set specific targets for efficiency, it acts as a tool to improve a ship's energy efficiency through a cycle of plan-do-check-act, leading to reduced emissions (Joung et al., 2020) (MEPC, 2022).

Besides, the IMO has introduced two new measures to reduce carbon emissions from ships: the Carbon Intensity Indicator (CII) and the Energy Efficiency Existing Ship Index (EEXI). These two measures come into effect throughout 2023 and 2024, building on top of current EEDI and SEEMP regulations. The CII is an operational measure that requires ships to reduce their carbon emissions on a year-by-year basis. Every ship (above 5000 gross tons) is required to have a CII.

The covered ships are subsequently rated A to E in accordance with their yearly carbon intensity. Therefore, the CII can be understood as a direct emission-related reflection of the ship's actual operation. In contrast, the EEXI is a framework to analyze the energy efficiency of all vessels currently in operation (above 400 gross tons). The EEXI requires ship operators to assess their ships' energy consumption and CO_2 emissions. In order to comply with EEXI standards, ship owners are expected to implement technical measures to adjust their vessels' emissions to the required level (IMO, 2021).

To conclude, the IMO targets a wide range of decarbonization strategies and perspectives for maritime transport. While the EEDI has been effective in reducing emissions from new ships, the CII and EEXI are designed to improve the energy efficiency of existing ships. The SEEMP, on the other hand, is an operational measure that encourages best practices for fuel-efficient ship operation. Together, these measures form a comprehensive strategy to reduce carbon emissions from the current shipping industry.

European Regulations: Phase out of fossil fuels

In parallel to the mandatory international regulations led by IMO, the European Union has been proactive in its approach towards decarbonizing the maritime sector. Key EU regulations mainly include the Emissions Trading System (ETS) as well as the Fuel EU Maritime Initiative.

The EU ETS is a cornerstone of the EU's policy to combat climate change and its key tool for reducing industrial greenhouse gas emissions cost-effectively. It operates on a cap-and-trade principle, where a cap is set on the total amount of greenhouse gases that can be emitted by installations covered by the system. Each year, a reduction factor is applied in order to decrease linearly the allowed emissions of included European industries. The EU ETS has been activated in 2005 and further developed in 2008, 2013, and 2021. Since the introduction of the policy framework, targeted European sectors have reduced their emissions due to their increase of internalized costs (European Commission, 2022). The shipping industry is expected to join the EU ETS primarily in 2024, after a surveillance phase of one year in 2023. The percentage of emissions covered by the scheme are steadily increasing from 40% in 2024 to 70% in 2025 and 100% in 2026. Carbon dioxide is the initially covered GHG, while methane and nitrous oxide will be included from 2026 onwards (European Council, 2022a). An illustration of the introduction timeline for shipping in the EU ETS is shown in Figure 2.

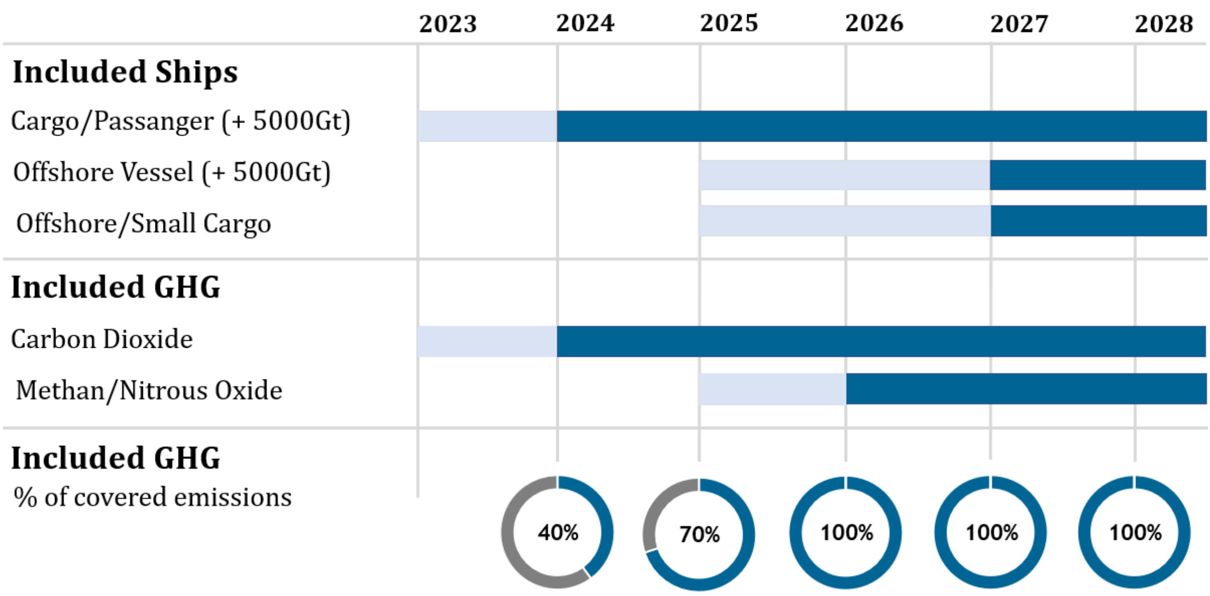

Figure 2: Introduction of the maritime sector in the EU ETS based on DNV (2023a).

The inclusion of maritime transport in the ETS is an important signal for the European shipping industry. By 2026, ship owners and operators have to buy and sell emission allowances as needed, providing a financial incentive to reduce their own emissions. The inclusion of the aviation industry in 2012 points out that the EU ETS can be a strong tool to reduce emissions in transport sectors such as the shipping industry (European Commission, 2023).

Besides the EU ETS, the Fuel EU Maritime Initiative is an EU policy that aims to support the production and uptake of sustainable fuels in the maritime sector. It sets a clear timeline, indicating when carbon dioxide emitting fuels can no longer be used, thus providing certainty for the industry to invest in sustainable alternatives. The initiative recognizes the need for a sector-specific approach, given the maritime industry's unique operational characteristics and the global nature of its regulatory framework. One of the main regulations from the initiative is the carbon fuel limit that provides a hard limit for the allowed carbon intensity of used fuels in the sector. This carbon intensity decreases each five years compared to the baseline scenario of 2020 – set at 91.2 g CO_2/MJ for VLSFO (Very Low Sulphur Fuel Oil) (European Council, 2022b). The limit in carbon intensity for currently used maritime fuels are shown in Figure 3.

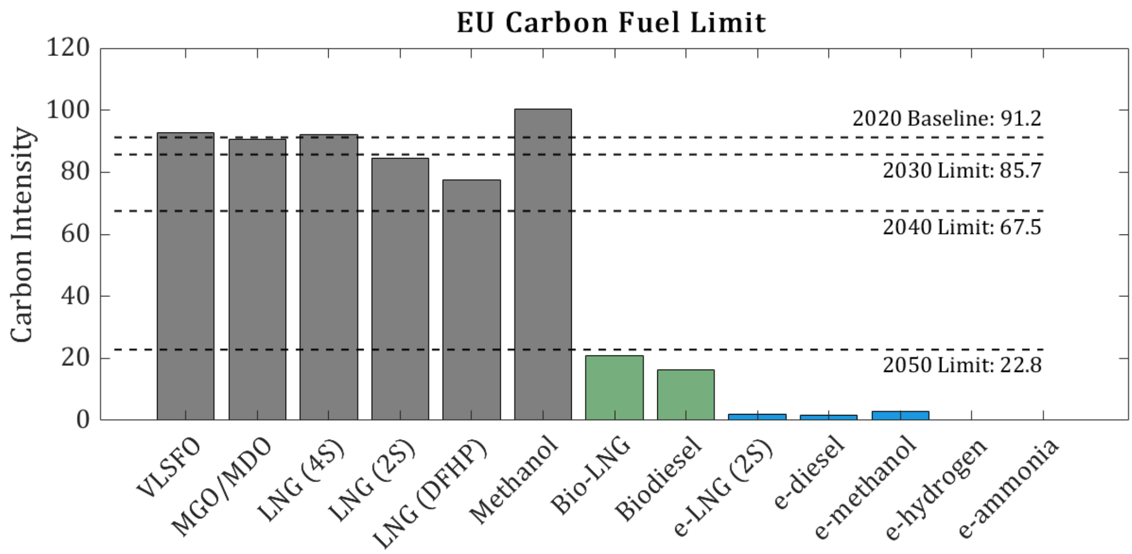

Figure 3: The Carbon Fuel Limit from the Fuel EU Maritime Initiative based on Gozillon (2023).

The diagram underlines the importance to develop low-carbon and net-zero fuels for the European industry. Conventional maritime fuels such as VLSFO and MGO/MDO will be phased out by 2030 due to the standard. Additionally, transition fuels such as LNG cannot be used as a fuel under European regulation after 2040. In the long-term, solely bio-based fuels as well as electrofuels (from clean electricity) are aligning with the standards of the EU.

Financial Frameworks

In addition to the international IMO and regional EU regulations, the Poseidon Principles represent a significant industry-led initiative for climate-aligned ship financing. By 2023, the Poseidon Principles include 30 financial institutions, covering approximately 70% of global financing in the maritime industry (Poseidon Principles, 2023). The principles are not specifically IMO regulations, however, they are consistent with IMO framework and European financial institutions have adopted the principles widely. In general, the Poseidon Principles are a wider guideline for the assessment and disclosure of shipping related financial portfolios, applicable for lenders, lessors, and financial guarantors. The Poseidon Principles are based on the following four foundations: Climate alignment, accountability, enforcement, and transparency (Poseidon Principles, 2019).

- *Climate alignment*: In a first step, participants need to measure and analyze the carbon intensity of their shipping portfolios. The assessment of their financial portfolio is based on the annual efficiency metric, including fuel consumption, traveled distance, and deadweight tonnage as input data. Subsequently, the assessment is measured against decarbonization baselines in order to estimate their specific performance publicly.

- *Accountability:* In a second step, participants agree on the role of the IMO as the regulatory authority in the maritime industry. Only classification societies complying with IMO regulations are accepted by the participants. This is an important step in order to ensure data validity for the sector, as all participants are agreeing to solely use data types, sources, standards, and providers that are in compliance with IMO. The result is reliable and un-biased information within the participant group.

- *Enforcement:* The implementation of the Poseidon principles is subsequently guaranteed as participants agree to enforce the framework in their business activities. Key to sustainable development is equal and appropriate data and information sharing of the participants with their business stakeholders. This includes continuous updates and reviews of established data sets.

- *Transparency:* Lastly, it needs to be mentioned that the outcome of the Poseidon principles should be communicated and published in a transparent and simplified way. All participants are therefore in agreement that their portfolio climate alignment score is presented on an annual basis.

By committing to these rules, the participants of the Poseidon principle try to establish a clear and visible playing field for investments in the maritime industry. In simple terms, the principles define the meaning of sustainability for maritime investors.

The combination of the Poseidon Principles with the previously introduced regulations from the EU and the IMO creates the fundamental basis for emission reduction in the maritime transport sector. Both the IMO's regulatory measures and the EU's stringent regulations signal a clear trend towards net-zero solutions in the maritime industry. The IMO has set the clear goal to achieve net-zero emissions by 2050, while the Poseidon Principles incentivize investments in this direction. The continuous tightening of the EEDI requirements and the broadening of the SEEMP are indicative of the IMO's commitment to a comprehensive strategy for decarbonization. On top of that, the EEXI and the CII lay the foundation for emission reduction of the already built fleet. Meanwhile, the EU ETS and the Fuel EU Maritime initiative provide additional support for the industry to reduce emissions. These policies and initiatives present a compelling case for the shipping industry to adopt net-zero technologies. As the world is rapidly decarbonizing, it becomes increasingly clear that the shipping industry must not only meet these targets but seek to exceed them. As such, more intensive research and investment into low-carbon and specifically net-zero solutions are necessary. In the next section, the technological pathways to decarbonize the maritime industry are presented and discussed.

2.2 Pathways for Decarbonization

The shipping industry is a crucial component of global commerce, facilitating the flow of goods around the world. Its environmental footprint is significant, contributing substantially to GHG emissions. Urgent action towards decarbonization is therefore vital. In general, there are a variety of pathways that shipowners can undertake in order to reduce their emissions. This can come from a diverse set of actions, e.g. a general reduction in global transport, the rollout of operational and technical measures or through a change to alternative fuels. This section focuses on the specific technical possibilities to reduce carbon emissions from the maritime industry. Therefore, the section will firstly give an insight into efficiency and emission reduction technologies. Secondly, the focus will shift towards potential net-zero fuels such as biofuels and synthetic fuels.

2.2.1 Operational and Technical Measures

As explained in Section 2.1, the improvement of the shipping fleet is already an essential topic in policy and legislation, where the EEDI standardizes energy efficient technologies in new build ships and the SEEMP provides a framework to further optimize the vessels operational behavior. In general, technologies and measures that decrease carbon emissions from existing ships can be categorized as operational improvements and retrofits (Green Voyage, 2022). In this context, operational improvements focus on an efficient usage of the current vessel, while retrofits integrate new or updated energy efficient technologies into the vessels system.

<u>Operational improvements</u>
Operational efficiency in the shipping sector pertains to optimizing a myriad of ship operation aspects to reduce fuel consumption and emissions. Typically, these improvements are basic measures with a high potential for fuel and emission savings, albeit low costs. Therefore, it is recommended to analyze and integrate operational measures before installing retrofits into the vessels system. The most common measures to increase the operational efficiency of a ship are defined by the IMO as hull and propeller cleaning, speed optimization, weather routing, optimum trim, and generator rationalization (Green Voyage, 2022).

A clean surface of the vessels hull and propeller is necessary for its efficient hydrodynamic performance. The accumulation of any substances on the exterior of the vessel can therefore lead to increased turbulence and cavitation. The build-up of biofouled accumulation by invasive species is an important reason for high energy losses during a vessel’s operation. Multiple studies have been conducted on the impact of fouling on the ship’s energy performance. Results show a potential decrease of fuel consumption by 5-10% through increased hull and propeller cleaning (Adland et al., 2020) (IMO, 2015).

Speed optimization is another significant measure to increase the operational efficiency of a ship. Speed to power – and subsequently fuel consumption - follows a cubic relationship for maritime transport. Following the cubics law, a 10% decrease in a vessels operational speed leads to a 27% decrease of fuel consumption at constant speed (Sherbaz and Duan, 2012). However, it needs to be mentioned that a lower ship speed increases the total voyage time as well as the necessary fleet size. The potential of slow steaming is already a common procedure for most shipping companies to reduce their fuel consumption. The International Council for Clean Transport (ICCT) estimates up to 10% emission reduction potential for container and cargo vessels due to speed optimization (ICCT, 2011). In addition, the operational speed of a vessel has an indirect impact through the trim of the ship on the energy consumption. Ships are designed to run at a design speed point with a predefined cargo and weight balance in order to have minimal fuel consumption. Dependent on the amount of cargo that is carried on the ship (loaded to unloaded), the optimal trim of weight balancing changes. Therefore, trim conditions need to be assessed continuously throughout the route in order to achieve the highest fuel savings. This can be done at ports, including cargo loading and unloading procedures as well as at sea by ballast shifting. Dependent on the application, fuel reduction of 1 to 5% can be achieved with a dynamic trim systems (Glomeep, 2020).

Even though ship routes are predefined, the exact route of a ship can vary depending on the specific weather conditions. Weather routing systems use predictive weather forecast models to optimize the exact shipping route based on favorable winds, waves, and currents. Results show that the inclusion of real-time weather data in route planning leads to faster and safer maritime transport. A reduced time at sea at calm weather conditions can further lead to a reduction in fuel consumption in the range of 1 to 5% (Sun et al., 2022).

Lastly, efficient vessel operation can be achieved with generator rationalization and optimization. Auxiliary loads onboard are typically provided by multiple generators operating at the same time. This redundancy of operation leads often to multiple generators providing power at low loads and henceforth low efficiency values. Decreased redundancy can lead to generator optimization - operation at higher loads and efficiencies. However, such measures reduce the security of operation at the same time. Additional control and monitoring systems are therefore essential (Glomeep, 2020). A short oversight on the emission reduction potential of operational measures is provided in Table 1

Table 1: Operational Measures for GHG reduction in maritime applications. Data has been obtained from IMO (2015), Adland et al. (2020), Glomeep (2020), Sun et al. (2022), Green Voyage (2022)

Operational Measure	GHG Reduction Potential
Hull and propeller cleaning	5 - 10%
Speed optimization	10%
Weather routing	5 – 10%
Optimum trim	1 – 5%
Generator rationalization	1 – 4%

The table shows a strong emission reduction potential from operational measures for the current ship fleet. Combining multiple operational improvements can further lead to emission reduction through lower cost, as such services are already offered in the market. In addition, retrofitting can be used to further unlock emission savings during the operation of a ship. The largest benefits of retrofits can be achieved through improvements of the hull, the propeller, and the propulsion system, as well as waste heat recovery.

Retrofitting Technologies

Retrofitting involves incorporating modern technologies into existing ships to improve their performance and subsequently reduce their environmental impact. Aerodynamic improvements focusing on the hull shape can reduce the drag of the ship, leading to less fuel consumption and lower emissions. The impact of hull retrofits is highly dependent on the ship class and type, however, estimations show a reduced fuel consumption by 4 to 8% (Ritari et al., 2021).

Additionally, propulsion system retrofits can also lead to considerable efficiency gains. Advanced propellers can offer better hydrodynamic performance, reducing energy losses and improving fuel efficiency. Vessels with dynamic operational behavior are recommended to integrate high-efficient propeller systems, as speed variation leads to increased losses. A study contracted by the European Commission on the emission reduction potential of European maritime transport estimates potential energy and efficiency savings of up to 5% due to propeller retrofits (Lindstad et al., 2015). Further efficiency improvements are achievable with propulsion improving devices (PIDs). PIDs (e.g. ducts, fins, caps or rudders) are connected to the hull or propeller in order to decrease fuel consumption by improving the waterflow around the vessels body. The exact GHG reduction potential depends on the specific PID and its implementation, however, the Global Maritime Energy Efficiency Project (Glomeep) estimates improvements in the range of 0.5 to 5% (Glomeep, 2020).

Lastly, waste heat recovery systems (WHRS) can be retrofitted to capture and reuse the thermal energy from exhaust gases. Depending on the vessel, the recovered thermal energy can then be used to supply auxiliary/hoteling loads for hot water and steam or be converted back into electricity and reduce the main engines load. Even though WHRS can be implemented in all type of ships, larger vessels above 10 MW are typically the target due to the necessary implementation of large machinery such as boilers, turbines, and alternators. Albeit the high cost, WHRS can reduce GHG emissions from vessels by 3 to 8% (Glomeep, 2020). A summary of the introduced retrofits is presented in Table 2.

Table 2: Retrofit Technologies for GHG reduction in maritime applications. Data has been obtained from Lindstadt et al. (2015), Glomeep (2020), and Ritari et al. (2021).

Retrofit Technology	GHG Reduction Potential
Hull retrofitting	5 - 10%
Propeller retrofitting	10%
PID	5 – 10%
Waste Heat Recovery	1 – 5%

Even though the list of presented retrofits and operational measures is non-exhaustive, it underlines the limits of energy efficiency improvement and emissions reduction potential of these measures. The implementation of multiple measures and retrofits can lead to strong decrease of GHG emission, nonetheless, they cannot achieve full decarbonization of the industry. In order to align with the renewed IMO targets as well as the Paris Agreement, ship operators need to invest into technologies that can secure net-zero emissions under operation. Therefore, net-zero fuels are gaining importance in the scientific and regulatory discourse.

2.2.2 The Potential of Net-Zero Fuels

In general, net-zero fuels can be defined as energy vectors that a) do not emit GHGs during their production and use-phase, or b) offset related emissions through other means (e.g. carbon capture and storage). By that, net-zero fuels are balancing produced and removed GHGs emissions throughout their whole lifecycle (Fankhauser, 2021). There are several pathways to produce net-zero fuels, involving different processes and technologies. Most commonly, net-zero-fuels are divided into biofuels and synthetic fuels.

Biofuels are energy vectors derived from biological materials that can be regenerated. Subsequently, a large variety of biofuels exist, derived from different processes and feedstocks. Hydro vegetable oil (HVO) is the most commonly used biofuel in the maritime industry, however, other possibilities such as fame, bio-ethanol, and F-T diesel are also used. Most, commonly, biofuels are used as drop-in fuels, as they are blended with conventional fuels in order to decrease carbon emission. Strong advantages of biofuels are their substitutional properties as well as their price competitiveness compared to fossil fuels. Bio-ethanol and bio-LNG are completely substitutional compared to their fossil fuel-based variant, while biodiesel and other bio liquids can be blended into fossil fuel-based propulsion systems up to a certain degree. The ability to use biofuels without complex changes to the engine system is the main reason they are recognized as short-term solution for emission reduction (DNV, 2023b). However, concerns arise regarding their sustainability and scalability. Due to the necessary feedstock volume, biofuels are limited by their production capacity. Additionally, feedstock resources such as corn or wood are competing with other industrial sectors, where they are needed for production processes. This underlines the perspective that biofuels are an important part of the decarbonization of the shipping industry, but are unlikely to be the only solution for sustainable shipping in the long-term (IEA, 2021) (DNV, 2023b).

Besides biofuels, synthetic fuels provide a possible solution towards net-zero emissions. Synthetic fuels are liquid or gaseous fuels produced from diverse carbon sources through chemical conversion processes. They can be produced from non-renewable sources such as coal, natural gas, and oil shale, as well as renewable sources such as biomass. Synthetic fuels can also be produced using electric energy and CO_2 captured from stack gases or separated from ambient air. Most commonly though, synthetic fuels are produced from feedstocks such as natural gas or oil derivatives (Al-Enazi et al., 2022).

There are two pathways to have net-zero emission synthetic fuels: Either by capturing the emission from their production pathways with CCS technology, or by producing them through electrochemical conversion processes. Even though most of the synthetic fuels are still produced from fossil fuels, the electrochemical conversion pathway is gaining more attention in recent years. Electrofuels are produced through electrolysis from renewable electricity, resulting in potentially clean hydrogen and ammonia (Al-Enazi et al., 2022) (ITF, 2018). Figure 4 illustrates different production pathways for synthetic fuels, divided into electrofuels and synthetic fuels with CCS technologies.

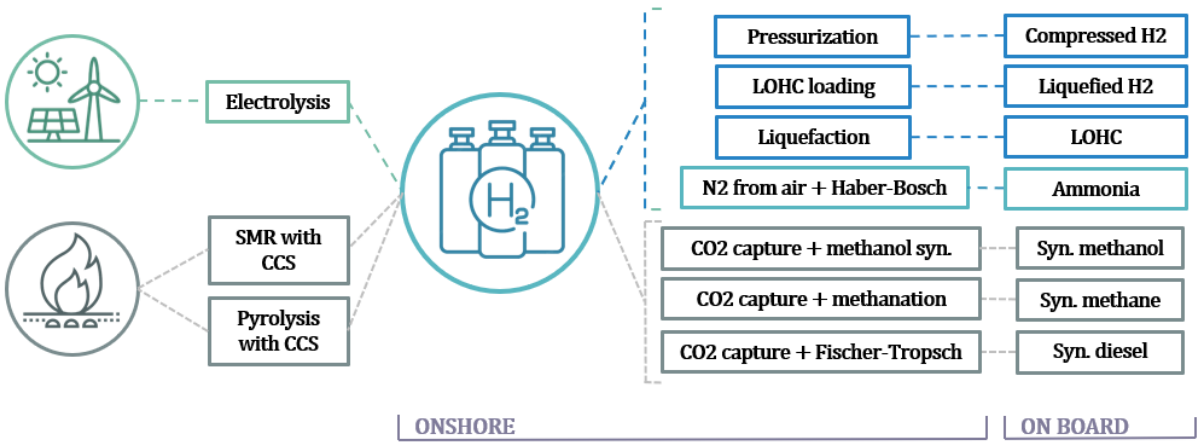

Figure 4: Production pathways for zero emission synthetic fuels based on Al-Enazi et al. (2022).

Electrofuels such as ammonia, hydrogen, and other hydrogen derivates represent one of the most promising pathways to decarbonize the shipping sector in the long-term. Especially, e-methanol is gaining increased momentum in the current shipping market as it can be used similar to biofuels as a substitute for fossil fuels. However, the production costs as well as the energy consumption for the fuel are high. Ammonia and hydrogen are other alternatives that can achieve net-zero emission in the maritime sector. Since ammonia and methanol are derivates of hydrogen, one of the main advantages of hydrogen as a maritime fuel comes from its lower energy consumption. This is subsequently followed by a cost advantage of e-hydrogen over e-methanol and e-ammonia. However, one of the main problems regarding hydrogen is its volumetric energy density. As a gas, hydrogen has a high mass energy density, but a low volumetric energy density, leading to high space requirements for integrated fuel systems. The high space requirements can be reduced due to different storage technologies, such as liquefaction, liquid organic hydrogen carriers, or ammonia, even though the conversion process increases the energy consumption and associated costs (Lloyds Register, 2020).

