Multi-perspective techno-economic comparison of decarbonization scenarios in the maritime transport sector

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Declaration

I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Abstract

The maritime transport sector acts as the backbone of world trade and is facing an imperative and challenging goal: to navigate towards sustainability, in the quest for decarbonization. High hopes are placed on alternative marine energy sources.

This study presents a comparative assessment of alternative marine energy sources and power system combinations, based on a multi-criteria decision analysis (MCDA) framework that focuses on the perspective of different decision makers' (DM) profiles: Environmentalist, Investor and a Balanced one. The combinations are compared in terms of quantifiable parameters including (i) Well-to-tank (WTT) energy intensity, (ii) well-to-wake emissions, (iii) volume per trip, (iv) mass per trip, and (v) total costs in two scenarios - including and excluding carbon taxation, (vi) energy vector production technology readiness level (TRL), and (vii) power system TRL; and qualitative criteria, namely (viii) infrastructure, all estimated from the literature. Five different vessels are analysed in the scope of this research: a container ship, a general cargo ship, a ro-pax ship, a pax-ferry, and a fishing trawler.

The study reveals that e-methanol paired with an internal combustion engine (ICE) stands out as the choice for eco-focused maritime decisions across all vessel types (Environmentalist perspective), followed by e-LNG+ICE. Nevertheless, current carbon taxes have limited sway in pushing Investor DMs towards green alternatives for large ships, suggesting a necessity for aggravating taxation. Notably, a Balanced decision-making approach consistently highlights top sustainable options across all vessel types, suggesting that combining environmental and cost factors effectively guides maritime transport towards decarbonization.

Key Words: alternative energy sources, maritime transport sector, multi-criteria decision analysis, GHG emissions, decarbonization, sustainability

Resumo

O sector do transporte marítimo atua como pilar do comércio mundial e enfrenta um objetivo desafiador: atingir a sustentabilidade, na busca pela descarbonização. Expectativas são depositadas em combustíveis marítimos alternativos.

O presente estudo apresenta uma avaliação comparativa de combinações de vetores energéticos alternativos e sistemas de potência, baseada num quadro de análise de decisão multicritério que se foca na perspetiva de diferentes perfis de decisores - o Ambientalista, o Investidor e o Equilibrado. As combinações são comparadas quantitativamente, incluindo (i) intensidade energética WTT, (ii) emissões WTW, (iii) volume por viagem, (iv) massa por viagem, e (v) custos totais em dois cenários - incluindo e excluindo taxação de carbono, (vi) TRL da produção do vetor energético, e (vii) TRL do sistema de potência; e qualitativamente, nomeadamente (viii) infraestrutura, todos estimados a partir da literatura. São analisadas cinco embarcações diferentes: um navio porta-contentores, um cargueiro (carga geral), um navio ro-pax, um ferry de passageiros, e uma traineira de pesca.

O estudo revela que o e-metanol combinado com um motor de combustão interna é a escolha de destaque para decisões marítimas focadas no ambiente para todos os tipos de navios analisados. No entanto, a taxação de carbono tem influência limitada em direcionar decisores Investidores para alternativas verdes em navios de grande porte, sugerindo uma necessidade de agravar a taxação. Notavelmente, uma abordagem de decisão Equilibrada destaca as melhores opções como sustentáveis em todos os navios, sugerindo que a combinação de fatores ambientais e custos guia o transporte marítimo em direção à descarbonização.

Palavras-chave: fontes de energia alternativas, setor de transporte marítimo, análise de decisão multicritério, emissões de GHG, descarbonização, sustentabilidade

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List of Acronyms and abbreviations

- AE – Auxiliary engine
- AEL – Alkaline electrolysis
- AEM – Anion exchange membrane
- BECCS – Bioenergy with carbon capture and storage
- CCS – Carbon capture and storage
- CH_4 – Methane
- CH_3OH – Methanol
- CI – Compression ignited (diesel cycle)
- CII – Carbon Intensity Indicator
- CO_2 – Carbon dioxide
- DAC – Direct air capture
- DM – Decision maker
- DF – Dual-fuel
- DWT – Deadweight
- EEA – European Environment Agency
- EMEP - European Monitoring and Evaluation Programme
- EU mix – European Union’s electricity mix
- EEXI – Energy Efficiency Existing Shipping Index
- GHG – Greenhouse gas
- GT – Gross tonnage
- GWP – Global warming potential
- GWP20 – Global warming potential in a 20-year time period
- GWP100 - Global warming potential in a 100-year time period
- H_2 – Hydrogen
- H_2O - Water
- HFO – Heavy fuel oil
- HPDF - High-pressure dual fuel engine (2-stroke)
- IMO – International Maritime Organization

- LF – Load factor
- LH_2 – Liquefied hydrogen
- LIB – Lithium-ion battery
- Li-ion – Lithium-ion
- LNG – Liquefied natural gas
- LoZeC – Low- or Zero-carbon
- MBM – Market bases measures
- MCDA – Multi-criteria decision analysis
- MDO – Marine diesel oil
- ME – Main engine
- MGO – Marine gas oil
- N_2 – Nitrogen
- N_2O – Nitrous oxide
- NG – Natural gas
- NH_3 – Ammonia
- NOx – Nitrogen oxides
- O_2 - Oxygen
- OH^- - Hydroxide
- PAX - Passengers
- PEM – Proton exchange membrane
- PEMFC - Proton exchange membrane fuel cell
- PM – Particulate matter
- RES – Renewable energy sources
- RO-PAX – Roll-on/ roll-off passenger
- SCR – Selective catalyst reduction
- SI – Sparkle ignited (Otto cycle)
- SOE – Solid oxide electrolysis
- SOFC – Solid oxide fuel cell
- SOx – Sulphur Oxides

- TEU – Twenty-foot equivalent unit
- TRL – Technology readiness level
- TTW – Tank-to-wake
- U.S.A – United States of America
- VLSFO – Very-low sulphur fuel oil
- WTT – Well-to-tank
- WTW – Well-to-wake

1. Introduction

1.1. Motivation/ Context

The global maritime sector acts as the backbone of international trade, delivering more than 80% of the world trade by volume. In 2021, above 11 billion tonnes of goods were carried via seaborn transport, which corresponds to an approximate growth of 85% since the beginning of the century (United Nations - UNCTAD, 2022).

According to the *Fourth IMO Greenhouse Gas Study*, up to 79% of total fuel consumption in international shipping was composed of heavy fuel oil (HFO) in 2018, the rest of maritime transport was mainly powered by marine diesel oil (MDO) and liquefied natural gas (LNG) (IMO - International Maritime Organization, 2020). HFO is an extremely pollutant fuel and an enormous greenhouse gas (GHG) emitter, whose use has resulted in prejudicious effects, not only for the environment but also for human safety and health (Abdul Jameel et al., 2019). In consequence of using such polluting fuels, the shipping sector alone was responsible for 2.89% of the global CO_2 emissions in 2018, which have been growing. In April of 2022, the amount of the world fleet's carbon emissions reached 847 million tons and the trend is clearly heading in the wrong direction, as the United Nations have stated in the *Review of Maritime Transport – Navigating Stormy Waters* (United Nations - UNCTAD, 2022).

All these factors have inspired the strategic plan designed by the International Maritime Organization (IMO) in 2018 (IMO, 2018), to align with the Paris Agreement's temperature goals to reduce annual GHG emissions from the maritime transport sector . In fact, IMO has committed to reduce international shipping's GHG emissions by at least 50% by 2050, compared to 2008 values.

As concerns over climate change escalate, urgent action is required to decarbonize this vital industry and align it with ambitious sustainability targets. The IMO has set forth ambitious greenhouse gas reduction goals, emphasizing the need for the adoption of zero or low-carbon and sustainable energy solutions.

The urgency to reduce greenhouse gas emissions is underscored by the detrimental impact of shipping activities on the environment, with significant effects on air quality and marine ecosystems (Islam Rony et al., 2023; Mueller et al., 2023). The transition to cleaner and more sustainable energy alternatives is essential to mitigate these adverse effects and foster a greener maritime transport industry. Moreover, the fluctuating prices of traditional fossil fuels and increasing concerns over their long-term availability further accentuate the significance of exploring viable alternative energy sources.

In response to these challenges, the present research endeavours to address the pressing question of identifying the most suitable energy vector and power system combinations for achieving decarbonization in the maritime transport sector. To tackle the complexities of selecting optimal combinations for diverse vessel types, a Multi-Criteria Decision Analysis (MCDA) based model is proposed to address different profiles of decision makers. This model is uniquely tailored to accommodate the intricate interplay between environmental, technical, and economic factors. The examination of different vessel types, including container ships, general cargo ships, ro-pax ships, pax-ferries, and fishing trawlers, consist of an innovative feature of this model, since it considers the influence of distinct operational requirements and voyage patterns on the requirements for the decarbonization process.

By providing comprehensive decision support through the MCDA based model, this study aims to bridge the gap between theory and practice in the pursuit of sustainable maritime transport. The findings are expected to yield valuable insights for key stakeholders, including policymakers, shipowners, investors, and environmental advocates, as they navigate the complex landscape of decarbonization strategies in this sector.

Overall, the present study is driven by a strong motivation to contribute to the collective effort to combat climate change, reduce GHG emissions, and pave the way for a more sustainable and resilient maritime transport sector. Through a robust and integrated approach, this research provides actionable solutions that align environmental responsibility with economic viability, thus steering the shipping industry towards a cleaner and greener future.

1.2. Objective

The objective of this work is to perform a techno-economic comparison of pre-selected energy vectors and promising power system combinations to serve different vessels, taking new ships and retrofits into consideration. Consequently, the study aims to answer the following research question: « Which energy vector and power system combinations should stakeholders bet on to effectively decarbonize different vessel types in the maritime transport sector? ».

The overarching purpose of this work is to provide decision support through different future decarbonization scenarios of the maritime transport sector. To reach for an answer, a Multi-Criteria Decision Analysis (MCDA) based model will be implemented, considering environmental, technical, and economic aspects, to evaluate optimal solutions for different vessel types according to different profiles of decision makers (DMs).

The study focuses on analysing five distinct vessels: a container ship, a general cargo ship, a roll-on/roll-off passenger ship (ro-pax), a passenger ferry (pax-ferry), and a fishing trawler. These vessels, having their unique characteristics and different regular voyages with diverse operational profiles, will be studied throughout their assumed lifetime of 30 years. The diversity of ship types and their contrasting purposes provides valuable insights into how the type of regular voyage and the onboard available fuel capacity might influence the optimal energy vector and power system combinations over the ships' operational lifespan.

The analysis will encompass a pre-selected range of alternative energy vectors and promising power systems, considering possible retrofit options to ensure the feasibility of transition towards decarbonization. By evaluating different decarbonization scenarios, the study aims to determine a likely path for choosing the most suitable energy solutions that align with environmental, technical, and economic objectives by the perspective of different profiles of DMs. The findings of the present research are expected to contribute significantly to the maritime transport sector, policymakers, and stakeholders, providing vital guidance in making informed decisions for a sustainable and low-carbon future in the sector.

1.3. Structure and organization

The present dissertation is organized in six main chapters:

Chapter 1 – Introduction: This section provides an overview of the dissertation, introducing the research motivation, objectives, research question, and the document's organization. It establishes the context and significance of the study, laying the groundwork for the subsequent chapters.

Chapter 2 – State of the Art: This chapter presents a comprehensive review of the existing relevant literature and studies related to decarbonization in the maritime sector. It explores the current state of the world merchant fleet, sustainable energy vectors, power systems, regulations and policies towards decarbonization, and MCDA based studies in the maritime transport sector. By analysing the literature, this chapter identifies gaps, challenges, and opportunities, providing valuable insights for the research.

Chapter 3 – Methodology: In this section, the research methodology is detailed, explaining the design of the Multi-Criteria Decision Analysis (MCDA) based model used to evaluate energy vector and power system combinations for different vessels. The chapter presents data collection, the selection and definition of criteria, the performance values of each option across every criterion, the normalization process, and the assignment of weights in the viewpoint of different profiles of decision makers.

Chapter 4 – Results and Discussion: This section presents the key findings of the research derived from the MCDA based model. It provides a comprehensive and detailed analysis of the best performing energy vector and power system combinations for two contrasting vessel types, the container ship and the pax-ferry, based on environmental, technical, and economic criteria. The chapter also interprets the overall results for the 5 analysed vessels, addressing trade-offs and implications for decision makers. The discussion analyses the impact of vessel characteristics and their regular voyages on the optimal choices.

Chapter 5 – Conclusion: This section synthesizes the entire research journey, restating the research question and objectives. It presents a concise summary of the main contributions and significant outcomes of the study. The chapter discusses the implications of the findings for decarbonizing the maritime transport sector and provides recommendations for future research. It concludes by reinforcing the importance of pursuing sustainable energy solutions in the maritime transport sector.

Chapter 6 – References: This section includes a comprehensive list of all the sources cited in the dissertation.

2. State of the Art

In this section, some recently published work relevant to the topic at hand is presented and analysed. It explores the current state of the world merchant fleet, sustainable energy vectors, emerging power systems, regulations and policies towards decarbonization, and MCDA based studies in the maritime transport sector.

2.1. The Maritime Transport Sector

The shipping industry acts as the backbone of international trade, delivering more than 80% of the world trade by volume. In 2021, above 11 billion tonnes of goods were carried via seaborn transport, which corresponds to an approximate growth of 85% since the beginning of the century (United Nations - UNCTAD, 2022).

2.1.1. World merchant fleet

Ship categories can be aggregated in 13 main types, according to Equasis (2021):

- General Cargo Ships: transport general cargo, i.e., packaged items;
- Specialized Cargo Ships: include barge, heavy load, livestock, and nuclear fuel carriers;
- Container Ships: transport containers;
- Ro-Ro (roll-on roll-off) Cargo Ships: carry wheeled cargo;
- Bulk Carriers: transport unpackaged bulk;
- Oil and Chemical Tankers: transport oil and liquid chemicals;
- Gas Tankers: transport gas;
- Other Tankers;
- Passenger Ships: transport passengers;
- Offshore Vessels: serve specific offshore operations like construction at the high seas;
- Service Ships: large ships that provide propulsion to other vessels;
- Tugs: small ship that provides propulsion to other vessels in harbour;
- Fishing vessels: catch and transport fish.

Table.1 shows the number of ships in the World Merchant Fleet in 2021 by type and size, dividing them in four different size categories (Equasis, 2021). It is clear to see that the 5 most common ship types, by number, are a). Fishing vessels (21.8%), b). Tugs (16.6%), c). General cargo ships (13.6%), d). Oil and chemical tankers (12.0%), and e). Bulk carriers (10.8%), accounting for almost three quarters of the world fleet.

Table.1 - World Fleet: Total number of ships by type and size (Equasis, 2021)

Ship Type	**Small** (GT<500)	**Medium** (500≤GT<25,000)	**Large** (25,000≤GT<60,000)	**Very Large** (GT≥60,000)	**Total**	
General Cargo ships	4 089	11 814	264	0	16 167	13.6%
Specialized Cargo ships	8	266	64	7	345	0.3%
Container ships	19	2 315	1 629	1 554	5 517	4.6%
Ro-ro Cargo ships	39	601	549	268	1 457	1.2%
Bulk carriers	286	3 847	6 842	1 899	12 874	10.8%
Oil and chemical tankers	1 979	7 372	2 773	2 185	14 309	12.0%
Gas tankers	36	1 145	433	591	2 205	1.9%
Other tankers	437	741	16	0	1 194	1.0%
Passenger ships	3 435	825	71	187	4 518	3.8%
Offshore vessels	2 812	5 235	119	298	8 464	7.1%
Service ships	3 197	2 994	35	7	6 233	5.2%
Tugs	18 860	933	0	0	19 793	16.6%
Fishing vessels	20 186	5 762	4	0	25 952	21.8%
Total	55 383	43 850	12 799	6 996	119 028	100%

On the other hand, the analysis of the global fleet by gross tonnage (GT) enables identifying the three most important ship types in maritime transport: a) Bulk carriers (34.4%); b) Oil and chemical tankers (25.4%); and c) Container ships (18.0%) - Table 2. These account for more than three quarters of the global fleet's total gross tonnage.

Table 2 - World fleet: gross tonnage (in 1000 Gt) by type and size (Equasis, 2021)

Ship Type	**Small** (GT<500)	**Medium** (500≤GT<25,000)	**Large** (25,000≤GT<60,000)	**Very Large** (GT≥60,000)	**Total**	
General Cargo ships	1 429	52 877	8 897	0	63 203	4.3%
Specialized Cargo ships	3	2 119	2 519	510	5 151	0.3%
Container ships	8	27 671	60 771	177 442	265 892	18.0%
Ro-ro Cargo ships	12	6 089	26 117	18 042	50 260	3.4%
Bulk carriers	116	56 626	256 861	195 576	509 179	34.4%
Oil and chemical tankers	637	45 008	97 244	232 331	375 220	25.4%
Gas tankers	14	7 265	18 905	66 514	92 698	6.3%
Other tankers	131	2 110	465	0	2 706	0.2%
Passenger ships	851	2 688	2 877	21 395	27 811	1.9%
offshore vessels	789	15 469	5 456	35 458	57 172	3.9%
service ships	774	9 683	1 255	952	12 664	0.9%
Tugs	4 583	812	0	0	5 395	0.4%
Fishing vessels	4 398	7 892	142	0	12 432	0.8%
Total	13 745	236 309	481 509	748 220	1479 783	100%

To ensure completeness and diversification of analysis, the present thesis will focus on 5 different categories of ships with contrasting purposes, analysing a container ship, a general cargo ship, a roll-on/ roll-off passenger ship (ro-pax), a passenger (pax) ferry, and a fishing trawler. These together account for 25% of the global fleet's total gross tonnage.

2.1.2. Emissions and impacts

According to the *Fourth IMO Greenhouse Gas Study*, up to 79% of total fuel consumption in international shipping was composed of heavy fuel oil (HFO) in 2018, the rest of maritime transport was mainly powered by marine diesel oil (MDO) and liquefied natural gas (LNG) (IMO, 2020). HFO is an extremely pollutant fuel and an enormous greenhouse gas (GHG) emitter, whose use has resulted in prejudicious effects, not only for the environment but also for human safety and health (Abdul Jameel et al., 2019).

In consequence of using such polluting fuels, the shipping sector alone was responsible for 2.89% of the global CO_2 emissions in 2018, which have been growing non-stop. In April 2022, the amount of the world fleet's CO_2 emissions reached 847 million tons and the trend is clearly increasing, as the United Nations have stated in its *Review of Maritime Transport – Navigating Stormy Waters* (United Nations - UNCTAD, 2022) – as presented in Figure 1.

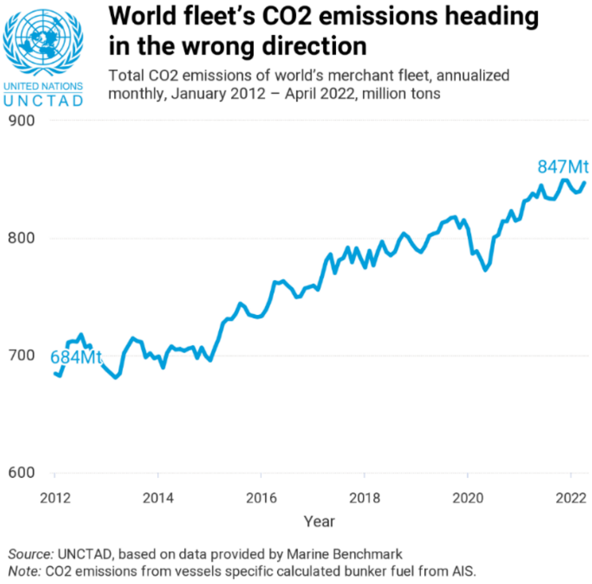

Figure 1 - World fleet's CO_2 emissions through the years, taken from (United Nations - UNCTAD, 2022)

Regarding the types of ships that represent the largest share of the global merchant fleet's deadweight – oil tankers, bulk carriers, general cargo ships and container ships –, their carbon emissions in Europe are described in Table 3, with container ships occupying the first place as the most intensive polluter type of vessel, having emitted 40 602 097.36 million tonnes of CO_2 in 2021. As indicated in Table 3, container ships, oil tankers, and bulk carriers emerge as the primary contributors to carbon emissions in the maritime sector. This can be attributed to the extensive distances covered by these vessel types, which often involve international and intercontinental voyages, in contrast to shorter domestic and coastline routes (Balcombe et al., 2019).

Table 3 - Total CO_2 emissions in Europe (in metric tonnes) in 2021 (EMSA, 2023)

2021	**Total CO_2 emissions** ($\times 10^6$ metric ton)
Oil tankers	16 255
Bulk carriers	16 154
General cargo	6 289
Container ships	40 602

Although it is true that CO_2 emissions take up the greatest role as a global warming aggravator associated with anthropogenic activities, there are other greenhouse gases (GHG) emitted globally and by the maritime sector that make a considerable environmental dent. GHG are gases present in the atmosphere, whether by natural occurrence or because of anthropogenic causes. By absorbing and emitting radiation, they trap the heat within the surface-troposphere, causing a greenhouse effect and, consequently, contributing to the acceleration of global warming (IPCC, 2007). For instance, Figure 2 shows the GHG emissions' shares by gas that occurred in 2020 in the United States, which provides a viable comparison with the GHG emissions globally (EPA, 2022). Carbon emissions cover for 79% of the total GHG emissions while other GHG like methane (CH_4), nitrous oxide (N_2O) and fluorinated gases cover the rest, with CH_4 being the second most accentuated one.

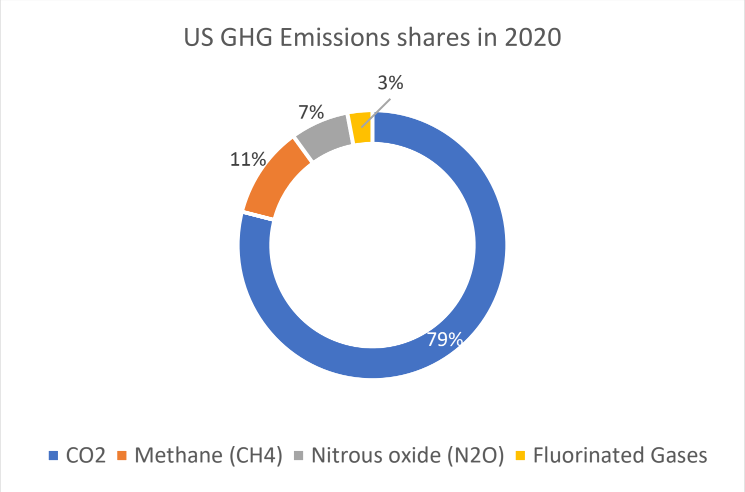

Figure 2 - United States' GHG emissions shares in 2020, adapted from (EPA, 2022)

A study conducted by the World Health Organization identified shipping as the third most significant cause of air pollution (Chen et al., 2019), which makes this sector the cause of various environmental and health impacts due to its emissions (Aspen & Sparrevik, 2020). Air pollution resulting from shipping operations releases a diverse range of pollutants, including non-methane volatile organic compounds, particulate matter (PM), nitrogen oxides (NO_x), and sulphur oxides (SO_x). Human exposure to these pollutants is associated with increased rates of respiratory illnesses, such as asthma attacks, and an elevated risk of developing lung cancer from people living in coastal urban centres (Aspen & Sparrevik, 2020; Islam Rony et al., 2023). Mueller et al. (2023) estimated that, in 2020, approximately 265 000 premature deaths, accounting for almost 0.5% of global mortality, were attributable to emissions from international shipping.

In addition to contributing to air pollution, the shipping sector plays a considerable role in climate change. Besides the GHG mentioned above, short-lived climate pollutants mentioned above, like methane (CH_4), black carbon, NO_x, and SO_x, also have a substantial impact on climate change (Fuglestvedt et al., 2014). Such emissions affect diverse maritime locations, contributing to changes in climate patterns (Islam Rony et al., 2023).

On top of that, shipping operations engender other environmental consequences: discharges of untreated wastewater, bilge, scrubber water, sewage, and antifouling paint have detrimental effects on the marine environment (Endres et al., 2018). Scrubber wash water and SO_X deposits contribute to acidification, whereas hull fouling and ballast water facilitate the spread of invasive species (Koski et al., 2017; Raudsepp et al., 2019; Tiselius & Magnusson, 2017; Ytreberg et al., 2020). Furthermore, shipping emissions contribute to the processes of eutrophication and acidification. Eutrophication results from the influx of excessive nutrients, often originating from ship discharges, leading to the overgrowth of algae and detrimental effects on marine life. Acidification arises from the dissolution of acidic compounds, such as SO_x deposits, in seawater, causing imbalances in marine ecosystems. Both eutrophication and acidification processes have long-term consequences for the health and stability of marine ecosystems (Islam Rony et al., 2023; Jalkanen et al., 2012).

To mitigate the adverse environmental and health impacts of shipping emissions, rigorous regulations, cleaner technologies, and sustainable practices must be adopted across the industry. These measures are essential to safeguard both the environment and human health in the face of shipping-related challenges.

2.1.3. Emerging technologies

The maritime transport sector is undergoing a paradigm shift towards sustainability, driven by the urgent need to reduce greenhouse gas emissions which have been in an all-time high, as seen in the previous subchapter, and transition to low-carbon emitting alternatives. In this section, the current state of emerging technologies that hold promise for decarbonizing this sector is explored, including dual-fuel internal combustion engines (ICE) running mostly on sustainable alternative fuels, lithium-ion (Li-ion) batteries, and fuel cell (FC) technologies, namely proton exchange membrane fuel cells (PEMFC) and solid-oxide fuel cells (SOFC).

Dual-fuel internal combustion engines (ICE):

The dual-fuel engine is not a novel concept, in fact, it was first developed by Ghazi A. Karim in 1980 (Karim, 1980). This technology represents an ICE that uses an alternative fuel as main fuel and a small quantity of diesel oil for injection, normally in a ratio of 5% diesel to 95% main fuel, and has been widely researched for maritime applications recently (Benvenuto et al., 2017; Marques et al., 2019; Tadros et al., 2023). Several manufacturers in the maritime industry have already launched dual-fuel engines running on alternative fuels like ammonia, methanol, and hydrogen, namely MAN Engines and Wartsilä

(MAN Engines, 2022; Wärtsilä, 2023), corroborating their commercial viability.

Kurien & Mittal (2022) conducted a literature review on the performance of dual-fuel engines with ammonia as the main fuel, and with various injection fuels, namely, diesel, dimethyl ether, kerosene, and even hydrogen. Findings suggest that ammonia's higher auto-ignition temperature poses some challenges to combustion and performance. Nevertheless, these drawbacks can be overcome through the implementation of advanced injection strategies, leading to enhanced performance.

Methanol is another alternative fuel that can be used in a dual-fuel engine. In fact, the literature review conducted by Saxena et al. (2021) studied the performance, combustion and emissions of such a fuel in a dual-fuel ICE with diesel for injection. This review paper concludes that methanol improves the engine performance due to higher presence of oxygen, enhances efficiency, and reduces GHG emissions substantially. However, the authors also highlight the challenges associated with fuel premixing in dual-fuel operation, such as higher pressure rise rate, partial burn, misfire, and knocking.

Deheri et al. (2020) investigated the performance of gaseous fuels in dual-fuel engines, namely biogas and hydrogen. The authors have concluded that hydrogen is regarded as a potent source of energy owing to its elevated heating value, higher flame speed, and low ignition energy. Additionally, its lack of a carbon atom renders H_2 a valuable resource for emission control and performance enhancement in compression-ignition (CI) dual-fuel engines.

Lithium-ion batteries:

Full electrification has been proposed as a path to zero-emitting shipping at the point of use, being widely researched and proposed mainly for short-sea navigation.

Li-ion batteries (LIB) seem to be the most prominent solution as highlighted by Perčić et al. (2022) in a study that compares Li-ion, nickel-metal hydride (Ni-MH), and lead-acid batteries in a life cycle assessment (LCA) and life cost cycle assessment (LCCA) investigation performed on a Croatian passenger ferry. Findings of this research state that LIBs are the most cost effective and environmentally friendly option for short voyages, defending that further investigation on the performance of this technology would open the path to longer trips. LIB systems are composed of a cathode, anode, electrolyte, current collectors, and battery management system (Sharmili et al., 2023). Peralta et al. (2019) conducted a comprehensive study on the integration of a LIB within a hybrid system alongside a diesel generator. Their investigation revealed promising outcomes, indicating a substantial reduction in CO_2 emissions, approximately around 40%, in comparison to a traditional diesel ICE. Additionally, the incorporation of LIBs resulted in less frequent equipment renewals, leading to significant reductions in operational costs for the hybrid system. Nonetheless, according to the results of the authors' research, Vakili & I. Ölçer (2023) have rightfully stated that a vessel can only be sustainable if its primary source of energy is sourced from renewables, it is not enough to be fully electric if the electricity comes from fossil origins.

Fuel cell (FC) technology:

FC arose as a promising tool to help decarbonize the maritime transport sector, especially for their capacity of reaching near zero emissions with the right fuel. Since 2000, more than 30 international funded projects for this technology application onboard ships have been developed, where PEMFC seem to be most used type of FC and hydrogen the most used fuel (Elkafas et al., 2023). FCs operate based on electrochemical reactions occurring between the anode and cathode interfaces. In essence, this technology shares similarities with batteries; however, the fundamental distinction lies in their energy generation mechanism. Unlike batteries, fuel cells do not store energy but continuously produce electricity and heat as long as a consistent fuel supply is maintained (US Department of Energy, 2023). The exclusive reliance on electrochemical reactions for electrical energy production offers several advantages over conventional energy systems. The efficiency of fuel cells is considerably high due to the absence of intermediate mechanical processes.

Proton exchange membrane fuel cells (PEMFC), also known as polymer electrolyte membrane FC, have been gaining momentum as a clean energy solution for transportation applications in recent years, including for maritime transport. In fact, the PEMFC market has grown around 26% from 2017 to 2021. PEMFC operate with an aqueous electrolyte, a polymer that facilitates the transport of hydrogen ions, enabled by the presence of liquid water on the component, and have efficiencies around 45-55%. These FC function at relatively low temperatures (80ºC), which gives this technology the ability of quick start, as it needs less time to warm-up, presenting an average lifespan of 25 000 hours or operation (Elkafas et al., 2023).

Solid Oxide Fuel Cells (SOFC) offer a notable advantage in terms of electrical efficiency when compared to PEMFC (around 55-65% efficiency) as they operate at elevated temperatures, reaching up to 1000ºC. This high operating temperature facilitates internal reforming of fuels, resulting in a reduced reliance on external reforming systems. Moreover, SOFCs exhibit commendable durability, with an expected operational lifespan of up to 80 000 hours (Elkafas et al., 2023).

2.1.4. Regulations and Policies towards decarbonization

The maritime shipping sector faces significant challenges in achieving sustainability transitions, and policy guidance is essential to enable it. In fact, according to Leeuwen & Koppen (2016), the response of companies to economic stimuli generated by Market-Based Measures is contingent on their chosen environmental strategy. The authors found that the shipping sector tends to adopt a crisis-oriented approach, where the primary ambition is solely “staying within compliance”, hence the importance of effective regulation measures for this sector.

Bach & Hansen (2023) stated that, although the shipping sector is regulated by a single international body – the International Maritime Organization (IMO), the current policy mix lacks consistency and comprehensiveness, which hinders the achievement of emission reduction targets of the sector. Nonetheless, IMO has demonstrated effectiveness in regulating air polluting substances, as evidenced by the implementation of a limit for sulphur content in ship fuel, which led to a significant reduction of approximately 77% in SO_x emissions from ships since 2020 (Mandra, 2022a), indicating the potential that effective regulating measures might have regarding the reduction of GHG emissions (Bach &

Hansen, 2023).

Notably, more focus is currently being given to addressing GHG emissions' reduction in the maritime sector, to achieve IMO's ambitious and indispensable sustainable goals. The IMO's Marine Environment Protection Committee (MEPC) oversees the main regulatory framework for air emissions through the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI. Still, Bach & Hansen (2023) suggest that the introduction of economic instruments such as a global carbon tax, emission trading scheme, or funding for sustainable fuels is urgently needed to establish a more effective policy mix, as the instruments implemented through MARPOL Annex VI have mainly been regulatory. Other researchers have also defended that a balance between regulatory, economic and soft instruments is key to ensure an effective policy mix (Rogge & Reichardt, 2016; Schmidt & Sewerin, 2019).

Amendments of the MARPOL Annex VI entered into force in November 2022. From the January 1st of 2023, it is mandatory that all ships calculate and report their Energy Efficiency Existing Ship Index (EEXI) and start collecting data to report their annual operational carbon intensity indicator (CII) (IMO, 2023). These amendments represent a decisive and concerted effort to initiate the decarbonization movement of this sector.

Another great example of the recent commitment to lower the sector's GHG emissions is the FuelEU Maritime regulation, introduced by the European Union (EU) in 2021, which enters into force in 2025. This proposal represents a landmark initiative in the global pursuit of maritime decarbonization (Malmborg, 2023). As part of the broader 'Fit for 55' package, this regulatory framework aims to stimulate the increased adoption of renewable and low-carbon fuels within the fuel mix of international maritime transport. By establishing a common EU regulatory framework, the legislation seeks to align the shipping sector with the EU's ambitious climate targets for 2030 and 2050 (European Commission, 2021a).

According to the European Commission (EC), the successful implementation of the FuelEU Maritime proposal is crucial for achieving the EU's economy-wide GHG emissions' reduction targets. Regarding sustainable alternative fuels, also known as low/zero carbon fuels (LoZeC), the proposal sets targets for these energy vectors to comprise 6-9% of the international maritime transport fuel mix by 2030, and an impressive 86-88% by 2050. A key feature of the EC's proposal is its "technology-neutral approach", recognizing the diversity of technologies utilized in the maritime sector. By focusing on stimulating fuel demand rather than prescribing specific fuel choices, the regulation aims to facilitate innovation and promote the development of various sustainable fuel options (European Commission, 2021b).

The FuelEU Maritime regulation exemplifies the EU's commitment to policy experimentation and learning best practices in policy design, implementation, and enforcement. As the most ambitious pathway to maritime decarbonization (Malmborg, 2023), this legislation serves as a crucial model for other regions and countries seeking to address the environmental impact of shipping emissions. It represents a significant step towards transforming the maritime industry into a more sustainable and environmentally responsible sector.

Concluding, the realization of clear political goals, the availability of public funding opportunities, and a clear and comprehensive regulation play a pivotal role in encouraging shipowners, ship designers, shipyards, and all types of stakeholders to embrace and invest in LoZeC fuels and technologies. These incentives provide a crucial impetus for the maritime industry to transition towards more sustainable and environmentally friendly solutions, thereby contributing to the overall decarbonization efforts in the shipping sector.

2.2. Promising alternative maritime energy vectors

From 2000 to 2020, 583 articles have been published on cleaner alternative marine fuels by 1610 authors from 558 research institutes, originating from 54 countries/regions. The research field has grown significantly since the start of the 21st century, with an annual growth rate of 15.8% (Ampah et al., 2021).

Regarding which fuel and power system combination will prevail in the future of the maritime transport sector, there are already some promising contesters, but one size does not fit all. As Bergek et al. (2021) have stated “LoZeC energy solutions would need to be implemented in a wide variety of user segments, ranging from inter-continental freight and bulk carriers to local passenger vessels, which differ in terms of market conditions as well as vessel types and operational profiles.”

There are several recent scientific studies and papers defending that the future of maritime fuels will be sustained by liquefied natural gas (LNG), methanol, ammonia, hydrogen, and even synthetic diesel from renewables. LNG will most likely act as a transition fuel (Balcombe et al., 2019; Lagemann et al., 2022; Lindstad & Rialland, 2020), making way to the other alternative fuels in need of more technologic advances. Methanol is emerging as a promising alternative fuel for the maritime industry, as evidenced by the recent announcements by MAN Energy Solutions and Wärtsilä regarding the availability of commercially viable methanol engines for ships (Islam Rony et al., 2023; Oloruntobi et al., 2023).

On the other hand, ammonia will likely take its seat at the table in the medium/long run, being commercially available around 2030 (Korberg et al., 2021; Mallouppas et al., 2022), and ultimately hydrogen will likely take its place as a greener maritime fuel in the long run, around 2050 (Balcombe et al., 2019; Gray et al., 2021), mainly because of the challenges related to its storage conditions and current lack of infrastructure - challenges that will be addressed in the chapters ahead. The role of synthetic diesel will closely depend on the fuel’s production supply chain, since it is still too expensive to produce compared to its peer fuels at today’s state of the art (Schemme et al., 2017). Finally, full electrification of vessels using Li-ion batteries for short navigation as proven to be a valuable alternative to reduce emissions and even costs (Perčić et al., 2022).

The following sections present detailed definition of promising alternative energy vectors for the maritime transport sector, namely liquefied natural gas, methanol, ammonia, and liquefied hydrogen.

2.2.1. Liquefied Natural Gas

In Figure 3, it is clear to see Europe’s commitment in embracing LNG as a maritime fuel, throughout the number of infrastructure points already in operation, like LNG storage bunkers or liquefaction and refuelling stations.

Figure 3 - Spatial representation of LNG infrastructure clusters in operation in 2022, taken from (DNV GL, 2022)

LNG's popularity as a maritime fuel has been growing: it was recognized as the most researched alternative maritime fuel between 2000 and 2020 by Ampah et al. (2021). In terms of carbon content per unit of energy, this fuel exhibits a lower value compared to conventional shipping fuels, resulting in reduced CO_2 emissions during combustion. Consequently, it has garnered considerate attention in discussions surrounding the production of LNG from renewable sources. However, around 85-95% of LNG's composition is methane (DOE - USA, 2013), which is a potent GHG, capable of trapping 86 times more heat than CO_2, in a 20-year time horizon (Pavlenko et al., 2020).

A study conducted by Lindstad & Rialland (2020) examines the potential positive impact of LNG-powered cruise ships on public opinion. The research aims to compare the greenhouse gas (GHG) emissions, specifically well-to-wake (WTW)[1] and well-to-tank (WTT)[2] emissions, from LNG against traditional fuels used in the maritime industry, such as heavy fuel oil (HFO), marine gas oil (MGO), and very-low sulphur fuel oil (VLSFO), across different engine types. The authors stated that LNG, "with its low sulphur content, its favourable hydrogen-to-carbon ratio, and the lower nitrogen oxide emission when combusted compared to conventional fuels" meets all IMO's air emissions regulations. Nevertheless, the study also reveals that the WTT emissions associated with the LNG supply chain are at a critical standpoint. Additionally, the presence of methane (CH_4) slip in the ship's engine "more than nullifies any GHG gains". CH_4 slip refers to the incomplete combustion of methane in the engine, leading to its release into the atmosphere (Burel et al., 2013). These findings show a necessity of new policies adoption in order to address other GHG emissions from shipping beyond carbon emissions.

A review published in 2019 addressed different strategies to decarbonize the maritime sector, by investigating alternative fuels, energy efficiency technologies, and by discussing existing decarbonization policies while proposing new ones (Balcombe et al., 2019). The authors strongly defend LNG as the most promising alternative shipping fuel and have even stated the urgency for its implementation: "With LNG being economically feasible, technologically secure and guaranteeing environmental benefits in the short term, a combination of subsidies and port dues can effectively

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[1] Well-to-wake emissions, also known as life-cycle emissions, are the sum of well-to-tank (WTT) and tank-to-wake (TTW) GHG emissions.

[2] Well-to-tank emissions are the GHG emissions released upstream, i.e., in the production, processing and transportation of a fuel until it reaches the tank inside the vessel.

accelerate its implementation”.

Furthermore, in a more recent study by Balcombe et al. (2021), the authors delve into the question of how LNG-fuelled ships can align with decarbonization targets. Their publication incorporates new emissions measurements and supply chain data for various fuels. The study encompasses an extensive lifecycle assessment (LCA) and cost analysis of LNG as a maritime fuel, comparing it to traditional marine fuels such as HFO and MDO, as well as alternative fuels like methanol, and renewable options, namely ammonia and hydrogen. Among the four LNG engines examined, the high-pressure dual fuel 2-stroke (HPDF) engine demonstrated the most promising outcomes, exhibiting the "lowest climate impacts, costs, and air quality impacts," while acknowledging slightly higher nitrogen oxide (NOx) emissions. This engine achieved GHG emissions reductions of up to 28% compared to HFO on a GWP100 basis”. The author had also stated that, for LNG to provide a climate benefit across all time scales over liquid fuels, its engine’s methane slip must be shortened to 0.8-1.6% w/w.

Although LNG has been tremendously popular as an alternative maritime fuel to reduce GHG emissions, some authors have proved the exact opposite. Pavlenko et al. (2020) carried on a working paper for the *International Council of Clean Transportation*, from 2020 to 2022, where they addressed the climate implications of using LNG as a marine fuel. This paper studied the lifecycle GHG emissions of currently used shipping fuels - MGO, VLSFO and HFO - comparing them with the emissions from LNG. The analysis includes upstream emissions, combustion emissions and methane slip, evaluated in GWP20 and GWP100 basis. Results show that over a 100-year period, LNG could provide a 15% reduction in the lifecycle GHG benefits, in contrast with MGO, but only if an HPDF engine were to be used and if methane emissions were thoroughly controlled. The authors have boldly stated that “using LNG does not deliver the emissions reductions required by the IMO’s initial GHG strategy, and using it could actually worsen shipping’s climate impacts”.

2.2.1.1. LNG production

LNG production entails cooling and depressurizing natural gas (NG) by applying different cryogenic processes with the goal to transform it into a liquid state for simpler and less hazardous transportation and storage. The natural gas must be cooled to nearly -162°C and depressurized to atmospheric conditions to be suitable for liquefaction. The cooling process can be performed using a variety of methods, such as refrigeration cycles, expansion turbines, or a combination of both. Once liquefied, natural gas can be transported in cryogenic tanks to various sites to be used as LNG fuel (Kumar et al., 2011).

He et al. (2018) conducted a comprehensive review pertaining to onshore and offshore NG liquefaction processes. The authors specifically focused on three prominent liquefaction methods: the cascade process, the mixed refrigerant liquefaction process, and the expander-based process. The cascade process is recognized for its high thermal efficiency and low energy consumption, primarily utilized in onshore applications. On the other hand, the mixed refrigerant liquefaction process is employed in both onshore and offshore settings. Lastly, the expander-based process, known for its versatility, can be implemented for liquefaction purposes both onshore and offshore.

In the review published by Zhang et al. (2020), the LNG processes are divided into three alternative categories: onshore large-scale, onshore small-scale, and offshore. The authors provide a technical and economic analysis of the different processes used in each category, based on data retrieved from industrial practices. It was found that the mixed-refrigerant process still dominates the LNG industry.

2.2.1.2. LNG storage and distribution

The study conducted by Kumar et al. (2011) focuses on the storage and transport of liquefied natural gas (LNG). The research discusses various LNG storage facilities, which are classified based on their intended function of meeting winter gas shortages or providing base load gas via long-distance transportation. The study underlines the importance of tank insulation to decrease losses from evaporation and ensuring that the LNG cargo is kept separate from the ship construction, since the use of mild steel in ship structures can pose risks due to the material's brittleness below 223K. The research highlights that with sufficient insulation, evaporation losses for LNG tank contents can be as low as 0.1% per day. For ocean-going vessels, the inclusion of reliquefaction facilities is common to manage boil-off gas, which typically amounts to approximately 0.3%.

2.2.1.3. LNG powered ships

For over four decades, liquefied natural gas has been employed as a propulsion fuel in LNG carriers, using the boil-off gas generated within the LNG tank for propulsion in traditional boiler/steam turbine systems and, later on, using it in dual-fuel engines with diesel serving as the pilot fuel for combustion (Burel et al., 2013).

According to the journal Marine Insight, the initial implementation of LNG as a maritime fuel in a general cargo ship took place in 2012 with the introduction of MS Høydal, a Norwegian fish feed carrier (MI News Network, 2012) - Figure 4. Manufacturers have reported significant environmental benefits associated with this vessel, including a noteworthy 90% reduction in nitrogen oxide (NO_x) emissions and a 25% reduction in carbon emissions compared to conventional diesel engines (Offshore Energy, 2012).

Figure 4 - MS Høydal, retrieved from (MI News Network, 2012)

As stated in DNV GL's *Alternative Fuels Insight* report, the year 2022 witnessed the operation of 354 LNG-powered ships along with 142 infrastructure points (DNV GL, 2022). This data proves the significant recognition and rapid expansion of LNG as a maritime fuel, which is visually depicted in

Figure 5.

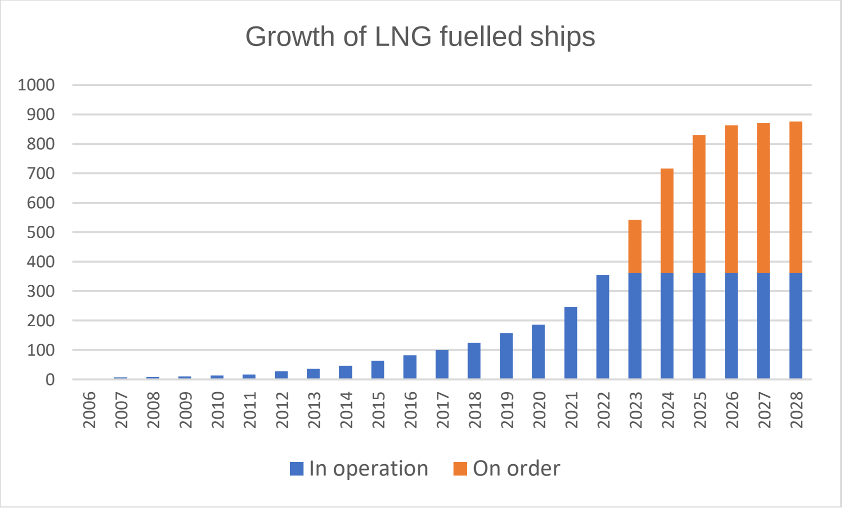

Figure 5 - Yearly evolution of LNG fuelled ships in operation and on order, adapted from (DNV GL, 2022)

2.2.2. Methanol

Methanol (CH_3OH), also referred to as methyl alcohol, plays a crucial role in contemporary society, being an essential chemical compound with a deep-routed supply chain and infrastructure. Its multifaceted applications encompass a wide array of everyday commodities, including plastics, construction materials, automotive paints and, more recently, as a fuel for ICE and fuel cell systems (F. Wang et al., 2023).