Still, hydrogen is seen as one of the most promising solutions alongside ammonia to decarbonize maritime transport. Especially, potential low-cost due to increased renewable energy production is seen as a major advantage in the long-term. Multiple studies predict a strong increase in hydrogen consumption as maritime fuels in prospective years, raising the question when investments in hydrogen-based vessels are feasible. Based on the potential of hydrogen as a shipping fuel, the technology is further investigated as the main fuel for the case study of the thesis. Still, hydrogen can be used as a fuel in different propulsion systems such as gas turbines, internal combustion engines, and fuel cells. The following section will discuss such potential prime movers for the case study.

2.2.3 Prime Movers

In maritime propulsion systems, a prime mover is integral for converting fuel into the necessary power to drive the vessel. This device transforms the chemical energy of the fuel into either electrical or mechanical energy, which subsequently propels the vessel. Traditional maritime propulsion systems often utilize internal combustion engines (e.g. powered by MDO) or gas turbines (e.g. powered by LNG). However, the application of hydrogen as a fuel introduces unique considerations. Given its nascent stage in maritime applications, there are three prime movers that appear suitable for hydrogen: Gas turbines, internal combustion engines (ICE), and fuel cells (Lloyd, 2020) (Alkahaledi et al., 2022).

Gas turbines have a well-established history in the maritime industry, predominantly serving auxiliary loads. However, when considering hydrogen as a main fuel, challenges arise notably due to the potential for elevated NOx emissions. Consequently, research primarily envisions hydrogen as a blend or substitute fuel in gas turbines in order to restrict their environmental impact (Ammar and Alshammari, 2018). In contrast, hydrogen's application in ICE and fuel cells has garnered significant attention in recent years. While ICEs have ubiquitously powered mobile applications, including maritime transport, their adaptation to hydrogen faces hurdles. Similar to gas turbines, hydrogen fueled ICE have elevated NOx emissions due to their high combustion temperature (Ammar and Alshammari, 2018). Furthermore, hydrogen-powered ICEs lag in maturity compared to hydrogen fuel cells, with the maritime industry offering limited practical examples of the former (Pawelec, 2020). Hydrogen fuel cells, however, present two distinct advantages: they operate at consistently high efficiencies compared to gas turbines and ICEs, and their operation results in negligible environmental impact due to minimal emissions. Although the technology remains in its developmental phase, hydrogen fuel cells present the most compelling case for clean maritime propulsion systems (IRENA, 2021). Therefore, the following case study will be mainly focused on a hybrid power system centered around a hydrogen fuel cell as the prime mover.

3 Techno-Economic Optimization

The following chapter focuses on current techno-economic frameworks used to analyze maritime investments. Additionally, a review on optimization strategies to improve economic and environmental performance is conducted. Focusing on net-zero vessels, the combination of techno-economic frameworks based on optimal system design is essential to be cost competitive with already established technologies. Hence, the chapter is divided into the following two sections. Firstly, in Section 3.1, the idea behind techno-economic assessments for ship investments is explained. This includes in particular different scopes to analyze the technical and economic relationships, as well as their economic assessment indices. Secondly, Section 3.2 shows different optimization models used in the maritime industry for vessel sizing, their specific design, and integration into larger TEA frameworks. Additionally, energy management systems for the optimization of hybrid power splits are surveyed and analyzed for their use case.

3.1 TEA in the Maritime Industry

Techno-economic analysis (TEA) is a methodology used to evaluate the economic feasibility of a technology or process. TEA combines engineering and economic principles to assess the technical and economic performance of a system. Typically, the goal of a TEA is to identify the most cost-effective solution for a given problem, even though this can be widened by taking environmental and social aspects into account. TEAs are widely used across all sectors to evaluate the economic feasibility of energy systems (Gargalo et al. 2016). The energy sector is facing significant challenges, including the need to reduce greenhouse gas emissions, increase energy efficiency, and ensure energy security. Subsequently, a TEA can help policymakers, investors, and researchers to identify the most cost-effective solutions to these challenges.

TEAs are an established and known concept in the industry and the scientific literature. However, the maritime industry paints a very specific case with high initial investment costs as well as dynamic market behavior. Therefore, a short introduction to TEAs in the maritime sector is provided before the underlaying optimization models for hybrid power systems are analyzed in detail.

3.1.1 Fundamental Ideas

In general, TEAs are a tool with broad scope of applicability across a variety of technology systems. These assessments can be used to evaluate a wide range of energy systems. Notwithstanding the diversity of technological applications, TEAs adhere to a structured systemic approach. This approach allows for robust analyses that captures a wide array of system dimensions. Thus, the strength of TEAs lies in their capacity to provide comprehensive, quantitative evaluations, regardless of the technology under consideration (Murthy, 2022). This adaptability facilitates the comparability between different energy systems by applying a uniform framework of analysis, finally creating a broader basis for informed decision-making, reducing the risk of investment, and policy decisions (Barahmand and Eikeland, 2022).

To conduct a TEA, in-depth knowledge regarding the used technologies, components, and processes are inevitable to accurate system modelling. However, the technical model underlaying the economic model is highly dependent on the analyzed technology itself. The design question behind the technical model becomes especially important in newly applied technologies, where system size and operation are still questionable. An in-depth analysis of this design question is conducted in the Section 3.2. As soon as the design process is identified, the economic assessment becomes the center of the framework. It becomes important to focus on the economic rationale behind the assessment since a TEA can be conducted with different levels of detail (Barahmand and Eikeland, 2022). Murthy et al. (2022) differentiates between three different methods for TEAs: Zero-order estimates, discounted cash flows, and real option analysis.

Zero-order estimates are classified as less detailed, preliminary economic assessments. Accordingly, Zero-order estimates are known as quick methods for analyzing the economic impact of a technology. Static cost-benefit assessment, annuity, and net cash flow methods are the most commonly used preliminary assessments. In most cases, such assessments are not used as a final tool, but more as a first economic insight into the cost-benefit of a technology. A more in detail analysis would then use this first assessment as a resource for the investment decision process (Murthy et al. 2022).

In contrast, methods based on *Discounted Cash Flows (DCF)* such as the net present value (NPV) and the internal rate of return (IRR), incorporate the time value of money into the economic assessment. The time value of money follows the concept of lost opportunities. In principle, it can be assumed that the sum of money will grow over time once invested – typically shown by deposit interest rates or the capital value of money as the base case. A delayed investment is henceforth a lost opportunity and results in discounted value of money in the present. This discounted value is typically embodied by a discount rate, reflecting the risk of the investment. An investment is assessed as viable if the NPV is positive or if the IRR is higher than the assumed discount rate. Even though the time value of money increases the accuracy and comparability of investment projects, a major challenge lies within the determination of the discount rate and future cash flows as they are based on uncertainties (Murthy et al. 2022).

The two previously mentioned TEA methods are based on a committed strategy towards a specific technology. Investments are made based on predictions for price development and risks are incorporated into the discount rate, if possible. This neglects the fact that real investment decisions are influenced by delayed investments, re-evaluations, and additional financing (Rau and Spinler, 2017). *Real Option Analysis (ROA)* widens this concept by including the possibility to acquire, expand, contract, or switch economic assets within the timeline of the investment. These additional options provide flexibility to the investment strategy, typically resulting in higher returns on the achievable investment. ROA becomes especially useful in uncertain markets, investments with large capital assets, and potential abandoning value, as well as processes with especially long lifetime (Rau and Spinler, 2017) (Yin et al. 2018). The conceptional difference between DCF and ROA is illustrated in Figure 5.

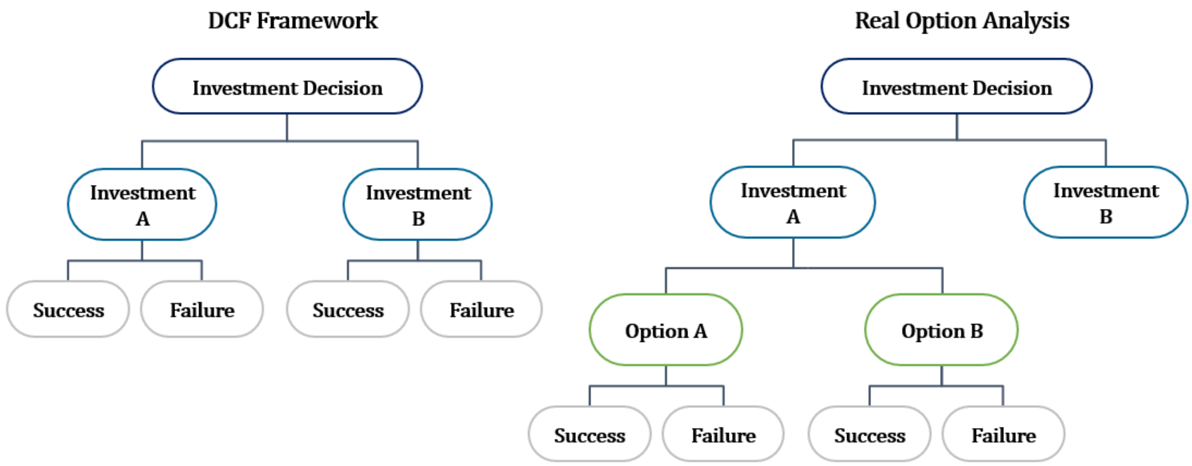

Figure 5: Schematic overview of DCF and ROA frameworks based on Murthy et al. (2022)

In the past, ROA as well as DCF methods have been widely applied in the maritime sector. While ROA models can illustrate more accurate decision-making processes, they are highly complex and in need of complete certainty of information. It seems reasonable to use ROA to analyze an investment decision for a conventional ship or the ship retail market. In contrast, when analyzing modern net-zero vessels based on optimization strategies, DCF methods are a reasonable option due to missing information and high complexity (Kavussanos and Visvikis, 2017). Looking forward, the DCF method is chosen as the TEA approach to analyze the investment case behind net-zero vessels.

3.1.2 Key Performance Indices

As shown, a TEA can be conducted on many different levels with different focal points. One of the most important aspects regarding TEAs is the assessment parameter used to evaluate the economic viability of a technology. These metrics include the total cost of ownership, net present value, internal rate of return, payback period, return on investment and many more. The most commonly used cost metrics in TEAs are mentioned below (Agajie et al. 2023):

1. Total Cost of Ownership (TCO): TCO is an assessment of the comprehensive cost of an asset throughout its lifespan. This involves the sum of the initial purchase price and the cost of operation over a defined timeframe. TCO provides an estimation of an asset's value over its operational life without considering potential revenue streams. It is often employed in business scenarios to assess the financial viability of potential investments and acquisitions.

2. Net Present Value (NPV): The NPV is a financial metric that calculates the difference between the present value of cash inflows and outflows over a particular period. It is a standard tool used in budgeting and investment planning to evaluate the profitability and feasibility of projects. Projects with a positive NPV are generally considered worthwhile, whereas those with a negative NPV are not, although this may vary based on the applied discount rate.

3. Return on Investment (ROI): The ROI is a performance metric typically employed to evaluate the profitability of investments. ROI measures the return from an investment relative to its cost, providing a simple percentage that indicates the gains or losses from an investment decision. However, ROI does not account for the opportunity cost of assets. While ROI is more commonly associated with investments in stocks, shares, or

partial investments in shipping systems within fixed periods. Comprehensive reports also use ROI as an economic parameter for vessel investments.

4. Payback Period (PBP): The PBP is a rudimentary investment evaluation tool, utilized to determine the time required to recoup the original investment. It offers a wider understanding regarding the duration of risk exposure in an investment, with shorter payback periods generally being more desirable. However, the PBP does not consider the time value of money, nor does it account for cash flows after the payback period has ended, which can limit its utility in long-term investment evaluations.
5. Internal Rate of Return (IRR): The IRR computes the discount rate at which the NPV of cash inflows equals the NPV of cash outflows, i.e., the NPV is zero. In essence, the IRR represents the interest rate at which an investment breaks even. Investments with an IRR exceeding the required rate of return are typically deemed profitable. However, the calculation of IRR can become complex for cash flow patterns with alternating positive and negative values, leading to multiple or even no IRR solutions.

The NPV of the investment decision is chosen as the main cost metric for the framework. In contrast to other metrics (e.g. PBP), the NPV provides information about the feasibility of an investment as well as its comparability to other investments throughout the entire lifetime of the asset. Additionally, the NPV method can further provide other important information and indices such as the annualized cost or the IRR.

3.1.3 Overview of Past Studies

In the past, multiple studies have been conducted on the cost composition of ship investments. These are typically divided into three primary cost categories: capital expenditures (e.g propulsion system), operational expenditures (e.g. maintenance), and voyage costs (e.g fuel cost). Understanding these cost elements is critical for the development of accurate investment models, which can inform strategic decisions, particularly those related to the adoption of new technologies and fuels in the sector.

GL (2012) analyzes the costs to introduce LNG as a novel ship fuel in container vessel in cooperation with MAN. Five different container ship sizes are investigated and compared to a reference vessel running on marine fuel oil. The authors assume reduced space for container transportation on the LNG vessels due to increased system space requirements mainly coming from the fuel tank. The largest losses in cargo are expected for medium-sized container ships with an estimate of 3%. The results show advantages for the LNG fueled container vessels. Even though initial investment costs are higher and annual cash flows are reduced from cargo reduction, the LNG fueled container ships lead to higher profit streams due to lower fuel cost. The expected payback period for the LNG based vessels ranges between 24 and 84 months dependent on the size of the ship and its operation on global or regional routes (GL, 2012).

Schinas and Butler (2016) analyze potential incentives to switch from conventional fueled vessels to LNG based vessels for feeder size container ships. Their economic comparison is based on the TCO, including the ship investment cost, the operational cost, the voyage cost, and the cost of lost cargo. Their findings show that LNG based ships can be competitive against conventionally fueled ships. Their higher CAPEX is alleviated by the energy price of LNG, resulting in lower voyage cost. This is further underlined by the anticipated increase of emission related cost from regulatory side (Schinas and Butler, 2016).

Livanos et al. (2014) analyze alternative propulsion systems in ferries and RoRo vessels. The authors analyze diesel engines and dual-fuel engines (diesel and LNG), with a focus on minimal fuel consumption. The results are shown as the annualized propulsion machinery cost, underlining the importance of minimal fuel consumption. In all studied cases, fuel consumption accounts to the highest share of cost in the range of 70 to 80%. The highest impact of the fuel consumption can be found in diesel engines, while LNG engines tend to have a smaller impact due to their lower fuel prices and higher capital cost (Livanos et al., 2014).

Percic et al. (2021) conduct an LCA and LCC on different shipping types– cargo, passenger, and dredgers – for short sea shipping applications in Croatia. The authors analyze specific routes for the three ship types based on average fuel consumption data for diesel, methanol, ammonia, hydrogen, and electric propulsion systems. Using DCF and the NPV of the different investments, their results show that electrification is the favored solution for short sea shipping. Furthermore, their results underline that the cost of the used fuel has the largest impact on the NPV of the investment in all analyzed cases. This increases further for potential net-zero solutions such as hydrogen, ammonia, and methanol due to their high fuel prices (Percic et al., 2021).

Korberg et al. (2021) are focusing on the potential of renewable fuels in prospective shipping propulsion systems. Their fuel analysis includes biofuels, electrofuels, and electricity from 18 different production pathways. Similar to Schinas and Butler (2016), they use the TCO as cost metric to compare candidate solutions. Their results show a high share of fuel cost for internal combustion engines (89%) and fuel cells (72%) for container ships. The only solution with a low share of fuel cost (17%) is based on electrification. However, this was evaluated to be only applicable for short distance ferry transport, as battery solutions for large-distance transport is not yet technical feasible. In general, an increasing cost trend can be observed from bio-fuels (low cost) to bio-electrofuels (medium cost) to electrofuels (high cost) (Korberg et al. (2021).

A different study analyzes the environmental and economic impact of four different hybrid power systems including batteries, fuel cells, as well as diesel- and gas-fueled engines. The study includes investment, maintenance and operational costs for each component, fuel carbon footprints, and their related operational emissions. Dynamic energy system models are used to analyze the economic optimal solution. The results show superior economic and environmental behavior for fuel cells from a long-term perspective. The outcome of the study is dependent on a decrease of fuel cell investment cost and low-priced synthetic fuels in prospective years (Kistner et al. 2021).

Electric hybrid propulsion systems for container ships are further investigated by Ye et al. (2022). The authors analyze PEM FC (Proton Exchange Membrane Fuel Cell) electric propulsions based on compressed and liquified hydrogen as well as ammonia for a water taxi and a 2600 TEU container ship. The study focuses on scenario analysis to determine the break-even point for low-carbon technologies compared to a fossil fuel baseline (ULSFO and MGO). Their results show that compressed hydrogen storage decreases the freight capacity of the container ship, while liquified hydrogen and ammonia-based solution are fulfilling their volumetric constraints. The constraint is based on a statistical analysis for typical tank sizes in container vessels conducted by the ICCT. A carbon price of 88 to 223 USD/ ton of CO_2 is necessary for cost competitive low-carbon fuels. In all analyzed cases, the fuel costs have the strongest impact on the annualized costs, in an increasing trend from compressed hydrogen over liquified hydrogen to ammonia (Ye et al. 2022).

While it is important to analyze ship investments on a case-by-case basis, analyzing fleet perspective investments for low carbon solutions is necessary to understand the potential uptake of those investments. Stolz et al. (2022) provide an assessment of the techno-economic suitability of hydrogen, ammonia, methane, methanol, and diesel - produced from renewable electricity – for the European bulk cargo fleet. Their evaluation of energy density, electricity requirements, and total production costs of various fuels indicates that 93% of transport work can be achieved with a cargo capacity reduction of less than 3%. The transition towards carbon-neutral bulk shipping could potentially increase Europe's electricity consumption by 4-8%. Among the fuel options, ammonia and methanol stand out as the most balanced solutions for carbon-free and carbonaceous fuels, respectively. Yet, the transition could result in an increase of 2-6 times for operational costs by 2030, compared to conventional fuels by 2030 (Stolz et al., 2022).

A short overview of the analyzed papers is provided in the Figure 6. Data from different papers has been extracted and transformed into annualized cost in order to understand the cost structure behind investments in shipping technologies. However, it has to be mentioned that the analyzed papers only reference the CAPEX and the OPEX to the propulsion system, not the entire vessel.

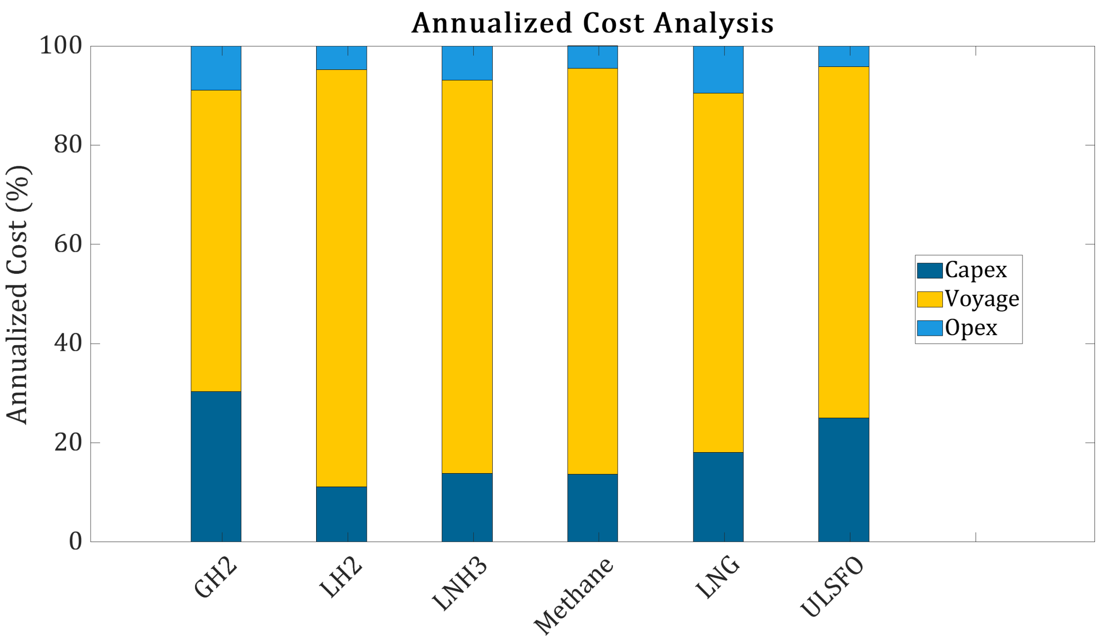

Figure 6: Annualized cost comparison for different fuel based technolgies. Data has been extracted from Ye et al. (2022), Kistner et al. (2021), Korberg et al. (2021), Percic et al. (2021), and Livanos et al. (2014).

The graph underlines the significance of voyage cost in the annual expenditure of a ship, with fuel cost being the main contributor. For net-zero fuels, these costs are usually higher than for fossil fuels, thus emphasizing the necessity of minimizing fuel consumption throughout the operational lifetime of the vessel. The analyzed data shows that any investment model for net-zero shipping has to minimize fuel consumption of the vessel in order to achieve a feasible business case. The following chapter introduces such optimization frameworks that can be used for sizing the system as well as for operational optimization.

3.2 Optimization Frameworks

Designing propulsion systems necessitates a precise understanding of the systems dynamical behavior. The load profile, including energy and power limitations, as well as the power variability are important inputs for the engines design. While sizing propulsion systems for powertrains with single energy sources - operating in load following mode - is relatively simple, it becomes significantly more complex for hybrid power systems because of the necessary energy management and integration requirements.

Hybrid power systems leverage the strengths of multiple power and energy components to create an efficient propulsion system. The integration of energy storage devices, such as batteries, flywheels, or supercapacitors, allows for an optimized operational point of the main engine, thereby reducing fuel consumption. However, the combination of various power components calls for an effective division of power amongst them. This necessitates the implementation of advanced control mechanisms. The implementation of these systems, although complex, is a key step in the successful deployment of hybrid power systems (Inal et al., 2022). The following section provides an overview over different methodologies to size a hybrid propulsion system. In the first subsection, the focus is on a high-level understanding of such frameworks, including the concept of double layer optimization. While in the second subsection, a deeper understanding of different EMSs and their respective design strategies is provided.

3.2.1 Optimizing Hybrid Energy Systems for Ships

Designing and optimizing hybrid energy systems for specific load profiles presents a complex optimization problem. Typically, the design process spreads over multiple optimization problems itself, including the systems topology, size, and control strategy. System level optimization problems have been widely studied for the automotive industry, however, are relatively uncommon for the maritime use case. Studies on EV and FCEV include common optimization architectures, coupling the optimization problem of the plant design and the control structure into one larger optimization architecture. The coupling of such subproblems can be done in a variety of approaches. Silvas et al. (2017) analyzes three different optimization architectures for hybrid vehicles: Alternating, nested, and simultaneous. The mentioned optimization architectures are illustrated in Figure 7.

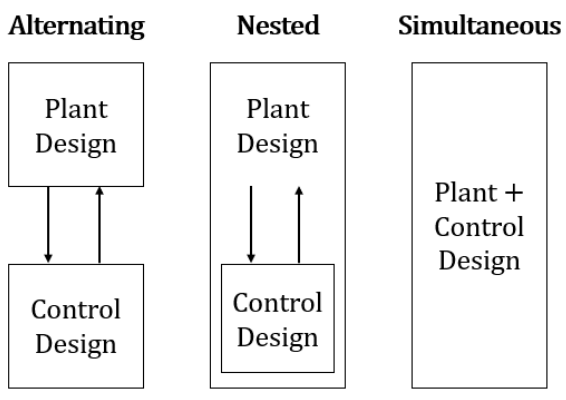

Figure 7: Optimization Architectures for Hybrid Power Systems (Silvas et al. (2017).

The alternating architecture employs an iterative approach: The control strategy is fine-tuned following the optimal design of the initial plant. This optimized control strategy then serves as an input for a new iteration of plant design. The iterative process continues until the plant and control designs are harmonized. Conversely, the nested architecture necessitates a full optimization of the control design for each plant design. Each outer layer design is optimized based on its operational strategy. When the two optimization problems are fused into a single optimization task, addressing both the plant design and control strategy, a simultaneous architecture is adopted (Silvas et al., 2017).

The nested optimization architecture is widely used in the automotive industry, typically employing a double layer optimization framework. Here, the inner loop tackles the control strategy optimization, which is nested within the outer loop that optimizes the propulsion system design. The choice of algorithms for these inner and outer loop optimizations differs strongly based on the specific application and design space, resulting in a variety of unique nested architectures despite its widespread application (Wang et al. 2021).

The plant design, the outer layer, is typically defined by a large design space with a wide set of possible solutions. Such a solution landscape has multiple regional minima and maxima. Hence, an exhaustive algorithm is best suited for the optimization of the outer loop. Algorithms that cover a large design space focus on global optimization problems. Statistic optimization, including examples such as Particle Swarm (PSO), Grey Wolf (GWO), and Genetic Algorithms, (GA) are algorithms that can be applied as solvers (Wang et al. 2021). In contrast, the inner optimization problem is defined by a control strategy for the EMS. A variety of solutions can be applied to solve the EMS ranging from deterministic solutions over dynamic programming to automatic control systems. Subsequently, the design problem will be analyzed in detail, while an overview over different control strategies is provided in Section 3.2.2.