Over the past decade, methanol has garnered considerable interest as a prospective maritime fuel, primarily due to its ability to generate lower GHG emissions when compared to conventional fuels and because of its solubility in water (Verhelst et al., 2019). In fact, the attention surrounding methanol as a marine fuel has significantly intensified since 2021, specifically in response to the IMO's interim guidelines (MSC.1/Circ. 1621) regarding the use of methyl or ethyl alcohol as fuel for ships (DNV GL, 2023).

According to Gray et al. (2021), methanol has the potential to become a carbon-neutral fuel in the future if produced sustainably through biomass, biogas, or renewable electricity. In comparison to conventional fuels, renewable methanol has been demonstrated to achieve substantial reductions in CO_2 emissions of up to 95%, NO_x emission's reduction by up to 80%, and complete elimination of sulphur oxide and particulate matter emissions (Methanol Institute, 2023; Y. Wang et al., 2022).

On the other hand, methanol is not without its drawbacks. It possesses toxic properties and can cause corrosion to specific materials. Ingestion or inhalation of methanol can result in severe consequences such as blindness, asphyxiation, coma, or even fatality. Additionally, methanol is highly flammable and produces a nearly invisible flame (Verhelst et al., 2019), posing a significant risk as it can be difficult for onboard crew members to early detect it (Oloruntobi et al., 2023; Svanberg et al., 2018). However, research and studies have demonstrated that methanol does not pose a significant risk to marine life, thereby indicating a minimal environmental hazard in the event of fuel spills into the ocean (Van Hoecke et al., 2021).

2.2.2.1. *Methanol production*

Due to methanol's wide usage in diverse sectors, methanol synthesis is a mature and developed technology. In an industrial scale, methanol is mainly produced from natural gas reforming. Because of the process's high exothermicity, the operation of the methanol synthesis reactor system occurs at a pressure of 70 bar and a temperature of 250°C. In commercial methanol production processes, the heat generated during the reaction is frequently harnessed for electricity generation (F. Wang et al., 2023).

In recent years, there has been a growing interest in the technical pathway of CO_2 hydrogenation to methanol driven by the increasing focus in achieving carbon neutrality. The conversion of carbon dioxide into high-value fuels and chemicals represents a valuable process of transforming waste into valuable resources. The synthesis of methanol from CO_2 offers the dual benefits of mitigating the greenhouse effect associated with CO_2 emissions and enabling the production of a diverse range of chemical products and clean fuels (Tian et al., 2022). According to S. Marlin et al. (2018), methanol's production from CO_2 has already achieved a high technology readiness level (TRL). When methanol is produced from fossil sources using carbon capture and storage (CCS) it is entitled blue methanol.

E-methanol, a form of green CH_3OH, is derived through the integration of captured CO_2 and hydrogen produced by using renewable electricity to electrolyze water. The sources of CO_2 can originate from industrial carbon capture processes, encompassing bioenergy with carbon capture and storage (BECCS)[3] and direct air capture (DAC)[4] (Lloyd's Register, 2023).

2.2.2.2. *Methanol storage and distribution*

Methanol, being one of the extensively traded chemicals globally, benefits from a robust and already established infrastructure, ensuring its widespread availability across major international ports. On top of that, there is existing literature evidence suggesting that LNG infrastructure and gas tanks can be readily and rapidly adapted for the handling of CH_3OH (Bilgili, 2023; Svanberg et al., 2018; Verhelst et al., 2019).

The fact that methanol is a liquid in ambient conditions makes its handling, transportation and distribution simpler (Nemmour et al., 2023). Additionally, according to the research conducted by Van Hoecke et al. (2021), methanol's storage onboard a vessel presents a compelling advantage compared to other fuel types. Given its low toxicity to marine life, methanol can be safely stored within the double hulls of ships. This unique characteristic eliminates environmental risks associated with potential spills into the ocean, thereby enabling the utilization of available space within the hulls for storage purposes.

2.2.2.3. *Methanol powered ships*

According to DNV's Alternative Fuels Insight platform, as of March 2023, there were 25 methanol-fuelled ships in operation (DNV GL, 2022).

The Stena Germanica, a ro-pax ferry with a capacity for 1300 passengers and 300 vehicles, was the

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[3] Technology where CO_2 from a biogenic source, released during energy generation from biomass, is captured and stored (Gough & Upham, 2010).

[4] Technology that captures and storages CO_2 directly from air (McQueen et al., 2021).

world's first green methanol powered ferry, encompassing a retrofitted power system capable of running on both methanol and diesel (Stena Line, 2021) - Figure 6. Another pioneering example of methanol usage as a fuel is the Waterfront Shipping's 50.000 deadweight tonnage methanol tankers, with a two stroke dual-fuel engine by MAN Energy Solutions (Waterfront, 2019).

Figure 6 - Stena Germanica, retrieved from (Wärtsilä, 2021)

The deployment of 500 kW methanol fuel cells on the AIDAnova cruise ship from AIDA Cruises in 2021 marked a significant milestone in the advancement of methanol-based propulsion technology - Figure 7. This ship became the first passenger vessel to successfully test the use of methanol FCs, reaching 35.000 operating hours (Mandra, 2020).

Figure 7 - AIDAnova cruise ship, retrieved from (Vessel Finder, 2023)

2.2.3. Ammonia

Like methanol, ammonia (NH_3) is one of the most produced and shipped chemical product worldwide. NH_3 saved the world once as a fertilizer for food; it might do it again for energy (F. Wang et al., 2023). Ammonia was initially conceived to support fertilizer requirements; therefore, it has been strongly linked to the last century's population growth (Philadelphia & co. & R.D. Wood, 2012). Yet, interest in fuel applications of ammonia has gathered significant momentum in recent years. For instance, when searching for the word "ammonia" in past issues of the journal *Fuel* (ISSN 0016-2361) over the last dozen years (considering only studies that focus on ammonia as a fuel) results are of a clear trend of increased interest and a growing body of works (Science Direct, 2022).

However, considering ammonia as a fuel is not a new concept at all. There are records of ammonia-fuelled buses in the 19th century. For instance, during World War II, in 1943, a hybrid ammonia, coal and gas engine was developed in Brussels to overcome the shortage of oil, rather than to meet any environmental requirements (NewScientist, 2013).

Different from past scenarios, which were mainly based on the economic climate and available resources, the current period has seen a renewed interest in the use of ammonia due to the significance of developing low GHG emissions with safe, reliable, and economically viable fuelling solutions. Nevertheless, evolving computational techniques and much more advanced experimental systems are essential in assisting the decarbonization efforts that have been legally established by some countries and have also spurred the creation of new nitrogen-based technologies for global deployment in the near future.

Korberg et al. (2021), analysed some promising renewable fuels for the maritime industry, including biofuels, bio-electrofuels, electrofuels, namely ammonia and liquefied hydrogen, and electricity. This study aims to calculate the total cost of ownership (TCO) for each analysed fuel, studying production costs, propulsion costs, onboard fuel storage costs and the cost of reduced cargo space. It was found that, when cryogenic storage is a must, which is the case for liquefied hydrogen (LH_2), infrastructure costs have the larger share of the TCO (25-35% of the fuel cost). This report concludes that among the 18 fuel production pathways analysed, methanol, DME or ammonia have lower costs than other fuels in their respective fuels categories. However, this paper disregards future inflation in its calculations, which is a significant approximation since all the costs were estimated for the year 2030.

In a more recent study, Mallouppas et al. (2022), reviewed the latest trends in the use of green ammonia in the maritime industry, examining the key barriers to using NH_3 as a shipping fuel, being them: high production costs, low availability of bunkering locations, ramping up ammonia production and developing regulations on toxicity, safety and storage.

Even so, in 2020 a study comparing hydrogen and ammonia as future shipping fuels had already taken place with approximations for energy requirements from an LNG tanker (C J McKinlay et al., 2020). The project's goal was to focus on the engineering challenges involved in using these two fuels, comparing emissions, supply, refuelling, performance, safety and storage. It was concluded that volume requirements for hydrogen are not sufficiently high for it to be disregarded as an option for future fuel in the maritime sector. Nevertheless, it was suggested that ammonia has much more advantages over hydrogen showing less space needed for storage when using the same amount of energy.

There is also some literature addressing the decarbonization of not only the maritime sector but also the aviation and haulage industries (Gray et al., 2021). This paper reviews a range of low-carbon energy carriers, including ammonia, that could be used to help in the decarbonization of these three industries. For the shipping sector, in the long run, it was concluded that “zero-carbon energy carriers such as hydrogen or ammonia offer the most promising pathways to low-carbon shipping”.

2.2.3.1. NH_3 production

Ammonia (NH_3) can be produced by two methods: using the Haber-Bosch process or by direct electrochemical production. If the production of NH_3 is powered by renewable energy sources (RES), it is called green ammonia.

The Haber-Bosch process was the first industrial chemical process to use high pressures in a chemical reaction, and it is still the most popular ammonia production method (Encyclopaedia Britannica, 2022; MacFarlane et al., 2020). In this process, described in Equation 1, ammonia is produced from a reaction of hydrogen and atmospheric nitrogen under great pressures, between 100 to 250 bar, and temperatures between 350 and 550°C.

$$N_2 + 3H_2 \rightarrow 2NH_3 \qquad (1)$$

The hydrogen used for the ammonia production is traditionally obtained from natural gas, coal or oil from the steam reformation of methane or partial oxidation, such processes emit significant amounts of carbon dioxide (CO2) into the atmosphere (Giddey et al., 2017). Although this releases significant carbon emissions, the impact can be minimised if the hydrogen gas used in the process comes from water electrolysis, using RES to power it. The NH3 production from this method, referred to as green ammonia, contrasts with the conventional Haber-Bosch processes, which uses natural gas or coal as fuel, in the way that this process provides close to zero carbon emissions.

Green ammonia production has its challenges because, generally, the pressure of the hydrogen produced by water electrolysis is lower than desired, and the kinetics of the ammonia reaction are decreased at lower pressures (Ye et al., 2017).

The high cost of water electrolysis in comparison with the cost of natural gas or coal makes the traditional Haber-Bosch process more economically attractive than the greener adaptation of the process. However, the electrochemical synthesis appears as an alternative since it allows the direct reaction of nitrogen with water to form NH_3 at atmospheric pressure. The major challenge in this process is to reduce, at an industrial rate, the highly stable nitrogen molecule, N_2, in the presence of easier to reduce molecules such as water, H_2O (Ye et al., 2017).

Although this is a very promising process, its feasibility in industrial installations has not yet been achieved. Nevertheless, alternative models such as reverse fuel cells are being developed. These cells would preferably use electricity from renewables in order to diminish or even neutralize their carbon footprint. In these cells, the water reacts in the anode to make hydrogen ions release oxygen, and the H^+ protons migrate to the cathode reacting with N_2 to form ammonia. The anode and cathode reactions are described by Equations 2 and 3, respectively. This process, although effective, is still a very slow one (Service, 2018).

$$Anode: 3H_2 \rightarrow\ 6H^+ + 6e^- \qquad (2)$$

$$Cathode: N_2 +\ 6H^+ + 6e^- \rightarrow 2NH_3 \qquad (3)$$

A variety of fuel cells with different electrodes, electrolytes, and combinations of both are being developed and researched to improve the rate of this process. New processes using molten salts as electrolytes have shown to be quite successful, known as molten salts electrolyte batteries (MSB), operating at temperatures between 200°C and 500°C. These cells contain lithium nitride (Li_3N) dissolved in the molten salt mixture which provides the electrolyte with nitride ions (N^{3-}). So, the nitrogen supplied to the cathode is reduced to N^{3-} which travels through the electrolyte and reacts with hydrogen in the anode to produce ammonia, described by Equation 4.

$$N^{3-} + \frac{3}{2}H_2 \rightarrow NH_3 + 3e^- \qquad (4)$$

Ammonia formation in these cells was first studied by Murakami et al., 2003. The highest rate observed in this study was 3.33 × 10−9 mol s−1 cm−2 at 400°C and 0.7 V vs the Li+/Li electrode, achieving a

Faradaic Efficiency of 72%. This example is only one of many different attempts to improve ammonia's production using this kind of cells (Kyriakou et al., 2017).

2.2.3.2. NH_3 storage and distribution

Like propane or liquid petroleum gas (LPG), ammonia is gaseous at normal temperature – its boiling point is at -33°C and atmospheric pressure, but it is a liquid at higher pressures. It is typically transported in the liquid state and used as a gas; therefore, it needs to be compressed, cooled, or both. Large-scale ammonia storage is a topic that has suffered vast research and development over the last few decades since NH_3 is already one of the most transported substances in the world as a fertilizer (Hofstrand, 2009). A reliable storage system needs to be secured for all ammonia's ends, since NH_3 is considered toxic to all vertebrates, being able to cause convulsions, coma and even death when one is exposed to high quantities (Randall & Tsui, 2002).

Currently, there are three main methods widely used for ammonia storage: semi-refrigerated storage and pressure storage are used for small-scale ammonia storage, and low-temperature storage is used for large-scale storage. Whereas, a combination of the three methods can also be applied (Appl, 2011):

- Low-temperature storage: insulated atmospheric (0.11 - 0.12 MPa) cylindrical vertical storage tanks at 240 K (-33 ºC) utilising two-stage refrigeration compressors capacity of up to 50,000 tons);
- Pressure storage: pressurised (typically 1.6 - 1.8 MPa) spherical or cylindrical vessels at ambient temperature (capacity of up to 2000 tons);
- Semi-refrigerated storage: insulated reduced-pressure spherical vessels at 273 K (0 ºC) utilising single-stage refrigeration compressors (capacity of up to 2500 tons).

Pressure and semi-refrigerated storage are only economically viable for storing smaller quantities of ammonia used in downstream pressurised ammonia processes, hence their preferred utilization for small-scale storage. This is mainly due to the compression and insulation/material costs. The low-temperature storage has significantly lower capital investment costs when compared to the other methods. This process shows even more appeal in cases where ammonia is already cooled to a relatively low temperature, such as in ammonia synthesis plant outlets or loading and unloading of refrigerated vehicles (Elishav et al., 2021).

Cavern/underground storage is an alternative large-scale resort for ammonia storage. However, the lack of available geologic sites and the fact that contaminants are common in this kind of storage handicap the use of this approach (Hofstrand, 2009).

2.2.3.3. Ammonia powered ships

Seo & Han (2021) conducted an analysis on two distinct design scenarios for ammonia fuel storage in a target vessel, specifically an ammonia carrier. The first concept explored the utilization of ammonia from the cargo tank as fuel, resulting in some cargo loss but incurring no additional costs. The second concept involved the installation of an additional fuel tank on the vessel, avoiding cargo loss but incurring supplementary costs – see Figure 8. The hypothetical ammonia carrier employed a 2-stroke dual fuel engine developed by MAN Energy Solutions. The study evaluated the costs and profits associated with each scenario by considering life-cycle costs (LCC), encompassing design, construction, operation, maintenance, and disposal expenses. The findings indicated that installing an additional fuel tank on the ship would yield higher profitability compared to utilizing the cargo ammonia as fuel. However, it should be noted that the results are not entirely straightforward, as the additional weight of the supplementary fuel tank in the second scenario was not accounted for. The increased weight could potentially have a detrimental effect on the ship's performance, necessitating higher fuel consumption.

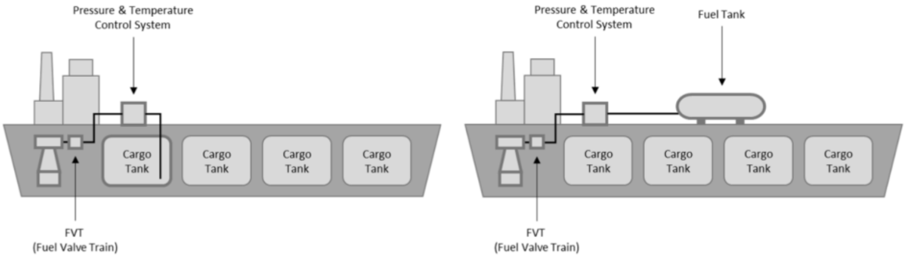

Figure 8 - Concepts proposed by (Seo & Han, 2021) for ammonia storage onboard

Despite the numerous studies addressing the potential of ammonia as a maritime fuel, there are still no ships capable of sailing on ammonia as of today. An organization under the Nordic Council of Ministers – Nordic Innovation - has started a project in 2021 for developing the first ammonia powered gas carrier, entitled the NoGAPS project (Fahnestock et al., 2021) – Figure 9. The project is now under its second phase, where the focus lays on producing an initial ship design for the gas carrier named M/S NoGAPS, with a cargo capacity of 22 000 m^3 (*Nordic Green Ammonia Powered Ships (NoGAPS)*, 2023).

Figure 9 - Initial ship design from the NoGAPS project, retrieved from (Habibic, 2023)

Nevertheless, according to CEO Jan Fredrik Meling from *Eidesvik Offshore*, the vessel known as Viking Energy is scheduled to undergo retrofitting in order to become the world's first ship powered by green ammonia, with its inaugural voyage planned for 2024. The retrofit will incorporate a 2 MW ammonia fuel cell system (zpiritas, 2020) - Figure 10.

Figure 10 - Viking Energy, retrieved from (Wärtsilä, 2023)

2.2.4. Hydrogen

Regarding green hydrogen as an alternative maritime fuel, Atilhan et al. (2021) conducted a study that evaluates hydrogen's production routes, its techno-economic performance and other important features, like storage and safety. These features are compared to the ones in existing 'grey' and 'blue' production routes linked to the shipping industry. This study reached the conclusion that nowadays, green hydrogen production costs are 3-4 times higher than the ones regarding grey hydrogen, meaning that this production process is still yet to be developed in terms of costs associated with renewable energy production. Some key challenges on the LH_2 global supply chain are also pointed out in this project: establishing globally accepted liquefied hydrogen regulations and standards; defining a clear path to provide safe operation guidelines of "loading-transit-offloading routines"; and issues regarding on-board storage and bunkering.

A review conducted by faculty members of the University of Antwerp, in Belgium, highlights the principal challenges existing with H_2 as a shipping fuel and hydrogen carriers (Van Hoecke et al., 2021), focusing on different storage methods. Using electrolysis for hydrogen production was highly defended in this paper since it is a process with zero carbon emissions during its entire lifecycle. It was also concluded that there is no preferred hydrogen storage method since none of the analysed ones could combine "high energy density, a low energy input, has all resources readily available, is non-toxic and easy to handle and store".

A more practical case study, conducted in 2021 by Ortiz-Imedio et al., developed an optimized model that forecasts the energy supply in the European Atlantic coast in 2050, "which envisions a cost-optimal infrastructure with 100% renewable energy across all of Europe, employing hydrogen as an energy vector". Results indicate that Ireland will play a crucial role as a hydrogen supplier, with key routes being by pipelines through the United Kingdom and France to export H_2 to central Europe.

2.2.4.1. H_2 production

Hydrogen's production methods are classified by colours: black/brown, grey and blue H_2 refer to production processes from fossil fuels (coal gasification, methane reforming using natural gas, and adding CCS, respectively); green H_2 refers to the production process from renewable electricity (water electrolysis). Since methanol and ammonia are hydrogen energy carriers, depending on the method and feedstock used, their production processes can also be classified within these colours.

The present thesis will focus on green hydrogen production, with electrolyse powered by renewables, which has a zero-carbon footprint throughout its lifecycle since this dissertation's overarching goal is to find ways to decarbonize the shipping sector.

By simplification, electrolysis (Equation 5) is the process of decomposing a compound down, in this case water (H_2O), when an electric current passes through it (Kreuter & Hofmann, 1998).

$$2\,H_2O\ (l) \rightarrow\ 2\,H_2\ (g) + O_2\ (g) \tag{5}$$

Currently, four electrolysis technologies are considered mature or in development, being the most used ones the alkaline (AEL) and PEM, which can both take part in producing hydrogen using renewables to create electricity:

- Alkaline Electrolysis (AEL)
- Proton Exchange Membrane (PEM)
- Solid Oxide Electrolysis (SOE)
- Anion Exchange Membrane (AEM)

Regarding AEL, the alkaline electrolyser decomposes water at the cathode to H_2 and OH- (Equation 6). The latter migrates through the electrolyte and a separating membrane, discharging at the anode and releasing O_2 (Rashid et al., 2015). This method is the most elementary one to produce hydrogen and it is widely used, however, it requires very high energy consumption, installation costs and operation and maintenance costs (Manabe et al., 2013).

$$2\,H_2O\ (l) + 2\,e^- \rightarrow\ H_2(g) + 2\,OH^-(aq.) \tag{6}$$

The PEM technology has seen great development in recent years, mainly because it has a great ability to be ramped down and ramped up (DNV, 2022b). When an acidic solid polymer is used as the electrolyte in place of a liquid electrolyte, it is called a polymer electrolyte membrane (PEM) electrolysis or proton exchange membrane electrolysis. PEM has some advantages over alkaline water electrolysis, like "ecological cleanness, small size and mass, high purity of hydrogen gas, low gas crossover, lower power consumption, high proton conductivity, control over electrical power variations, high-pressure operation, higher safety level, easy handling and maintenance" (Grigoriev et al., 2006; Manabe et al., 2013).

Comparing both methods, AEL is the most mature technology, and it has achieved a suitable production amount for the current hydrogen global supply needs (1000 m^3/h) with low manufacturing costs, while PEM production is in the range of 400 m^3/h with significant manufacturing costs. However, PEM brings some advantages to the table, including a much faster start-up and no corrosion with a simpler configuration and thus, easier and cheaper maintenance (Guo et al., 2019).

In the Hydrogen Forecast to 2050 (DNV, 2022a), DNV GL, one of the greatest maritime and energy companies in the world, states that the future will be composed of a perfect mix, meaning that there will most likely be a place for each of the H_2 production technologies presented above.

2.2.4.2. H_2 storage and distribution

One of the main challenges in including hydrogen as a contending future maritime fuel is its storage procedures. The most utilized methods for storing H_2 are as pressurized gas and liquefied Hydrogen (LH_2).

Whereas hydrogen is gaseous at ambient temperatures and at 1 bar, it has a very modest volumetric density of 0.09 kg/m^3, meaning it would require an enormous tank to store significant amounts in these conditions, hence the need for a storage method of high-pressured hydrogen (up to 700 bar) that can reach densities of 42 kg/m^3. The casing of such tank would need to be made of steel (C J McKinlay et al., 2020), which has a density of 7850 kg/m^3 («Engineering ToolBox», 2004). Such a heavy material would not be suitable for onboard storage since the extra weight would depreciate the vessel's performance.

Transforming hydrogen into a liquid would massively increase its volumetric density to 71 kg/m^3 (DEMACO, 2022), but for this to happen, it would require cryogenic temperatures (-252.9°C). To reach such low temperatures a colossal amount of energy is needed. Also, studies suggest that capital costs can increase up to 4-5 times when compared to pressurized storage (Mazloomi & Gomes, 2012).

There is also a third (less utilized) method for storing and transporting hydrogen in development: metal hydrides. It consists in storing large amounts of H_2 into metals using chemical bonding (Jain, 2009) and it has been proven to be the most feasible solution in terms of volume and safety compared to the previously stated methods (Rusman & Dahari, 2016). Besides this, as stated before, ammonia has a higher volumetric energy density than liquid hydrogen, making it a great alternative as a hydrogen carrier.

Hydrogen transportation can be executed by ships, trucks, rail, or transmission pipelines. Nowadays, there are 3 million km of natural gas pipelines worldwide and only around 5,000 km of hydrogen ones. With the increase in H_2 demand, whether as a fuel or for its derivatives production, and the global tendency in trying to discard fossil fuels, it should only make sense to start transforming/ redesigning some already in place natural gas pipelines into hydrogen ones (DNV, 2022a).

2.2.4.3. Hydrogen powered ships

In January 2021, the HyShip project, a collaborative endeavour involving 14 European partners, was initiated. Its primary objective is to design and develop a roll-on/roll-off (ro-ro) demonstration vessel propelled by green liquid hydrogen (LH_2), featuring a hybrid configuration comprising a 1000 kWh battery capacity and a 3 MW PEMFC (HyShip, 2022). The anticipated timeline envisions the vessel embarking on its maiden voyage in the end of 2023.

MAN Engines has successfully developed and implemented the industry's pioneering marine dual-fuel hydrogen engines, marking a significant advancement in the field. This achievement involved retrofitting a V12 marine diesel engine with a power output of 749 kW, requiring a minimal 5% injection of diesel as pilot fuel to initiate the combustion process (MAN Engines, 2022). Commencing its operation in May

2022, this engine is currently deployed in a crew transfer vessel, resulting in an impressive 80% reduction in CO_2 emissions. CTV Hydrocat 48 was the first vessel to be powered by the MAN's hydrogen dual fuel V12 engine - Figure 11.

Figure 11 - CTV Hydrocat 48, retrieved from (Blenkey, 2022)

In late 2022, the Norwegian company Norled successfully carried out the world's first voyage utilizing zero-emission liquid hydrogen aboard their ferry, the MF Hydra (Mandra, 2022b) - Figure 12. This large ferry, capable of accommodating 300 passengers and 80 cars, operates on a hybrid-electric system, employing two 200 kW PEMFC supplied by Ballard – the FCWave™ modules. Norled has stated that the Hydra ferry is expected to diminish its annual carbon footprint by 95%.

Figure 12 - MF Hydra, retrieved from (FuelCellsWorks, 2021)

2.3. MCDA on alternative maritime energy vectors

Multi-criteria decision analysis (MCDA) is a methodical approach aimed at selecting the most favourable solution from a set of pre-defined alternatives, tailored to address intricate real-life decision-making problems, and has been widely used for the evaluation of alternative maritime energy vectors. Such problems often encompass diverse and interconnected criteria, necessitating simultaneous consideration to capture the inherent complexities. The primary objective of MCDA is to identify the optimal solution from the perspective of the decision maker (DM), taking into account their preferences and priorities, across the multiple criteria involved in the decision-making process (Jahan et al., 2016; Jahan & Edwards, 2013).

Ren & Lützen (2017) proposed a new MCDA approach that integrates the Dempster-Shafer theory with a trapezoidal fuzzy Analytic Hierarchy Process (AHP). Their method was specifically employed to address the challenge of selecting sustainable energy sources in the presence of incomplete information for seaborne shipping. The study focuses on four dimensions of criteria to evaluate the options' sustainability, namely technological, economic, environmental, and social-political aspects. Results show that nuclear power is the most suitable choice in the viewpoint of the decision maker profile considered, followed by LNG and wind power. Despite the comprehensive criteria selection, the research's application of the proposed model is limited to only three alternative energy vectors: LNG, nuclear power, and wind power. This limited scope fails to represent the full spectrum of alternatives that stakeholders must consider nowadays when addressing the decarbonization of the maritime industry. A more diverse range of energy sources is essential to provide a comprehensive analysis that accurately reflects the complexities and challenges of sustainable energy transition in the maritime sector.

In a research conducted by Hansson et al. (2019), a MCDA model was proposed based on the AHP, to find the alternative maritime fuel that is best ranked among the others, in the perspectives of 5 stakeholder groups: Swedish governmental authorities, ship owners, fuel manufacturers, engine manufacturers, and the combined group, which give different importance and, therefore, different weightage, to the several analysed criteria. The study evaluates 7 different fuels, including fossil fuels, biofuels, and renewably sourced ones. As a result, for the combined group and for ship owners and fuel/engine producers, LNG and HFO are ranked in the top two. For authorities, renewable hydrogen takes the win, followed by renewable methanol. This research offers a comprehensive analysis that incorporates real stakeholders' viewpoints, providing valuable insights into the weightage of criteria and pair-wise comparisons in performance. By considering the perspectives of relevant stakeholders, the study enhances the validity and importance of its findings, contributing to a more robust understanding of the factors influencing decision-making processes. The incorporation of diverse viewpoints ensures that the research accounts for various interests and concerns, ultimately leading to more informed and well-balanced conclusions.

Aspen & Sparrevik (2020) assessed the inclusion of uncertainty in the selection of alternative maritime fuels by developing a stochastic MCDA based model, that combines the "Technique for Ordering of Preference by Similarity to Ideal Solution" (TOPSIS) with the "Stochastic Multicriteria Acceptability Analysis" (SMAA) technique, obtaining a TOPSIS-SMAA model that is applied to a Norwegian pax-ferry. The authors also add a deterministic approach by evaluating more three types of DMs, instead of just including the stochastic view: the first gives priority to economic criteria, the second gives priority to environmental criteria, and the last one gives priority to social criteria, namely public acceptance. The study demonstrates that all-electric propulsion emerges as the preferred option, while plug-in hybrid solutions incorporating LNG also exhibit sturdy performance.

Law et al. (2021) developed a comprehensive MCDA based comparison of 22 alternative fuel's pathways that includes HFO as a baseline, blue fuels produced from natural gas and green fuels sourced from biomass and renewables (wind and solar power), to score each fuel against each other. The study offers a comprehensive exploration of various fuel alternatives, encompassing both ICEs and FCs. However, it falls short in considering diverse decision makers' perspectives, as it assumes a single scenario of criteria weightage. Consequently, the best-performing option under these conditions is the combination of LNG with an ICE and Carbon Capture and Storage (CCS) technology.

To sum up, the reviewed studies underscore the significance of MCDA based models in evaluating alternative maritime energy vectors and addressing the complexities of sustainable energy transition in the maritime sector. While each study employs distinct MCDA approaches and perspectives, key observations highlight a literature gap in the evaluation of marine alternative fuels combined with different power systems, employed to distinct vessels. The present study addresses this gap by incorporating multiple techno-economic criteria dimensions, evaluating different stakeholder’s profiles, exploring various fuel and power system alternative combinations, and applying the data to different case study vessels with contrasting purposes and operating profiles.

3. Methodology

The research methodology is detailed in this chapter, describing the case study and explaining the design of the MCDA based model used to evaluate energy vector and power system combinations for different vessels. The chapter presents data collection, the selection and definition of criteria, the performance values of each option across every criterion, the normalization process, and the assignment of weights in the viewpoint of different profiles of decision makers.

Figure 13 provides an overview of the research methodology employed in this research. The study starts with the choice and delineation of alternative fuel/ energy vector pathways, followed by the acquisition of data to establish a comprehensive database for quantitative and qualitative maritime energy vectors assessment. Subsequently, a rigorous assessment and comparative analysis of the chosen alternative combinations were employed to different vessels, to demonstrate the practical utility of the findings. Finally, after defining research scenarios, a MCDA based model was applied to each vessel to obtain the final scoring of every combination of energy vector and power system, from different perspectives.

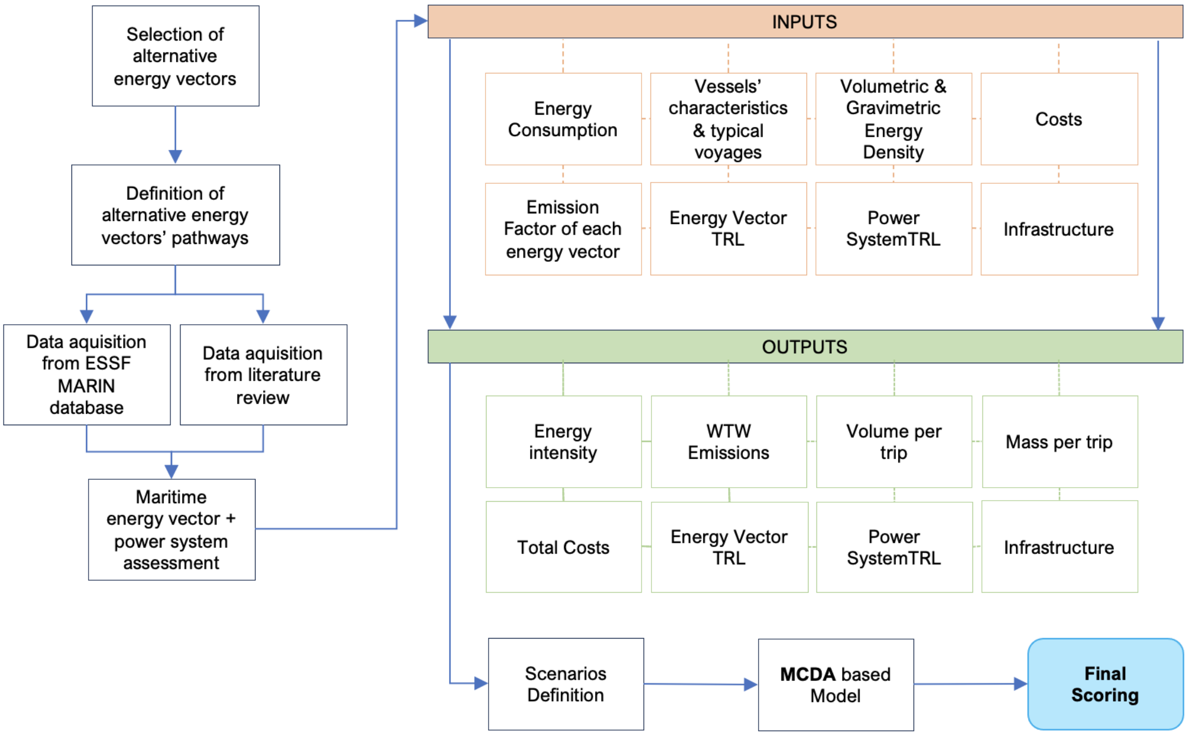

Figure 13 - Research process flow diagram

3.1. Case study description

The present work builds a Multi-Criteria Decision Analysis (MCDA) based model to guide the maritime industry's key stakeholders, being investors, ship manufacturers, environmentalists, or even academics, on what alternative energy vector and power system combination is more adequate for the future of the maritime transport sector, in order to help decarbonize it. To achieve this, the present study focuses on five particularly different vessels with contrasting purposes and diverse regular voyages, namely a container ship, a general cargo ship, a roll-on/roll-off passenger ship (ro-pax), a passenger (pax) ferry and a fishing trawler.

Each vessel's typical voyage will be studied with different combinations of alternative energy vectors and power systems. This analysis approaches one default fuel (HFO) for comparison purposes and nine different alternative energy vectors: f-LNG, e-LNG, e-diesel, f-methanol, e-methanol, f-ammonia (NH3), e-ammonia (NH3), e-LH2 (liquefied hydrogen) and the European Union electricity mix (EU-mix).

For the scope of this research, the energy vectors with the prefix 'f-' are defined as the ones that come from fossil origins; the energy vectors with the prefix 'e-' are defined as the ones produced with electric renewable energy sources.

The power systems to be analysed for this study are internal combustion engines (ICE), low-temperature proton-exchange membrane fuel cells (PEMFC), solid-oxide fuel cells (SOFC), and lithium-ion batteries.

Some power systems are not compatible with every fuel and vice-versa and so, the complete list of possible combinations is the following: HFO+ICE, f-LNG+ICE, e-LNG+ICE, e-diesel+ICE, f-methanol+ICE, e-methanol+ICE, e-methanol+PEMFC, f-NH3+ICE, f-NH3+PEMFC, f-NH3+SOFC, e-NH3+ICE, e-NH3+PEMFC, e-NH3+SOFC, e-LH2+ICE, e-LH2+PEMFC, and EU-mix+batteries – described in detail in Table 4.

The objective is not limited to analysing a typical voyage for each vessel but also to study the techno-economic performance of each combination of energy vector and power system over the entire ship's operational lifespan since its commissioning. Therefore, when considering OPEX costs per combination, including energy vector costs or potential scenarios with and without carbon taxation measures, a three-decade timeframe was selected to scrutinize these expenses, considering it as the assumed lifetime for every selected vessel (30 years).

Table 4 - Energy vector and power system combinations description, adapted from (MARIN, 2022)

Combination	Energy vector	Pre-treatment	Energy Conversion	After treatment	Power distribution
HFO+ICE	HFO, 3.5% sulphur	HFO heating (up to 60º)	ICE CI[5]	Scrubber[6], SCR[7], soot filter[8]	ICE direct propulsion
f-LNG+ICE	LNG fossil	Evaporation	ICE SI[9]	-	ICE direct propulsion
e-LNG+ICE	e-LNG: H_2 from RES + flue gas CO2	Evaporation	ICE SI	-	ICE direct propulsion
e-diesel+ICE	Synthetic diesel (EN15940): H_2 from RES + flue gas CO2	-	ICE CI	SCR, soot filter	ICE direct propulsion
f-methanol+ICE	CH_3OH fossil (from NG)	DF treatment	DF ICE	-	ICE direct propulsion
e-methanol+ICE	e-CH3OH (95%) + diesel (5%): H_2 from RES, DAC[10] CO_2	DF treatment	DF ICE	-	ICE direct propulsion
e-methanol+PEMFC	e-CH_3OH: H_2 from RES, DAC CO_2	Reformer CH_3OH	LT PEMFC	-	FC electric propulsion
f-NH3+ICE	NH_3 fossil (95%) + diesel (5%): from NG	Evaporation, DF treatment	DF ICE	SCR, soot filter	ICE direct propulsion
f-NH3+PEMFC	NH_3 fossil (from NG)	NH_3 cracker	LT PEMFC	-	FC electric propulsion
f-NH3+SOFC	NH_3 fossil (from NG)	-	SOFC	-	FC electric propulsion
e-NH3+ICE	e-NH_3 (95%) + diesel (5%): H_2 from RES, N_2 capture	Evaporation, DF treatment	DF ICE	SCR, soot filter	ICE direct propulsion
e-NH3+PEMFC	e-NH_3: H_2 from RES	NH_3 cracker	LT PEMFC	-	FC electric propulsion
e-NH3+SOFC	e-NH_3: H_2 from RES	-	SOFC	-	FC electric propulsion
e-LH2+ICE	e-LH_2 (96%) + diesel (4%): H_2 from RES	Evaporation, DF treatment	DF ICE	SCR, soot filter	ICE direct propulsion
e-LH2+PEMFC	e-LH_2: H_2 from RES	Evaporation	LT PEMFC	-	FC electric propulsion
EU-mix+batteries	EU mix electricity stored in a Li-ion battery	-	-	-	Battery electric propulsion

3.1.1. Selected vessels' characteristics

Container ships play one of the most crucial roles in product globalization, "enabling consumer goods and products to be manufactured in developing, lower-cost countries for export to higher-cost countries" («International Chamber of Shipping», 2023). The container ship examined in this study is known as the Emma Maersk, which held the title of the largest container ship ever constructed at the time of its inaugural voyage in 2006. With a capacity of 11 000 TEU (1 TEU representing one 20-foot container), the typical voyage considered starts from Tanjung Pelepas port in Malaysia and ends at Port Said in Egypt. The total duration of this voyage is 256 hours, covering a distance of 5 005 nautical miles. The specifications of the chosen container ship and its route information are presented in Table 5, sourced from (Minnehan & Pratt, 2017).

The *Spiegelgracht* is a **general cargo ship** registered in the Netherlands that is capable of transporting both containers and bulk cargo. For the purpose of the present study, this ship's typical voyage begins at Zeebrugge port in Belgium and concludes at Philadelphia in Pennsylvania, U.S.A. The total duration of this voyage is 271 hours, covering a distance of 3 431 nautical miles. Detailed specifications of the

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[5] Internal combustion engine compression ignited.

[6] Scrubber to reduce SO_x emissions.

[7] Selective catalytic reduction to reduce NO_x emissions.

[8] To filter small particles.

[9] Internal combustion engine spark ignited.

[10] Direct air capture of CO_2

chosen general cargo ship and the specific route are provided in Table 6 (Minnehan & Pratt, 2017).

Table 5 - Emma Maersk's specifications (a) and route information (b)

a)

Container ship Specifications	
Name	*Emma Maersk*
Type	Container Ship
Overall Length (m)	397
Beam (m)	56
Main Engine Power (MW)	80.08
Fuel Capacity (m^3)	15 000
Maximum Speed (knots)	25.5
Available Volume (m^3)	18 615
Available Mass (MT)	15 082
Gross Tonnage	171 542

b)

Route information	
Departure Port	Tanjung Pelepas
Arrival Port	Port Said
Distance (nm)	5005
Total voyage time (h)	256
Average Speed (knots)	19.6
Average Shaft Power (MW)	36.1
Energy needed per trip (MWh)	9240

Table 6 - Spiegelgracht's specifications (a) and route information (b)

a)

General Cargo ship Specifications	
Name	*Spiegelgracht*
Type	General Cargo
Overall Length (m)	168
Beam (m)	25
Main Engine Power (MW)	12.1
Fuel Capacity (m^3)	1 880
Maximum Speed (knots)	19.6
Available Volume (m^3)	2 350
Available Mass (MT)	1 837
Gross Tonnage	16 641

b)

Route information	
Departure Port	Zeebrugge
Arrival Port	Philadelphia
Distance (nm)	3431
Total voyage time (h)	271
Average Speed (knots)	12.7
Average Shaft Power (MW)	3.25
Energy needed per trip (MWh)	881

The *Pride of Hull*, a large **ro-pax ship**, was selected for analysis. This vessel has the capacity to accommodate 1 360 passengers and transport 1 380 vehicles. The ship's typical voyage under consideration commences at Hull port in England and concludes at Rotterdam port in the Netherlands. The total duration of this voyage is approximately 11.9 hours, covering a distance of 211 nautical miles. Table 7 provides detailed specifications of the chosen RO-PAX ship along with pertinent route information, sourced from (Minnehan & Pratt, 2017).

Zalophus, a **pax-ferry**, belongs to a smaller category of vessels when compared to the previously mentioned ships (Minnehan & Pratt, 2017). The analysed route for Zalophus is a one-hour bay tour cruise that begins and ends at the Port of San Francisco, U.S.A – see Table 8. This particular route allows for a shorter duration trip compared to the previous voyages, catering to a different type of passenger experience and geographical context.

Table 7 - Pride of Hull's specifications (a) and route information (b)

a)

Ro-pax ship Specifications	
Name	*Pride of Hull*
Type	Ro-pax
Overall Length (m)	215
Beam (m)	32
Main Engine Power (MW)	37.8
Fuel Capacity (m^3)	1 000
Maximum Speed (knots)	22
Available Volume (m^3)	2 660
Available Mass (MT)	1 451
Gross Tonnage	59 925

b)

Route information	
Departure Port	Hull
Arrival Port	Rotterdam
Distance (nm)	211
Total voyage time (h)	11.9
Average Speed (knots)	17.8
Average Shaft Power (MW)	20
Energy needed per trip (MWh)	237

Table 8 - Zalophus' specifications (a) and route information (b)

a)

Passenger ferry Specifications	
Name	*Zalophus*
Type	Passenger
Overall Length (m)	47
Beam (m)	10
Main Engine Power (MW)	0.8
Fuel Capacity (m^3)	30
Maximum Speed (knots)	13
Available Volume (m^3)	40
Available Mass (MT)	28
Gross Tonnage	500

b)

Route information	
Departure Port	San Francisco
Arrival Port	San Francisco
Distance (nm)	11
Total voyage time (h)	1
Average Speed (knots)	11
Average Shaft Power (MW)	0.485
Energy needed per trip (MWh)	0.485

Table 9 - Northwestern's specifications (a) and route information (b)

a)

Fishing Trawler Specifications	
Name	*Northwestern*
Type	Fishing Trawler
Overall Length (m)	38
Beam (m)	8.8
Main Engine Power (MW)	0.95
Fuel Capacity (m^3)	174
Maximum Speed (knots)	12
Available Volume (m^3)	191
Available Mass (MT)	150
Gross Tonnage	310

b)

Route information	
Departure Port	Seattle
Arrival Port	Dutch Harbor
Distance (nm)	1707
Total voyage time (h)	217
Average Speed (knots)	7.9
Average Shaft Power (MW)	0.267
Energy needed per trip (MWh)	58

The final vessel selected for this study is the *Northwestern*, a **fishing trawler** that also belongs to the smaller category of vessels but remains at sea for longer durations compared to the pax-ferry and even to the ro-pax ship. The typical voyage of the Northwestern begins in Seattle, U.S.A., and concludes in Dutch Harbor, U.S.A., with a total duration of 217 hours. Table 9 provides detailed specifications of the fishing trawler and its corresponding route information (Minnehan & Pratt, 2017).

3.1.2. Energy intensity (TTW)

After establishing the typical voyage for each vessel, the useful energy requirements for a one-way trip were computed for each operating mode or phase using Equation 7. Each trip is divided into three distinct operation modes: cruising, manoeuvring, and hotelling, which play a critical role in determining shipping emissions and energy consumption, as they vary across these phases. During the cruising operational mode, the ship transitions from the port's boundary to the manoeuvring stage, which involves activities such as approaching and departing from the harbour. Both of these phases need the utilization of both main and auxiliary engines. In the hotelling phase, the main engines are turned off, and the auxiliary engines are employed to generate power for maintaining onboard services (Nguyen et al., 2022). In addition to analysing the voyage by phase, the present study will also differentiate between the main engine (ME) and auxiliary engine (AE) contributions.

$$Energy_{Trip,e,m,i} = P_{e,i} \times LF_e \times T_{m,i} \tag{7}$$

Where:
Energy$_{Trip}$ = useful energy necessary to perform a one-way trip (MWh),
P = engine nominal power (MW),
LF = engine load factor (%),
T = time (hours),
e = engine category (main or auxiliary),
m = operational mode of the ship (cruising, manoeuvring, hotelling),
i = ship type (container, general cargo, ro-pax, passenger ferry, fishing trawler).

The engine load factor (LF) indicates the proportion of power that a ship's engine is generating in relation to its maximum capacity. The load factors for both the ME and AE were obtained from the research paper titled "Emission estimate methodology for maritime navigation" by Trozzi, 2010 – see Table 10. These values and calculation methods have continued to be employed in the “EMEP/EEA air pollutant emission inventory guidebook” in 2019 (Fontelle et al., 2019).