Mashayekh et al. (2012) apply the double layer optimization framework to minimize the fuel consumption of a hybrid electric ferry. A dynamic optimization strategy is chosen for the optimal loading strategy of the vessel’s generator. On top of this nested inner loop, a second optimization problem is defined to size the energy storage capacity, minimizing a cost-savings relationship. The results of the dispatch model show that changes in the load profile lead to strong differences in the optimal dispatch and subsequently their economic benefits (Mashayekh et al., 2012).

A different approach is taken by Skinner et al. (2009) for the optimal design of submarine drive topologies. The authors use a multi-objective genetic algorithm (MOGA) to size integrated electric propulsion drives, hybrid steam turbines, and electric motors. The MOGA is used to increase the entire system efficiency by maximizing the propeller efficiency, the electric motor efficiency, the steam turbine efficiency, while minimizing the electrical motor size and the total energy consumption, creating a five-dimensional optimization problem. The inner layer control strategy is defined as a deterministic rule-based model. Their results underline the superior performance of hybrid propulsion systems, as the hybrid steam turbine/electric motor drive achieves higher efficiencies compared to purely electric/mechanical systems (Skinner et al., 2009).

A different multi-objective optimization approach for hybrid supply vessels is proposed by Zhu et al. (2018). Their MOGA is based on a non-dominant sorting genetic algorithm II (NSGA-II), minimizing fuel consumption, emissions, and related costs. Their algorithm is chosen in order to explore a large design space of candidate solutions. The power split of the inner loop is based on a rule-based system, differentiating between three battery and genset modes. The authors point out that an explorative statistical algorithm is advantageous when covering a large design space and a deterministic power split model (Zhu et al., 2018).

A similar approach is proposed by Wang et al. (2021). Their study focuses on the hybridization of offshore support vessels, including diesel engines, batteries and FC technologies. Their optimization architecture uses a NSGA-II for the outer layer problem, while mixed-integer linear programming (MILP) is used for the inner layer problem. The GA defines the power and energy rating of the propulsion system as the design variables. This is the foundation for their CAPEX model. Step-wise linearization is used to minimize the fuel consumption in the inner loop, defining the OPEX model of the study. The study estimates a 10% emission reduction potential due to the integration of batteries. The authors observe nearly constant power output of the FC at its design point, while the battery and the diesel engines are used for balancing purposes (Wang et al., 2021).

Ancona et al. (2018) investigate energy efficiency on a cruise ship traveling from Mariehamm to Stockholm (Sweden). Their study is focused on achieving higher energy efficiency by integrating energy storage systems on the diesel power vessel. The authors introduce a new GA in order to minimize the operational costs of the vessel, by sizing the energy storage system. Their power split is optimized with an energy grid optimizer tool (EGO), which allocates the optimal load distribution to grid connected components. The authors conclude a payback period of 2 to 6 years for the investments in energy storage systems due to significant reductions in fuel consumption (Ancona et al., 2018).

Cao et al. (2023) optimize the power allocation strategy and size of a FC-Battery electric hybrid ship. On one side, the outer layer optimization model is solved via a hybrid PSO/GWO algorithm for the minimal cost of the energy system. On the other side, the inner layer optimizes the power allocation to the FC and the battery for the minimal operational cost. In order to achieve the cost-optimal solution, the PSO/GWO chooses a possible system size as input to the control strategy. Subsequently, the inner layer optimizes the operational cost by defining control variables, simulating power components, as well as estimating the component degradation. The minimal operational costs are passed to the outer layer again before a new system size is evaluated. This process is continued until the optimal system size is found. Their results show that real-time simulation can provide a more detailed perspective on the systems operation, however, only marginally decreases the optimal results compared to other EMS solutions (Cao et al., 2023). An overview of the analyzed studies is provided in Table 3.

Table 3: Summary of nested double-layer optimization architectures in maritime literature.

Reference	Objective	Plant Sizing	EMS	Engine	ESS	FC
Mashayekh et al.(2012)	Single	fmincon	fmincon	Yes	Yes	No
Skinner et al.(2009)	Multi	GA	RB	Yes	No	No
Zhu et al.(2018)	Multi	NSGA-II	RB	Yes	Yes	No
Wang et al.(2021)	Multi	NSGA-II	MILP	Yes	Yes	Yes
Ancona et al.(2018)	Single	GA	EGO	Yes	Yes	No
Cao et al.(2023)	Single	PSO/GWO	ECMS	No	Yes	Yes

A review of the cases reveals a spectrum of potential optimization architectures and algorithms for addressing the nested double-layer optimization challenge. Although the literature on hybrid energy systems and their optimization networks is vast and offers an even broader range of solutions than presented, certain trends are evident.

Firstly, there is a growing consensus in current literature towards separating the two optimization problems, endorsing the nested optimization architecture. Secondly, large design spaces tend to benefit from exploratory or statistical algorithms, thereby underscoring the significance of GA and PSO. Lastly, the inner layer optimizes for all proposed configurations of the outer layer, suggesting that computational power could pose a constraint in double layer optimization frameworks. To enhance the comprehension of the inner layer optimization problem, the next section will provide a brief overview of potential EMSs.

3.2.2 Energy Management Systems

Hybrid energy systems leverage multiple power sources, operating across a range of modes through an electromechanical configuration. This coupling gives rise to a propulsion system characterized by increased redundancy, safety, flexibility, and economic efficiency. Each power source inherently exhibits unique system dynamics and characteristics, which, along with the overall system dynamics, accentuates the need for an appropriate control strategy. This requirement is typically fulfilled by a specialized EMS, designed to efficiently manage the diverse operational behaviors within the hybrid system (Yuan et al., 2020).

EMSs can be divided into two different approaches: Logic-based control strategies and optimization-based control strategies. Logic-based control strategies are rule-based layouts for specific engineering applications. The rule structure is determined by system understanding, meaning an in-depth analysis of the ship's dynamic performance requirements, the operational behavior and limits of each power source, and the general operation of the ship is necessary. In contrast, optimization-based control strategies compute the most efficient operation of the ship based on energy supply and demand matching. The outcome of an optimization-based control strategy is highly dependent on the applied algorithm and logic (Yuan et al., 2020). Figure 8 illustrates the classification of EMS into their specific strategy types.

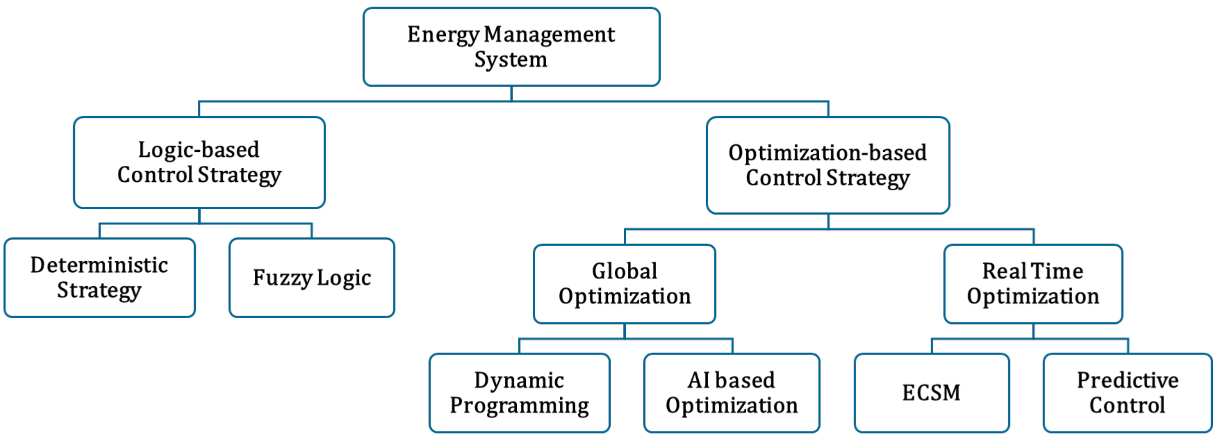

Figure 8: Classification of energy management systems for ships (Yuan et al., 2020)

The figure above shows that logic-based control strategies can further be divided into deterministic strategies and fuzzy logic. The main difference between the two approaches lays within the defined clarity of the applied rules. Tang et al. (2017) use a rule-based energy management system in order to optimize the power split in a fuel cell hybrid ship. They use the state of charge (SOC) of the ultracapacitor and the demanded power compared to the fuel cell reference power as their state definition. Their results show that the designed strategy is able to support the different characteristics and strengths of the ultracapacitor and the fuel cell, respectively. Logic-based control strategies cannot only lead to an alignment with the system dynamics, but also to an improved fuel consumption. Han et al: (2014) design a rule-based system with 11 different operational modes based on the state of charge of the battery and the design area of the fuel cell. They design their operational modes, the states of the rule-based strategy, so the fuel cell can steadily operate at high efficiency values. This further shows that rule-based systems can be established by following a constant methodology. Lana et al. (2019) establish such a methodology for the design of rule-based EMS in short sea shipping. Their approach necessitates information about the load profile, the power components, and their configuration. The steady state-based EMS achieves results within 1% accuracy compared to a dynamic simulation model, while reducing the computational time from 8 hours to 30 seconds.

Rule-based EMS can be combined with fuzzy logic to improve transient behavior of the EMS. The main idea behind the rule-based system stays the same, however, fuzzification is used to transform the initial relationships into linguistic variables. Alankrita et al. (2022) apply fuzzy logic on a hybrid power system. The transient between different rule-based states is based on a gaussian curve for operational changes. Similar to a rule-based system, the fuzzy logic EMS ensures safe operation of the system components, including smooth operation between states. Similar to Tang et al. (2017), Tang and Wang (2021) use the wavelet transformation for their deterministic EMS. However, they apply fuzzy logic on the rule-based system to improve transient behavior. Their results are underlining that logic-based systems can reduce fuel consumption and ensure system stability.

Yuan et al. (2022) analyze fuel cell/battery hybrid power systems under four different control strategies: Rule based, rule-based fuzzy logic, dynamic programming, and optimized rule-based. While the logic-based strategies can model system properties with limited accuracy and low computational power, the optimized control strategies surpass them in terms of their possible outcome. Multiple sources have investigated global optimization frameworks for EMS in ship application. Dynamic programming and intelligent optimization algorithms (eg. GA, PSO, and GWO) are able to find the optimal power split for hybrid systems (Herrera et al., 2015) (Celli et al., 2018) (Gao et al., 2018) (Zhu et al., 2021). However global optimization comes at the cost of substantial computational resources and time (Wang et al., 2015). In contrast, real-time optimization strategies optimize the instantaneous power flow of the propulsion system. This necessitates a power prediction or energy consumption model for efficient behavior (Yuan et al., 2020) (Sun et al., 2023).

The literature shows that optimal power distribution within a hybrid propulsion system can be achieved using a variety of control strategies, each varying in technical, economic, and computational aspects. For instance, dynamic programming offers a highly accurate control strategy, capable of identifying the global optimum for fuel efficiency. However, global optimization comes at the cost of substantial computational resources and time. Alternatively, real-time optimization control strategies emphasize the system's technical performance, which while essential for the propulsion system's design, may not be crucial for determining the vessel's investment viability. Consequently, for the purpose of this study, a deterministic rule-based control strategy, which demands less computational effort, is preferred. While this approach may not guarantee optimal fuel consumption, it provides a solution whose impact lies within an acceptable range, making it an appropriate choice for the studied use case.

4 Methodology

Investing in marine vessels is an intricate process, entangled with various uncertainties. Among numerous aspects, literature identifies efficient fuel utilization as a critical element in justifying a viable business proposition. Consequently, appropriate sizing and optimization of the ship's propulsion system becomes vital for robust operational efficiency. In order to accurately comprehend these complex interconnections, from economic investment considerations to fuel economy, it is crucial to introduce a sufficient level of granularity in the simulation of individual system components. The forthcoming methodology presents a modeling technique that prioritizes computational efficiency without compromising the detailing of subsystem simulations, facilitating the fundamental understanding of the ship's operational performance. Furthermore, the proposed methodology is designed with a level of versatility allowing for repetition and customization across different scenarios, independent of external sources.

In order to achieve this, Section 4.1 introduces the structure of the optimization model from a high-level perspective. Section 4.2 describes the generation of the ship load profile and the necessary data processing. Lastly, Section 4.3 and Section 4.4 dive into the underlaying technical and economic model respectively.

4.1 Double Layer Optimization Architecture

A double layer architecture is chosen in order to optimize the investment case of the analyzed vessel. The architecture follows the aforementioned nested approach, including the plant design in the outer layer and a simplified control design in the inner layer. The plant design defines the main characteristics of the vessel's hybrid propulsion system. Its design parameters include the rated battery power, the rated fuel cell power, the battery energy capacity, and the fuel tank energy capacity. The GA designed in MATLAB is chosen to size the energy system using the aforementioned design parameters (MATLAB, 2023). The fitness function of the algorithm is the NPV of the investment case. The GA is combined with a deterministic control strategy in the inner layer. The strategy is a rule-based EMS, splitting the power between the fuel cell and the battery at each time step. The combination of GA and rule-based EMS allows for a wide coverage of the design space of the outer layer optimization problem, while the deterministic EMS leads to improved computational run time. By that, the GA is directly optimizing the NPV and indirectly optimizing the operational efficiency of the vessel by sizing the propulsion system accordingly. The introduced double layer optimization architecture is illustrated in Figure 9.

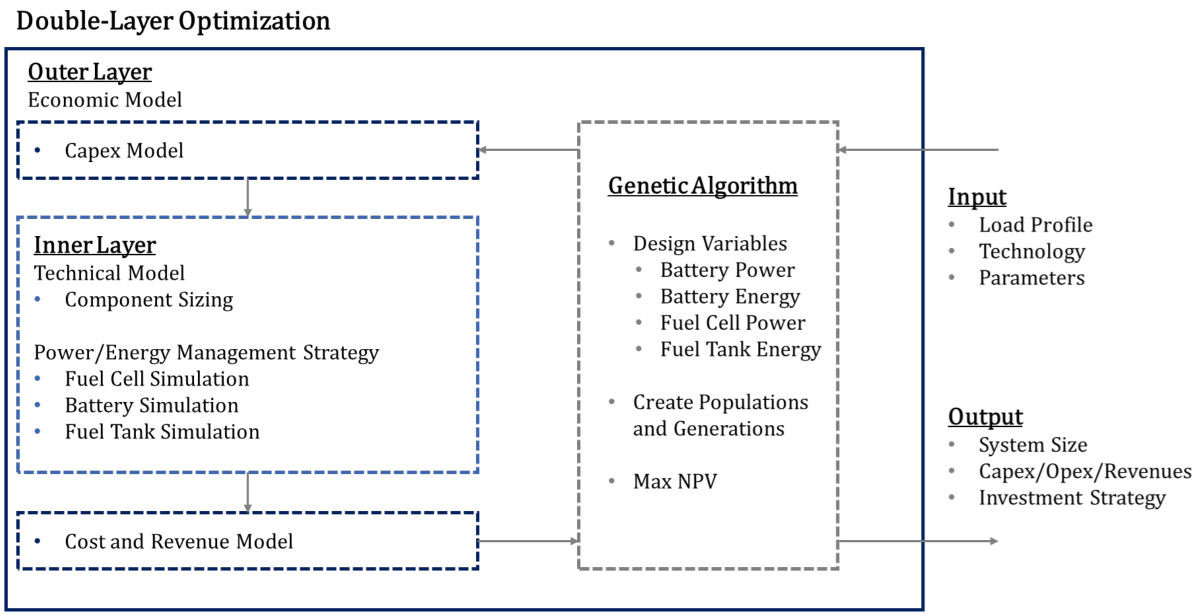

Figure 9: Double-layer optimization architecture for maritime vessels

The presented figure outlines the double layer optimization framework. The necessary inputs for this framework include a predetermined load profile, the technology under consideration, and the relevant technical and economic parameters. The load profile depicts the power required from the hybrid propulsion system at every operational time step of the vessel. Once these inputs are defined, the GA generates an initial batch of individuals for the first population. Each individual in the population represents a distinct combination of the four design variables. Using this first-generation design of the plant and the load profile, the rule-based control strategy can allocate the necessary power for each time step between the battery and the fuel cell. Subsequently, the battery system, fuel cell system, and fuel tank are simulated to compute the energy consumption for each individual member within the population. In addition, a basic component degradation model is applied to assess the operational behavior of the fuel cell and batteries. The CAPEX model of the ship depends on the propulsion system and the vessel's size. Hence, once the GA defines the propulsion system, the CAPEX can be calculated. From the vessel's operational behavior, the OPEX, voyage cost, and revenues can be derived. Finally, the NPV for each population within a generation is computed and used as the fitness function. After the completion of each iteration, the GA recombines a new set of individuals, initiating the next generation as a new iteration of the system. The iterations cease when no significant change in the fitness value is observed, leading to the final design variables as the output of the double layer optimization.

The following sections are explaining each step of the algorithm in its solving order. But before these technical and economic relationships are shown, the formulation of the load profile is explained in detail.

4.2 Load Profile Generation

The first step in the methodology is to generate a ship load profile for a specific route. This profile outlines the engine load demand at each timestep of the journey. While the timestep size can vary based on the detail level of the analysis, it is crucial to accurately determine the actual load required for the ship's operation. To create this load profile, it is firstly necessary to gather data on the vessel's speed profile, which can then be translated into engine power.

4.2.1 AIS Data Extraction

The tracking of ships plays a crucial role in generating accurate ship load profiles. The foundation for ship tracking was layed out by IMO in 1974 with the International Convention on Safety of Life at Sea (IMO, 1974). This convention, specifically Regulation V/12 and 33 CFR Part 161, mandates ships to transmit data regarding their location. The primary objective is to enhance safety and security in maritime transport. In 2016, the IMO further refined the standards for reporting international ship tracking data through the development of the IMO Data Collection System under MEPC 70 (IMO, 2016). This system resulted in the emergence of numerous API (Application Programming Interface) data providers for vessel tracking. The data collection regulation imposes a requirement on commercial ships above a certain size threshold to transmit tracking data. To facilitate ship tracking and monitor maritime traffic, vessel traffic services utilize the Automatic Identification System (AIS). AIS enables such services to effectively track ships and ensure the efficient management of maritime traffic.

In order to produce a load profile for the case study, AIS data was extracted for the analyzed ship with the ships MMSI number (unique vessel ID) from maritime traffic (MarineTraffic, 2023). The generated data set includes a variety of ship related information (e.g. flag, ship name, build year, TEU size, length and company name) as well as ship position data (latitude, longitude, speed, heading, course, status, timestamp, etc.). Spire provides exhaustive instructions on how to access AIS data (Spire, 2023). However, it needs to be mentioned that the location of the vessel is tracked by automatically send GPS data. Therefore, the data retrieved from such sources is low quality and needs to be cleaned from outliers, and restructured as missing data points are common. Once the dataset is cleaned, the ship speed needs to be transformed into the vessel engine load. This can either be done via ship resistance and propeller models or via estimations based on the cubic law. While ship resistance and propeller models can create high accuracy in predicting the actual engine load, they are very data intensive. Furthermore, they need a vast understanding of the ships behavior and hull design. Subsequently, a simple approach following the cubic law is preferred and explained in the following subsections.

4.2.2 Speed to Power Relationship

A statistical relationship between the speed of the vessel and the demanded load at the engine is necessary to create the load profile. This can be done in two subsequent steps. Firstly, the vessel speed is used as an input to calculate the necessary power at the propeller for acceleration. Secondly, electrical and mechanical efficiency losses for the propeller, the engine shaft and converters are included to estimate the demanded power from the engine. The speed-power relationship of a ship is typically described by the cubic law or the propeller law (Brown and Aldridge, 2019). The power at the propeller P_{Pr} is defined by the ship speed v, a ship design constant k, and an engine parameter a.

$$P_{Pr} = k * v^a \tag{1}$$

The engine factor is dependent on the actual engine type used in the vessels propulsion system. For conventional diesel engines, a factor of a = 3 is used. In contrast, the vessel design constant is a dimensionless parameter dependent on the operational design of the ship. The constant is used to reference the cubic law to the specific ship in operation (MAN, 2018) (Brown and Aldridge, 2019). Therefore, the constant can be calculated with the engine power at design speed P_{D,v_d} and the actual design speed of the vessel v_d shown in the formula below.

$$k = \frac{P_{D,v_d}}{{v_d}^3} \quad (2)$$

A power factor of three is applied on the design speed based on statistical analysis of past diesel engines. Additionally, it needs to be mentioned that the rated power of the diesel engine at design speed is typically in the range of 70-80% of the rated power of the engine (MAN, 2018). For the specific analyzed case, the engine power at design speed is set to 75%. The design speed of the vessel needs to be analyzed on a case-by-case approach and is typically provided by international organizations.

As a last step, the propeller power needs to be converted to the engine power necessary at the shaft, using mechanical and electrical efficiencies. Subsequently, the demanded power at the engine (P_e) can be calculated with the efficiency of the propeller (μ_{Pr}), as well as the electrical efficiency of the propulsion system (μ_{el}).

$$P_e = \frac{P_{Pr}}{\mu_{el} * \mu_{Pr}} \quad (3)$$

Due to simplification, the physical relationships are based on static efficiency values. Accurate modeling would need to provide dynamic efficiencies based on the operational point of the engine, the shaft, the electrical system as well as the propeller. The electrical efficiency is set at 0.98 and 0.97, respectively for converter and electrical machine, while the mechanical propeller efficiency is set at 0.7 (Shakeri et al., 2020). The constant propeller efficiency was derived from the Wageningen propeller curves (Bernitsas et al., 1981). Once this conversion is included in the calculation, the load demanded by the hybrid power system – fuel cell and battery – is provided. Subsequently, the load needs to be split between the two components. This is done by the technical model, explained in the next section.

4.3 Technical Model

The technical model of the previously described double layer optimization algorithm is defined as the inner layer of the framework. The inner layer of the optimization model has the four design variables (rated battery power, battery energy capacity, rated fuel cell power, and fuel tank capacity) as their main input. Additionally, the generated load profile for the ship is provided as the necessary power requirement. The main goal of the technical model is to simulate the behavior of the vessel's operation for the predefined route. Therefore, the technical model needs to decide on the power split between the battery and the fuel cell as well as simulate their respective fuel consumption. The propulsion system of the ship, including all components, is illustrated in Figure 10 below. The figure illustrates the included power components for the optimization model. The load profile of the ship is generated from AIS data, including speed to power relationship, and efficiencies of the mechanical and electrical components (electrical machine, converter, propeller). The load demanded at the grid is subsequently provided by the battery and the fuel cell.

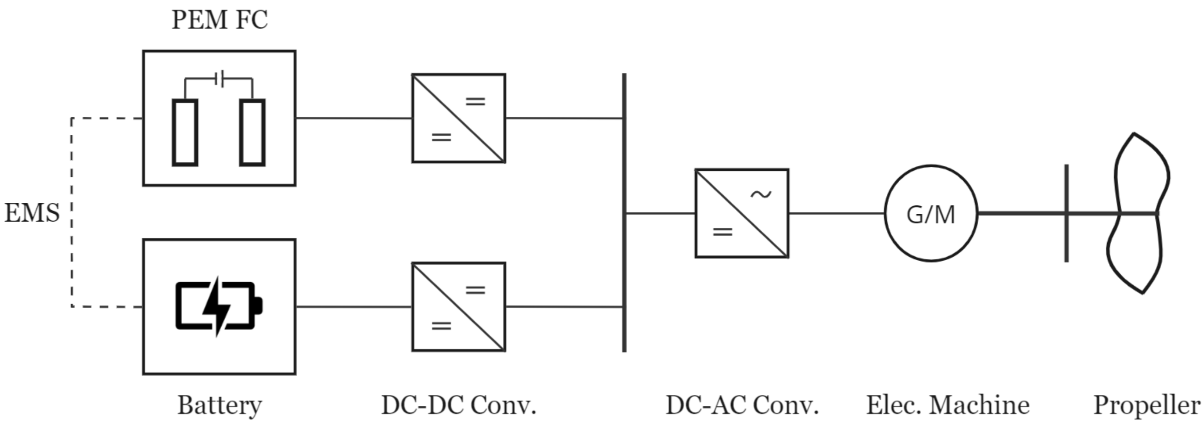

Figure 10: Component overview for the investigated fuel cell/battery hybrid power system

The power split between the two components is based on the EMS of the vessel. Once the power split for both components is defined, the power consumption is calculated for the fuel cell and the battery respectively. Finally, the power consumption is calculated in terms of hydrogen in order to size the fuel tank systems. The power split of the EMS is explained in the next section.

4.3.1 Deterministic Energy Management

The EMS plays a crucial role in the efficient functioning of the vessel. Its primary objective is to reduce the fuel consumption of the vessel's main engine. In the context of the given use case, the EMS is specifically engineered to decrease the hydrogen consumption of the fuel cell. To accomplish this, it is essential for the fuel cell to maintain a constant operational level within its design area. Hence, the EMS's goal is to ensure the fuel cell operates within this design area. It achieves this by utilizing the battery to balance any discrepancies between the power supplied by the fuel cell and the load demand. Designing a rule-based EMS requires an in-depth understanding of the operational boundaries of the propulsion system, particularly the proposed battery and fuel cell system. To facilitate this, a comprehensive analysis of the fuel cell system has been conducted, focusing on its peak operational efficiency, operational constraints, and its ramp-up and ramp-down rates. The efficiency map of the fuel cell, in relation to its power coefficient, is depicted in the subsequent figure.