Table 10 - Load factors for main and auxiliary engines for manoeuvring and hotelling operation modes (Trozzi, 2010)

Operational Mode	ME Load Factor	AE Load Factor
Cruising	-	30%
Manoeuvring	20%	50%
Hotelling	20%	40%

To determine the main engine LF during the cruising phase, Equation 8, derived from the research conducted by Minnehan & Pratt (2017), was employed. This approach aims to obtain conservative results, resulting in higher energy requirements than the actual values. Table 11 provides an overview of the useful energy needed for each one-way trip, referred to as *EnergyTrip*, based on the calculations from Equation 7.

$$LF\ (\%) = \left(\frac{Average\ speed}{Maximum\ speed}\right)^{3} \times 100 \tag{8}$$

Table 11 - Useful energy needed for each one-way trip (MWh)

	Useful Energy (Energy$_{trip}$) (MWh)									
	CONTAINER SHIP		GENERAL CARGO		RO-PAX		PASSENGER		FISHING	
Phase	ME	AE	ME	AE	ME	AE	ME	AE	ME	AE
Cruising	9272.82	1531.53	888.78	225.42	218.23	29.67	0.39	0.03	58.63	24.04
Manoeuvring	16.02	9.80	2.42	1.39	7.56	4.54	0.03	0.01	0.13	0.13
Hotelling	224.22	203.28	94.38	43.41	113.40	54.43	0.08	0.03	5.13	4.00

To calculate the tank-to-wake (TTW) energy consumption per trip, the efficiency of each power system was taken into consideration. The efficiency values for different power systems were obtained from MARIN (2022) and are utilized in Equation 9.

$$\text{TTW } Energy\ Consumption_{j,e,m,i}(MWh) = \frac{Energy_{Trip,e,m,i}}{Efficiency_{j}} \tag{9}$$

Where:
j = fuel and power system combination
e = engine category (main or auxiliary),
m = operational mode of the ship (cruising, manoeuvring, hotelling),
i = ship type (container, general cargo, ro-pax, passenger ferry, fishing trawler).
$Efficiency_j$ = efficiency of the power system in combination j.

The available power systems include (MARIN, 2022):

i. Internal Combustion Engines (ICE) running on:

- Heavy Fuel Oil (HFO): 49% power system efficiency
- Liquefied Natural Gas (LNG): 45% efficiency
- Synthetic Diesel: 46% efficiency

ii. Dual Fuel ICEs running on:

- 95% Methanol or Ammonia and 5% Diesel: 46% efficiency
- 96% Liquefied Hydrogen (LH_2) and 4% Diesel: 48% efficiency

iii. Low-Temperature Proton Exchange Membrane Fuel Cells (PEMFCs) running on:

- Methanol, Ammonia, or LH_2: efficiencies between 41% and 43%

iv. Solid Oxide Fuel Cells (SOFCs) running on:

- Ammonia: 62% efficiency

v. Li-ion batteries: 90% efficiency

Li-ion batteries, PEMFCs, and SOFCs all operate with electric engines, having an assumed efficiency of 95% (Hansen & Wendt, 2015). This efficiency value is multiplied by the respective power system's efficiency to obtain the overall efficiency of the complete system.

Now that the energy consumption per engine type and per operational mode is calculated, to obtain the total energy required for each vessel, the energy required by the ME in every operational mode is added to the one required by the AE in every operational mode, to obtain a global energy requirement per trip. It was assumed that each vessel would have consistent energy consumption per decade, based on an estimated number of trips per year and so, the total TTW energy consumption for the three decades would be the sum of the energy consumption per decade.

Regarding the Emma Maersk's number of trips per annum, the manufacturer as stated that the container ship sails approximately 170.000 nautical miles per year (Maersk, 2013), accounting for 34 typical voyages. Since the general cargo ship has a similar typical voyage time as the container ship and the same operational purpose, which is to transport cargo, it was assumed the same number of voyages per annum for both ships. The fishing trawler also has a similar typical voyage time as the two ships mentioned before, however, assuming that a fishing trawler of this size would spend less time loading and unloading its goods, it was assumed the trawler could complete 40 trips per year. According to the Pride of Hull's website (https://www.poferries.com/en#route), the ro-pax ship performs one voyage per day all year round, accounting for 365 trips per year. For the passenger ferry, since it performs one hour bay tours it was assumed an average of 5 tours per day during the summertime (4 months), accounting for 600 annual voyages. The specific values for the assumed number of trips per year are presented in Table 12.

Table 12 - Number of trips that each vessel performs per year and per decade, adapted from (Maersk, 2013) and https://www.poferries.com/en#route

Vessel	**No. of trips per year**	**No. of trips per decade**	**Time of operation** (h/year)
CONTAINER	34	340	8704
GEN CARGO	34	340	9214
RO-PAX	365	3650	4343.5
PAX	600	6000	600
FISHING	40	400	8680

After computing the total TTW energy consumption for each vessel's lifetime, it is now possible to calculate the TTW energy intensity of every possible combination for each vessel, utilizing Equation 10.

$$TTW\ Energy\ Intensity_{j,i} = \frac{TTW\ Energy\ Consumption_{j,i}\ (kWh)}{Available\ mass\ (ton) \times distance\ (km)} \tag{10}$$

Where:
TTW Energy Intensity = TTW (tank-to-wake) Energy intensity per ton transported per distance travelled ($kWh/(ton \times km)$),
TTW Energy Consumption = TTW (tank-to-wake) Energy consumed (kWh),
j = fuel and power system combination,
i = ship type (container, general cargo, ro-pax, passenger ferry, fishing trawler),
Available mass = Mass available onboard each ship (ton),
Distance = Distance travelled by each ship (km).

In adopting the tank-to-wake (TTW) energy consumption to calculate the Energy Intensity, a deliberate choice was made to portray the vessel operator's perspective, since the overarching purpose of the present thesis is to decarbonize the maritime transport sector, adding to the fact that the WTW emissions of each combination are already being considered in another indicator to be mentioned ahead (chapter 3.1.3). By focusing on TTW energy, this indicator takes into account the energy required for propulsion, to transport a given amount of cargo over a specific distance, from the energy vector transportation stage (tank) to the energy utilized during the vessel's operation and its wake (energy consumed during the voyage). To ensure a robust evaluation, it was assumed that the vessels would operate at their maximum cargo capacity, thereby optimizing their transport efficiency.

3.1.3. Lifetime emissions

The life-cycle emissions of each energy vector and power system combination, also known as well-to-wake (WTW) emissions – Equation 11, are the sum of upstream GHG emissions in the fuel's production phase (including the whole supply chain), also known as well-to-tank (WTT) emissions, and downstream GHG emissions in the fuel's combustion phase: from the fuel tank to the movement in the sea – tank-to-wake (TTW).

$$WTW\ Emissions_{j,e,m,i}(kgCO_2\mathrm{e}) = EF\_GWP100_{\ j,e,m,i} \times Energy\ Consumption_{j,e,m,i} \qquad (11)$$

Where:

EF_GWP100 = emission factor GWP in a 100-year time period ($kgCO2/MWh$).

The emission factors accounting for the Global Warming Potential over a 100-year time horizon (GWP100) for each fuel and power system combination were obtained from MARIN (2022) and are presented in Table A.1. The Paris Agreement recommends the GWP100 metric usage (Forster et al., 2021), which has become prevalent in GHG emission research (Solakivi et al., 2022). Given that the energy consumption remains constant throughout each decade, the WTW emissions for each combination will also have the same values across all decades. This assumption allows for consistent estimation of the WTW emissions and facilitates the comparison of emission levels between different combinations over time.

3.1.4. Volume and Mass requirements

The volume and mass requirements were determined by calculating the energy vector consumption for each combination. This computation considered the volumetric and gravimetric energy density of each fuel, presented in Table. 13. Additionally, the volume and mass of the fuel cells or batteries, if applicable, were incorporated into the calculation for a one-way trip.

Table.13 – Volumetric and gravimetric energy density of the selected fuels (LHV)

	HFO	Diesel	LNG	Methanol	Ammonia	LH2
Vol. En. Density (MWh/m^3)	9.86	9.98	5.83	4.33	2.79	2.36
Grav. En. Density (kWh/kg)	11.22	11.94	14.72	5.53	5.17	33.33
Reference	a.	b.	a.	a.	c.	a.

a. (MARIN, 2022)
b. (Staffell, 2011)
c. (Cheliotis et al., 2021)

The calculation of the required number of PEMFCs for each vessel was based on the power demands of both the ME and AE – Table . The selected PEMFC for this study is the 200 kW FC Wave™ by Ballard (Ballard, 2021), with an efficiency of 53.5%, which weights 1000 kg and occupies a volume of 1.97 m^3. The quantity of fuel cells needed to fulfil the power requirements was rounded up to approximately include a battery management system. For simplification purposes, it was assumed that this specific PEMFC, which originally operates on liquefied hydrogen, could also function on ammonia and methanol, by adding a cracker to the system, and that it has the same emission factor (EF) as the one mentioned previously.

Table 14 – PEMFC design to serve the main engine for each vessel

Main Engine	CONTAINER	GEN.CARGO	RO-PAX	PAX-FERRY	FISHING
ME Power (MW)	80.08	12.10	37.80	0.80	0.95
# PEMFC needed	401	61	189	4	5
PEMFCs mass (metric ton)	401.0	61.0	189.0	4.0	5.0
PEMFCs volume (m^3)	788.5	119.9	371.6	7.8	9.8

Table 15 - PEMFC design to serve the auxiliary engine for each vessel

Aux. Engine	CONTAINER	GEN.CARGO	RO-PAX	PAX-FERRY	FISHING
AE Power (MW)	20.02	2.78	9.07	0.13	0.37
# PEMFC needed	101	14	46	1	2
PEMFC mass (metric ton)	101.0	14.0	46.0	1.0	2.0
PEMFC volume (m^3)	198.6	27.5	90.4	1.9	3.9

The calculation of the required number of SOFCs for each vessel was also based on the power demands of both the ME and AE – Tables 16 and 17.

The selected SOFC is the 330 kW *Bloom Energy Server 5.5* by Bloomenergy® (Bloom Energy, 2023), with an efficiency of 65%, which weights 15800 kg and occupies a volume of 31.33 m^3. The number of fuel cells needed to fulfil the power requirements was rounded up to include a battery management system, approximately. For simplification purposes, it was assumed that this specific SOFC, which originally operate on liquefied hydrogen, could also function on ammonia, and that it has the same emission factor (EF) as the one mentioned previously.

Table 16 - SOFC design to serve the main engine for each vessel

Main Engine	CONTAINER	GEN.CARGO	RO-PAX	PAX-FERRY	FISHING
ME Power (MW)	80.08	12.10	37.80	0.80	0.95
# SOFCs needed	243	37	115	3	3
SOFCs mass (metric ton)	3 839.4	584.6	1 817.0	47.400	47.400
SOFCs volume (m^3)	7 612.0	1 159.0	3 602.4	93.9	93.9

Table 17 - SOFC design to serve the auxiliary engine for each vessel

Aux. Engine	CONTAINER	GEN.CARGO	RO-PAX	PAX-FERRY	FISHING
AE Power (MW)	20.02	2.78	9.07	0.13	0.37
# SOFCs needed	61	9	28	1	2
SOFCs mass (metric ton)	963.8	142.2	442.4	15.8	31.6
SOFCs volume (m^3)	1 910.8	281.9	877.1	31.3	62.6

To have an approximation of the fuel consumption rate of both the PEMFC and the SOFC, equation 12 was used, with the lower heating value (LHV) of hydrogen being 33.33 kWh/kg, the LHV of methanol being 5.55 kWh/kg (MARIN, 2022), and ammonia's being 5.16 kWh/kg (Cheliotis et al., 2021). The decision was made to use the LHV instead of the higher heating value, because it would lead to more conservative results. To obtain the fuel consumption in kg/MWh the fuel consumption rate obtained by equation 12 (kg/h) needs to be divided by the electrical output (MW) of the FC in use, attaining the values in Table 18 for both fuel cell types.

$$Fuel\ consumption\ rate\ (kg/h) = \frac{FC\ Electrical\ output\ (kW)}{FC\ efficiency\ (\%) \times LHV\ (kWh/kg)} \tag{12}$$

Table 18 – Estimated fuel consumption rate (kg/MWh) for the chosen PEMFC and SOFC (own calculation)

Fuel Consumption rate (kg/MWh)

	PEMFC	SOFC
LH_2	56.08	46.15
NH_3	361.75	297.75
CH_3OH	336.42	276.90

The Li-ion battery chosen for the purpose of this analysis is the M3 Energy Module™ developed by Leclanché (Leclanché, 2023), exhibiting an efficiency of 90%. With a weight of 55.4 kg and a volume occupancy of 0.04 m3, the number of modules required to meet the power demands was rounded up to accommodate the inclusion of a battery management system, as an approximation. To quantify the number of Li-ion batteries needed, it was considered the energy required per one-way trip (energy output) for this combination, for both ME and AE (Table 11), as a design basis – Tables 19 and 20.

Table 19 – Li-ion batteries' design to serve the main engine requirements for a one-way trip, for each vessel

Main Engine	**CONTAINER**	**GEN.CARGO**	**RO-PAX**	**PAX-FERRY**	**FISHING**
Energy Required per trip (MWh)	11 126.39	1 152.72	396.71	0.58	74.73
# Batteries needed	1 278 896	132 497	45 599	68	8 590
Batteries' mass (metric ton)	70 850.8	7 340.3	2 526.2	3.7	475.9
Batteries' volume (m^3)	51 527.04	5 338.34	1 837.20	2.74	346.09

Table 20 - Li-ion batteries' design to serve the auxiliary engine requirements for a one-way trip, for each vessel

Aux. Engine	**CONTAINER**	**GEN.CARGO**	**RO-PAX**	**PAX-FERRY**	**FISHING**
Energy Required per trip (MWh)	2040.47	316.06	103.66	0.08	32.95
# Batteries needed	234 538	36 329	11 916	10	3 788
Batteries' mass (kg)	12 993.4	2 012.6	660.1	0.55	209.8
Batteries' volume (m^3)	9 449.6	1 463.7	480.1	0.4	152.6

3.1.5. Onboard technology and tank costs

In the current research, capital expenditures (CAPEX) encompass two components: the expenses associated with onboard technology, and the costs related to the tanks that store different fuels/ energy vectors - Table A.2 and Table A.3.

The costs of onboard technology vary depending on the specific combination, as power systems require distinct components from one another. In the case of combinations with an ICE as their power system, the onboard technology costs solely encompass the engine cost, which is estimated at 366.82 €/kW (Lloyd's Register, 2020). Alternatively, for combinations employing PEMFC, SOFC, or Li-ion batteries as their power system, the onboard technology costs include not only the costs of fuel cells/batteries but also an electric motor priced at 106.38 €/kW (Lloyd's Register, 2020). The individual costs for each remaining power system are as follows: PEMFCs and SOFCs are priced at an average of 765 €/kW and 1980 €/kW, respectively, and Li-ion batteries at 107.29 €/kWh (Elkafas et al., 2023; Lloyd's Register, 2020).

The operational lifespans of PEMFCs, SOFCs, and Li-ion batteries also vary, necessitating replacement upon reaching their end-of-life periods. The replacement of these power systems incurs increased onboard technology costs, demanding careful attention. Specifically, PEMFCs are projected to endure up to 25,000 hours of operation, whereas SOFCs boast a more extended operational lifetime of up to 80,000 hours (Elkafas et al., 2023). For Li-ion batteries in the maritime context, the average lifetime is assumed to be 10 years (Perčić et al., 2022).

To estimate the frequency of power system replacements over the 30-year operational period, the number of annual operating hours for each vessel (as detailed in Table 12 - Chapter 3.1.2) can be utilized to calculate the power system's years of operation for both PEMFCs and SOFCs. The number of replacements, detailed in Tables 21 and 22, will differ regarding the set of possible lifetime combinations (explained ahead in chapter 3.2):

- The “retrofit set” of combinations will only use the mentioned power systems for 20 years. For the Li-ion batteries, the “retrofit set” of combinations will need 1 power system replacement between the second and third decades.
- The “new set” of combinations will use them for 30 years. For the Li-ion batteries solutions, the “new set” will need 2 replacements, one in 2030 and the other in 2040.

Equation 13 was used to calculate both types of fuel cells’ lifespan in years (PEMFC and SOFC), equation 14 was used to estimate the number of fuel cell replacements, where the time of FC use is equal to 20 years in the “retrofit set” and equal to 30 years in the “new set”.

$$FC\ Lifespan\ (years)\ =\ \frac{Vessel's\ time\ of\ operation\ (h/year)}{FC\ Lifespan\ (h)} \tag{13}$$

$$No.of\ FC\ replacements\ =\ \frac{Time\ of\ FC\ use\ (years)}{FC\ Lifespan\ (years)} \tag{14}$$

Table 21 – Estimation of PEMFC’s replacements throughout the vessels’ lifetime

Vessel	**PEMFC’s lifespan** [years]	**No. of FC replacements “Retrofit set”** (in 20 years)	**No. of FC replacements “New set”** (in 30 years)
CONTAINER	2.8	6	10
GEN CARGO	2.7	7	11
RO-PAX	5.7	3	5
PAX-FERRY	41.6	0	0
FISHING	2.8	6	10

Table 22 - Estimation of SOFC’s replacements throughout the vessels’ lifetime

Vessel	**SOFC’s lifespan** (years)	**No. of replacements “Retrofit set”** (during 20 years)	**No. of replacements “New set”** (during 30 years)
CONTAINER	9.2	2	3
GEN CARGO	8.6	2	3
RO-PAX	18.4	1	1
PAX	133.3	0	0
FISHING	9.2	2	3

It is worth emphasizing that the cost of PEMFC, SOFC and Li-ion batteries are anticipated to experience a significant reduction of 50% by 2030, primarily attributable to the advantages derived from economies of scale (Berckmans et al., 2017; Cigolotti et al., 2021). This anticipated cost decline has been considered into the calculation of the onboard technology costs associated with the replacements of fuel cells and Li-ion batteries. It is assumed that this reduced cost will remain constant for the last two decades of the study. By incorporating this expected price trend, the present study aims to provide a more accurate and forward-looking assessment of the economic implications related to the adoption of fuel cell technologies in the maritime domain.

The tank costs, which have been sourced from Al-Breiki & Bicer (2020), are provided in Table 23.

Table 23 - Tank costs per fuel (€/m^3)

	HFO / diesel	**LNG**	**Methanol**	**Ammonia**	**Liq. Hydrogen**
Tank cost (€/m^3)	458.52 €	1100.46 €	687.79 €	931.72 €	1242.6 €

3.1.6. Energy vector costs and carbon taxes

The operational expenditures (OPEX) considered in the present dissertation include energy vector/ fuel costs and carbon taxes for each combination over the three analysed decades - Table A.4 to Table A.8. Aspects such as operation and maintenance (O&M) costs and onboard staff were not included in the analysis as they were assumed to be uniform across all energy vector and power system combinations.

To calculate the energy vector/ fuel costs (shown in Table 24), the lower bound price scenarios proposed by Lloyd's Register (2020) were utilized for the majority of vectors. For the price scenario of f-methanol, a similar trend as f-LNG was assumed, considering that f-methanol is derived from natural gas. The price of the EU electricity mix in the first decade was obtained from Eurostat's statistics (Eurostat, 2023). Price scenarios for electricity in the second and third decades (2030-2040 and 2040-2050) were based on the World Energy Outlook 2022 by the International Energy Agency (IEA, 2022), considering a renewable energy share of 40% in the second decade and 60% in the final one.

The carbon tax applied in this study followed a linear increase, starting from an average of 45.9 €/tCO$_2$ in the first decade and reaching an average of 219.3 €/tCO$_2$ in the last decade. This approach was adopted based on the research conducted by Lagemann et al. (2022), and assumed to act on the whole energy vector and power system combination's life-cycle, applying the taxation over the WTW emissions.

Table 24 – Energy vector/ fuel costs scenarios per decade (€/kWh)

Combinations	**2020-2030**	**2030-2040**	**2040-2050**
HFO + ICE	44.19 €	74.79 €	99.63 €
f-LNG + ICE	29.25 €	47.34 €	64.80 €
e-LNG + ICE	208.98 €	179.82 €	150.66 €
e-diesel + ICE	395.28 €	345.06 €	294.84 €
f-methanol + ICE	57.53 €	93.11 €	127.45 €
e-methanol + ICE	254.34 €	220.32 €	186.30 €
e-methanol + PEMFC	254.34 €	220.32 €	186.30 €
f-NH3 + ICE	90.27 €	89.10 €	89.37 €
f-NH3 + PEMFC	90.27 €	89.10 €	89.37 €
f-NH3 + SOFC	90.27 €	89.10 €	89.37 €
e-NH3 + ICE	165.24 €	139.32 €	111.78 €
e-NH3 + PEMFC	165.24 €	139.32 €	111.78 €
e-NH3 + SOFC	165.24 €	139.32 €	111.78 €
e-LH2 + ICE	155.52 €	129.60 €	103.68 €
e-LH2 + PEMFC	155.52 €	129.60 €	103.68 €
EU-mix + Batteries	252.50 €	180.00 €	125.00 €

3.1.7. Construction cost

The new building cost of each vessel encompass the financial considerations associated with the construction of a novel vessel propelled by each energy vector type – Table 25. The calculation of these expenses was derived from the research conducted by Lagemann et al. (2022), in which the costs of a newly constructed vessel utilizing a combination with a certain alternative energy vector were determined as a percentage increase over the default vessel's cost – powered by HFO with an ICE. It was assumed that a fully electric vessel's construction would cost the same as the default one, since the onboard technology expenditures already encompass the electric engine and the batteries' costs.

The Emma Maersk building cost was retrieved from Vessel Tracking (2023); the Spiegelgracht's cost was assumed to be the same as the general cargo ship present in the study from Lagemann et al. (2022) since both vessels have similar characteristics; the new building cost of the Pride of Hull was retrieved from its manufacturer's website (Clifford Denn Design, 2023); for the Zalophus' construction cost an approximation of a similar vessel's cost was considered (https://www.atlanticship.dk/ship/ws-411/); Northwestern's costs were also an assumption based on a vessel with similar characteristics (https://commercial.apolloduck.com/).

Table 25 - Construction costs as a percentage of the default ship (in M€), based on the work of (Lagemann et al., 2022)

Construction cost (M€)	**HFO/Electric ship**	**LNG ship**	**Methanol ship**	**Ammonia ship**	**LH2 ship**
Compared to default (HFO ship)	100%	123%	117%	133%	150%
CONTAINER	145.00	178.83	169.17	193.33	217.50
GEN CARGO	30.00	37.00	35.00	40.00	45.00
RO-PAX	112.80	139.12	131.60	150.40	169.20
PAX-FERRY	5.05	6.23	5.89	6.73	7.58
FISHING	0.86	1.06	1.00	1.14	1.28

3.1.8. Retrofit cost

The estimation of retrofit costs for each vessel is also derived from the previously mentioned study conducted by Lagemann et al. (2022), employing a similar methodology to that used for determining construction costs. Specifically, retrofit expenses are calculated as a proportionate percentage of the corresponding construction cost. These calculations solely consider the expenses associated with the transition from a common HFO ship to an alternative fuel powered ship, as the costs related to onboard technology and storage already encompass the variations in power system and tank type's expenditures. Table 26 presents the retrofit costs, estimated in millions of euros.

Table 26 – Retrofit costs from HFO ship to alternative configurations for each vessel

Retrofit from/to (M€)	**HFO/Electric ship**	**LNG ship**	**Methanol ship**	**Ammonia ship**	**LH2 ship**
CONTAINER (HFO)	0.00	44.95	29.00	72.50	118.90
GEN CARGO (HFO)	0.00	9.30	6.00	15.00	24.60
RO-PAX (HFO)	0.00	34.97	22.56	56.40	92.50
PAX-FERRY (HFO)	0.00	1.57	1.01	2.53	4.14
FISHING (HFO)	0.00	0.27	0.17	0.43	0.70

3.2. Scenarios' definition

Two distinct sets of possible energy vector-power system combinations throughout the three decades of the vessels' lifetime are examined within the scope of this dissertation.

The initial set of combinations, denoted as the "retrofit set", involves having a ship powered by heavy-fuel oil (HFO) with an internal combustion engine (ICE) in the first decade of the analysis – combination HFO+ICE - for every analysed typology of vessel, assuming they were commissioned in 2020. In 2030, the beginning of the second decade, a retrofit is implemented, transitioning the vessels from the default HFO+ICE combination to one of the available alternative combinations. The proposed set aims to simulate the situation decision makers might currently encounter when having newbuilt vessels powered by fossil fuels that still have a long life-expectancy ahead and want to decarbonize their fleet. Figure 14 represents the retrofit set's schematics, revealing the initial implementation of the constructed HFO ship in 2020 and a subsequent retrofit to an alternative combination by 2030.

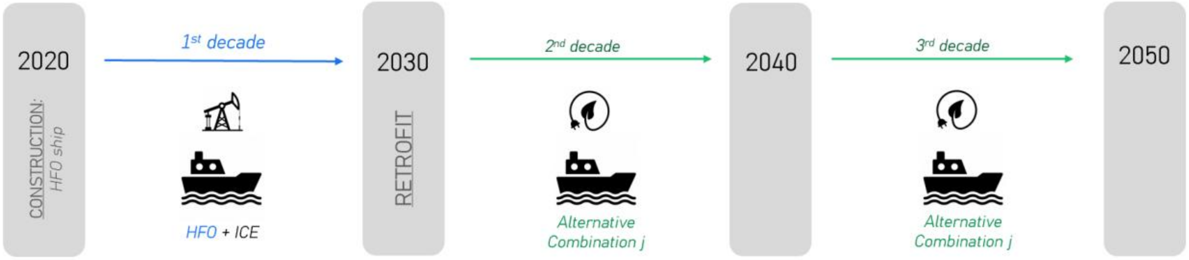

Figure 14 - Schematics of the "retrofit set" of combinations

In this particular case, the construction costs taken into consideration pertain to the HFO ship. The tank and onboard technology costs are CAPEX, which means they are only accounted for in the beginning of the decade when a specific combination is chosen. If a combination is chosen in both consecutive periods, as it happens in the two last decades, these costs are not considered, i.e., they are only accounted for once.

The subsequent set of possible lifetime combinations, referred to as "new set", entails the adoption of the alternative energy vector-power system combination throughout the vessel's entire lifespan of 30 years, without any retrofit interventions. Figure 15 represents this scenario's schematics, involving the construction of a vessel with an alternative combination already incorporated.

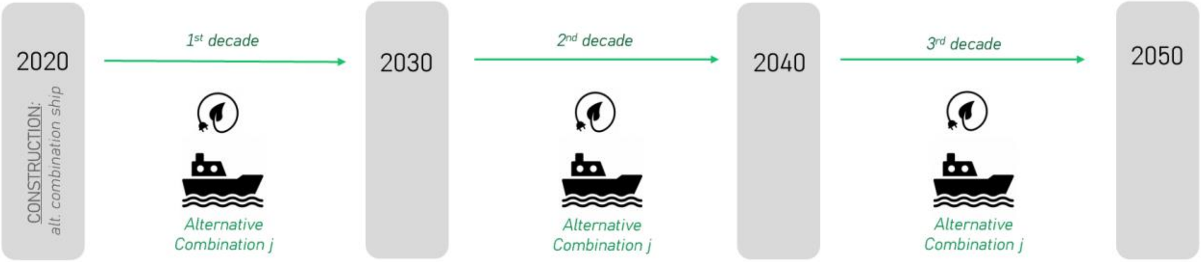

Figure 15 – Schematics of the "new set" of combinations

Consequently, the construction costs associated with the "new set" deviate from the default ship's costs and instead reflect the expenses incurred from implementing the selected alternative combination in the beginning of the first decade – Table 25 in chapter 3.1.7. These modified construction costs are determined by each specific combination chosen for the vessel in the beginning of the vessel's lifetime.

Both sets will be subjected to analysis under varying conditions. This approach allows for a comprehensive evaluation of the techno-economic performance of each scenario, considering the potential impact of carbon taxation on the outcomes. Overall, there are 31 possible energy vector and power system combinations to analyse for each vessel and two scenarios to explore: one without carbon taxes (A) and the other including this taxation (B).

3.2.1. Scenario A: excluding carbon taxation

Scenario A of the study explores the impact of alternative fuels in the maritime sector during a vessel's lifetime (assumed to be 30 years) without the implementation of carbon taxes.

In this framework, only the fuel price forecast scenarios until 2050, presented in Table 24 in chapter 3.6.1, are considered as OPEX, without the imposition of carbon taxes. It is noteworthy that the evaluation solely considers the cost of each energy vector, without penalizing fuels that emit higher levels of GHG.

3.2.2. Scenario B: including carbon taxation

In scenario B, the study encompasses the impact of alternative fuels in the maritime sector while incorporating carbon taxes. The energy vector price forecast scenarios until 2050 presented in Table are still accounted for, but with the addition of carbon taxation measures. Unlike scenario A, this approach introduces penalties on fuels emitting higher GHG levels, thus reflecting the broader environmental implications, and incentivizing more sustainable energy vector choices.

3.3. MCDA model formulation

The choice to implement a Multi-Criteria Decision Analysis (MCDA) based model in the present dissertation allows for a systematic assessment of alternative energy vectors and power systems combinations' performance applied to different vessels, on the perspectives of different profiles of decision makers, taking into account technical, economic, and environmental factors into the selection of criteria.

The chapter demonstrates the application of a MCDA based model within the context of the present research. It discusses the selected multiple criteria for assessment, the profiles of different decision makers (DM), criteria weightage according to each DM profile, and the methodology for achieving final scores for each combination. By employing MCDA, the study aims to facilitate well-informed and balanced decisions regarding the adoption of alternative energy systems in the maritime transport sector.

3.3.1. Criteria definition

As stated before, the possible energy vector-power system combinations selected for this study are the following: HFO+ICE, f-LNG+ICE, e-LNG+ICE, e-diesel+ICE, f-methanol+ICE, e-methanol+ICE, e-methanol+PEMFC, f-NH3+ICE, f-NH3+PEMFC, f-NH3+SOFC, e-NH3+ICE, e-NH3+PEMFC, e-NH3+SOFC, e-LH2+ICE, e-LH2+PEMFC, and EU_mix+batteries. Heavy fuel oil (HFO) is included as a benchmark energy vector, since it is the most common fuel used in the maritime sector. The MCDA based model will consider a total of 31 possible lifetime combinations for each vessel, for both scenarios with (B) and without (A) carbon taxation.

The assessment in this study encompasses three primary areas of focus: environmental, economic, and technical, based on the research conducted by (Ren & Lützen, 2017). Overall, a total of eight criteria are considered for evaluation; the total costs criterion differs for each scenario: including and excluding carbon taxation – Table 27.

The criteria selection was based on various significant characteristics of an ideal maritime fuel and power system combination (Law et al., 2021): low total costs, low lifecycle GHG emissions (WTW), high volumetric energy density (MWh/m^3) of the energy vector, high gravimetric energy density (MWh/kg) of the energy vector, low energy consumption per cargo unit transported, high power system's technology readiness level (TRL), high energy vector production TRL, and available and scalable infrastructure.

Concerning the qualitative infrastructure criterion, a ranking system from I to IV is employed, representing a spectrum from the least favourable to the most optimal conditions. Specifically, level IV indicates a fully mature infrastructure, level III signifies a relatively mature infrastructure with minimal modifications needed, level II designates a relatively immature infrastructure necessitating significant modifications, and level I denotes negligible infrastructure (Xing et al., 2021).

Table 27 – Criteria considered in the selection of alternative fuel and power system combinations.

Focus aspects	Criteria	Description
Environmental	WTW Emissions	Refers to the lifecycle GHG emissions (well-to-wake) during the vessel's lifetime (kt CO_2). Quantitative criterion.
Economic	A - Total Costs excluding carbon taxes	Total costs (A) encompass construction costs, retrofit costs, onboard technology costs (€/kW), tank costs (€/m^3), fuel costs and carbon taxes during the vessel's lifetime. Quantitative criterion.
	B - Total Costs including carbon taxes	Total costs (B) encompass construction costs, retrofit costs, onboard technology costs (€/kW), tank costs (€/m3), and fuel costs during the vessel's lifetime. Quantitative criterion.
Technical	Energy Intensity (TTW)	Refers to the tank-to-wake energy intensity of transport, measured in energy consumed per ton transported per kilometre travelled (kWh/(ton.km)). Quantitative criterion.
	Volume per trip	Refers to the volume needed per trip for each combination, includes fuel storage and FC/ batteries volume when applicable. Quantitative criterion.
	Mass per trip	Refers to the mass (kg) needed per trip for each combination, includes fuel mass and FC/ batteries mass, when applicable. Quantitative criterion.
	Energy vector production TRL	Technology readiness level (TRL) of the energy vector production according to the European Commission principles, retrieved from MARIN (2022). Quantitative criterion (1-9).
	Power system TRL	Technology readiness level (TRL) of the power system according to the European Commission principles, retrieved from MARIN (2022). Quantitative criterion (1-9).
	Infrastructure	Refers to compatibility with existing infrastructure, including ports and fuel infrastructure, and distribution, based on the research of (Hansson et al., 2019; Xing et al., 2021). Qualitative criterion (I-IV ranking, from worst to best).

The performance values for the infrastructure criterion were based on pairwise comparisons involving the investigations of Hansson et al. (2019) and Xing et al. (2021). Furthermore, it was assumed that the availability of infrastructure varies significantly across diverse vessel types, given their distinct operational purposes and types of regular voyages. For instance, container ships, by docking into large ports with connections to extensive industrial zones, tend to have better access to infrastructure suitable for accommodating liquid and gaseous fuels. However, their capacity to access vast amounts of electricity required to power the numerous lithium-ion batteries needed for propelling such large vessels, remains limited. Conversely, small passenger ferries predominantly operate in coastal and urban harbours, thus confronting challenges in obtaining gaseous fuels like LNG delivered from pipelines. Nonetheless, they benefit from relatively easier access to liquid fuels and moderate electricity requirements compared to larger ships. In light of these assumptions, the performance values of the infrastructure criterion will exhibit variation, depending on whether it is applied to a large vessel category, encompassing the container ship, the general cargo ship, and the ro-pax ship, or to a smaller vessel category, comprising the passenger ferry and fishing trawler.

3.3.2. Normalization

To standardize the performance values and bring them to a common scale, a normalization technique known as linear scale transformation (using the max method) was employed (Chakraborty & Yeh, 2007), which divides the performance values of each criterion by the best performer in the same criterion. This approach ensured that the performance values were uniformly adjusted to facilitate meaningful comparisons and analysis.

Initially, each criterion was classified into two categories: beneficial criteria, where higher values are desirable, and non-beneficial criteria, where lower values are preferable. The criterion that evaluates the energy vector production TRL, the one that evaluates the power system TRL, and the one that evaluates infrastructure are the only beneficial criteria in this study, all the remaining are non-beneficial criteria. To apply the chosen normalization technique to the beneficial criteria, equation 15 was used, where x_{ij} is the performance value of the *i*-th alternative for the criterion *j, Max(*x_j*)* is the maximum performance value for criteria *j* among all the alternatives, and n_{ij} is the normalized value.

$$n_{ij} = \frac{x_{ij}}{Max(x_{ij})} \quad (15)$$

Regarding the non-beneficial criteria, equation 16 was used.

$$n_{ij} = 1 - \frac{x_{ij}}{Max(x_{ij})} \quad (16)$$

It is important to acknowledge that the Volume criterion is constrained by the fuel capacity of each vessel. In line with the present project's environmental objectives and aspirations for a sustainable future, it was assumed that each vessel in the “new set” would incorporate a 15% buffer to augment the fuel capacity, if necessary, thereby accommodating potential cargo losses and aligning with more sustainable principles to allocate the alternative combinations of energy vector and power systems. If a combination exceeds this 15% buffer, the normalized value of the Volume criterion is null. Nevertheless, in the “retrofit set” of alternatives, this buffer is not accounted for, meaning the original fuel capacity of each vessel is the only available. If an alternative is incompatible in terms of volume, i.e., if it does not fit in the vessel, this alternative will not be accounted for in the final scores of the suitable combinations, because it is impossible to physically implement.

Similarly, the WTW Emissions criterion performance value is limited by the default combination’s emissions (HFO+ICE). If an alternative combination exceeds the default emissions, the normalized value for that specific alternative in the WTW Emissions criterion is treated as null. This approach aligns with the objective of the dissertation, which focuses on exploring more sustainable energy vector-power system combinations to facilitate the decarbonization of the maritime sector.

3.3.3. Weightage and final scores

The weight of each criterion expresses its importance to the decision maker into mathematical language: the higher the weight assigned to a criterion, the more important it is for the decision maker. And so, the criteria’s weightage plays a crucial role in determining the most suitable combination for each scenario, as the weights significantly influence the outcome when it comes to final scores.

It is important to note that for the scope of this dissertation, the weights attributed to each criterion were determined through subjective assumptions with the purpose of demonstrating the proposed model’s results. These assumptions were based on the perspective of two hypothetical decision makers, representing the environmentalist, prioritizing low GHG emissions, and the investor, emphasising cost considerations – Table 28: the criterion with the largest weight is highlighted in green. It was also added a balanced DM, who gives equal importance to the WTW Emissions criterion and to the Total Costs criterion.

Table 28 - Weightage of each criterion according to three types of decision makers

	Energy Intensity	**WTW Emissions**	**Volume per trip**	**Mass per trip**	**Total Costs**	**TRL energy vector production**	**TRL power system**	**Infrastructure**
Environmentalist	15%	**35%**	5%	5%	10%	15%	5%	10%
Balanced	10%	**20%**	10%	10%	**20%**	10%	10%	10%
Investor	10%	10%	10%	5%	**35%**	10%	10%	10%

To obtain the final scores for every alternative combination in each scenario, the weighted sum method was applied, obtained using equation 17, where $w_{j,m}$ is the weight of criterion *j* according to the decision maker *m,* and *i* represents each combination.

$$Total\ Score_{\ i} = \sum_{i=1}^{31} \sum_{j=1}^{7} w_{j,m} \times n_{ij} \quad , \quad for\ m = \{1,2,3\} \tag{17}$$

4. Results and Discussion

This chapter presents the key findings of the study derived from the MCDA based model. It provides a comprehensive and detailed analysis of the best performing energy vector and power system combinations, focused in two contrasting vessel types, the container ship and the pax-ferry, based on environmental, technical, and economic criteria. The chapter also interprets the overall results for the 5 vessels, addressing trade-offs and implications for different DM's profiles. The discussion analyses the impact of vessel characteristics and their regular voyages on the optimal choices.

4.1. Performance values

Each alternative combination will hold a performance value for each criterion. The collection of performance values for all alternatives across each criterion constitutes the performance matrix.

In the current thesis, five vessels have been comprehensively analysed, categorized into two groups based on their design. The larger category includes the container ship, the general cargo ship, and the ro-pax ship, while the smaller category comprises the pax-ferry and the fishing trawler. The examination of these diverse vessels allowed for a comprehensive investigation into the techno-economic performance and environmental implications across various maritime operation styles.

Due to the extensive scope of the research and to streamline the main presentation, the decision was made to focus on the container ship and the pax-ferry to present detailed results. The container ship, being one of the largest vessels in the world and frequently engaged in long-distance cargo transportation, represents a pivotal point of interest in this study. Similarly, the pax-ferry, with its smaller scale and specialized purpose of transporting passengers on one hour bay tours, provides valuable insights into energy efficiency and sustainability for smaller coastline passenger vessels.

To ensure the completeness of the analysis, performance matrices for the remaining vessels are included in Table B.1 to Table B.4. By including these supplementary results in the annex, the study presents a comprehensive view of the overall techno-economic performance of each vessel, offering a holistic perspective on alternative energy vector and power system combinations in various operational contexts within the maritime sector. And so, the study includes results for large vessels that navigate long distances and transport cargo (container ship and general cargo ship), large vessels that navigate shorter distances but transport passengers and vehicles (ro-pax), small vessels that navigate short distances and transport passengers, and small vessels that navigate long distances and transport cargo (fishing trawlers).

4.1.1. Scenario A: excluding carbon taxes

Tables 29 and 30 showcase the performance matrix for each alternative, evaluated across the selected multi-criteria, for the container ship and for the pax-ferry, respectively, in the scenario without carbon taxation – scenario A.

Table 29 – Performance matrix for the container ship in scenario A (no carbon tax)

CONTAINER SHIP (A)

1st decade	**2nd+3rd decades**	**Energy Intensity** (kWh/ton.km)	**WTW Emissions** (Mt_CO_2)	**Volume per trip** ($x10^3$ m^3)	**Mass per trip** (metric kt)	**Total Costs A** ($x10^3$ M€)	**Energy vector TRL** (1-9)	**Power system TRL** (1-9)	**Infra-structure** (I-IV)
HFO+ICE	HFO+ICE	0.17	16.9	2.3	2.0	1.9	9	9	IV
	f-LNG+ICE	0.18	17.7	4.3	2.0	1.6	9	9	IV
	e-LNG+ICE	0.18	7.8	4.3	2.0	3.4	7	9	IV
	e-diesel+ICE	0.17	6.7	2.5	2.0	5.9	5	9	IV
	f-methanol+ICE	0.17	19.3	5.7	4.4	2.4	7	7	III
	e-methanol+ICE	0.17	6.2	5.7	4.4	4.0	7	7	III
	e-methanol+PEMFC	0.18	7.0	5.7	4.3	191 445.5	7	7	III
	f-NH3+ICE	0.17	28.6	8.8	7.0	2.1	5	5	III
	f-NH3+PEMFC	0.18	57.3	6.2	4.6	191 443.5	5	7	III
	f-NH3+SOFC	0.14	20.8	13.8	8.2	99 100.9	5	4	III
	e-NH3+ICE	0.17	7.1	8.8	7.0	2.7	5	5	III
	e-NH3+PEMFC	0.18	5.6	6.2	4.6	191 444.2	5	7	III
	e-NH3+SOFC	0.14	5.6	13.8	8.2	99 101.4	5	4	III
	e-LH2+ICE	0.17	7.5	10.4	2.0	2.6	6	7	I
	e-LH2+PEMFC	0.18	5.6	9.9	2.0	191 444.1	6	7	I
	EU-mix+batteries	0.12	10.3	61.0	83.8	706 344.2	9	9	II
f-LNG+ICE		0.18	18.1	4.3	1.7	1.4	9	9	IV
e-LNG+ICE		0.18	3.2	4.3	1.7	4.8	7	9	IV
e-diesel+ICE		0.18	1.6	2.5	2.0	8.8	5	9	IV
f-methanol+ICE		0.18	20.4	5.7	4.4	2.5	7	7	III
e-methanol+ICE		0.18	0.9	5.7	4.4	5.7	7	7	III
e-methanol+PEMFC		0.19	2.0	5.7	4.3	344 600.4	7	7	III
f-NH3+ICE		0.18	34.5	8.8	7.0	2.5	5	5	III
f-NH3+PEMFC		0.19	77.4	6.2	4.6	344 596.9	5	7	III
f-NH3+SOFC		0.13	22.7	13.8	8.2	198 200.1	5	4	III
e-NH3+ICE		0.18	2.2	8.8	7.0	3.7	5	5	III
e-NH3+PEMFC		0.19	0.0	6.2	4.6	344 598.3	5	7	III
e-NH3+SOFC		0.13	0.0	13.8	8.2	198 201.0	5	4	III
e-LH2+ICE		0.18	2.7	10.4	0.8	3.5	6	7	I
e-LH2+PEMFC		0.19	0.0	9.9	1.1	344 598.0	6	7	I
EU-mix+batteries		0.10	6.9	61.0	83.8	1 412 682.0	9	9	II

Upon evaluating the performance values of the TTW Energy Intensity criterion, a noticeable trend emerges, indicating that the container ship exhibits lower TTW energy consumption per ton transported per kilometre travelled compared to a smaller vessel like the pax-ferry. Although container ships are associated with higher CO_2 emissions, it is equally evident that they demonstrate higher efficiency in cargo transportation.

The EU-mix+batteries emerges as the top-performing combination in terms of TTW energy intensity. Following closely is NH3+SOFC. It's worth noting that both green and fossil ammonia configurations demonstrate competitive energy intensity profiles. However, a crucial takeaway from this analysis is that emphasizing high power system efficiency alone is insufficient to ensure an environmentally sound performance in emissions reduction. For instance, consider the f-NH3+SOFC configuration, which excels in TTW energy intensity because of its power system high efficiency. Despite this, a comprehensive evaluation reveals that it exhibits higher carbon intensity in terms of WTW emissions when compared to the conventional HFO+ICE configuration. This stark contrast emphasizes the limitations of relying solely on TTW energy intensity as the sole criterion for assessing these fuel and power system combinations.

As explained in chapter 3.3.1, the infrastructure criterion performance varies for different vessels with contrasting characteristics and purposes. Larger ships with longer regular voyages, like the container ship, tend to have better access to infrastructure suitable for accommodating liquid and gaseous fuels, whereas their capacity to access vast amounts of electricity remains limited. On the other hand, small passenger ferries predominantly operate in coastal and urban harbours, thus confronting challenges in obtaining gaseous fuels like LNG delivered from pipelines. However, they benefit from relatively easier access to liquid fuels and moderate electricity requirements compared to larger ships. This is why the LNG fuelled combinations have better performance in the infrastructure criterion for the container ship when compared to the pax-ferry, and Li-ion batteries have better performance for the pax-ferry compared to the container ship.