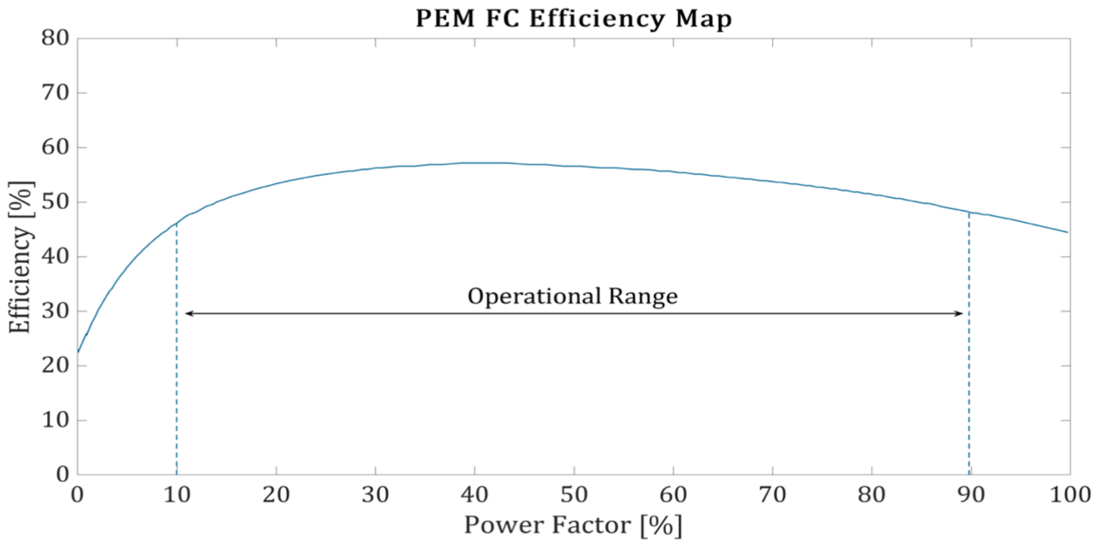

Figure 11: Generic PEM FC efficiency map for maritime application based on Shakeri et al. (2020)

Based on the PEM FC efficiency map, the EMS utilizes a sequence of predefined fuel cell power levels and battery SOC thresholds to manage the energy flow efficiently. The EMS ensures the fuel cell operates within its optimal power levels, while also preventing the battery from overcharging or deep discharging, thereby preserving system component longevity and safety. The EMS initially defines nine power levels for the fuel cell, each level a fraction of the rated capacity, ranging from 0.1 to 0.9. The first decision made by the EMS is to select the fuel cell power output level that most closely aligns with the load demand. Once this initial power level is set, the EMS then assesses the battery's SOC to make further decisions.

Two SOC thresholds, high and low, are established for the battery, along with corresponding exit points. The high threshold of the battery SOC is set at 0.85, while the low threshold for the SOC is set at 0.15, leaving a total depth of discharge (DOD) of 75% of the battery energy capacity for its operation. The EMS uses these thresholds to guide its decisions about power adjustments from the fuel cell, aiming to maintain the battery's SOC within an acceptable range. In response to these thresholds, system states are categorized into three groups: high SOC values, low SOC values, and normal SOC values. These states inform the EMS's actions in response to the battery's SOC and load demand. The decision process behind the SOC categories is shown in the table below.

Table 4: Decision process for fuel cell power level estimation

FC Power Demand	SOC	State	Action
Closest Load Power Level	SOC > 0.85	High SOC	Decrease FC Power Level
Closest Load Power Level	0.15 > SOC	Low SOC	Increase FC Power Level
Closest Load Power Level	0.85 > SOC > 0.15	Normal SOC	Closest FC Power Level

Once the fuel cell power is determined, the battery fulfills the remaining demand of the load profile. However, the implemented EMS does not only focus on keeping the battery within its SOC limits. It also includes a safety mechanism to prevent high frequency hysteresis of battery charge/discharge cycles as well as a stability mechanism in order to let the fuel cell operate at a constant power level. These mechanisms are included to guarantee a lifetime extension of the battery and the fuel cell. The following flowchart encapsulates the decision logic of the EMS:

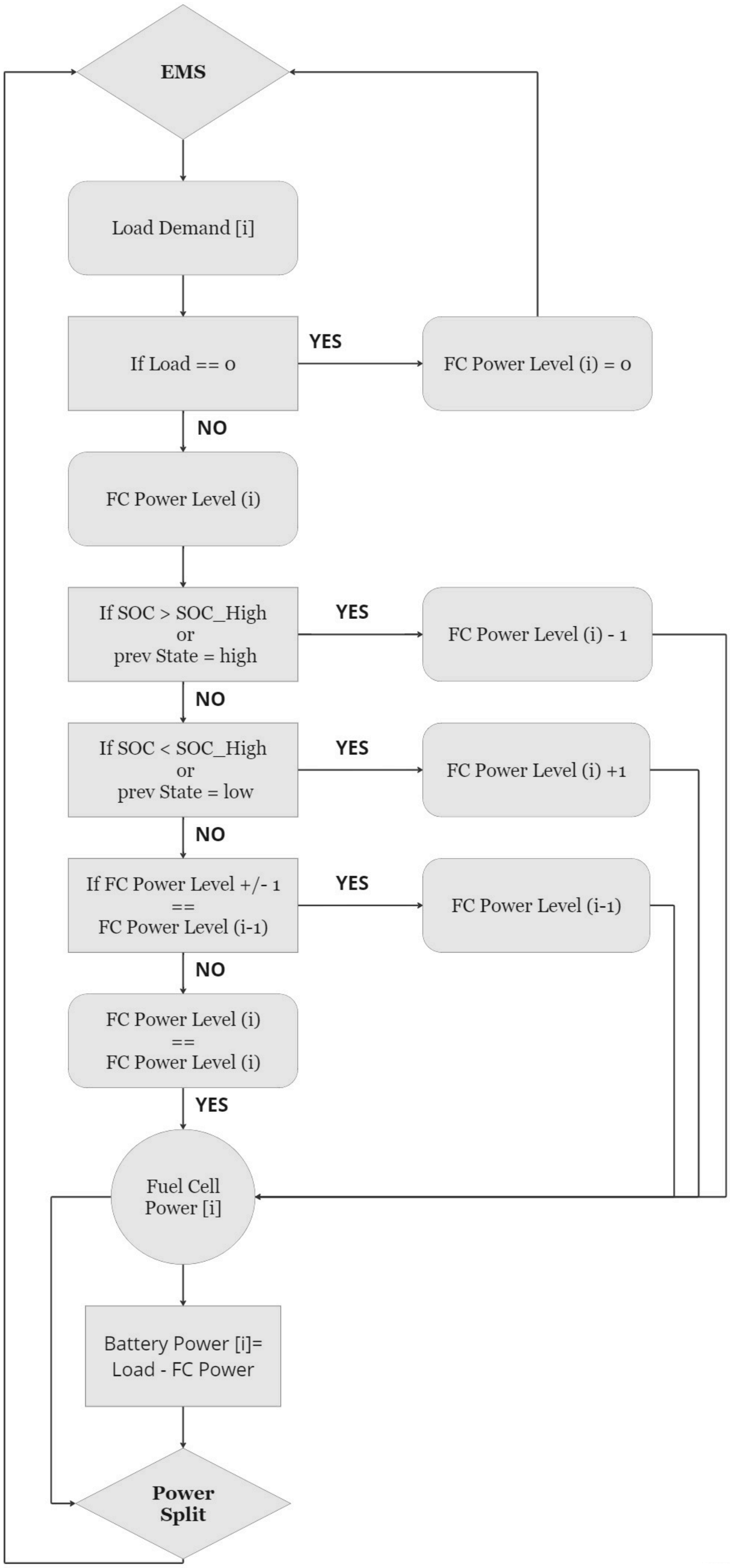

Figure 12: Flowchart of the deterministic EMS

If the load demand is zero, the EMS sets the fuel cell's power output to zero, conserving energy when no demand is present. To avoid battery hysteresis, which can occur with high charge/discharge cycles, a specific mechanism is incorporated. This mechanism is designed to ensure that a battery that has been in a low SOC continues to charge until it surpasses a designated 'low exit point', while a battery that has been in a high SOC continues to discharge until it drops below a designated 'high exit point'. Based on iterative simulations, the exit points for the battery have been determined, resulting in a SOC value of 0.5 for both charging and discharging processes. This mechanism is illustrated in Figure 12 above. When the SOC exceeds the high SOC exit point and the previous state was a high SOC value or if the SOC crosses the upper limit, the EMS reduces the power output from the fuel cell and transitions to a lower state. This action prevents the battery from overcharging. Conversely, if the SOC is below the low SOC exit point and the previous state was a low SOC value, or if the SOC drops below the lower limit, the EMS increases the power output from the fuel cell and transitions to a higher state, charging the battery. This strategy safeguards the battery from cyclic hysteresis around the lower or upper SOC limits.

In situations where the SOC lies between the high and low thresholds, the EMS strives to match the power output of the fuel cell with the load demand as closely as possible. This minimizes the power drawn from or supplied to the battery. The power drawn from the battery is then calculated as the difference between the load demand and the power generated by the fuel cell.

One additional check performed by the EMS is the "adjacent power level" check. If the battery's SOC is within the normal range and the previous power output from the fuel cell was an adjacent power level (one level higher or lower), the EMS maintains the previous fuel cell power output. This check helps the system avoid unnecessary fluctuations in power output, which can lead to decreased efficiency or a reduced component lifetime.

The deterministic EMS offers a structured approach for power flow management in a hybrid fuel cell and battery system. However, it is crucial to note that the system's performance is highly dependent on accurate SOC estimation and reliable load demand prediction. Inaccurate inputs could lead to suboptimal decisions that could affect the system's performance and potentially damage the components. In order to further understand the technical model on a more detailed level, the next subsection explains the simulation of the PEM FC the battery system, and the liquified hydrogen tank.

4.3.2 Simulation of System Components

Once the power distribution is managed by the EMS, both the battery and the fuel cell operate at each simulation timestep to meet the demanded power. The subsequent step involves calculating the energy input for each component to finally estimate the fuel consumption at each timestep. This is achieved by simulating each component using simplified thermodynamic properties and statistical relationships.

<u>PEM FC System</u>
A first introduction to the PEM FC system has already been given in Section 4.3.1, with the explanation of the EMS. The shown PEM FC efficiency map in Figure 11 is the main tool used to calculate the hydrogen consumption throughout the operation of the component. The operation of the fuel cell is limited to its operational range, in order to sustain efficient performance. The operational limit is defined by P_{FC}^{min} and P_{FC}^{max} for each timestep.

$$P_{FC}^{min} \leq P_{FC}[i] \leq P_{FC}^{max} \tag{4}$$

The power of the consumed hydrogen in the fuel cell $P_{H2}[i]$ is then calculated from the PEM FC efficiency map expressed as with the efficiency $\mu[i]$ as a function of the power factor at each time.

$$P_{H2}[i] = \frac{P_{FC}[i]}{\mu_{FC}[i]} \tag{6}$$

With the efficiency $\mu[i]$ as a function of the power factor at each time. The relationship between the fuel cell efficiency and the power factor is shown below.

$$\mu_{FC}[i] = f(PF) \tag{7}$$

$$PF[i] = \frac{P_{FC}[i]}{P_{FC}^{rated}} \tag{8}$$

The power factor $PF[i]$ is the relationship of the fuel cell power to the rated capacity P_{FC}^{rated} of the fuel cell. The simulation is conducted with a resolution of 60 seconds for each timestep, signifying that every power level is held steady for each timestep. Lastly, the power of the consumed hydrogen in the fuel cell is converted into energy and then summed up over the entire voyage time expressed as

$$E_{FC,H2}^{Voyage}[i] = \sum_{i}^{n} \frac{P_{H2}[i]}{60} \tag{9}$$

Moreover, the fuel cell's lifespan is computed to anticipate its replacement schedule. Predicting the lifespan of a fuel cell system in maritime applications is challenging due to the complexity of fuel cell degradation modeling, which requires highly accurate modeling of system components. Hence, the decision to replace the stack is based on the system's operational hours. For maritime applications on a container ship, the estimated value ranges from 30,000 to 40,000 hours (Taljegard et al., 2014) (US Department of Energy, 2023). This estimate surpasses those for fuel cell electric vehicles (FCEVs) and fuel cell heavy-duty transport, which is plausible given the fuel cell's steady operation with fewer fluctuations.

Battery System

In contrast to the PEM FC, the battery efficiency is modeled with constant charge and discharge efficiencies. The efficiency of the battery μ_{Bat} is set at 95% of charging and discharging events. Subsequently, the energy exiting the battery at discharge E_{Bat}^{D} and the energy arriving at the battery at charge (E_{Bat}^{C}) is expressed as

$$E_{Bat}^{D}[i] = E_{Bat}[i] * \mu_{Bat} \tag{10}$$

$$E_{Bat}^{C}[i] = \frac{E_{FC}[i]}{\mu_{Bat}} \tag{11}$$

where the energy exiting the battery is provided to the load, while the energy arriving at the battery is supplied by the fuel cell. The relation between power and energy of the battery is calculated similar to the fuel cell, based on the time step.

$$E_{Bat}[i] = \frac{P_{Bat}[i]}{60} \quad (12)$$

The demanded power from the battery $P_{Bat}[i]$ can be positive or negative. A charging event leads to a negative power value, while a discharging event leads to a positive power value. However, the battery power is limited at all time to its rated power capacity defined by the design variable x(1) or P_{Bat}^{rated}.

$$abs(P_{Bat}[i]) \leq P_{Bat}^{rated} \quad (13)$$

Besides the power constraint of the battery, the battery SOC is constrained within a higher and a lower threshold. The SOC of the battery is defined as the energy in the battery divided by the battery energy capacity ($E_{Bat}^{capacity}$), the design variable x(3). The initial SOC at time step 0 is set at 0.5, while the SOC at each time step is expressed as

$$SOC[i] = \frac{E_{Bat}^{ESS}[i]}{E_{Bat}^{capacity}} \quad (14)$$

while being under the constraint

$$SOC_{min} \leq SOC[i] \leq SOC_{max} \quad (15)$$

where the SOC_{min} is the lower limit at 15% and the SOC_{max} is the higher limit at 85% of the energy capacity of the battery. The SOC is updated during each time step of the simulation. The SOC can be updated with the energy throughput of the battery. The energy stored in the battery $E_{Bat}^{ESS}[i]$ is defined as the sum of energy in the battery at the previous time step $E_{Bat}^{ESS}[i-1]$ added by the demanded energy from the propulsion system at the current time step $E_{Bat}[i]$.

$$E_{Bat}^{ESS}[i] = E_{Bat}^{ESS}[i-1] + E_{Bat}[i] \quad (16)$$

In a next step, the degradation of the battery needs to be analyzed to provide information about the replacement for the economic model. The battery degradation model is based on the Wh-throughput method (Masaud et al., 2020). The model analyzes the relationship of the cyclic behavior of the battery and the depth of discharge in order to estimate the batteries lifetime. Typically, the overall throughput of the battery can be gained from the manufacturer itself, as they provide datasheets relating different DODs to their respective cycle to failure (CTF) (Cao et al., 2023). The relationship of DOD to CTF for the used battery is expressed as

$$N = 4375 * DOD^2 - 10280 * DOD + 10610 \quad (17)$$

where N is the cycle life for a specific DOD. Since the ship is under dynamic behavior, there is not a predefined DOD constant throughout each time step. In contrast the DOD is changing constantly, based on the fluctuating SOC of the battery. The maximum possible DOD of the battery is defined as the difference between the operational limits of the batteries SOC. Additionally, the DOD at each simulation step ($DOD\ [i]$) can be defined by the relation of energy stored in the battery to its rated energy capacity.

$$DOD_{max} = SOC_{max} - SOC_{min} = 0.7 \quad (18)$$

$$DOD\,[i] = 1 - SOC[i] = 1 - \frac{E_{Bat}^{ESS}[i]}{E_{Bat}^{capacity}} \quad (19)$$

Following this, the DOD at each time step must be translated into the DOD for each partial cycle performed by the system. This necessitates cycle counting, which is achieved by monitoring the SOC of the battery at each time step. Cycle counting for the battery is done in three steps:

1. Calculating the turning points (local minima and maxima) of the battery by simulating through each SOC of the operated battery.

2. Calculating the depth of discharge and depth of charge (DOC) for each turning point. A positive difference is defined as a charging event (DOC), while a negative difference is defined as a discharging event (DOD).

3. Analyzing and sorting the conducted partial cycles (charge and discharge) for all DODs

The finally obtained DODs for all discharging events can then be defined as the DOD of all partial cycles of the batteries' operation expressed as

$$DOD_{pc} = DOD_{tp} - DOD_{tp-1} \quad (20)$$

where DOD_{tp} and DOD_{tp-1} are the previously analyzed subsequent turning points. Finally, the equivalent cycle life of the battery under a certain load profile can be calculated by using the CFT relationship of the manufacturer. The equivalent cycle life of the battery (N_{eqv}) is then the sum of the number of performed cycles, iterating k through m, related to the CFT at each DOD_{pc}.

$$N_{rep} = \frac{1}{N_{eqv}} = \frac{1}{\sum_{k}^{m} \frac{1}{N(DOD_{pc})}} \quad (21)$$

The equivalent cycle life of the battery for the specified operational profile then needs to be translated into the number of repeatable operations, denoted as N_{rep}, by taking its reciprocal (Masaud et al., 2020). With the number of repeatable operations and the voyage schedule, the economic model can estimate the replacement schedule for the battery for the vessels' lifetime.

<u>LH2 Fuel Tank</u>
In the final stage of the technical mode, the simulation incorporates the vessel's liquefied hydrogen tank. Liquid hydrogen needs to be stored at cryogenic temperatures below -253°C and 1 bar. This process significantly increases the density of liquefied hydrogen to 70.85 kg/m^3 (gaseous hydrogen at 0.08987 kg/m^3). Although the liquefaction process is not included in the model, it is important to note that it consumes a significant amount of energy. Moreover, the entire storage system must be technically designed and equipped to handle such extreme temperatures. During the storage and transmission of liquid hydrogen, heat leakage is inevitable, which is particularly crucial for long-duration storage or long-distance transport (Zhang et al., 2023). The evaporation of liquid hydrogen during storage, the boil-off, is include into the model as an efficiency metric (μ_{BO}) for the storage tank expressed as

$$E_{H2}^{Tank} = \sum_{i}^{n} \frac{P_{H2}[i]}{60s * \mu_{BO}} \tag{22}$$

$$\mu_{BO} = 1 - r_{BO} \tag{23}$$

where r_{BO} is the boil-off rate of hydrogen per simulation step. The boil-off rate of liquified hydrogen is estimated at 0.2% per volume per day (Zhang et al., 2023). The data has been obtained from studies on liquified hydrogen tanks for maritime applications, ranging from 1,250 to 40,000 m^3 in size (IRENA, 2022). Space related assumptions are included in the economic model.

4.4 Economic Model

The overarching structure of the optimization framework is shaped by the economic model, which translates technical parameters into economic values. The final fitness function, optimized by the genetic algorithm, is defined as the NPV of the investment decision. However, to accurately model the NPV for the investment case of a vessel, multiple cost and revenue streams need to be considered. This includes incorporating market conditions to generate a realistic business case. Therefore, the following section will delve into the cost and revenue relationships, focusing on CAPEX, OPEX, voyage cost, replacement cost, cost of lost cargo, and shipping revenues.

4.4.1 Capital Expenditures

The CAPEX of a maritime vessel can be modeled in multiple different ways. Typically, studies calculate such costs as fixed costs at the beginning of the investment. However, in the maritime industry, CAPEX can be seen as annual cost depending on charter rates and loan rates through debt financing. However, for the purpose of this investment decision analysis, we model the CAPEX as a fixed cost, also known as 'overnight costs', to maintain consistency with similar studies in the field.

<u>PEM Fuel Cell System</u>
The fuel cell system cost modeling follows an approach based on economy of scale. Typically, an increase in system size does not lead to a linear increase in cost. For the PEM FC system, a scaling approach was chosen. A 10 time increase in system size leads to a 10% less than linear increase in system cost (Yates et al., 2020). The cost curve for the FC System can be modeled with the following formula

$$C_{FC} = \left(a + \log\left(P_{FC}^{rated}\right) + b\right) * P_{FC}^{rated} \tag{24}$$

where C_{FC} is the CAPEX of the fuel cell system and P_{FC}^{rated} is the rated power of the fuel cell. The values of a and b have been defined with a curve fitting approach as -19.1162 and 842.8541 respectively. The modeled cost function follows a logarithmic approach for cost fitting. The initial fuel cell system cost are assumed to be at 1000 USD/kW for the model approach based on the literature (Ballard and Deloitte, 2020) (Aarskog et al., 2020). The cost decrease of the function for large scale fuel cell systems (10 to 100 MW) can be seen in the following diagram.

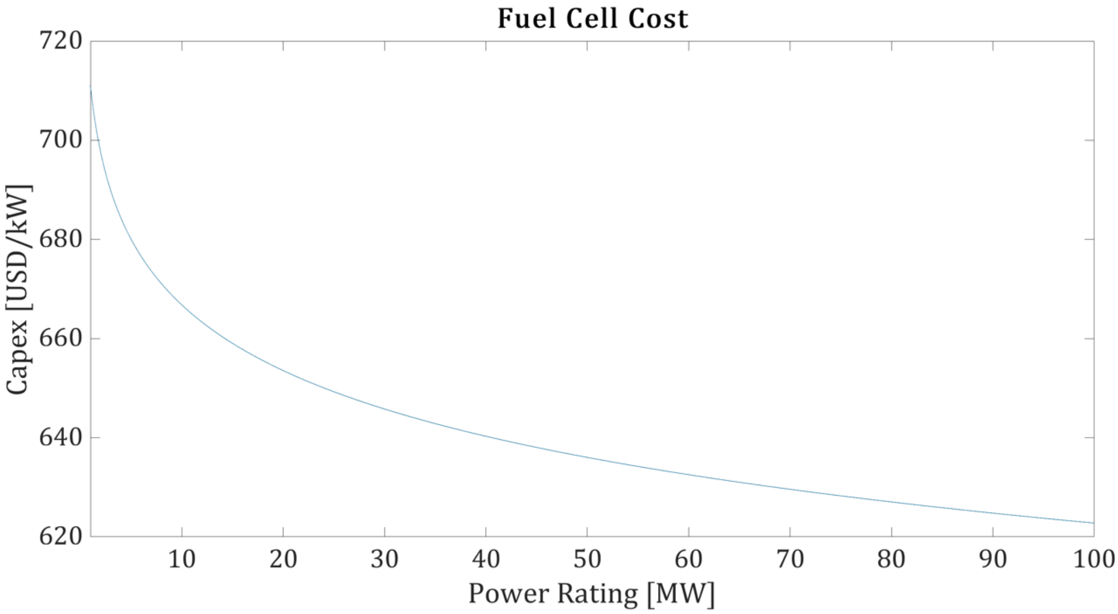

Figure 13: Fuel cell cost function based on Yates et al. (2020).

Once the fuel cell system is in operation, its lifetime becomes a major aspect for cost modeling. After a certain expected lifetime is reached, the fuel cell stack needs replacements to ensure secure operation. For this purpose, only the stack replacement costs are taken into consideration, while other auxiliary power components are excluded. Following the literature, stack replacement costs ($C_{FC}^{Replace}$) can be expressed as partial costs of the initial investment (Taljegard et al., 2014).

$$C_{FC}^{Replace} = 0.33 * C_{FC} \tag{25}$$

The lifetime of a fuel cell system in maritime application is modeled based on the technical degradation. Following the given route, the replacement schedule is calculated with the operational hours per trip.

<u>Battery System</u>

The cost function for the Battery system follows the idea of splitting the cost into different related impact factors. The capital costs of the battery components are divided into costs related to rated power and energy (Lie at al., 2018) (Cao et al., 2023). There is a variety of different power and energy related prices in the literature. For the case study, an approach by the ENREL is followed. The CAPEX of the battery system ($C_{Battery}$) can be estimated with the following function (NREL, 2021)

$$C_{Battery} = c_p * P_{Bat}^{rated} + c_e * E_{Bat}^{capacity} \tag{26}$$

where c_p equals 700 USD/kw as the power electronics related cost factor and c_e equals 200 USD/kwh as the energy related cost factor. The cost factors associated with battery replacement are primarily concerned with the energy components (cells) of the battery, which are most affected by degradation. As such, the replacement cost is focused on these energy-related costs. Therefore, the replacement cost is modeled using the following formula.

$$C_{Battery}^{Replace} = c_e * E_{Bat}^{capacity} \quad (27)$$

The replacement costs ($C_{Battery}^{Replace}$) are therefore a partial function of the initial investment cost, not including the power component cost. Second life sales values for the replaced batteries are not included in the cost model. The timeline for battery replacement, much like the fuel cell, is determined by the technical degradation model and the rate of degradation per trip. The results from the technical model can be directly applied to establish this replacement schedule.