Table 30 – Performance matrix for the pax-ferry in scenario A (no carbon tax)

PAX-FERRY (A)

1st decade	**2nd+3rd decades**	**Energy Intensity** (KWh/ton.km)	**WTW Emissions** (kt_CO$_2$)	**Volume per trip** (m^3)	**Mass per trip** (metric t)	**Total Costs A** (M€)	**Energy vector TRL** (1-9)	**Power system TRL** (1-9)	**Infra-structure** (I-IV)
HFO+ICE	HFO+ICE	36.63	15.07	0.12	0.10	6.91	9	9	IV
	f-LNG+ICE	39.00	15.76	0.22	0.10	8.46	9	9	II
	e-LNG+ICE	39.00	6.92	0.22	0.10	10.13	7	9	II
	e-diesel+ICE	38.23	5.97	0.12	0.10	10.79	5	9	IV
	f-methanol+ICE	38.23	17.17	0.29	0.22	8.69	7	7	III
	e-methanol+ICE	38.23	5.57	0.29	0.22	10.07	7	7	III
	e-methanol+PEMFC	40.20	6.21	10.07	5.19	10.83	7	7	III
	f-NH3+ICE	38.23	25.54	0.44	0.35	9.89	5	5	III
	f-NH3+PEMFC	40.20	51.05	10.10	5.21	10.52	5	7	III
	f-NH3+SOFC	31.59	18.53	125.52	63.37	11.96	5	4	III
	e-NH3+ICE	38.23	6.34	0.44	0.35	10.43	5	5	III
	e-NH3+PEMFC	40.20	5.02	10.10	5.21	11.10	5	7	III
	e-NH3+SOFC	31.59	5.02	125.52	63.37	12.37	5	4	III
	e-LH2+ICE	38.23	6.65	0.52	0.10	11.91	6	7	I
	e-LH2+PEMFC	40.20	5.02	10.28	5.03	12.57	6	7	I
	EU-mix+batteries	26.21	9.14	3.14	4.32	7.19	9	9	III/IV
f-LNG+ICE		40.19	16.11	0.22	0.09	7.65	9	9	II
e-LNG+ICE		40.19	2.85	0.22	0.09	10.69	7	9	II
e-diesel+ICE		39.02	1.41	0.12	0.10	13.07	5	9	IV
f-methanol+ICE		39.02	18.22	0.29	0.22	8.30	7	9	III
e-methanol+ICE		39.02	0.82	0.29	0.22	11.14	7	7	III
e-methanol+PEMFC		41.99	1.78	10.07	5.19	12.04	7	7	III
f-NH3+ICE		39.02	30.77	0.44	0.35	9.07	5	7	III
f-NH3+PEMFC		41.99	69.05	10.10	5.21	9.75	5	5	III
f-NH3+SOFC		29.07	20.26	125.52	63.37	10.97	5	7	III
e-NH3+ICE		39.02	1.98	0.44	0.35	10.16	5	4	III
e-NH3+PEMFC		41.99	0.00	10.10	5.21	10.93	5	5	III
e-NH3+SOFC		29.07	0.00	125.52	63.37	11.79	5	7	III
e-LH2+ICE		39.02	2.44	0.52	0.04	10.80	6	4	I
e-LH2+PEMFC		41.99	0.00	10.28	5.03	11.55	6	7	I
EU-mix+batteries		20.99	6.18	3.14	4.32	7.55	9	7	III/IV

4.1.2. Scenario B: including carbon taxes

Table 31 showcases the performance matrix for each alternative, evaluated across total costs criterion since the other criteria have the same performance values as scenario A, for the container ship and for the pax-ferry, respectively, in the scenario that includes carbon taxation – scenario B. When compared to scenario A, it is clear to see that fossil alternative combinations are more expensive.

In larger vessels, like the container ship, it is clear to see the absurdly higher costs for fuel cells and batteries, since it would be needed a great amount of these technologies onboard to cover for great voyages.

Table 31 – Performance matrix for the container ship in scenario B (with carbon tax)

		CONTAINER SHIP (B)	PAX-FERRY (B)
1st decade	**2nd+3rd decades**	**Total Costs B** (x10^3 M€)	**Total Costs B** (M€)
HFO+ICE	HFO+ICE	4.1	8.92
	f-LNG+ICE	4.0	10.59
	e-LNG+ICE	4.1	10.70
	e-diesel+ICE	6.3	11.18
	f-methanol+ICE	5.1	11.06
	e-methanol+ICE	4.3	10.39
	e-methanol+PEMFC	191 446.0	11.27
	f-NH3+ICE	6.5	13.75
	f-NH3+PEMFC	191 452.9	18.89
	f-NH3+SOFC	99 103.9	14.58
	e-NH3+ICE	3.3	10.89
	e-NH3+PEMFC	191 444.4	11.33
	e-NH3+SOFC	99 101.6	12.60
	e-LH2+ICE	3.2	12.43
	e-LH2+PEMFC	191 444.3	12.80
	EU-mix+batteries	706 345.3	8.15
f-LNG+ICE		3.8	9.79
e-LNG+ICE		5.3	11.07
e-diesel+ICE		9.0	13.26
f-methanol+ICE		5.2	10.72
e-methanol+ICE		5.8	11.25
e-methanol+PEMFC		344 600.7	12.28
f-NH3+ICE		7.1	13.17
f-NH3+PEMFC		344 607.2	18.94
f-NH3+SOFC		198 203.1	13.67
e-NH3+ICE		4.0	10.43
e-NH3+PEMFC		344 598.3	10.93
e-NH3+SOFC		198 201.0	11.79
e-LH2+ICE		3.9	11.13
e-LH2+PEMFC		344 598.0	11.55
EU-mix+batteries		1 412 683.0	8.37

4.2. Normalized matrices

Similar to the presentation of results regarding the performance matrices, a decision was made to focus on the container ship and the pax-ferry for the detailed normalized results, presented in a scale of 0-worst to 100-best, obtained using the linear scale transformation method described in chapter 3.3.2. Normalized matrices for the remaining studied vessels are included in Table B.5 to Table B.8.

The values presented in blue in the WTW Emissions' criterion represent the combinations that perform worse than the default one in this criterion, i.e., the ones that emit more GHG than the HFO+ICE combination have an imposed null normalized score. In the same way, the values in blue in the volume criterion have an imposed null normalized score because the volume requirements of those combinations cannot comply with the available fuel capacity of the vessel in question. The values in blue in the costs criterion have a null normalized score because they represent much greater costs when compared to the other combinations, with a much larger order of magnitude (>10^5 times larger) and so, it was assumed that neither decision maker would be willing to score those expensive options against the rest in the costs criterion, hence their imposed zero normalized value.

4.2.1. Scenario A after Normalization: excluding carbon taxes

Table 32 and 33 present the normalized matrices for each alternative, evaluated across the selected multi-criteria, for the container ship and for the pax-ferry, respectively, in the scenario without carbon taxation – scenario A.

Table 32 - Normalized matrix (0-100, worst to best) for the container ship in scenario A (without carbon taxes). Cells in blue are imposed null values, as explained in the text above.

CONTAINER SHIP (A)

1st decade	2nd+3rd decades	TTW Energy Intensity	WTW Emissions	Volume per trip	Mass per trip	Total Costs A	Energy vector TRL	Power system TRL	Infra-structure
HFO+ICE	HFO+ICE	12.8	0.0	96.2	97.6	78.5	100.0	100.0	100.0
	f-LNG+ICE	7.1	0.0	92.9	97.6	82.1	100.0	100.0	87.5
	e-LNG+ICE	7.1	24.3	92.9	97.6	60.8	77.8	100.0	87.5
	e-diesel+ICE	9.0	34.8	96.0	97.6	33.0	55.6	100.0	100.0
	f-methanol+ICE	9.0	0.0	90.7	94.7	72.3	77.8	77.8	75.0
	e-methanol+ICE	9.0	39.1	90.7	94.7	54.7	77.8	77.8	75.0
	e-methanol+PEMFC	4.3	32.1	90.6	94.9	0.0	77.8	77.8	75.0
	f-NH3+ICE	9.0	0.0	85.6	91.7	75.8	55.6	55.6	75.0
	f-NH3+PEMFC	4.3	0.0	89.8	94.5	0.0	55.6	77.8	75.0
	f-NH3+SOFC	24.8	0.0	77.4	90.3	0.0	55.6	44.4	75.0
	e-NH3+ICE	9.0	30.6	85.6	91.7	68.9	55.6	55.6	75.0
	e-NH3+PEMFC	4.3	45.1	89.8	94.5	0.0	55.6	77.8	75.0
	e-NH3+SOFC	24.8	45.1	77.4	90.3	0.0	55.6	44.4	75.0
	e-LH2+ICE	9.0	27.3	0.0	97.6	70.0	66.7	77.8	25.0
	e-LH2+PEMFC	4.3	45.1	83.8	97.6	0.0	66.7	77.8	25.0
	EU-mix+batteries	37.6	0.0	0.0	0.0	0.0	100.0	100.0	50.0
f-LNG+ICE		4.3	0.0	92.9	98.0	83.7	100.0	100.0	87.5
e-LNG+ICE		4.3	68.9	92.9	98.0	44.9	77.8	100.0	87.5
e-diesel+ICE		7.1	84.6	96.0	97.6	0.0	55.6	100.0	100.0
f-methanol+ICE		7.1	0.0	90.7	94.7	71.3	77.8	77.8	75.0
e-methanol+ICE		7.1	91.1	90.7	94.7	35.1	77.8	77.8	75.0
e-methanol+PEMFC		0.0	80.5	90.6	94.9	0.0	77.8	77.8	75.0
f-NH3+ICE		7.1	0.0	85.6	91.7	71.9	55.6	55.6	75.0
f-NH3+PEMFC		0.0	0.0	89.8	94.5	0.0	55.6	77.8	75.0
f-NH3+SOFC		30.8	0.0	77.4	90.3	0.0	55.6	44.4	75.0
e-NH3+ICE		7.1	78.4	85.6	91.7	57.9	55.6	55.6	75.0
e-NH3+PEMFC		0.0	100.0	89.8	94.5	0.0	55.6	77.8	75.0
e-NH3+SOFC		30.8	100.0	77.4	90.3	0.0	55.6	44.4	75.0
e-LH2+ICE		7.1	73.3	83.0	99.1	60.2	66.7	77.8	25.0
e-LH2+PEMFC		0.0	100.0	83.8	98.6	0.0	66.7	77.8	25.0
EU-mix+batteries		50.0	32.4	0.0	0.0	0.0	100.0	100.0	50.0

In the WTW Emissions criterion, a number of alternatives' normalized performances were constrained to null values for every ship, as their emission factors (EF) were equal to or greater than the baseline combination (HFO+ICE). Notably, all fossil-sourced alternative energy vectors displayed inferior performance compared to the default option in terms of emissions. These findings highlight the insufficiency of solely adopting alternative fuels to achieve decarbonization in the maritime transport sector. Instead, the key lies in sourcing these fuels sustainably through renewable energy sources (RES).

In terms of volume requirements per trip, the container ship boasts a fuel capacity of 15,000 m^3. Consequently, the combinations from the "retrofit set" that are physically unfeasible to implement include e-LH2+ICE and EU-mix+batteries, whereas the only combination from the "new set" that cannot be implemented is EU-mix+batteries. This observation underscores the significance of the 15% buffer considered for new built vessels in the "new set", as it enables the accommodation of more alternative combinations within the fuel capacity constraints. For the pax-ferry, the alternatives which were cut out of the final assessment because of volume incompatibility were the ones involving SOFCs in both sets of combinations, in this case the 15% buffer made no difference.

Table 33 - Normalized matrix (0-100, worst to best) for the pax-ferry in scenario A (without carbon taxes).
Cells in blue are imposed null values, as explained in the text above.

PAX-FERRY (A)

1st decade	2nd+3rd decades	TTW Energy Intensity	WTW Emissions	Volume per trip	Mass per trip	Total Costs A	Energy vector TRL	Power system TRL	Infra-structure
HFO+ICE	HFO+ICE	12.8	0.0	99.9	99.8	47.1	100.0	100.0	100.0
	f-LNG+ICE	7.1	0.0	99.8	99.8	35.3	100.0	100.0	50.0
	e-LNG+ICE	7.1	24.3	99.8	99.8	22.5	77.8	100.0	50.0
	e-diesel+ICE	9.0	34.8	99.9	99.8	17.5	55.6	100.0	100.0
	f-methanol+ICE	9.0	0.0	99.8	99.6	33.6	77.8	77.8	75.0
	e-methanol+ICE	9.0	39.1	99.8	99.6	23.0	77.8	77.8	75.0
	e-methanol+PEMFC	4.3	32.1	92.0	91.8	17.2	77.8	77.8	75.0
	f-NH3+ICE	9.0	0.0	99.6	99.4	24.4	55.6	55.6	75.0
	f-NH3+PEMFC	4.3	0.0	92.0	91.8	19.5	55.6	77.8	75.0
	f-NH3+SOFC	24.8	0.0	0.0	0.0	8.5	55.6	44.4	75.0
	e-NH3+ICE	9.0	30.6	99.6	99.4	20.2	55.6	55.6	75.0
	e-NH3+PEMFC	4.3	45.1	92.0	91.8	15.1	55.6	77.8	75.0
	e-NH3+SOFC	24.8	45.1	0.0	0.0	5.4	55.6	44.4	75.0
	e-LH2+ICE	9.0	27.3	99.6	99.8	8.9	66.7	77.8	25.0
	e-LH2+PEMFC	4.3	45.1	91.8	92.1	3.8	66.7	77.8	25.0
	EU-mix+batteries	37.6	0.0	97.5	93.2	45.0	100.0	100.0	87.5
f-LNG+ICE		4.3	0.0	99.8	99.9	41.5	100.0	100.0	50.0
e-LNG+ICE		4.3	68.9	99.8	99.9	18.2	77.8	100.0	50.0
e-diesel+ICE		7.1	84.6	99.9	99.8	0.0	55.6	100.0	100.0
f-methanol+ICE		7.1	0.0	99.8	99.6	36.5	77.8	100.0	75.0
e-methanol+ICE		7.1	91.1	99.8	99.6	14.8	77.8	77.8	75.0
e-methanol+PEMFC		0.0	80.5	92.0	91.8	7.9	77.8	77.8	75.0
f-NH3+ICE		7.1	0.0	99.6	99.4	30.6	55.6	77.8	75.0
f-NH3+PEMFC		0.0	0.0	92.0	91.8	25.4	55.6	55.6	75.0
f-NH3+SOFC		30.8	0.0	0.0	0.0	16.1	55.6	77.8	75.0
e-NH3+ICE		7.1	78.4	99.6	99.4	22.2	55.6	44.4	75.0
e-NH3+PEMFC		0.0	100.0	92.0	91.8	16.4	55.6	55.6	75.0
e-NH3+SOFC		30.8	100.0	0.0	0.0	9.8	55.6	77.8	75.0
e-LH2+ICE		7.1	73.3	99.6	99.9	17.4	66.7	44.4	25.0
e-LH2+PEMFC		0.0	100.0	91.8	92.1	11.6	66.7	77.8	25.0
EU-mix+batteries		50.0	32.4	97.5	93.2	42.3	100.0	77.8	87.5

4.2.2. Scenario B after Normalization: including carbon taxes

The normalized column of the Total Costs criterion for each vessel in scenario B, with carbon taxes, are presented in Table 34.

Table 34 - Normalized matrix (0-100, worst to best) for the container ship and the pax-ferry in scenario B (with carbon taxes). Cells in blue are imposed null values, as explained in the text above.

		CONTAINER SHIP (B)	PAX-FERRY (B)
1st decade	**2nd+3rd decades**	**Total costs B**	**Total costs B**
HFO+ICE	HFO+ICE	58.6	52.9
	f-LNG+ICE	60.4	44.1
	e-LNG+ICE	59.2	43.5
	e-diesel+ICE	36.9	41.0
	f-methanol+ICE	49.0	41.6
	e-methanol+ICE	56.5	45.1
	e-methanol+PEMFC	0.0	40.5
	f-NH3+ICE	35.4	27.4
	f-NH3+PEMFC	0.0	0.3
	f-NH3+SOFC	0.0	23.0
	e-NH3+ICE	67.4	42.5
	e-NH3+PEMFC	0.0	40.2
	e-NH3+SOFC	0.0	33.5
	e-LH2+ICE	67.8	34.4
	e-LH2+PEMFC	0.0	32.4
	EU-mix+batteries	0.0	57.0
f-LNG+ICE		61.6	48.3
e-LNG+ICE		47.3	41.6
e-diesel+ICE		9.9	30.0
f-methanol+ICE		47.6	43.4
e-methanol+ICE		41.7	40.6
e-methanol+PEMFC		0.0	35.2
f-NH3+ICE		29.3	30.5
f-NH3+PEMFC		0.0	0.0
f-NH3+SOFC		0.0	27.8
e-NH3+ICE		60.0	45.0
e-NH3+PEMFC		0.0	42.3
e-NH3+SOFC		0.0	37.8
e-LH2+ICE		61.3	41.3
e-LH2+PEMFC		0.0	39.0
EU-mix+batteries		0.0	55.8

4.3. Final scores

Final scores for the container ship and pax-ferry, obtained using the weighted sum method described in chapter 3.3.3, are presented in Table 35 and 36 for each profile of decision maker and for both scenarios. It is worth mentioning that the alternatives that present a score equal to zero are the ones whose volume requirements are physically impossible to attain, and so, the alternative becomes inviable for consideration. A colour scale was applied for better comprehension of the results, where dark green values are the ones with higher scores and the dark red ones represent the lower final scores and, consequently, the worst performing alternatives for each type of decision maker. Final scores for the remaining vessels are presented in Table B.9 to Table B.11.

4.3.1. Container ship

The total scores (0-100) of the presented alternatives for the container ship in both scenarios (A and B), with and without carbon taxation measures, are presented in Table 35.

Table 35 - Final scores (0-100, worst to best) of each decision maker for the container ship, in scenarios A and B.
Colour scale: dark green values are the ones with higher scores and the dark red ones represent the lower final scores.

CONTAINER		A - without carbon taxes			B - with carbon taxes		
1st decade	**2nd+3rd decades**	**Total Score Environmentalist**	**Total Score Balanced**	**Total Score Investor**	**Total Score Environmentalist**	**Total Score Balanced**	**Total Score Investor**
HFO+ICE	HFO+ICE	49.5	66.4	73.2	47.5	62.4	66.3
	f-LNG+ICE	47.5	64.9	72.4	45.4	60.6	64.8
	e-LNG+ICE	50.6	63.3	65.1	50.4	63.0	64.6
	e-diesel+ICE	49.8	59.4	56.0	50.2	60.1	57.3
	f-methanol+ICE	40.9	57.0	63.1	38.6	52.3	54.9
	e-methanol+ICE	52.8	61.3	60.8	53.0	61.6	61.5
	e-methanol+PEMFC	44.2	48.4	40.5	44.2	48.4	40.5
	f-NH3+ICE	36.4	52.4	59.2	32.4	44.3	45.1
	f-NH3+PEMFC	29.6	39.7	35.0	29.6	39.7	35.0
	f-NH3+SOFC	30.2	36.7	32.2	30.2	36.7	32.2
	e-NH3+ICE	46.4	57.1	59.8	46.3	56.9	59.3
	e-NH3+PEMFC	45.3	48.7	39.5	45.3	48.7	39.5
	e-NH3+SOFC	45.9	45.7	36.7	45.9	45.7	36.7
	e-LH2+ICE	0.0	0.0	0.0	0.0	0.0	0.0
	e-LH2+PEMFC	41.9	44.5	35.1	41.9	44.5	35.1
	EU-mix+batteries	0.0	0.0	0.0	0.0	0.0	0.0
f-LNG+ICE		47.3	65.0	72.7	45.1	60.6	64.9
e-LNG+ICE		64.2	68.8	63.8	64.4	69.3	64.6
e-diesel+ICE		63.7	62.5	49.2	64.7	64.5	52.7
f-methanol+ICE		40.5	56.6	62.5	38.1	51.8	54.2
e-methanol+ICE		68.8	67.5	59.0	69.4	68.9	61.3
e-methanol+PEMFC		60.5	57.7	44.9	60.5	57.7	44.9
f-NH3+ICE		35.7	51.4	57.6	31.5	42.9	42.7
f-NH3+PEMFC		28.9	39.3	34.5	28.9	39.3	34.5
f-NH3+SOFC		31.1	37.3	32.8	31.1	37.3	32.8
e-NH3+ICE		61.8	64.3	60.6	62.0	64.7	61.3
e-NH3+PEMFC		63.9	59.3	44.5	63.9	59.3	44.5
e-NH3+SOFC		66.1	57.3	42.8	66.1	57.3	42.8
e-LH2+ICE		58.2	62.6	59.3	58.3	62.8	59.7
e-LH2+PEMFC		60.5	55.2	40.3	60.5	55.2	40.3
EU-mix+batteries		0.0	0.0	0.0	0.0	0.0	0.0

The findings demonstrate consistent trends across all decision maker (DM) profiles. Combinations utilizing renewable energy sourced vectors exhibit equal or higher final scores in the scenario with carbon taxes (scenario B) compared to scenario A. Conversely, for combinations relying on fossil fuels, the final scores in scenario B are lower than those in scenario A. These results suggest that carbon taxes influence the performance of various fuel-power system combinations, favouring greener alternatives and discouraging fossil-based options.

The total scores (0-100) of the presented alternatives for the pax-ferry in both scenarios, with and without carbon taxation measures, are presented in Table 36.

Table 36 - Final scores (0-100, worst to best) of each decision maker for the pax-ferry, in scenarios A and B.
Colour scale: dark green values are the ones with higher scores and the dark red ones represent the lower final scores.

PAX-FERRY		A - without carbon taxes			B - with carbon taxes		
1st decade	**2nd+3rd decades**	**Total Score Environmentalist**	**Total Score Balanced**	**Total Score Investor**	**Total Score Environmentalist**	**Total Score Balanced**	**Total Score Investor**
HFO+ICE	HFO+ICE	46.6	60.7	62.7	47.2	61.8	64.8
	f-LNG+ICE	39.6	52.7	53.0	40.5	54.5	56.1
	e-LNG+ICE	43.5	52.8	48.8	45.6	57.0	56.1
	e-diesel+ICE	48.6	56.9	51.0	50.9	61.6	59.2
	f-methanol+ICE	37.7	50.6	50.7	38.5	52.2	53.5
	e-methanol+ICE	50.4	56.3	50.9	52.6	60.7	58.6
	e-methanol+PEMFC	45.8	51.7	46.5	48.2	56.4	54.7
	f-NH3+ICE	32.3	44.3	43.0	32.7	44.9	44.1
	f-NH3+PEMFC	31.5	43.5	41.9	29.6	39.7	35.1
	f-NH3+SOFC	0.0	0.0	0.0	0.0	0.0	0.0
	e-NH3+ICE	42.7	49.6	44.6	44.9	54.0	52.4
	e-NH3+PEMFC	46.8	51.7	44.8	49.3	56.7	53.6
	e-NH3+SOFC	0.0	0.0	0.0	0.0	0.0	0.0
	e-LH2+ICE	38.1	45.0	38.6	40.7	50.1	47.6
	e-LH2+PEMFC	42.4	45.5	37.0	45.2	51.2	47.0
	EU-mix+batteries	48.4	60.6	62.7	49.6	63.0	66.9
f-LNG+ICE		39.8	53.7	54.9	40.5	55.1	57.3
e-LNG+ICE		58.2	60.6	51.4	60.6	65.3	59.6
e-diesel+ICE		64.0	63.1	49.7	67.0	69.2	60.2
f-methanol+ICE		38.9	53.2	53.7	39.5	54.6	56.1
e-methanol+ICE		67.4	64.9	53.0	70.0	70.0	62.1
e-methanol+PEMFC		61.2	59.1	47.7	64.0	64.6	57.2
f-NH3+ICE		33.8	47.6	47.2	33.8	47.6	47.2
f-NH3+PEMFC		30.3	42.1	41.3	27.8	37.0	32.4
f-NH3+SOFC		0.0	0.0	0.0	0.0	0.0	0.0
e-NH3+ICE		58.7	58.2	48.8	61.0	62.8	56.7
e-NH3+PEMFC		64.4	60.3	48.1	67.0	65.4	57.2
e-NH3+SOFC		0.0	0.0	0.0	0.0	0.0	0.0
e-LH2+ICE		53.2	52.4	42.7	55.5	57.2	51.1
e-LH2+PEMFC		61.7	57.7	44.8	64.5	63.1	54.4
EU-mix+batteries		60.2	65.5	64.0	61.6	68.2	68.7

4.4. Key findings

To summarize key findings, it was decided to present a resume table for both the container ship and the pax-ferry, showcasing the top three scored combinations for each type of DM for both vessels –Table 37. The combinations presented in blue represent fossil energy vectors, and the green ones represent renewable energy vectors. ‘R:’ represents a combination from the “retrofit set”, meaning those alternatives had the HFO+ICE combination in the 1st decade and then went through a retrofit in 2030; ‘N:’ represents a combination from the “new set”. The complete table including every analysed vessel’s results is in Table B.12.