LH2 Storage

The final component of the hybrid power system to be modeled is the liquified hydrogen storage tank. Despite its simplified simulation, the cost of this tank constitutes a significant portion of the propulsion system's expenses. Estimates for the cost of liquified hydrogen storage systems have varied widely in recent literature, ranging from 3,000 USD/m^3 up to 35,000 USD/m^3 (James et al., 2016) (Argonne, 2019) (Ye et al., 2022) (US Department of Energy, 2022). These cost fluctuations are understandable given the nascent state of large-scale industry adoption of this technology. Each year brings new developments that drive costs down. Recent data from manufacturers, particularly in the U.S., highlight the potential for significant cost reductions, which supports a cost assumption in the lower end of the presented cost range (US Department of Energy, 2022). The cost function for the liquified hydrogen tank is expressed as

$$C_{H2Tank} = saf * c_{Tank} * E_{H2Tank}^{capacity} \quad (28)$$

where C_{H2Tank} is the CAPEX of the liquified hydrogen tank, c_{Tank} is the cost factor set at 5000 USD/m^3 and $E_{H2Tank}^{capacity}$ is the required energy capacity of the tank in cubic meters. Additionally, a safety factor of 1.3 is used to ensure continuous operation during bad weather events or other occurrences that result in prolonged traveling time. Replacement cost are not foreseen for the liquified hydrogen tank.

Diesel System

In contrast, the cost modeling for a diesel-based energy system can be done in a more simplified way. The capital costs of a diesel engine are known from the industry, as the engine system has been used for many years. Typical two to four stroke ICE diesel engines are ranging from 300 to 450 USD/kW, depending on their size. For a medium size container ship 400 USD/kW haven been used as a cost assumption (Korberg et al., 2021).

The storage cost for HFO can also be estimated from a wide set of known data. Diesel storage systems are less complex to handle compared to LH2 systems as they do not require high surrounding conditions. Typical specific capital cost for such a storage system can be estimated around 100 USD/m^3 (Argonne, 2019) (Korberg et al., 2021). A simple cost function for the diesel-based energy propulsion system is therefore proposed as

$$C_{Diesel} = c_{Engine} * P_{Diesel} + c_{Tank} * E_{Diesel}^{capacity} \quad (29)$$

The cost function for the diesel case is necessary one side to estimate the total CAPEX of the ship, while on the other side they can be used as reference case for the cost analysis.

Capital Cost Function

Drawing from the capital cost functions discussed earlier, we can formulate a comprehensive cost function for the entire vessel. By analyzing literature and examining the costs of newly built ships, a cost function for new container ships has been established as a function of the loaded container TEU (Twenty-foot Equivalent Unit). This function can be utilized to estimate the costs of new builds with conventional propulsion systems. Given that the primary fixed cost of net-zero ships will stem from the propulsion system, this function can be adapted to suit the objectives of this study. The total cost function is expressed as

$$C_{H2}^{Vessel} = C_{Diesel}^{Vessel} - C_{Diesel} + C_{H2Tank} + C_{Battery} + C_{FC} \tag{30}$$

where C_{Diesel}, C_{H2Tank}, $C_{Battery}$, and C_{FC} are the previously determined capital cost of the conventional, and the net-zero propulsion system. In contrast, the cost of a newbuild container vessel that primarily uses diesel as fuel is represented as C_{Diesel}^{Vessel} with the following formula.

$$C_{Diesel}^{Vessel} = 0.0068 * TEU + 24.417 \tag{31}$$

The cost function for the price of new constructions is derived from literature, where a regression analysis was performed on container ships with carrying capacities of 5600, 8500, 9600, 14000, and 18000 TEU (Ge et al., 2019).

4.4.2 Operational Expenditures

The operational expenditures of the vessel are further included into the economic model. The operational expenses are categorized in five different cost factors, namely: Crew wages, total insurance costs, repair and maintenance costs, marine insurance, and management costs. Moore (2023) publishes data on the OPEX on various ship types including container vessels. Linear regression and extrapolation are used to estimate cost functions for the five different cost factors. An illustration of the different cost functions dependent on the TEU is presented in Figure 14.

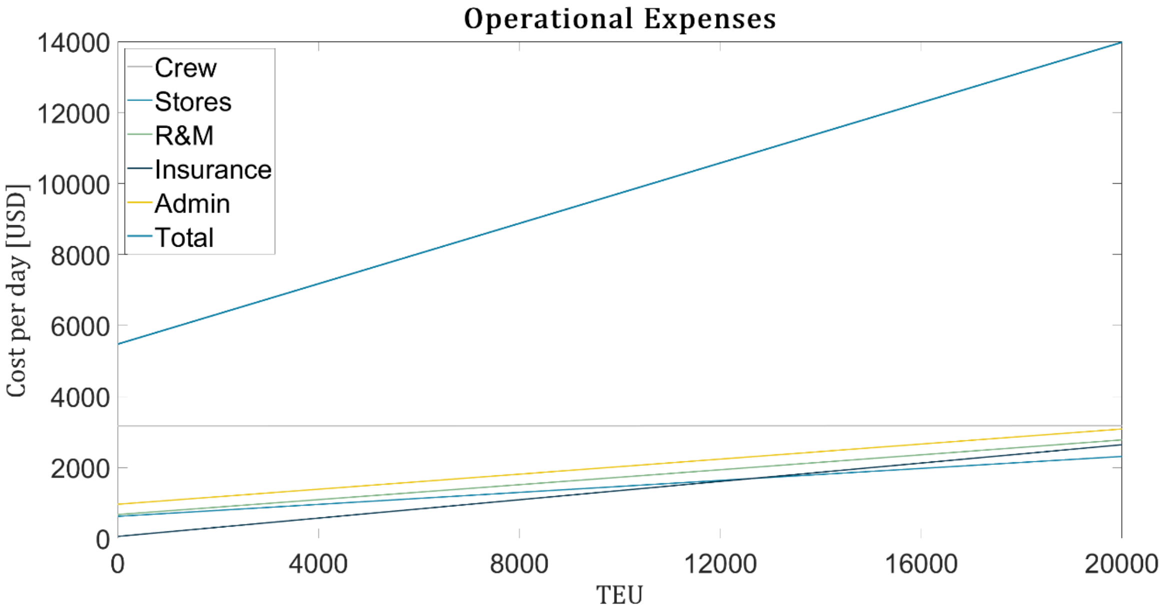

Figure 14: Operational Expenses as a function of TEU. Data has been obtained from Moore (2023).

The figure is a result of the linear regression and extrapolation model. The five different cost functions used for the case study are shown below

$$Opx_{crew} = 0.002 * TEU + 3167.33 \quad (32)$$

$$Opx_{stores} = 0.422 * TEU + 518.667 \quad (33)$$

$$Opx_{rm} = 0.526 * TEU + 442.333 \quad (34)$$

$$Opx_{insurance} = 0.646 * TEU + 1000 \quad (35)$$

$$Opx_{admin} = 0.530 * TEU + 667.667 \quad (36)$$

where the TEU is defined as the total carrying capacity of the vessel. Combining the different cost functions results in the final cost function for the OPEX of the vessel as shown in the figure. Additionally, it is assumed that the operational cost of the vessel increase on a year by year basis with an annual rate of 1.3% (Ge et., al 2019).

4.4.3 Voyage Cost

The voyage cost of the vessel include all variable cost directly resulting from and during the vessels trip. This includes annual fuel cost, annual port cost, as well as voyage related canal costs. Due to the lack of data, the annual port cost and the canal cost are excluded from the voyage cost. Hence, the main focus of the voyage are the fuel cost of consumed hydrogen. The voyage cost are therefore a function of the consumed hydrogen per trip

$$C_{Voyage} = C_{Fuel} = E_{H2Tank}^{capacity} * c_{H2} \quad (37)$$

where c_{H2} is the hydrogen price at the harbour. For the case study an initial hydrogen price is assumed at 5 USD/kg of hydrogen (Ye et al., 2022).

4.4.4 Shipping Revenues

The revenue generated by a container vessel is determined by several factors: the freight capacity, the freight rate, the load factor, and the number of trips made on a specific route. Accurately calculating shipping revenues can be challenging due to the high volatility of the container market. The revenue for a container ship per round trip can be calculated using the following formula:

$$Rev = TEU * r_{load}^{west} * p_{fr} + TEU * r_{load}^{east} * p_{fr} \quad (38)$$

The revenues are calculated separately for the eastbound and westbound routes. Load factors for both directions ($r_{load}^{east}, r_{load}^{west}$) are applied to model the realistic behavior of the container market, and these are supplemented by an additional freight rate (p_{fr}) for the route (Ge et al., 2019).

Additionally, the total container freight capacity of the vessel needs to be considered. One of the significant challenges of net-zero fuels in shipping is the size of the systems they require. The introduction of a hybrid propulsion system in a container ship increases the space occupied by the propulsion system. However, the primary impact of the system increase doesn't come from the fuel cell or the battery, but from the hydrogen fuel tank. The low volumetric energy density of hydrogen as a fuel leads to a higher space requirement for the same energy capacity compared to conventional fuels such as diesel (Ye et al., 2022). Therefore, a simplified framework is used to investigate whether the container ship can operate on the provided route without reducing its carrying capacity – the cost of reduced cargo.

The ICCT conducted a study in 2020, examining the feasibility of hydrogen-fueled container shipping from China to the US. They performed a statistical analysis on over 304 individual container carriers, establishing a relationship between the container carrying capacity and the potential size of the fuel tank. The findings from their study are utilized in this analysis to formulate a function that determines the maximum possible space for the fuel tank in the vessel under consideration (ICCT, 2020).

$$FT_{H2}^{max} = f(TEU) \tag{39}$$

Once the maximum size for the fuel tank (FT_{H2}^{max}) of the vessel is calculated, the difference between the necessary fuel tank size for the route (FT_{H2}) and the maximum carrying capacity is used to calculate the cost of lost cargo expressed as

$$C_{Cargo} = \frac{(FT_{H2} - FT_{H2}^{max})}{V_{TEU}} * p_{fr} \tag{40}$$

where difference between the necessary fuel tank size (FT_{H2}) and the maximum available fuel tank size (FT_{H2}^{max}) is divided by the volume of one TEU unit (V_{TEU}) and then multiplied by the average freight rate of the route p_{fr}. The necessary fuel tank size is on the other hand calculated with the already presented energy demand of hydrogen, a safety factor, and a hydrogen system specific energy density shown in the formula below.

$$FT_{H2} = \frac{E_{H2Tank}^{capacity}}{d_{H2System}} * saf \tag{41}$$

The volumetric density of a liquified hydrogen fuel system, $d_{H2System}$, is defined as 1,332 kWh/m^3. The number is based on the energy density of hydrogen at 33.3 kWh/kg and a reduced volumetric energy density of liquified hydrogen systems at 40 kg/m^3 (typical liquified hydrogen density is around 71kg/m^3). The volumetric hydrogen density is reduced in order to account for the needed space of additional components, such as the insulated tanks and other fuel system components (Minnehan and Pratt, 2017) (Hall et al., 2018).

Additionally, the new carrying capacity (TEU_{H2}) is calculated by the difference between the initial fuel tank size and the necessary size as follows.

$$TEU_{H2} = \frac{(FT_{H2} - FT_{H2}^{max})}{V_{TEU}} \tag{42}$$

In case a reduction of carrying capacity is necessary, the final revenues are calculated with the updated carrying capacity, substituting the initial carrying capacity of the vessel.

4.4.5 Net Present Value

At last, all the components necessary for the final fitness function, the NPV, have been calculated. The NPV depends on various factors including the vessel's CAPEX, OPEX, voyage costs, revenues, and the associated cost of lost cargo. These different costs and revenues streams are then organized according to their annual occurrence, resulting in a vector of cash flows. The final NPV is computed by discounting these future cash flows.

$$NPV = \sum_{i}^{n} \frac{P}{(1+\ \tau)^{i}} - C_{H2}^{Vessel} \tag{43}$$

The cash flows are included in the formula on a year by year basis as variable P, while the capital cost of the newbuild hydrogen vessel is estimated as C_{H2}^{Vessel}. Furthermore, a discount rate, (τ) of 8% is applied for the investment decision.

The following chapter will provide a short introduction to the case study, before the results of the established methodology are analyzed.

5 The German Maritime Sector

The following chapter aims to introduce the case study. For this purpose, the chapter summarizes general information about the maritime industry in Germany (Section 5.1) and the analyzed vessel with its analyzed route (Section 5.2).

5.1 General information

As a leading maritime nation, Germany presents a unique case for studying the potential employment of net-zero vessels. Accounting for over 90% of the country's foreign trade by volume, the shipping sector is an important contributor to the German economy. The industry boasts an annual turnover approaching approximately 50 bil. USD and generates around 400,000 direct and indirect jobs (BMWi, 2017). These figures reflect Germany's economic dependency on the sector and its necessity to commit to sustainable growth. Internationally, Germany is recognized for its export of high-quality manufactured goods, including automobiles, machinery, and chemicals. The nation also depends strongly on imports of raw materials and energy resources, in addition to various consumer goods. This trade dynamic underscores the crucial role of container ships, which facilitate the bulk of Germany's import and export activities (BMWi, 2017).

To navigate the future challenges and opportunities of the maritime sector, the Federal Ministry for Economic Affairs and Energy has initiated the 'Maritime Agenda 2025'. This comprehensive strategy outlines Germany's vision for a maritime industry that leverages technological advancements to remain competitive on the global stage. Key components of the agenda include fostering technological leadership, ensuring international competitiveness, promoting maritime transport sustainability, and digitalization pathways. In the context of promoting maritime sustainability, there is increasing pressure on the shipping industry to minimize its carbon footprint (BMWi, 2017). Hydrogen fuel cells present a potential solution, offering a propulsion mechanism for container ships that could significantly reduce greenhouse gas emissions. Germany is a global leader in hydrogen technologies and has started advanced research and investigations to promote fuel cell technologies in maritime transport. The NIP and NIP II programs are the main initiative of the German government with the goal to integrate hydrogen technology in market-oriented applications (BMVI, 2016) (BMDV, 2020).

Given Germany's prominence in the maritime industry and its forward-looking approach to sustainability and technological innovation, it serves as an ideal subject for further investigation. The subsequent sections will therefore develop the case study for the German maritime industry.

5.2 The Valparaiso Express

Germany's maritime industry includes a wide range of container shipping lanes, with vessels traversing predefined routes. One route that has garnered significant attention is the shipping lane from Germany to Chile. The route passes through two of the busiest canals in the world, the English-channel and the Panama-canal (WE Forum, 2022). Originating in Hamburg and culminating in Valparaiso, Chile, the route is a key lane for German container ships. The analysis of the AIS data revealed three container ships operating on the lane: The Valparaiso Express, the Maersk Batur, and the Safmarine Benegula. It should be noted that while this is not a comprehensive list of container ships on the route, the three examples provided sufficed for the purposes of the case study. Among these, the Valparaiso Express is a Post-Panamax class vessel with a capacity to carry 10,500 TEU. In contrast, both the Maersk Batur and the Safmarine Benegula are Panamax class ships, each with a cargo volume of 3,050 TEU. The decision to select the Valparaiso Express for a detailed case study was influenced by its significant size, representing a larger segment of the shipping fleet, and its relatively recent construction in 2016. Comprehensive specifications and attributes of the Valparaiso Express are mentioned in Table 5.

Table 5: Data sheet on the Valparaiso Express (Port of Hamburg, 2023).

Vessel	Valparaiso Express
IMO Number	8777589
Ship Type	Container Carrier
Owner	Hapag Lloyd AG
Flag	German
Construction Year	2016
Length (LOA)	333 m
Width	48.2 m
Depth	14 m
TEU	10500
Engine	Man Diesel (34224 kW)
Top Speed	21 knots

The container vessel operates under the German flag and is managed by the global container lining company, Hapag-Lloyd. Measuring 333 meters in length, 48.2 meters in width, and 14 meters in depth, the Valparaiso Express fits the specifications of the Post-Panamax category, tailored for the dimensions of the Panama Canal after its 2016 redesign. The ship is powered by a two-stroke diesel engine, crafted by MAN, boasting a built-rated power of around 34 MW and a maximum speed of 21 knots.

As previously mentioned, the vessel's route commences in Hamburg, Germany, extending to Valparaiso, Chile. The entire voyage spans a duration of 755 hours, or 31 days, starting on the 11th of June and projected to conclude on the 13th of July, as derived from AIS data. The vessel makes scheduled stops at several significant ports. These include Antwerp in Belgium, Santo Domingo in the Dominican Republic, and Cartagena in Colombia. Additionally, the vessel navigates through the Panama Canal and makes subsequent stops in Lima, Peru and Mejillones, Chile, before its final destination in Valparaiso, Chile. The conducted route is illustrated in Figure 15.

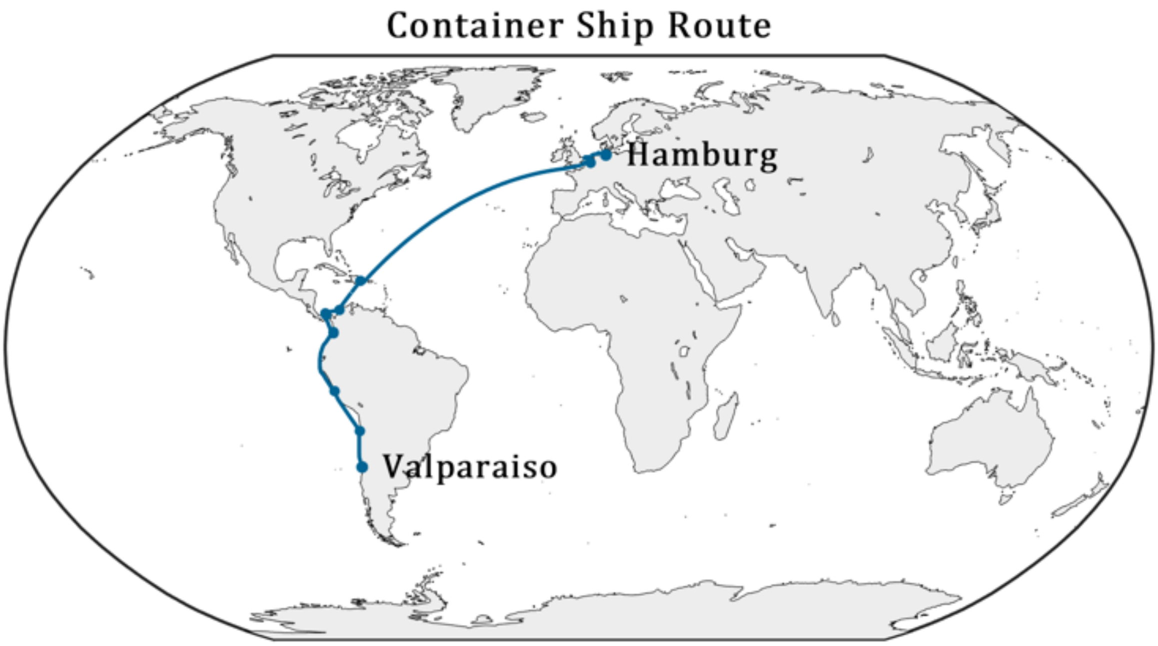

Figure 15: Shipping route from Hamburg to Valparaiso

Referencing back to Section 4.2, AIS data is used to track the ship for its operation on the container lane. With the data on the vessels ship speed for the entire 31 days of voyage, a load profile can be generated for the Valparaiso Express. The vessels specific load profile, from Hamburg to Valparaiso, is illustrated in Figure 16 below.

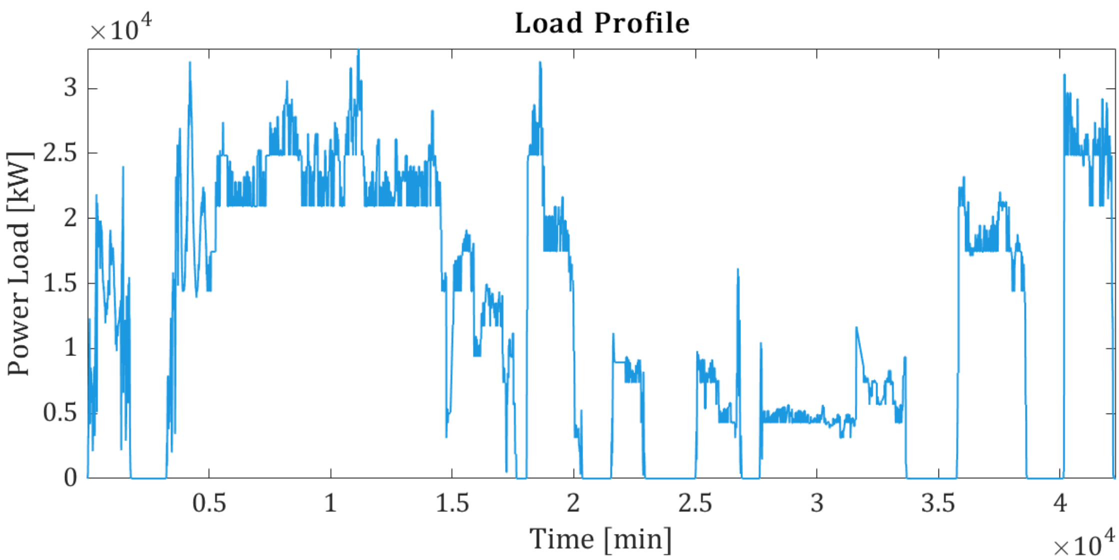

Figure 16: Extracted load profile for the Valparaiso Express on the route Hamburg to Valparaiso.

The shown load profile is one of the main input into the optimization algorithm, besides the used technology. The maximum demanded power of the vessel throughout the trip sits at 33 MW, within the range of the rated power of the diesel engine of the Valparaiso Express. Auxiliary power demand are not considered for the purpose of the study. The stops made by the Valparaiso Express in Antwerp, Santo Domingo, Cartagena, Lima, Mejillones can be seen on the map and the load profile, marked at times with no demanded power. Having established the foundation of the case study and explained the rationale behind the selection of the specific case, the subsequent chapter will show the findings and outcomes of the case study.

6 Case Study

In this chapter, the case study of the Valparaiso Express is evaluated from a technical and an economic perspective. In the following sections, the two assessments are presented separately. First, the focus is layed on the results from the technical model. A secure technical operation needs to be ensured before the economic feasibility can be analyzed. This includes the operation of the fuel cell and the battery based on the proposed EMS as well as the degradation and replacement schedule of the components. Second, the focus shifts towards the investment case behind the vessel under current market conditions. The NPV as well as other cost metrics are analyzed in order to justify the investment case. Third, a sensitivity analysis is conducted in order to analyze the circumstances for investments in net-zero container shipping.

6.1 Technical Results

The technical results of the double-layer optimization algorithm focus on the system size and its operation. The optimization was conducted multiple times to prove convergence regarding the best solution. The optimal results show the necessary size of the components of the hybrid power system including the rated battery power, the rated fuel cell power, the battery energy capacity, and the fuel tank energy capacity, presented in Table 6.

Table 6: Design of the LH2 Propulsion System

Hybrid Propulsion	Size
Battery Power Rating	5,881 kW
Fuel Cell Power Rating	39,304 kW
Battery Energy Capacity	52,068 kWh
LH2 Tank Energy Capacity	16,810,355 kWh

The findings indicate a significant surge in the rated power of the hybrid propulsion system compared to the traditional diesel setup. The combined power output from the battery (5,881 kW) and the fuel cell (39,304 kW) is 45,185 kW. This is a 31.60% increase compared to the conventional diesel propulsion system, which has a rated power of 34,334 kW. This highlights a fundamental distinction between the engines used in each system. Maritime diesel engines are typically designed to operate consistently at 70-80% of their rated power, ensuring optimal efficiency. However, the operational range is expected to shift when considering a fuel cell/battery hybrid system. The peak efficiency of the integrated PEM FC is achieved at just 34% of its rated power. As a result, the algorithm increases the size of the PEM FC, allowing it to operate at lower loads, thereby enhancing its efficiency and reducing hydrogen consumption. The battery's role further accentuates this by catering to a portion of the load, enabling the fuel cell to operate closer to its optimal efficiency point. The average power output of the fuel cell demonstrates this observation, as it is at 32% of its rated power for the voyage.

Zooming in on the battery system, its power rating is complemented by an energy capacity of 52,068 kWh, allowing it to operate at its maximum power for roughly 8 hours. This capability is crucial in harbors and low-speed zones where prolonged periods of low power are required. In such scenarios, the battery supplies the necessary power to maintain the ship's speed. However, the primary energy source remains the fuel cell, with the liquified hydrogen tank boasting an energy capacity of 16,810,355 kWh. Thereby, the energy capacity of the LH2 tank is estimated to be 322.85 times greater than the battery's energy capacity. The results underline the role of the fuel cell and the battery in the hybrid power system. The fuel cell is the main engine, supplying power to the propeller, while the battery is the additional engine balancing the fuel cell for high-efficient operation. The operation of the fuel cell over the conducted route is illustrated in Figure 17.

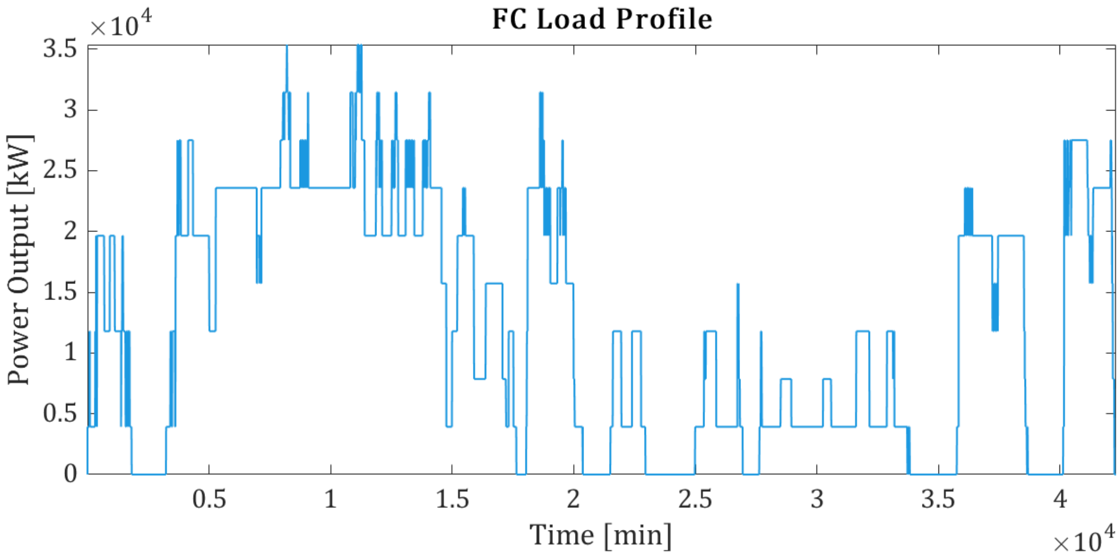

Figure 17: Load profile of the fuel cell for the route Hamburg to Valparaiso.

In the analyzed journey from Hamburg to Valparaiso, inclusive of port durations, the fuel cell's operation, driven by the Energy Management System (EMS), remains notably consistent. Throughout each segment between ports, the EMS chooses a stable power level for the fuel cell, adjusting primarily when the battery approaches operational thresholds. Data analysis reveals minimal deviations in the fuel cell's power output over time. The ramp-up and ramp-down rates of the fuel cell are defined by the EMS as a typical 10-20% change in power per minute of simulation. Fluctuations between different power level rarely occur due to the large time span of the route, underlining the impact of the EMS on reducing fluctuations and hysteresis. Most importantly, the fuel cell's operational range predominantly resides between 11 MW and 24 MW, signifying its efficient utilization between 30% and 60% of its rated power output. This operational bandwidth corresponds to efficiency levels of 54% to 57%, underscoring that the fuel cell is sized for efficient fuel consumption of the system.

In contrast to the fuel cell, the battery is designed to operate at different power levels constantly, supplying the difference in power of the fuel cell and the demanded load. This leads to a highly fluctuating load profile as can be seen in Figure 18.

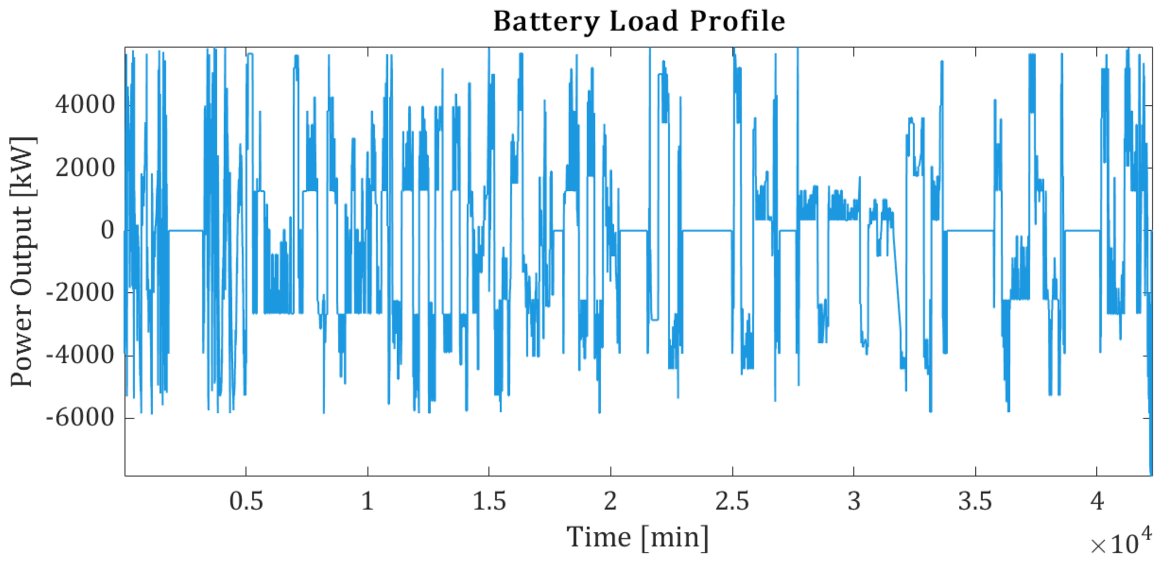

Figure 18: Load profile of the battery for the route Valparaiso to Hamburg.

During the journey, the battery's load profile emphasizes its role in balancing the required and supplied power. Typically, the EMS identifies an average power level for the fuel cell that corresponds to the propeller's demand over a port-to-port segment. Consequently, the battery serves a dual purpose: supplying additional power when the fuel cell's output falls short of the demand, and storing excess energy when the fuel cell's output surpasses the requirement. However, there are instances where the EMS struggles to identify an average power level that aligns with prolonged load demands. During such periods, the fuel cell may either underproduce or overproduce for an extended duration. As a result, the battery assumes a critical role, adjusting its output to compensate for these discrepancies, which involves handling significant energy transfers, either consuming or storing vast amounts of energy. Such cases can be identified when the battery's energy output remains consistently positive, oscillating around a specific benchmark. This phenomenon is illustratively captured in Figure 18, particularly between the time frame of 29000 to 30000 minutes. Such operational behavior marks the limitations of a deterministic EMS, resulting in static behavior compared to other control strategies.

In addition to the power output of the battery, the SOC of the battery is an important aspect to analyze. The results of the SOC for the analyzed route are illustrated in Figure 19.

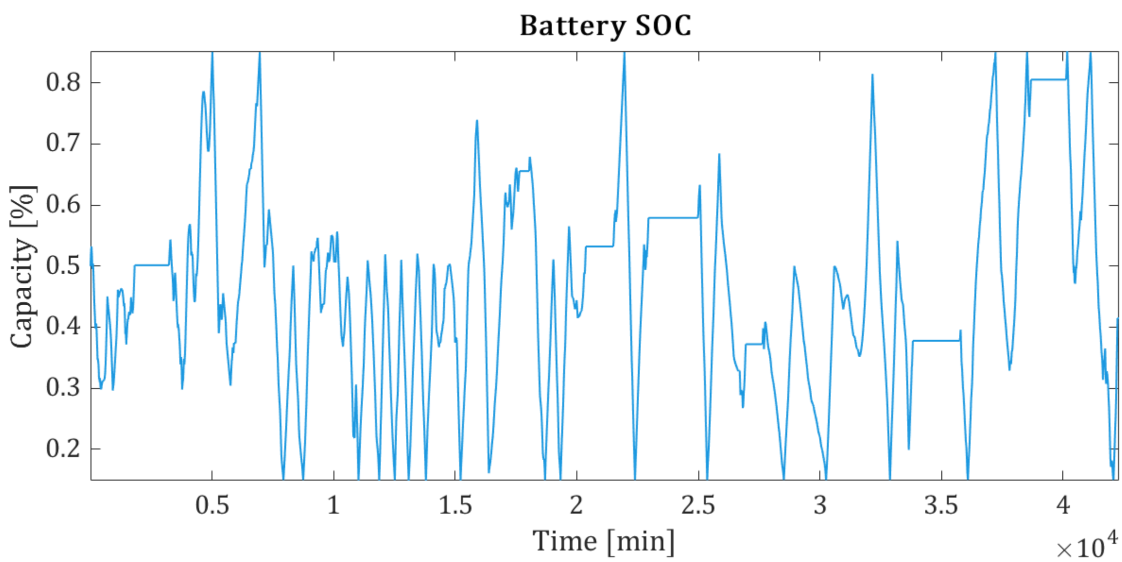

Figure 19: State of Charge of the battery throughout the analyzed route.

The graph demonstrates the capability of the EMS to maintain the SOC within its defined operating limits. The SOC of the battery system is consistently operating within its lower and higher threshold of 15 and 85%, respectively. Upon analyzing the SOC profile, it is evident that the battery undergoes substantial discharge at both the start and end of the journey. Closing in on harbor areas, the ship derives its power from the battery, with the fuel cell in a dormant state. This operational choice leads to extended periods of significant battery usage, highlighting the necessity for its sizable energy capacity. As the ship departs from the harbor, the propulsion responsibility shifts to the fuel cell, with the battery returning to its role of power balancing. This pattern is mirrored as the ship approaches its final port, underscoring a consistent energy management approach throughout the voyage.

The analyzed fluctuations in the battery and fuel cell power output are additionally a strong impact factor for their degradation. Based on the aforementioned degradation models, a replacement schedule is necessary for the component stacks. The component degradation is shown in the table below.

Table 7: Degradation results for the power components of the hybrid power propulsion system

Component Degradation	PEM FC	Battery System
Degradation per Trip	2.35%	3.14%
Degradation per Year	11.75%	15.68%
Expected Lifetime	8.51 Years	6.42 Years
Replacement Schedule	8; 16; 24	6; 12; 18; 24
Replacement Cost	10,821,358 USD	10,413,600 USD

The analysis reveals a projected lifespan of 8.51 years for the PEM FC and 6.42 years for the battery. As a result, component replacements are strategically planned every 8th and 6th year for the fuel cell and battery, respectively. By evaluating the degradation on a per trip (roundtrip) basis, the wear and tear of both components over an anticipated two-month operation can be better understood. Within this timeframe, the fuel cell shows an estimated degradation of 2.35%, whereas the battery's degradation stands at 3.14% relative to their maximum lifetimes. For the battery, this translates to 52.28 equivalent full charging cycles per roundtrip. In terms of financial implications, the replacement expenses are expected at 10.82 million USD for the fuel cell stack, while the battery incurs a cost of 10.41 million USD.

Additionally, the results need to be validated in terms of energy consumption and production. The fuel cell and the battery are expected to provide the exact energy demanded by the propeller throughout the entire voyage. The load profile, as well as the power split between the fuel cell and the battery are visualized in Figure 20.

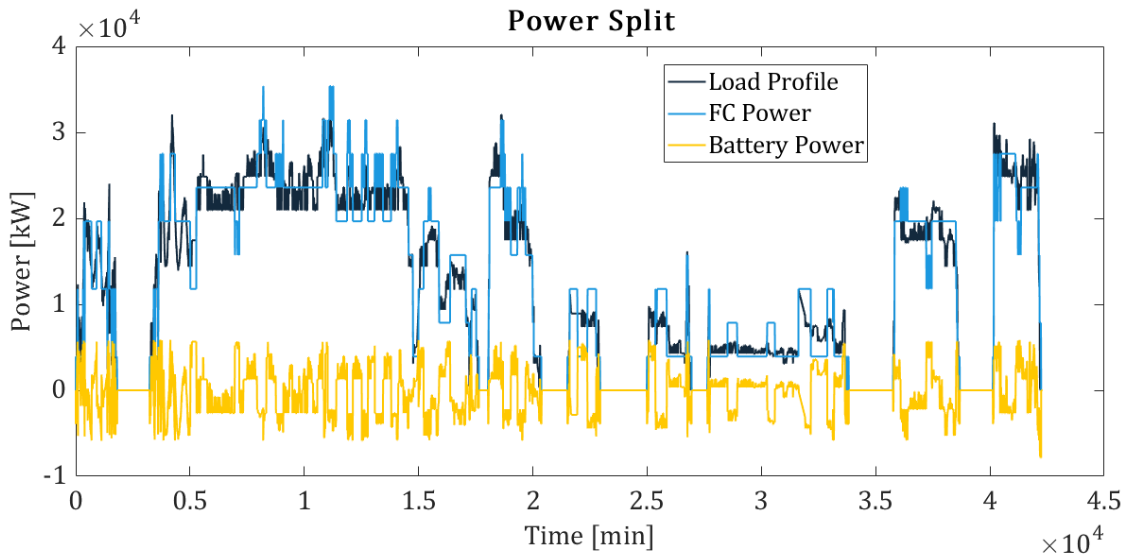

Figure 20: Power split of the load profile into FC and battery power demand.

Overlaying the three graphs provides a clear illustration of the operational dynamics between the battery and the fuel cell, as previously discussed. The load profile is consistently matched with the provided power at every simulation timestep, achieved by the combined power output of both the battery and the fuel cell. Throughout the entire voyage, the propeller's energy demand totals 8,695 MWh. Given the EMS settings, the fuel cell contributes 8,699 MWh, resulting in a minor deficit of approximately -4 MWh attributed by the battery. This energy deficit from the battery is reflected in the discrepancy between its starting and ending SOC. While the journey begins with the battery at 50% of its energy capacity, it concludes at a SOC of 41.47% after a one-way trip. A closer examination of the individual power contributions reveals that the fuel cell addresses on average 88.14% of the load, with the battery catering to the remaining 11.86%. This distribution is congruent with their respective rated powers: the fuel cell's rated power stands at 39.30 MW, constituting 86.98%, while the battery's rated power is 5.88 MW, making up the remaining 13.01%.

The obtained technical outcomes underline the performance of the selected EMS approach throughout the vessel's journey. Although this approach employs a deterministic strategy, it provides clarity on the functioning of the hybrid system and its limitations. The data indicates that the EMS operates consistently, aligning with the research objectives set for this thesis. The power systems are able to match the demanded load throughout every time step. Additionally, the oversizing of the propulsion system by the GA leads to a reduction in fuel consumption. This highlights that the chosen approach leads to indirect optimization of the deterministic EMS. In contrast, more detailed strategies should particularly address the hybrid power system's response during port calls, as these periods of prolonged low power demand present challenges to the system. With the technical findings affirming the vessel's operation, attention pivots to its economic implications. The subsequent section will delve into the investment decision of the liquefied hydrogen vessel in comparison to a conventional diesel vessel.

6.2 Economic Results

The case study's financial analysis aims to contrast the investment considerations between a net-zero propulsion container ship and a traditional diesel container ship. To discern the cost differences between the two container ships, their respective cost sources need to be analyzed in detail. From an investors perspective, it is crucial to compare the CAPEX of both ship types respectively. Table 8 presents the capital costs for the net-zero vessel, factoring in the replacement costs for the fuel cell and battery. For the diesel vessel, replacement costs are not considered due to the diesel engine's extended lifespan. Other CAPEX values are related to necessary investments besides the propulsion system (e.g hull, outfitting, and technological equipment).

Table 8: CAPEX distribution for the LH2 and the diesel vessel.

CAPEX	LH2 Vessel	Diesel Vessel
FC System	32,791,995 USD	-
Battery System	14,530,300 USD	-
Diesel Engine	-	13,689,600 USD
Storage Tank	81,958,676 USD	1,540,150 USD
CAPEX Propulsion	129,280,971 USD	15,229,750 USD
Other CAPEX	80,488,227 USD	80,488,227 USD
Total CAPEX	209,769,198 USD	95,717,977 USD
Replacements	74,118,474	-
Lifetime CAPEX	283,887,672 USD	95,717,977 USD

The estimated CAPEX of the LH2 container vessel stands at 283.89 mil USD, in stark contrast to the 95.72 mil USD for a conventional diesel vessel. This denotes an approximate three-fold increase in the capital cost for the LH2 vessel. Several factors are identified to account for this marked escalation:

1. The hybrid power system, which including fuel cells and batteries, possesses a higher unit cost. Even when comparing systems of equivalent scale, the hybrid propulsion system will lead to greater expenditures.

2. The technical results underlined that the hybrid system's rated power exceeds that of its diesel counterpart by approximately 15%. This increase in rated power inevitably raises the CAPEX of the system.

3. A significant proportion of the CAPEX for the hybrid propulsion system is attributed not to the engines, but to the fuel storage. The tank designed for liquified hydrogen storage demands an investment of 81.96 mil USD, whereas its diesel counterpart requires a mere 1.54 mil USD. This disparity stems from the complex technology necessitated for liquified hydrogen storage, particularly the elevated material costs associated with insulation.

4. Lastly, the lifetime CAPEX of the net-zero vessel includes replacement cost for the hybrid propulsion system. While replacements in the diesel system can be neglected, the entire replacement cost of the hybrid power system amount to 74.12 mil USD. This includes three fuel cell stack and four battery cell replacements.

To further analyze the financial implications of the investment, the study incorporates annualized costs as a key metric. Upon evaluating the LH2 vessel's financial components, it becomes evident that its annualized costs are a function of its CAPEX, OPEX, voyage cost, and replacement costs. The high CAPEX associated with the liquified hydrogen tank constitutes 33.9% of the vessel's annual cost. Replacement components for the fuel cell and battery add an additional of 4.1% to the annualized capital cost. In alignment with the previously analyzed literature, voyage-associated costs are projected to generate the largest share in annualized costs. The annualized voyage costs - hydrogen fuel expenses - account for 43.5% of the final expenses. The vessel's OPEX is responsible for the residual 18.4%. A comprehensive delineation of these expenditures over the vessel's operational tenure is illustrated in Figure 21.

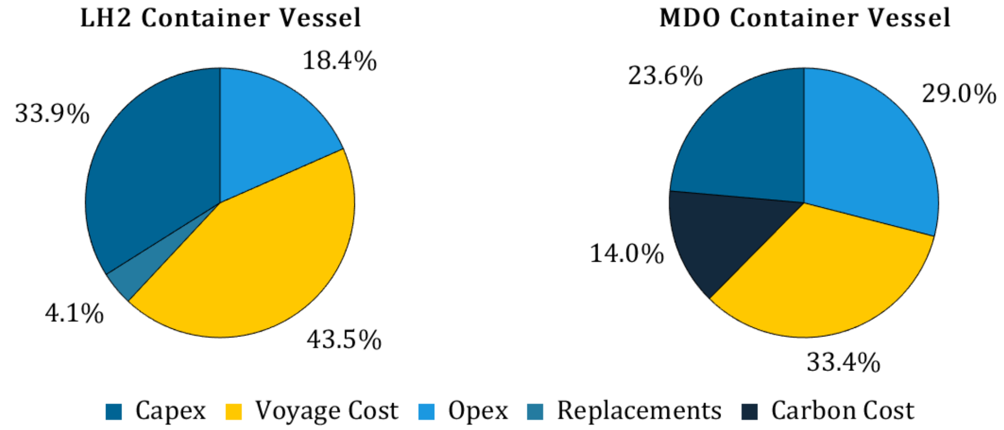

Figure 21: Annualized cost of the LH2 and diesel container vessel.

The figure provides a comparative analysis of annualized costs for vessels powered by LH2 and the base scenario of MDO. For the MDO vessel, both capital (23.6%) and voyage costs (33.4%) constitute a smaller fraction of the annualized costs than for the LH2 vessel. This reduction is attributed to the MDO vessel's lower CAPEX for the propulsion system and its use of cost-effective maritime diesel. In the examined case study, the fuel prices are set at 0.8 USD/kg for MDO and 5 USD/kg for hydrogen. While this denotes a 6.25-fold increase on a per kilogram basis, the disparity narrows when assessing the cost on an energy content basis. Specifically, MDO costs 63.3 USD/MWh, whereas hydrogen is priced at 126.8 USD/MWh, roughly a two-fold increase. Conversely, the MDO vessel displays a higher proportion of operational expenditures at 29%. This is a reflection of the reduced total annualized costs since the total operational costs for both vessels are assumed to be roughly similar as a function of the total carrying capacity of the vessels. As previously stated, replacement costs of the MDO vessel are not integrated in the cost analysis due to the extended lifespan of the components. However, the MDO-powered vessel, burning diesel, incurs carbon emission costs. Anticipating the integration of the maritime sector into the ETS, carbon costs have been incorporated into the analysis, based on a carbon price of 100 USD/ton. A short overview of the avoided cost of carbon for the LH2 vessel and internalized costs for MDO vessel are shown in Table 9 below.

Table 9: Carbon emissions and carbon related costs for the diesel container vessel.

Cost of Carbon	Emissions	Internalized Cost
Carbon Price	1 ton-	100 USD
Per Trip	10,672 tons	1,067,245 USD
Per Year	53363 tons	5,336,226 USD
Lifetime	1,334,075 tons	133,405,650 USD

To make a well-informed investment decision, it's essential to compare the costs with the potential earnings given the current market conditions. Table 10 presents an estimate of the yearly costs and revenues for both the LH2 and MDO vessels.

Table 10: Total annualized cash flow for the LH2 and diesel container vessel.

Annualized Cash Flow	LH2 Vessel	Diesel Vessel
CAPEX	19,660,199 USD	8,976,019 USD
Replacement Cost	2,403,567 USD	-
Voyage Cost	25,183,781 USD	12,720,822 USD
OPEX	10,685,947 USD	11,049,209 USD
Carbon Cost	-	5,336,226 USD
Total Cost	57,933,494 USD	38,082,276 USD
Revenues	69,107,575 USD	69,300,000 USD
Profits	11,174,081 USD	31,217,724 USD

The annualized cost analysis for both vessels indicates that they are competitively priced. The LH2 vessel's total annualized revenues amount to 69.11 mil USD. Subtracting the total annualized cost of 57.93 mil USD, the net-zero vessel is projected to yield annual profits of 11.17 mil USD. In contrast, the conventionally-fueled container vessel is anticipated to achieve profits nearly three times greater, amounting to 31.22 mil USD, due to its reduced costs.

Most interestingly, the revenues from the LH2 vessel are projected to be slightly below the revenues of the diesel vessel. A difference of 192,425 USD is projected for one year of operation under current freight rates. This shortfall can be attributed to the cost associated with lost cargo opportunities. The cost of lost cargo estimate the impact of the increased space requirements for the LH2 tank compared to the diesel tank. The results show space requirements for liquified hydrogen storage in the dimensions of 16,293 cubic meters. This storage tank is expected to store 9222 cubic meters of LH2. In contrast, the diesel tank is expected to occupy approximately 15,402 cubic meters, storying 11,560 cubic meters of diesel for traveling purposes. This space discrepancy translates to a decrease in cargo space by 990 cubic meters, equivalent to 30 containers or 0.2% of the vessel's total carrying capacity. The space limitation leads to an anticipated reduction in revenue by about 36,000 USD per voyage. A detailed comparison of the reduced cargo space and the fuel tank system is provided in the table below.

Table 11: Cost of lost cargo for the LH2 container vessel.

Cost of Lost Cargo	LH2 Vessel	MDO Vessel
Tank System Volume	16,392 m3	15,402 m3
Fuel Volume	15,402 m3	11,560 m3
Energy Content	21.853 MWh	115,138 MWh-
Travel Distance	7681 nm	32965 nm
Carrying Capacity	10470 TEU	10500 TEU
Cost of Lost Cargo	36,000 USD	-

The analysis indicates that the reduced cargo space impacts the revenues of the container vessel, albeit incrementally. Beyond cargo capacity, it's crucial to address the distance the vessel can cover with its full energy capacity. Simplified calculations at a design speed of 17 knots provide insights into the potential travel distance for both vessels. With a full tank, the LH2 container vessel is projected to cover about 7,680 nautical miles before requiring refueling. In comparison, the traditional MDO-fueled vessel can traverse an estimated 32,865 nautical miles before needing a refill. The LH2 vessel's limited range could pose challenges in rerouting flexibility and market accessibility. However, for vessels operating on fixed routes, the impact of reduced travel distance is expected be less pronounced, given their consistent pathways. In order to estimate the total distance of the container vessel, the entire energy in the storage tank was taken into consideration. This includes the previously introduced safety factor (c.f. formula 41).

The final results of the economic analysis result in the NPV of the investment case. Diagram 22 illustrates the yearly net cash flow and the cumulative NPV for the 25 years lifetime of the LH2 container vessel.

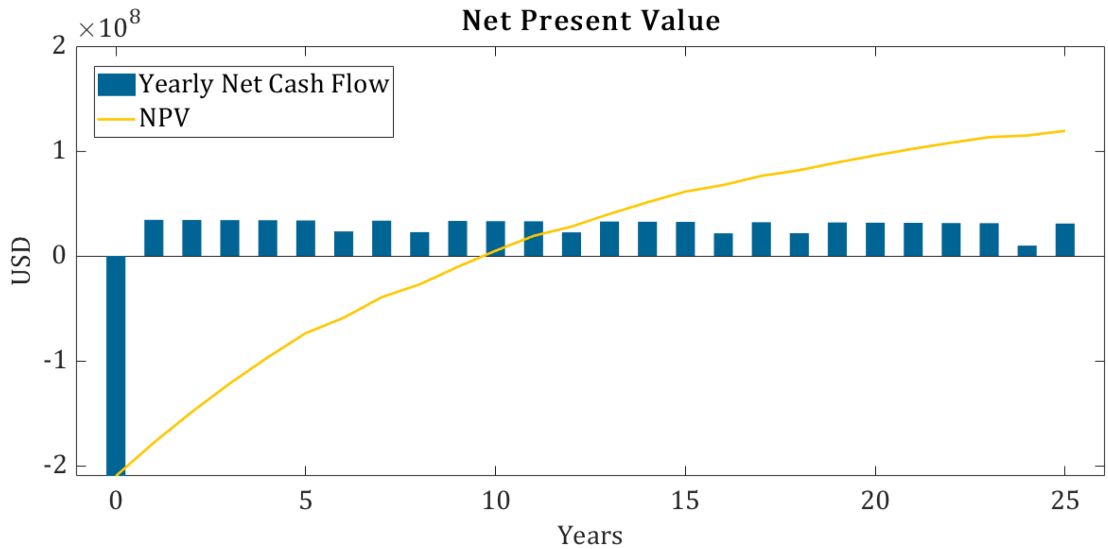

Figure 22: Net present value of LH2 container vessel.

The net-zero vessel has higher initial costs and voyage expenses than the diesel vessel, but its financial projection is still positive. The large initial investment for the LH2 vessel is offset over time by its operational income. However, this income decreases gradually due to rising operational costs and the need for replacements like the battery and fuel cell. Over 25 years, the LH2 vessel's estimated net present value (NPV) is 119.28 mil USD. Investors can expect to recover their initial investment by the 9.8-year mark, with a return rate of 14.53%. On the other hand, the MDO vessel, with its lower costs and higher profits, has an NPV of 322.90 mil USD, roughly three times that of the LH2 vessel. Given its lower initial costs and higher revenues, the investment payback period is only 3.39 years. This duration aligns with standard industry values under good market conditions. A detailed comparison of these financial metrics for both vessels is provided in Table 12.

Table 12: Financial metrics for the LH2 and the diesel container vessel.

Financial Metric	LH2 Vessel	Diesel Vessel
NPV	119,280,806 USD	322,902,944 USD
IRR	14.53 %	34.89%
PBP	6.48 Years	2.86 Years
Discounted PBP	9.68 Years	3.39 Years

The analysis presents a favorable financial perspective for LH2 container vessels, with a commendable IRR and a relatively brief payback period. However, it's crucial to contextualize these findings within the maritime industry. Investments in this sector often adopt a "high-risk, high-reward" approach. Under consistent and favorable market conditions, container vessels can recoup their initial investments in just 2 to 3 years, as illustrated by the base case scenario for the MDO vessel. Thus, while the LH2 vessel investment remains positive, there are more attractive alternatives in the market, even when considering emission taxes at 100 USD/ton. The most prominent differences in investment opportunities between the two vessels arise from their capital expenses and fuel costs. For an LH2 vessel, both these costs are projected to be approximately twice as high. The elevated cost of the LH2 propulsion system not only impacts direct expenses but also inflates replacement costs, increasing the total financial burden for the investment. It is therefore imperative to bridge this cost gap to make LH2 vessels more commercially viable. To find different strategies that could make investing in net-zero vessels more appealing, a sensitivity analysis focusing on various cost components is conducted.

6.3 Sensitivity Analysis

The results of Section 6.1 and Section 6.2 show that a container vessel running on liquified hydrogen can be technical and economical feasible. However, the technical complexity of the vessel leads to high investment costs, resulting in a less cost-effective solution compared to established polluting technologies. In order to further analyze this economic discrepancy, the following section conducts a second analysis on the sensitivity of cost parameters. The question to be answered as part of the second analysis is the following:

'Under what circumstances can an investment in a zero-emission vessel achieve a break-even point compared to conventional technologies?'

The analyzed different cost sources for the two container vessels are the fuel price, the CAPEX, the OPEX, and the carbon price. The replacement costs for the propulsion system of the LH2 vessel are included in the capital costs for the analysis. The results of the sensitivity for the two container vessels are shown in Figure 23 and Figure 24, respectively.

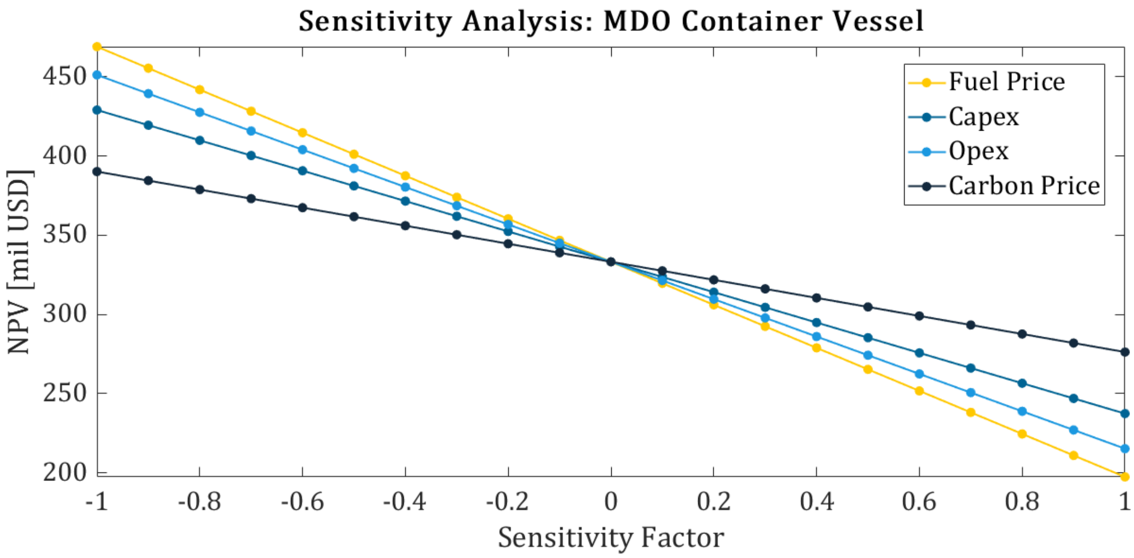

Figure 23: Sensitivity analysis for the diesel container vessel.

The analysis reveals a high sensitivity of the NPV for the MDO container vessel, particularly with respect to diesel fuel prices. An elevation of fuel prices by 100% can curtail the vessel's NPV by a substantial 40.84%. On the other hand, fluctuations in carbon pricing have a muted effect. A doubling in carbon prices, reduces the vessel's NPV by approximately 17.11%. This disparity arises from the direct dependency of the container vessels on its fuel. In contrast, carbon costs are an added burden based on the vessels fuel consumption, acting as a consequence of burning fuel rather than the act of purchasing it. Every emitted kilogram of CO_2 corresponds to a previously consumed kilogram of diesel. Consequently, a tax on the fuel has a more immediate and pronounced effect on expenses than a carbon tax. The capital and operational expenditures have a mediocre impact on the NPV. A twofold increase in capital expenses results in a 28.82% decline in NPV, while a similar rise in operational costs sees a 35.44% reduction. The conducted sensitivity points out the leverages for regulators to reach a break-even point between investments in carbon neutral vessels compared to conventional vessels. The strongest and most direct impact results from an increase in fuel costs, possibly through targeted taxation. In order to have a more strenghtened and combined effect, fuel taxation can be accompanied by carbon pricing. Additionally, regulators are able to influence investment decisions by adjusting costs associated with ship construction or by modifying fees associated with canals and harbors, which form part of operational expenses.

The LH2 vessel, much like the MDO vessel, is highly sensitive to the price of its primary fuel - hydrogen. A half in hydrogen prices at the pump, can potentially increase the NPV of the vessel by 160%. To put this into perspective, if hydrogen costs average out at 2.5 USD/kg, the vessel's NPV is expected to increase to 193 mil. USD. This is in parity with a NPV of the MDO vessel when diesel prices are at 1.6 USD/kg. Another significant factor influencing the NPV of the LH2 vessel is its high capital expenditure. If the CAPEX of the vessel were to drop by 50%, its NPV could rise by 148%. The pronounced influence of the CAPEX on the NPV stems from the high unit cost of the propulsion system: Battery, fuel cell, and fuel tank. Operational costs, including harbor and canal fees, have a lower effect on the LH2 vessel. A 50% reduction in these operational expenditures yields a comparably similar rise in the NPV. It's worth noting that the case study is conducted under the assumption that the vessel's hydrogen source is green, making it immune to carbon pricing. However, this highlights the important role of carbon prices. They internalize external costs, penalizing polluters while leaving non-polluters unaffected, even though both operate under the same regulatory framework. The sensitivity analysis of the LH2 container vessel is illustrated in Figure 24.

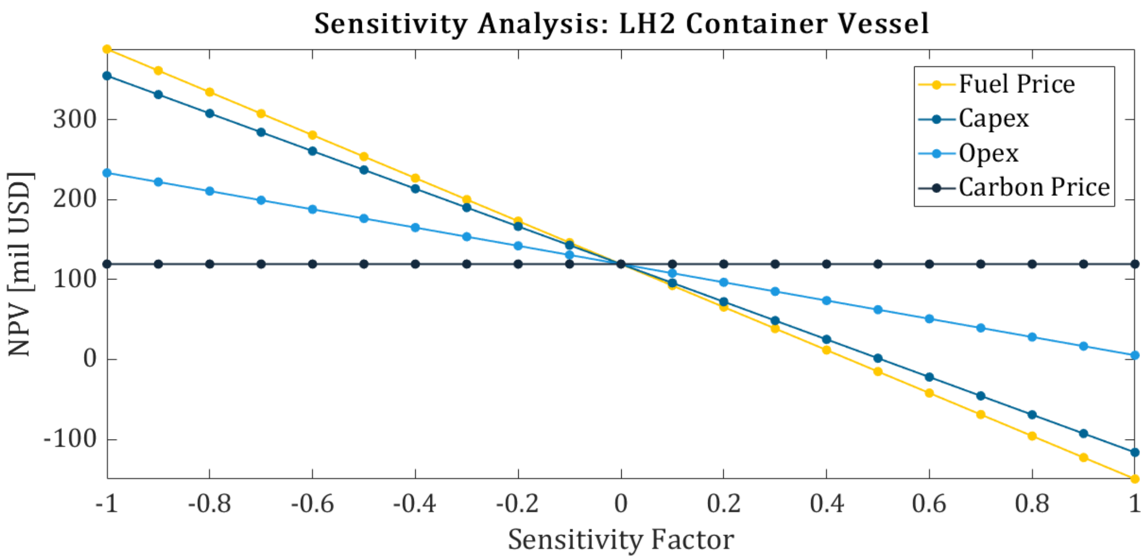

Figure 24: Sensitivity analysis for the LH2 container vessel.

The sensitivity analysis outlines various scenarios where the two container vessels could reach a price parity. For regulators aiming to encourage a shift towards more sustainable shipping solutions, there are several tools and policies at their disposal. Taxing carbon-intensive fuels is one of the most direct ways to affect a vessel's feasibility. By making such fuels more expensive, ships relying on them become less economically attractive. In a parallel move, supporting net-zero fuels is vital to push their adoption within the industry. By setting a price ceiling on net-zero fuels, regulators can not only make sustainable shipping solutions more appealing but also provide stability in volatile and uncertain markets. Most interestingly, even local regulators and authorities have a significant role to play in this transition. By adjusting port and canal fees based on a vessel's environmental impact, they can effectively incentivize more sustainable shipping choices. This idea is similar to urban policies where older, high-emitting vehicles face restrictions or higher fees in city centers. Lastly, while carbon taxes might not have an as immediate and significant impact compared to fuel taxes, they are an essential tool for regulators. Imposing costs on carbon emissions ensures that polluters and non-polluters are operating under a consistent framework, pushing the industry towards greener solutions.

However, it is important to recognize that no single policy tool or regulation will be sufficient on its own to achieve cost parity between the two technologies. Instead, a diverse policy framework is necessary, leveraging a combination of tools to create a holistic and effective decarbonization strategy. To understand the potential of this combined approach, a final case is presented. This "policy scenario" simulates the combined effects of the previously conducted sensitivity in order to show one potential pathway, where investments in a zero-emission vessel achieves a break-even point compared to conventional technologies. The results are shown in Table 13.

Table 13: Break-even scenario for net-zero vessel compared to diesel base case.

Financial Impact	Base Case	Impact	Break-Even
MDO Fuel Tax	0.8 USD/kg	+14%	0.912 USD/kg
Hydrogen Price	5 USD/kg	-30 %	3.5 USD/kg
Carbon Price	100 USD/ton	+76 %	176 USD/ton
LH2 Lifetime CAPEX	283,887,672 USD	-30 %	198,721,370 USD
LH2 NPV	119,280,806 USD	+127 %	270,939,447 USD

The results from the case study illustrate a scenario in which the net-zero vessel can achieve economic parity with the conventional container ship. To diminish the attractiveness of diesel as a container fuel, a 14% fuel tax on diesel combined with a carbon price set at 176 USD/ton is required. On top of that, the promotion of liquified hydrogen as a net-zero fuel is necessary. The price of hydrogen should be capped at a price ceiling of 3.5 USD/kg, representing a 30% reduction from current estimated price levels. Additionally, the upfront CAPEX of the hydrogen-powered ship must decrease by 30%, amounting to 198.72 mil. USD. However, it needs to be mentioned that the projected CAPEX is still roughly double the cost of the MDO vessel, leaving substantial space for prospective cost reductions. Under these circumstances, both vessel types would achieve an NPV of 270.93 mil. USD.

The findings highlight the pivotal role of holistic policy frameworks, driving a shift to more sustainable maritime transport. Combining different policies, such as fuel taxes, carbon taxes, and incentives for net-zero technology producers, is key to push cleaner technologies forward. While achieving cost parity solely through carbon taxes is possible, the model predicts steep prices at approximately 460 USD/ton of CO_2. In contrast, the more distributed approach spreads emission reduction costs more fairly along consumers. Moreover, the proposed policy measures align with the maritime industry's current direction. Rapid developments in hydrogen technologies lead to declining unit costs of fuel cell, electrolyzers, and hydrogen storage solutions (IRENA, 2020). This not only forecasts a reduction in capital expenditure but also predicts a fall in hydrogen fuel prices. Several studies project a hydrogen price of 3 to 4 USD/kg as plausible by 2030 (IEA, 2019) (IRENA, 2021) (BNEF, 2022). Lastly, todays carbon prices are fluctuating around price levels of 90 to 100 USD/ton (Ember, 2023). Even though a price of 176 USD/ton has not been reached yet, it has been demanded in order to align with sustainable development scenarios (OECD, 2021) (IPCC, 2023). Overall, the results suggest that decarbonization of the maritime industry is possible and achievable with current predictions and cost developments. However, this transformation requires more than acknowledgment; it demands decisive action.

7 Conclusion

In this chapter, the results of the work are summarized, limitations are discussed, and further implications and recommendations for policy makers and investors are presented.

7.1 Summarizing Remarks

The goal of the thesis was the design of a framework for the economic assessment of zero-emission vessels under a given ship class, technology, and route. The framework assesses the viability of net-zero vessels compared to conventional technologies, using the German container industry as an example. The research question to be answered as part of the thesis was the following:

‘Under what circumstances can an investment in a zero-emission vessel achieve a break-even point compared to conventional technologies?’

The presented research question is essential for the future of sustainable maritime transport, especially under the strengthened climate targets set out by the United Nations and IMO. Achieving this ambitious target - net-zero emissions by 2050 - necessitates a transition to net-zero fuels. The spectrum of potential net-zero solutions for shipping is large, encompassing biofuels, electrification, and synthetic fuels. Although a definitive choice remains elusive, hydrogen emerges as a compelling option due to its scalability and sustainability potential.

To precisely forecast the investment potential in shipping, an in-depth understanding of the cost breakdown is essential. Previous research highlights the significant influence of fuel costs throughout the vessel's entire lifespan. Simultaneously, capital expenditures also constitute a substantial fraction. The cost share of the upfront investments and the fuel cost is further expected to increase for fuel cell-battery hybrid vessels. As a result, any investment model should particularly concentrate on these two components to anticipate the investment scenario accurately. Several optimization algorithms exist for this modeling purpose. Most commonly, the literature favors a nested approach, where the outer layer optimizes the system cost and the inner layer decides on the control strategy for fuel consumption.

Such a double layer optimization model is proposed, designed to both size and simulate the vessel’s technical variables, while subsequently optimizing for the NPV of the investment. The inner layer of the architecture is defined by a deterministic energy management system, while the outer layer uses a genetic algorithm for optimization. The model is analyzed based on its technical and economic performance. The technical results show that the EMS of the vessel is able to secure its operation under the necessary system constraints. Additionally, the layered structure of the model enables the GA to calibrate the propulsion system, ensuring the fuel cell operates at its peak efficiency, consequently reducing the vessel's fuel consumption. The total power output of the hybrid container vessel increases by 31% compared to the initial diesel engine. This reflects in the capital expenditures for the two vessels. While the conventional MDO container vessel (10500 TEU) has an expected CAPEX of 95.72 mil USD, the CAPEX increases for the LH2 vessel by 2.95 times to 283.89 mil USD. The main contribution to the increase in capital expenditures are the high cost for the battery, the fuel cell, and the LH2 tank. Still, the LH2 container vessel is expected to have a positive NPV at 119.28 mil USD, with a payback after 6.48 years. However, this is below industry averages, as typical payback times in container vessels are achieved after 2-3 years – providing strong freight rates.

To determine the break-even point between the LH2 and the MDO vessels, a sensitivity analysis was conducted. The findings highlight a pronounced sensitivity of both vessels to fuel expenses. Moreover, technological advancements that reduce the LH2 vessel's CAPEX have significant effects. The two vessels achieve cost parity when combined with a 14% diesel fuel tax, a hydrogen price ceiling at 3.5 USD/kg, a 30% CAPEX reduction, and a carbon price of 176 USD/ton. This emphasizes that common industry policies aligning with current predictions and proposals can indeed bolster net-zero shipping.

Concluding, the thesis underlines the financial discrepancy between net-zero vessels and conventional vessels. Capital expenditures as well as fuel costs are the main driver for the large cost gap between sustainable and polluting technologies. However, the results show that the investment case is already profitable. A break-even point can be reached with current demanded carbon prices and projected developments in cost decreases.

7.2 Limitations and research ideas

The conducted case study refers to the German container industry with a focus on liquified hydrogen as a fuel, and FC-Battery hybrid power systems. In contrast, the maritime sector relies on a diverse option of fuels, potentially even increasing for sustainable solutions. A notable trend in the industry is the increasing interest in multi-fuel engines. Thus, future research should a) incorporate a broader spectrum of fuels as well as technologies and b) analyze the potential of multi-fuel engines. Especially, dual-fuel engines running on low-carbon fuels and net-zero fuels could be an interesting investment opportunity as they could achieve cost and environmental superiority over other solutions.

Additionally, a general decrease in fuel consumption is essential to enhance the vessels feasibility, given that fuel costs constitute the majority of the container vessels total costs. Minimizing fuel consumption is therefore one of the key factors in order to achieve the highest NPV for the vessel. As demonstrated, the implemented deterministic EMS can indirectly reduce fuel consumption through propulsion system sizing, however it does not directly optimize the control strategy of the hybrid power system. Future research should prioritize the incorporation of fuel optimization strategies into the model to further improve the investment case.

Even though the case study shows that maritime transport can be sustainable by changing the propulsions systems of current ships, it remains questionable if this is the right approach overall. Current vessels are based on the idea of economy of scale, with ships carrying up to 25000 containers, sized larger than football pitches or skyscrapers. However, sustainable technologies are not yet technical or economic feasible to operate under such conditions. In contrast, hydrogen and electrification are already a solution in many short-distance cases, mostly applied on ferries and inland transport. Future research has to focus on route optimization from the perspective of the applied technology, and potentially on the feasibility of a larger set of small vessels for sustainable transport.

7.3 Implications for Policy Makers and Investors

The main motivation of the proposed framework is to determine circumstances for viable net-zero maritime transport. However, such conditions do not solely come from research and development. Regulatory support plays a pivotal role, incentivizing investors with clear price signals and ensuring stability for their investment decisions, as evidenced by the sensitivity analysis detailed in Section 6.3. Achieving cost parity between investments in LH2 and MDO container vessels necessitates financial backing from regulatory bodies. It should be imperative for policymakers to implement frameworks that encourages immediate investments, while also ensure long-term price stability. Four design ideas are proposed to support such policies.

Firstly, a rise in fuel taxes on conventional fuels should be prioritized. This is the most direct regulatory impact to diminish the attractiveness of pollutant propulsion systems. Moreover, a strong and robust taxing scheme can lead to less competitive pricing of low-carbon alternatives. Secondly, price stability for net-zero fuels need to be guaranteed. Instituting a price corridor/ceiling for net-zero fuels will ensure long-term financial predictability for investors, supporting sustainable investments. Thirdly, substantial initial cost for hybrid propulsion systems warrants support. Regulators should consider direct subsidies or policies stretching such costs over the maritime supply chain. Lastly, a robust carbon pricing system is important for cost parity. Even more important, robust carbon pricing sends a strong message: pollution incurs a tangible cost. By following these four core ideas, policy makers and investors are able to steer maritime transport into a sustainable direction.

Literature

Aarskog, F. G., Danebergs, J., Strømgren, T., & Ulleberg, Ø. (2020). Energy and cost analysis of a hydrogen driven high speed passenger ferry. *International Shipbuilding Progress*, *67*(1), 97–123. https://doi.org/10.3233/isp-190273

Adland, R., Cariou, P., Jia, H., & Wolff, F.-C. (2018). The energy efficiency effects of periodic ship hull cleaning. *Journal of Cleaner Production*, *178*, 1–13. https://doi.org/10.1016/j.jclepro.2017.12.247

Agajie, T. F., Ali, A., Fopah-Lele, A., Amoussou, I., Khan, B., Velasco, C. L. R., & Tanyi, E. (2023). A Comprehensive Review on Techno-Economic Analysis and Optimal Sizing of Hybrid Renewable Energy Sources with Energy Storage Systems. *Energies*, *16*(2), 642. https://doi.org/10.3390/en16020642

Al-Enazi, A., Bicer, Y., Okonkwo, E. C., & Al-Ansari, T. (2022). Evaluating the utilisation of clean fuels in maritime applications: A techno-economic supply chain optimization. *Fuel*, *322*, 124195. https://doi.org/10.1016/j.fuel.2022.124195

Alankrita, Pati, A., N. Adhikary, Sunil Kumar Mishra, Bhargav Appasani, & Taha Selim Ustun. (2022). *Fuzzy logic based energy management for grid connected hybrid PV system*. *8*, 751–758. https://doi.org/10.1016/j.egyr.2022.05.217

Alkhaledi, A. N. F. N. R., Batra, A., Sampath, S., & Pilidis, P. (2022). Techno-environmental assessment of a hydrogen-fuelled combined-cycle gas turbine for a liquid hydrogen tanker. *Energy Reports*, *8*, 10561–10569. https://doi.org/10.1016/j.egyr.2022.08.202

Ammar, N. R., & Alshammari, N. F. S. H. (2018). Overview of the green hydrogen applications in marine power plants onboard ships. *International Journal of Multidisciplinary and Current Research*. https://doi.org/10.14741/ijmcr.v6i01.10912

Ancona, M. A., Baldi, F., Bianchi, M., Branchini, L., Melino, F., Peretto, A., & Rosati, J. (2018). Efficiency improvement on a cruise ship: Load allocation optimization. *Energy Conversion and Management*, *164*, 42–58. https://doi.org/10.1016/j.enconman.2018.02.080

Argonne. (2019). *Total Cost of Ownership (TCO) Analysis for Hydrogen Fuel Cells in Maritime Applications*. Argonne National Laboratory. https://www.energy.gov/sites/prod/files/2019/10/f68/fcto-h2-at-ports-workshop-2019-viii5-ahluwalia.pdf

Ballard, & Deloitte. (2020). *Fueling the Future of Mobility: Hydrogen and fuel cell solutions for transportation* . https://info.ballard.com/deloitte-vol-1-fueling-the-future-of-mobility

Barahmand, Z., & Eikeland, M. S. (2022). Techno-Economic and Life Cycle Cost Analysis through the Lens of Uncertainty: A Scoping Review. *Sustainability*, *14*(19), 12191. https://doi.org/10.3390/su141912191

Bernitsas, B. B., Ray, D., & Kinley, P. (1981). *Kt, Kq and Efficiency Curves for the Wageningen B-Series Propellers*. Department of Naval Architecture and Marine Engineering.

BMDV. (2020). *Elektromobilität mit Wasserstoff / Brennstoffzelle*. Mobilität Und Förderung; Bundesministerium für Digitales und Verkehr. https://bmdv.bund.de/DE/Themen/Mobilitaet/Elektromobilitaet/Elektromobilitaet-mit-wasserstoff/elektromobilitaet-mit-wasserstoff.html

BMVI. (2016). Fortsetzung des Nationalen Innovationsprogramms Wasserstoff- und Brennstoffzellentechnologie (NIP) 2016 - 2026. In *Maßnahmen des Bundesministeriums für Verkehr und digitale Infrastruktur (BMVI) als Beitrag zur Entwicklung nachhaltiger Mobilität*. Bundesministerium für Verkehr und digitale

Infrastruktur. https://bmdv.bund.de/SharedDocs/DE/Anlage/G/nip-massnahmen.pdf?__blob=publicationFile

BMWi. (2017, January 10). *Maritime Agenda 2025: Für die Zukunft des maritimen Wirtschaftsstandorts Deutschland*. Wirtschaft Und Klimaschutz; Bundesministerium für Wirtschaft und Klimaschutz. https://www.bundesregierung.de/breg-de/service/publikationen/maritime-agenda-2025-731994

BNEF. (2022). *New Energy Outlook 2022 | Bloomberg NEF*. Bloomberg NEF. https://about.bnef.com/new-energy-outlook/

Brown, I. N., & Aldridge, M. F. (2019). Power models and average ship parameter effects on marine emissions inventories. *Journal of the Air & Waste Management Association*, *69*(6), 752–763. https://doi.org/10.1080/10962247.2019.1580229

Cao, W., Geng, P., & Xu, X. (2023a). *Optimization of battery energy storage system size and power allocation strategy for fuel cell ship*. *11*(6), 2110–2121. https://doi.org/10.1002/ese3.1441

Cao, W., Geng, P., & Xu, X. (2023b). *Optimization of battery energy storage system size and power allocation strategy for fuel cell ship*. *11*(6), 2110–2121. https://doi.org/10.1002/ese3.1441

Celli, G., Pilo, F., Pisano, G., & Soma, G. G. (2018). Distribution energy storage investment prioritization with a real coded multi-objective Genetic Algorithm. *Electric Power Systems Research*, *163*, 154–163. https://doi.org/10.1016/j.epsr.2018.06.008

DNV. (2023a). *EU ETS – Emissions Trading System - DNV*. DNV. https://www.dnv.com/maritime/insights/topics/eu-emissions-trading-system/index.html

DNV. (2023b). *Exploring the potential of biofuels in shipping - DNV*. DNV GL. https://www.dnv.com/expert-story/maritime-impact/Exploring-the-potential-of-biofuels-in-shipping.html

DNV. (2023c). *Transport in Transition: A deep dive into fuels, electricity, and infrastructure*. DNV.

Ember. (2023). *The price of emissions allowances in the EU and UK*. Carbon Price Tracker. https://ember-climate.org/data/data-tools/carbon-price-viewer/

European Commission. (2022). *EU Emissions Trading System (EU ETS)*. European Commission. https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets_en

European Commission. (2023). *Reducing emissions from aviation*. Climate.ec.europa.eu. https://climate.ec.europa.eu/eu-action/transport-emissions/reducing-emissions-aviation_en

European Council. (2022a). *Proposal for a Directive of the European Parliament and of the Council amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading scheme and Regulation (EU) 2015/757*. https://data.consilium.europa.eu/doc/document/ST-10796-2022-INIT/x/pdf

European Council. (2022b, June 2). *Proposal for a Regulation of the European Parliament and of the Council on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC*. https://data.consilium.europa.eu/doc/document/ST-9810-2022-INIT/en/pdf

Fan, L., & Xie, J. (2021). Identify determinants of container ship size investment choice. *Maritime Policy & Management*, *2*, 1–16. https://doi.org/10.1080/03088839.2021.1971784

Fankhauser, S., Smith, S. M., Allen, M., Axelsson, K., Hale, T., Hepburn, C., Kendall, J. M., Khosla, R., Lezaun, J., Mitchell-Larson, E., Obersteiner, M., Rajamani, L., Rickaby, R., Seddon, N., & Wetzer, T. (2021). The meaning of net zero and how to get it right. *Nature Climate Change*, *12*(1), 1–7. https://doi.org/10.1038/s41558-021-01245-w

Figueres, C. (2013). Meeting our Climate Challenge: A United Nations Perspective. In *UNFCCC*. https://unfccc.int/sites/default/files/20131804_world-affairs-council.pdf

Gao, D., Wang, X., Wang, T., Wang, Y., & Xu, X. (2018). An Energy Optimization Strategy for Hybrid Power Ships under Load Uncertainty Based on Load Power Prediction and Improved NSGA-II Algorithm. *Energies*, *11*(7), 1699. https://doi.org/10.3390/en11071699

Gargalo, C. L., Carvalho, A., Gernaey, K. V., & Sin, G. (2016). A framework for techno-economic & environmental sustainability analysis by risk assessment for conceptual process evaluation. *Biochemical Engineering Journal*, *116*, 146–156. https://doi.org/10.1016/j.bej.2016.06.007

Ge, J., Zhu, M., Sha, M., Notteboom, T., Shi, W., & Wang, X. (2019). Towards 25,000 TEU vessels? A comparative economic analysis of ultra-large containership sizes under different market and operational conditions. *Maritime Economics & Logistics*, *23*(4), 587–614. https://doi.org/10.1057/s41278-019-00136-4

GL. (2012). *Costs and benefits of LNG as ship fuel for container vessels: Key results from a GL and MAN joint study*. Germanischer Lloyd.

Glomeep. (2020). *Trim and draft optimization*. Energy Efficiency Technologies for Ships; IMO. https://glomeep.imo.org/technology/trim-and-draft-optimization/

Gozillon, D. (2023). *Can the EU ETS make the case for green e-fuels in shipping*. Ptxlablausitz.de. https://ptxlablausitz.de/news/das-bringt-der-emissionshandel-fuer-den-seeverkehr/

Green Voyage. (2022). A Practical Guide to the Selection of Energy Efficiency Technologies for Ships. In *GreenVoyage2050 Project Coordination Unit*. IMO.

https://greenvoyage2050.imo.org/wp-content/uploads/2022/10/energy-efficiency-tech-for-ships-online.pdf

Hall, D., Pavlenko, N., & Lutsey, N. (2018). *Beyond road vehicles: Survey of zero-emission technology options across the transport sector*. International Council on Clean Transportation. https://theicct.org/publication/beyond-road-vehicles-survey-of-zero-emission-technology-options-across-the-transport-sector/

Han, J., Charpentier, J.-F., & Tang, T. (2014). An Energy Management System of a Fuel Cell/Battery Hybrid Boat. *Energies*, *7*(5), 2799–2820. https://doi.org/10.3390/en7052799

ICCT. (2011). *Reducing Greenhouse Gas Emissions from Ships: Cost effectiveness of available options*. The International Council for Clean Transport. https://theicct.org/sites/default/files/publications/ICCT_GHGfromships_jun2011.pdf

ICCT. (2020). *Refueling assessment of a zero-emission container corridor between China and the United States: Could hydrogen replace fossil fuels?* International Council on Clean Transportation. https://theicct.org/sites/default/files/publications/Zero-emission-container-corridor-hydrogen-3.5.2020.pdf

ICCT. (2023, July 7). *IMO's newly revised GHG strategy: What it means for shipping and the Paris Agreement*. International Council on Clean Transportation. https://theicct.org/marine-imo-updated-ghg-strategy-jul23/

IEA. (2019, June). *The Future of Hydrogen*. International Energy Agency; IEA. https://www.iea.org/reports/the-future-of-hydrogen

IEA. (2021). *Net Zero by 2050: A Roadmap for the Global Energy Sector*. OECD. https://doi.org/10.1787/c8328405-en

IMO. (1974). *https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx*.

https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS),-1974.aspx

IMO. (2015). Third IMO GHG Study. In *IMO*. IMO. https://www.imo.org/en/OurWork/Environment/Pages/Greenhouse-Gas-Studies-2014.aspx

IMO. (2016). *Marine Environment Protection Committee (MEPC), 70th session*. https://www.imo.org/en/MediaCentre/MeetingSummaries/Pages/MEPC-70th-session.aspx

IMO. (2018). *INITIAL IMO STRATEGY ON REDUCTION OF GHG EMISSIONS FROM SHIPS*. https://www.imo.org/en/MediaCentre/PressBriefings/Pages/06GHGinitialstrategy.aspx

IMO. (2020). *Fourth IMO Greenhouse Gas Study*. Www.imo.org; International Maritime Organization. https://www.imo.org/en/OurWork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx

IMO. (2021). *Regulation for the Prevention of Air Pollution from Ships - MARPOL Annex VI*. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/MEPC.328%2876%29.pdf

IMO. (2023, July 7). *2023 IMO Strategy on reduction of GHG emissions from ships*. IMO. https://wwwcdn.imo.org/localresources/en/MediaCentre/PressBriefings/Documents/Resolution%20MEPC.377%2880%29.pdf

Inal, O. B., Charpentier, J.-F., & Deniz, C. (2022). Hybrid power and propulsion systems for ships: Current status and future challenges. *Renewable and Sustainable Energy Reviews*, *156*, 111965. https://doi.org/10.1016/j.rser.2021.111965

IPCC. (2023). *: Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the*

Intergovernmental Panel on Climate Change (Core Writing Team, H. Lee and J. Romero (eds.)). Intergovernmental Panel on Climate Change. https://www.ipcc.ch/report/sixth-assessment-report-cycle/

IRENA. (2020). *GREEN HYDROGEN COST REDUCTION SCALING UP ELECTROLYSERS CLIMATE GOAL H 2 O 2*. International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

IRENA. (2021). MAKING THE BREAKTHROUGH. In *Green hydrogen policies and technology costs*. International Renewable Energy Agency. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_Hydrogen_breakthrough_2021.pdf?hash=40FA5B8AD7AB1666EECBDE30EF458C45EE5A0AA6&la=en

IRENA. (2022). Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Technology Review of Hydrogen Carriers. In *International Renewable Energy Agency*. IRENA. https://www.irena.org/publications/2022/Apr/Global-hydrogen-trade-Part-II

ITF. (2018). Decarbonising Maritime Transport: Pathways to zero-carbon shipping by 2035. *OECD*, *International Transport Forum Policy Papers*. https://doi.org/10.1787/24108871

James, B. R., Jennie Mariko Huya-Kouadio, Houchins, C., & DeSantis, D. A. (2016). *Final Report: Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications (2012-2016)*. https://doi.org/10.2172/1346414

Joung, T.-H., Kang, S.-G., Lee, J.-K., & Ahn, J. (2020). The IMO initial strategy for reducing Greenhouse Gas(GHG) emissions, and its follow-up actions towards 2050. *Journal of International Maritime Safety, Environmental Affairs, and Shipping*, *4*(1), 1–7. https://doi.org/10.1080/25725084.2019.1707938

Kavussanos, M. G., & Visvikis, I. D. (2017). *INTERNATIONAL HANDBOOK OF SHIPPING FINANCE : theory and practice.* (Financial Analysis and the Modeling of Ship Investment). Palgrave Macmillan.

Kistner, L., Schubert, F. L., Minke, C., Bensmann, A., & Hanke-Rauschenbach, R. (2021). Techno-economic and Environmental Comparison of Internal Combustion Engines and Solid Oxide Fuel Cells for Ship Applications. *Journal of Power Sources*, *508*, 230328. https://doi.org/10.1016/j.jpowsour.2021.230328

Korberg, A. D., Brynolf, S., Grahn, M., & Skov, I. R. (2021a). Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. *Renewable and Sustainable Energy Reviews*, *142*, 110861. https://doi.org/10.1016/j.rser.2021.110861

Korberg, A. D., Brynolf, S., Grahn, M., & Skov, I. R. (2021b). Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships. *Renewable and Sustainable Energy Reviews*, *142*, 110861. https://doi.org/10.1016/j.rser.2021.110861

Lana, A., Pinomaa, A., Peltoniemi, P., Lahtinen, J., Lindh, T., Montonen, J.-H., Tikkanen, K., & Pyrhonen, O. P. (2019). Methodology of Power Distribution System Design for Hybrid Short Sea Shipping. *IEEE Transactions on Industrial Electronics*, *66*(12), 9591–9600. https://doi.org/10.1109/tie.2019.2892665

Li, X., Chalvatzis, K., & Stephanides, P. (2018). Innovative Energy Islands: Life-Cycle Cost-Benefit Analysis for Battery Energy Storage. *Sustainability*, *10*(10), 3371. https://doi.org/10.3390/su10103371

Lindstad, H., Verbeek, R., Blok, M., van Zyl, S., Hübscher, A., Kramer, H., Purwanto, J., Ivanova, O., & Boonman, H. (2015). GHG emission reduction potential of EU-related maritime transport and on its impact. In *European Comission*. TNO.

Livanos, G. A., Theotokatos, G., & Pagonis, D.-N. (2014). Techno-economic investigation of alternative propulsion plants for Ferries and RoRo ships. *Energy Conversion and Management*, *79*, 640–651. https://doi.org/10.1016/j.enconman.2013.12.050

Lloyds Register. (2020). Techno-Economic Assessment of Zero-Carbon Fuels. In *Lloyds Register*. https://www.lr.org/en/about-us/press-room/press-release/lr-and-umas-publish-techno-economic-assessment-of-zero-carbon-fuels/

MAN. (2018). Power Models and Average Ship Parameter Effects on Marine Emissions Inventories. In *MAN Energy Solution*. https://man-es.com/docs/default-source/marine/5510-0004-04_18-1021-basic-principles-of-ship-propulsion_web.pdf

MarinetTraffic. (2019). *MarineTraffic: Global Ship Tracking Intelligence | AIS Marine Traffic*. Marinetraffic.com. https://www.marinetraffic.com/

Masaud, T. M., & El-Saadany, E. F. (2020). Correlating Optimal Size, Cycle Life Estimation, and Technology Selection of Batteries: A Two-Stage Approach for Microgrid Applications. *IEEE Transactions on Sustainable Energy*, *11*(3), 1257–1267. https://doi.org/10.1109/tste.2019.2921804

MATLAB. (2023). *Genetic Algorithm*. Uk.mathworks.com; MathWorks United Kingdom. https://uk.mathworks.com/help/gads/genetic-algorithm.html?s_tid=CRUX_lftnav

MEPC. (2022). *2022 GUIDELINES FOR THE DEVELOPMENT OF A SHIP ENERGY EFFICIENCY MANAGEMENT PLAN (SEEMP)*. https://www.imo.org/en/OurWork/Environment/Pages/Improving%20the%20energy%20efficiency%20of%20ships.aspx#:~:text=The%20Energy%20Efficiency%20Design%20Index%20%28EEDI%29%20and%20the,the%20global%20fleet%20for%20more%20than%20a%20decade.

Minnehan, J. J., & Pratt, J. W. (2017). *Practical application limits of fuel cells and batteries for zero emission vessels*. Sandia National Laboratories. https://energy.sandia.gov/wp-content/uploads/2017/12/SAND2017-12665.pdf

Murthy, G. S. (2022). Techno-economic assessment. *Biomass, Biofuels, Biochemicals*, 17–32. https://doi.org/10.1016/b978-0-12-819242-9.00019-1

NREL. (2021). Cost Projections for Utility-Scale Battery Storage: 2021 Update. In *Technical Report. Golden, CO: National Renewable Energy Laboratory*. National Renewable Energy Labaratory. https://www.nrel.gov/docs/fy21osti/79236.pdf

OECD. (2021). World Energy Outlook 2021. In *World Energy Outlook*. OECD. https://doi.org/10.1787/14fcb638-en

Pawelec, G. (2020). Comparative report on alternative fuels for ship propulsion. *International Journal of Multidisciplinary and Current Research*, *Interreg North-West Europe: H2Ships*(European Regional Development Fund). Retrieved from https://vb.nweurope.eu/media/14694/210225_h2ships_t232_compassesmtaltfuels-02.pdf

Perčić, M., Vladimir, N., & Fan, A. (2021). Techno-economic assessment of alternative marine fuels for inland shipping in Croatia. *Renewable and Sustainable Energy Reviews*, *148*, 111363. https://doi.org/10.1016/j.rser.2021.111363

Port of Hamburg. (2023). *Valparaiso Express*. Die Offizielle Webseite Des Hamburger Hafens. https://www.hafen-hamburg.de/de/schiffe/valparaiso-express-46981/

Poseidon Principles. (2019). *A global framework for responsible ship finance*. https://www.poseidonprinciples.org/download/Poseidon_Principles.pdf

Poseidon Principles. (2023). *Responsible ship finance*. Poseidon Principles for Financial Institutions. https://www.poseidonprinciples.org/finance/about/

Rau, P., & Spinler, S. (2017). Alliance formation in a cooperative container shipping game: Performance of a real options investment approach. *Transportation Research Part E: Logistics and Transportation Review*, *101*, 155–175. https://doi.org/10.1016/j.tre.2017.02.005

Ricardo. (2022, August). *Study on the readiness and availability of low-and zero-carbon technology and marine fuels*. IMO.

https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/FFT%20Project/Study's%20technical%20proosal_Ricardo_DNV.pdf

Ritari, A., Spoof-Tuomi, K., Huotari, J., Niemi, S., & Tammi, K. (2021). Emission Abatement Technology Selection, Routing and Speed Optimization of Hybrid Ships. *Journal of Marine Science and Engineering*, *9*(9), 944. https://doi.org/10.3390/jmse9090944

Ritchie, H. (2020, October 6). *Cars, planes, trains: Where Do CO2 Emissions from Transport Come from?* Our World in Data; Global Change Data Lab. https://ourworldindata.org/co2-emissions-from-transport

Salman Mashayekh, Wang, Z., Li, Q., John Olav Lindtjorn, & Myklebust, T. (2012). *Optimum sizing of energy storage for an electric ferry ship*. https://doi.org/10.1109/pesgm.2012.6345228

Schinas, O., & Butler, M. (2016). Feasibility and commercial considerations of LNG-fueled ships. *Ocean Engineering*, *122*, 84–96. https://doi.org/10.1016/j.oceaneng.2016.04.031

Shakeri, N., Zadeh, M., & Bremnes Nielsen, J. (2020). Hydrogen Fuel Cells for Ship Electric Propulsion: Moving Toward Greener Ships. *IEEE Electrification Magazine*, *8*(2), 27–43. https://doi.org/10.1109/mele.2020.2985484

Sherbaz, S., & Duan, W. (2012). Operational options for green ships. *Journal of Marine Science and Application*, *11*(3), 335–340. https://doi.org/10.1007/s11804-012-1141-2

Silvas, E., Hofman, T., Murgovski, N., Etman, L. F. P., & Steinbuch, M. (2017). Review of Optimization Strategies for System-Level Design in Hybrid Electric Vehicles. *IEEE Transactions on Vehicular Technology*, *66*(1), 57–70. https://doi.org/10.1109/TVT.2016.2547897

Skinner, B. A., Parks, G. K., & Palmer, P. I. (2009). Comparison of Submarine Drive Topologies Using Multiobjective Genetic Algorithms. *IEEE Transactions on Vehicular Technology*, *58*(1), 57–68. https://doi.org/10.1109/tvt.2008.918732

Smith, T., Baresic, D., Fahnestock, J., Galbraith, C., Velandia Perico, C., Rojon, I., & Shaw, A. (2021). A Strategy for the Transition to Zero-Emission Shipping. In *World Economic Forum*. Global Maritime Forum. https://www.weforum.org/agenda/2021/10/net-zero-shipping-decarbonisation-new-strategy/

Spire. (2023). *Vessels API*. Spire Maritime Documentation. https://documentation.spire.com/vessels-api/

Stolz, B., Held, M., Georges, G., & Boulouchos, K. (2022). Techno-economic analysis of renewable fuels for ships carrying bulk cargo in Europe. *Nature Energy*, *7*(2), 203–212. https://doi.org/10.1038/s41560-021-00957-9

Sun, W., Tang, S., Liu, X., Zhou, S., & Wei, J. (2022). An Improved Ship Weather Routing Framework for CII Reduction Accounting for Wind-Assisted Rotors. *Journal of Marine Science and Engineering*, *10*(12), 1979. https://doi.org/10.3390/jmse10121979

Sun, X., Yao, C., Song, E., Liu, Z., Ke, Y., & Ding, S.-L. (2023). *Novel enhancement of energy distribution for marine hybrid propulsion systems by an advanced variable weight decision model predictive control*. *274*, 127269–127269. https://doi.org/10.1016/j.energy.2023.127269

Taljegard, M., Brynolf, S., Grahn, M., Andersson, K., & Johnson, H. (2014). Cost-Effective Choices of Marine Fuels in a Carbon-Constrained World: Results from a Global Energy Model. *Environmental Science & Technology*, *48*(21), 12986–12993. https://doi.org/10.1021/es5018575

Tang, D., Enrico Zio, Yuan, Y., Zhao, J., & Yan, X. (2017). *The energy management and optimization strategy for fuel cell hybrid ships*. https://doi.org/10.1109/icsrs.2017.8272834

Tang, D., & Wang, H. (2021). Energy Management Strategies for Hybrid Power Systems Considering Dynamic Characteristics of Power Sources. *IEEE Access*, *9*, 158796–158807. https://doi.org/10.1109/access.2021.3131168

UNACTAD. (2021). *Review Of Maritime Transport 2021.* United Nations. https://unctad.org/publication/review-maritime-transport-2021

UNCTAD. (2022). *REVIEW OF MARITIME TRANSPORT 2022*. United Nations. https://unctad.org/press-material/unctad-review-maritime-transport-2022#:~:text=The%20UNCTAD%20Review%20of%20Maritime%20Transport%202022%20Maritime,through%20a%20historic%20moment%20of%20crisis%20and%20disruption.

US Department of Energy. (2022). *Hydrogen Storage Cost Analysis*. https://www.hydrogen.energy.gov/pdfs/review22/st235_houchins_2022_p.pdf

US Department of Energy. (2023). *Fuel Cells*. Energy.gov; Office of Energy Efficiency & Renewable Energy. https://www.energy.gov/eere/fuelcells/fuel-cells

Victor Isaac Herrera, Haizea Gaztanaga, Milo, A., Andoni Saez-de-Ibarra, I. Etxeberria-Otadui, & Nieva, T. (2015). *Optimal energy management of a battery-supercapacitor based light rail vehicle using genetic algorithms*. https://doi.org/10.1109/ecce.2015.7309851

Wang, J., Wang, Q. N., Wang, P. Y., Wang, J. N., & Zou, N. (2015). *Hybrid electric vehicle modeling accuracy verification and global optimal control algorithm research*. *16*(3), 513–524. https://doi.org/10.1007/s12239-015-0053-y

Wang, X., Udai Shipurkar, Haseltalab, A., Polinder, H., Claeys, F., & Negenborn, R. R. (2021). *Sizing and Control of a Hybrid Ship Propulsion System Using Multi-Objective Double-Layer Optimization*. *9*, 72587–72601. https://doi.org/10.1109/access.2021.3080195

WE Forum. (2022, June 22). *These 6 maps show just how busy global shipping lanes are*. World Economic Forum. https://www.weforum.org/agenda/2022/06/shipping-lanes-maritime-traffic-global-maps/

Yates, J., Daiyan, R., Patterson, R., Egan, R., Amal, R., Ho-Baille, A., & Chang, N. L. (2020). Techno-economic Analysis of Hydrogen Electrolysis from Off-Grid Stand-Alone Photovoltaics Incorporating Uncertainty Analysis. *Cell Reports Physical Science*, *1*(10), 100209. https://doi.org/10.1016/j.xcrp.2020.100209

Ye, M., Sharp, P., Brandon, N., & Kucernak, A. (2022a). System-level comparison of ammonia, compressed and liquid hydrogen as fuels for polymer electrolyte fuel cell powered shipping. *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2021.12.164

Ye, M., Sharp, P., Brandon, N., & Kucernak, A. (2022b). System-level comparison of ammonia, compressed and liquid hydrogen as fuels for polymer electrolyte fuel cell powered shipping. *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2021.12.164

Yin, J., Wu, Y., & Lu, L. (2018). Assessment of investment decision in the dry bulk shipping market based on real options thinking and the shipping cycle perspective. *Maritime Policy & Management*, *46*(3), 330–343. https://doi.org/10.1080/03088839.2018.1520400

Yuan, H.-B., Zou, W.-J., Jung, S., & Kim, Y.-B. (2022). Optimized rule-based energy management for a polymer electrolyte membrane fuel cell/battery hybrid power system using a genetic algorithm. *International Journal of Hydrogen Energy*, *47*(12), 7932–7948. https://doi.org/10.1016/j.ijhydene.2021.12.121

Yuan, Y., Wang, J., Yan, X., Shen, B., & Long, T. (2020). A review of multi-energy hybrid power system for ships. *Renewable and Sustainable Energy Reviews*, *132*, 110081. https://doi.org/10.1016/j.rser.2020.110081

Zhang, T., Uratani, J., Huang, Y., Xu, L., Griffiths, S., & Ding, Y. (2023). Hydrogen liquefaction and storage: Recent progress and perspectives. *Renewable and Sustainable Energy Reviews*, *176*, 113204. https://doi.org/10.1016/j.rser.2023.113204

Zhu, D., Pritchard, E., Dadam, S., Kumar, V., & Xu, Y. (2021). Optimization of rule-based energy management strategies for hybrid vehicles using dynamic programming. *Combustion Engines*, *184*(1), 3–10. https://doi.org/10.19206/ce-131967

Zhu, J., Chen, L., Wang, B., & Xia, L. (2018). Optimal design of a hybrid electric propulsive system for an anchor handling tug supply vessel. *Applied Energy*, *226*, 423–436. https://doi.org/10.1016/j.apenergy.2018.05.131