Table 37 - Summary table with the top 3 choices for the container ship and pax-ferry for scenarios A and B.
Sustainable alternatives highlighted in green, fossil alternatives in blue; ‘N:’ means the combination is from the “new set” of combinations, ‘R:’ means the combination is from the “retrofit set” of combinations.

		A - No Carbon Tax		B - With Carbon Tax	
Vessel	**Decision Maker**	**Option**	**Score**	**Option**	**Score**
CONTAINER	Environmentalist	N: **e-methanol+ICE**	68.8	N: **e-methanol+ICE**	69.4
		N: e-NH3+SOFC	66.1	N: e-NH3+SOFC	66.1
		N: e-LNG+ICE	64.2	N: e-diesel + ICE	64.7
	Balanced	N: e-LNG+ICE	68.8	N: e-LNG+ICE	69.3
		N: e-methanol+ICE	67.5	N: e-methanol+ICE	68.9
		N: HFO+ICE	66.4	N: e-NH3+ICE	64.7
	Investor	N: **HFO+ICE**	73.2	N: **HFO+ICE**	66.3
		N: f-LNG+ICE	72.7	N: f-LNG+ICE	64.9
		R: f-LNG + ICE	72.4	R: f-LNG + ICE	64.8
PAX-FERRY	Environmentalist	N: **e-methanol+ICE**	67.4	N: **e-methanol+ICE**	70.0
		N: e-NH3+PEMFC	64.4	N: e-NH3+PEMFC	67.0
		N: e-diesel + ICE	64.0	N: e-diesel + ICE	67.0
	Balanced	N: EU-mix + Batteries	65.5	N: e-methanol+ICE	70.0
		N: e-methanol+ICE	64.9	N: e-diesel + ICE	69.2
		N: e-diesel+ICE	63.1	N: EU-mix + Batteries	68.2
	Investor	N: **EU-mix+batteries**	64.0	N: EU-mix + Batteries	68.7
		N: HFO+ICE	62.7	R: EU-mix + Batteries	66.9
		R: EU-mix+batteries	62.7	N: HFO+ICE	64.8

Container ship:

The environmentalist's top three options for the container ship align with the expected preference for “green” alternatives sourced from renewables, with the best scoring option being e-methanol+ICE. Notably, the top 3 alternatives do not involve any retrofits, which could be explained by the default combination's significant WTW emissions in the first decade. Despite the exorbitant costs associated with combinations involving SOFCs due to their frequent need for replacements during the container ship's lifetime, the second-best combination in both scenarios is e-NH3+SOFC from the "new set" of combinations, even though the cost criterion accounts for 10% of this environmentalist’s evaluation. The third-best option varies between the two scenarios, and this difference can be attributed to carbon taxation: in scenario B, e-diesel+ICE ranks higher than e-LNG+ICE because of carbon taxes, since e-LNG in an internal combustion engine has higher emissions than synthetic diesel, hence its higher costs and lower ranking.

Examining the top three options for the container ship from the Investor's perspective, it becomes evident that there is a preference for fossil energy vectors, as all three combinations are highlighted in blue in both scenarios (with and without carbon taxation). However, the top three options do not stand out as the most cost-effective, being surpassed by e-LH2+ICE and e-NH3+ICE from the “retrofit set”, and even by the e-LH2+ICE from the “new set”, in scenario B. Nonetheless, e-LH2+ICE from the “retrofit set” was excluded due to volume incompatibility, and e-NH3+ICE exhibited suboptimal performance concerning the energy vector production TRL and the power system TRL criteria. Thus, in these conditions of analysis, carbon taxation appears to be insufficient in persuading this particular decision maker to adopt more sustainable alternative combinations for a container ship. Notably, if the carbon tax were to be increased to an average of 100 €/tCO_2 in the 1st decade, 200 €/tCO_2 in the 2nd, and 250 €/tCO_2 in the 3rd, the investor DM would rank a sustainable combination as the best performing one: e-LNG+ICE from the “new set”, with a final score of 64, closely followed by HFO+ICE with a final score of 63.

It is worth mentioning that none of the best scoring options for the container ship in the viewpoint of the Investor feature FCs or batteries, possibly due to their exorbitant costs for a vessel of this size undertaking longer voyages. This outcome stems from the recurrent replacements required for FCs during the vessel's lifetime, and the elimination of Li-ion batteries due to volume incompatibility. Consequently, the highest-ranked combination involving a FC, namely e-NH3+PEMFC in the “new set”, occupies a modest 17th place in the overall ranking.

Nonetheless, when equal importance is given to the WTW Emissions and the Total Costs criteria, a more cost-balanced and environmentally friendly outcome is reached. For the Balanced decision maker results, carbon taxes exhibit greater efficacy, as there are no fossil sourced combinations among the top three choices of this DM in scenario B. The combination e-LNG+ICE from the "new set" of options claims the top spot in both scenarios. This equilibrated assessment is noteworthy for its absence of fuel cells (FC) and batteries in the top-ranked positions, highlighting their unviability for this particular type of ship, even when giving proportioned importance to emissions and costs.

Pax-ferry:

The pax-ferry's top-ranked options from the Environmentalist's viewpoint remain consistent across both scenarios, all hailing from renewable sources. The combination e-methanol+ICE from the "new set" of options claims the 1st place, followed by e-NH3+PEMFC, also from the "new set," securing the 2nd position, and e-diesel+ICE also from the “new set” of combinations in 3rd place. It is worth mentioning that, for the pax-ferry, the combinations involving PEMFCs do not require replacements due to their limited hours of operation, compared with larger vessels that endure longer journeys, rendering their total costs comparable and competitive to other alternatives, since they are within the same order of magnitude as the rest.

From the Investor's perspective, both scenarios point towards a more environmentally conscious podium when compared to the Investor’s choices for the container ship, as the best choice is the EU-mix+batteries combination from the "new set". This combination showcases significantly lower WTW emissions, less than half of the HFO+ICE combination (baseline). This result highlights the suitability of Li-ion batteries for smaller vessels engaged in shorter voyages, even for decision makers emphasizing costs with a 35% weightage. Furthermore, carbon taxation measures exhibit some effectiveness, as evidenced by the default combination's rankings. HFO+ICE is ranked 2nd without carbon taxes and 3rd in scenario B (with carbon taxes).

Lastly, the balanced decision maker’s podium options are all highlighted in green for both scenarios, encountering the same environmentally friendly top three options with different rankings - EU-mix+batteries, e-diesel+ICE, and e-methanol+ICE.

When examining the complete resume table that showcases the top three ranked options for every decision maker (DM) for the 5 analysed vessels (Table B.12), several overall key observations emerge:

Global Environmentalist DM’s Perspective:

The top three options for each vessel, as seen from the environmentalist's point of view, are all "green" and environmentally friendly, regardless of the ship and the scenario. This indicates that certain energy vector-power system combinations stand out as clear winners when prioritizing emissions reduction and sustainability.

For every vessel type and scenario, the best-scoring option is e-methanol+ICE from the "new set" of combinations. This implies that this combination is a strong contender for achieving significant environmental benefits across different vessel types and regular voyages.

Global Investor DM’s Perspective:

The container ship, general cargo ship, and ro-pax ship share the same top three fossil fuel options – N: HFO+ICE, N: f-LNG+ICE, R: f-LNG+ICE - regardless of the presence of carbon taxes. These top three options are also shared by the fishing trawler in scenario A. This suggests that longer voyages might favour specific fossil fuel options in the eyes of investors with high regard for costs.

The pax-ferry in both scenarios and the fishing trawler in Scenario B, are the only vessels that show a preference for "green" options in the investor’s viewpoint. EU-mix+batteries for the pax-ferry and e-methanol+ICE for the fishing trawler, both from the "new set" of combinations, are considered among the three best-scoring options. This indicates that smaller vessels might find "green" alternatives attractive to investors.

Fuel cells not yet competitive:

- It is noteworthy that no fuel cell-based options appear in the top three choices for either the investor or the balanced decision makers. This might suggest that, based on the criteria and weightages considered, FC technology might not currently offer the most attractive solutions for decarbonization in the maritime sector. Indeed, with the advancement of technology and improvements in FC design and materials, it is anticipated that FCs shall become more competitive in the future. As their lifespan increases, the need for frequent replacements will decrease, contributing to lower operational costs over the vessel's lifetime. Additionally, research and development efforts aimed at enhancing the efficiency and performance of FCs hold the potential to make them a viable and attractive option for maritime applications.

Liquefied hydrogen (LH_2) not yet competitive:

- No combinations powered by LH_2 emerged among the top three scoring options for any vessel. The most favourable rank achieved for liquefied hydrogen was the combination e-LH2+PEMFC, which secured the 4th place for the pax-ferry, as viewed from the environmentalist's perspective. While LH_2 exhibited subpar performance in certain criteria, particularly in the Energy Vector Production TRL and the Infrastructure ones, substantial research is ongoing in the domain of LH_2 production via electrolysis powered by renewables. This research is inevitably leading to significant investments in hydrogen infrastructure. Consequently, LH_2 may not currently offer the most enticing solution to decarbonize the maritime sector, but it is poised to play a pivotal role in the long run, as supported by the literature.

Consistency for Container and General Cargo ships:

- The container ship and general cargo ship have almost identical best-ranked options across all decision maker types. This indicates that larger vessels that endure longer voyages might have a relatively narrow range of optimal energy vector and power system combinations from different decision maker perspectives.

Balanced DM’s Perspective:

- The balanced decision maker's top three options for each vessel type consistently prioritize "green" alternatives. Another key observation is that there are no retrofit options in the best scoring options of this DM. This suggests that it is possible to achieve a more sustainable maritime transport sector by equally considering WTW emissions and total costs in the decision-making process, and that building a new vessel powered by a sustainable energy vector is more attractive than retrofitting after a decade.

5. Conclusion

5.1. Main contributions

The present dissertation embarked on a crucial quest to address the urgent challenge of decarbonizing the maritime transport sector, by identifying optimal energy vector and power system combinations across various decision criteria. This study sought to answer the pivotal research question: « Which energy vector and power system combinations should stakeholders bet on to effectively decarbonize different vessel types in the maritime transport sector? ». Through a comprehensive MCDA based model and a thorough analysis of diverse vessels, this research provides valuable insights into charting a sustainable and low-carbon course for the maritime industry.

The examination of different decision maker's (DM) perspectives has highlighted distinct priorities and preferences when choosing the optimal alternative combination that would better suit each vessel.

From the perspective of the Environmentalist DM, the top three choices for each vessel type and scenario analysed overwhelmingly favour "green" alternatives sourced from renewables. Notably, e-methanol+ICE emerges as a consistent top performer for every vessel type, showcasing its potential to significantly reduce emissions and foster sustainability in the maritime sector. Through a comparative analysis of this combination's emission factor (EF) with the default one derived from HFO+ICE, e-methanol+ICE yields an impressive reduction of over 94% in greenhouse gas (GHG) emissions. Nonetheless, such a notable emissions' reduction cannot come without a cost. In fact, to implement this combination, total costs increase more than 200% without considering carbon taxes, but there is only an increase of 17% in scenario B, compared to the baseline combination (HFO+ICE).

Conversely, the Investor DM's viewpoint still reflects a preference for fossil fuel options, with all three top choices originating from fossil sources for the container ship, the general cargo ship, and the ro-pax ship. Carbon taxation appears to have limited effectiveness in steering the investor towards sustainable alternatives for larger vessels, as other cost considerations outweigh the influence of carbon taxes on total costs. This suggests that, for larger vessels with longer voyages, additional incentives and regulations may be necessary to accelerate the adoption of greener energy alternatives for Investor's like profiles, namely more strict carbon taxation measures.

Nonetheless, the perspective of the Balanced DM yields important insights by giving equal and significant importance to emissions and costs and, perhaps, provides the most equilibrated and suitable answers. The consistent mostly "green" top three options for every vessel type emphasize that a balanced approach can effectively lead to more sustainable maritime transport, achieving feasible solutions without disregarding costs. By equally considering environmental impact and economic viability, decision makers can strike a harmonious balance between reducing emissions and managing costs, thereby fostering a greener and more sustainable maritime sector. And so, for the container ship, general cargo ship and ro-pax ship, the top performers are the same: in scenario A the winner is e-LNG+ICE with an 82% reduction in WTW emissions when compared to default, and in scenario B (with carbon taxes) the winner is e-methanol+ICE (94% reduction in emissions), both from the "new set" of alternatives. The pax-ferry best scoring options involve the EU-mix+batteries combination in scenario A, with a reduction of 28% in emissions, and e-methanol+ICE in B, both from the “new set”, which is also the best performing combination in both scenarios for the fishing trawler.

The absence of fuel cell (FC) based options in the top three choices, for both the Investor and the Balanced DM, highlights the current limitations of FC technology for larger vessels with longer journeys, primarily due to high costs and the need for recurrent replacements. However, the promising advancements in FC research and development offer hope for their future viability and competitiveness in maritime applications.

Liquefied hydrogen (LH_2) also did not emerge among the top three scoring options for any vessel, indicating that, in the current context, LH_2 might not offer the most enticing solution for decarbonization. Nonetheless, ongoing developments in LH_2 production from renewables and infrastructure underscore its potential role in the long run as a viable and sustainable energy source for the maritime sector.

Ultimately, this research presents a substantial contribution to the imperative task of decarbonizing the maritime sector by offering vital guidance to policymakers, ship owners, investors, and other stakeholders in making informed decisions. By leveraging the insights from the MCDA based model and considering different decision maker perspectives, stakeholders can chart a strategic course towards a sustainable maritime future. The path to effective decarbonization of this sector lies in the strategic adoption of alternative energy vector and power system combinations that balance environmental, technical, and economic considerations. Prompt action is necessary to embrace new technologies, foster collaboration between industry stakeholders and policymakers, promote innovation, and embrace greener alternatives. By collectively embodying these efforts, the maritime sector can set sail towards a cleaner and more sustainable future.

5.2. Future work

As the maritime industry forges ahead in its pursuit of sustainability, further research can explore emerging hybrid energy solutions for the transition period in the near future, where the main engine and auxiliary engine might be powered by different energy vectors or even have different power systems configurations that would better suit their operational format.

Additionally, there is still great uncertainty regarding the future state and costs of emerging technologies, and it is a considerable approximation to assume that the analysed vessels shall be representative of the whole world merchant fleet. These issues could be addressed by the implementation of advanced data collection methods and the employment of a stochastic model to deal with uncertainty (King & Wallace, 2012).

The cost of lost cargo in the “new set” of combinations should also be included in future work to assess how much the 15% buffer in fuel capacity would influence results. Also, instead of basing the research in a MCDA model with the simplifications used in this dissertation, a refined MCDA model could be applied, following the proper guidelines to engage real stakeholders in the industry as a focus group to delineate DM’s profiles, like the research of Hansson et al. (2019) has proposed.

Finally, research has proven that the combined approach of life-cycle assessment (LCA) techniques with a MCDA model offers the most appropriate and complete framework for evaluation of sustainable energy systems (Campos-Guzmán et al., 2019) and so, the inclusion of LCA approaches would greatly enhance future investigations.

References

Abdul Jameel, A. G., Alkhateeb, A., Telalović, S., Elbaz, A. M., Roberts, W. L., & Sarathy, S. M. (2019). *Environmental Challenges and Opportunities in Marine Engine Heavy Fuel Oil Combustion* (pp. 1047–1055). https://doi.org/10.1007/978-981-13-3119-0_72

Al-Breiki, M., & Bicer, Y. (2020). Comparative cost assessment of sustainable energy carriers produced from natural gas accounting for boil-off gas and social cost of carbon. *Energy Reports*, *6*, 1897–1909. https://doi.org/10.1016/j.egyr.2020.07.013

Ampah, J. D., Yusuf, A. A., Afrane, S., Jin, C., & Liu, H. (2021). Reviewing two decades of cleaner alternative marine fuels: Towards IMO's decarbonization of the maritime transport sector. *Journal of Cleaner Production*, *320*. https://doi.org/10.1016/j.jclepro.2021.128871

Appl, M. (2011). Ammonia, 2. Production Processes. Em *Ullmann's Encyclopedia of Industrial Chemistry*. Wiley-VCH Verlag GmbH & Co. KGaA. https://doi.org/10.1002/14356007.o02_o11

Aspen, D. M., & Sparrevik, M. (2020). Evaluating alternative energy carriers in ferry transportation using a stochastic multi-criteria decision analysis approach. *Transportation Research Part D: Transport and Environment*, *86*, 102383. https://doi.org/10.1016/j.trd.2020.102383

Atilhan, S., Park, S., El-Halwagi, M. M., Atilhan, M., Moore, M., & Nielsen, R. B. (2021). Green hydrogen as an alternative fuel for the shipping industry. *Current Opinion in Chemical Engineering*, *31*. https://doi.org/10.1016/j.coche.2020.100668

Bach, H., & Hansen, T. (2023). Flickering guiding light from the International Maritime Organisation's policy mix. *Environmental Innovation and Societal Transitions*, *47*, 100720. https://doi.org/10.1016/j.eist.2023.100720

Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A., & Staffell, I. (2019). How to decarbonise international shipping: Options for fuels, technologies, and policies. *Energy Conversion and Management*, *182*, 72–88. https://doi.org/10.1016/j.enconman.2018.12.080

Balcombe, P., Staffell, I., Kerdan, I. G., Speirs, J. F., Brandon, N. P., & Hawkes, A. D. (2021). How can LNG-fuelled ships meet decarbonisation targets? An environmental and economic analysis. *Energy*, *227*. https://doi.org/10.1016/j.energy.2021.120462

Ballard. (2021). *Fuel Cell Power Module for Marine Applications*.

Benvenuto, G., Campora, U., Laviola, M., & Terlizzi, G. (2017). Simulation Model of a Dual-Fuel Four Stroke Engine for Low Emission Ship Propulsion Applications. *International Review of Mechanical Engineering (IREME)*, *11*(11), Artigo 11. https://doi.org/10.15866/ireme.v11i11.11929

Berckmans, G., Messagie, M., Smekens, J., Omar, N., Vanhaverbeke, L., & Van Mierlo, J. (2017). Cost Projection of State of the Art Lithium-Ion Batteries for Electric Vehicles Up to 2030. *Energies*, *10*(9), Artigo 9. https://doi.org/10.3390/en10091314

Bergek, A., Bjørgum, Ø., Hansen, T., Hanson, J., & Steen, M. (2021). Sustainability transitions in coastal shipping: The role of regime segmentation. *Transportation Research Interdisciplinary Perspectives*, *12*, 100497. https://doi.org/10.1016/j.trip.2021.100497

Bilgili, L. (2023). A systematic review on the acceptance of alternative marine fuels. *Renewable and Sustainable Energy Reviews*, *182*, 113367. https://doi.org/10.1016/j.rser.2023.113367

Blenkey, N. (2022, junho 1). *MAN Engines introduces first hydrogen dual fuel engine for workboats*. Marine Log. https://www.marinelog.com/offshore/offshore-wind/man-engines-introduces-first-hydrogen-dual-fuel-engine-for-workboats/

Bloom Energy. (2023). *The Bloom Energy Server 5.5*.

Burel, F., Taccani, R., & Zuliani, N. (2013). Improving sustainability of maritime transport through utilization of Liquefied Natural Gas (LNG) for propulsion. *Energy*, *57*, 412–420. https://doi.org/10.1016/j.energy.2013.05.002

C J McKinlay, S R Turnock, & D A Hudson. (2020). *A Comparison of Hydrogen and Ammonia for Future Long Distance Shipping Fuels*.

Campos-Guzmán, V., García-Cáscales, M. S., Espinosa, N., & Urbina, A. (2019). Life Cycle Analysis with Multi-Criteria Decision Making: A review of approaches for the sustainability evaluation of renewable energy technologies. *Renewable and Sustainable Energy Reviews*, *104*, 343–366. https://doi.org/10.1016/j.rser.2019.01.031

Chakraborty, S., & Yeh, C.-H. (2007). *A Simulation Based Comparative Study of Normalization Procedures in Multiattribute Decision Making Big Data Analytics for sustainable healthcare supply chain View project Video Coding and Compression View project A Simulation Based Comparative Study of Normalization Procedures in Multiattribute Decision Making*. https://www.researchgate.net/publication/254468351

Cheliotis, M., Boulougouris, E., Trivyza, N. L., Theotokatos, G., Livanos, G., Mantalos, G., Stubos, A., Stamatakis, E., & Venetsanos, A. (2021). Review on the Safe Use of Ammonia Fuel Cells in the Maritime Industry. *Energies*, *14*(11), 3023–3023. https://doi.org/10.3390/en14113023

Chen, C., Saikawa, E., Comer, B., Mao, X., & Rutherford, D. (2019). Ship Emission Impacts on Air Quality and Human Health in the Pearl River Delta (PRD) Region, China, in 2015, With Projections to 2030. *GeoHealth*, *3*. https://doi.org/10.1029/2019GH000183

Cigolotti, V., Genovese, M., & Fragiacomo, P. (2021). Comprehensive Review on Fuel Cell Technology for Stationary Applications as Sustainable and Efficient Poly-Generation Energy Systems. *Energies*, *14*, 4963. https://doi.org/10.3390/en14164963

Clifford Denn Design. (2023). 215m Pride of Hull. *Clifford Denn*. https://clifforddenn.com/project/215m-pride-of-hull/

Deheri, C., Acharya, S. K., Thatoi, D. N., & Mohanty, A. P. (2020). A review on performance of biogas and hydrogen on diesel engine in dual fuel mode. *Fuel*, *260*, 116337. https://doi.org/10.1016/j.fuel.2019.116337

DEMACO. (2022). *The energy density of hydrogen: A unique property*.

DNV. (2022a). *HYDROGEN FORECAST TO 2050*.

DNV. (2022b). *MARITIME FORECAST TO 2050*.

DNV GL. (2022). *Alternative Fuels Insight*. https://afi.dnv.com/

DNV GL. (2023). *Methanol as fuel heads for the mainstream in shipping—DNV*. DNV GL. https://www.dnv.com/expert-story/DigitalMagazineDefault

DOE - USA. (2013). *Growing Demand for Natural Gas Emergence of the Global LNG Market*.

Elishav, O., Mosevitzky Lis, B., Valera-Medina, A., & Grader, G. S. (2021). Storage and Distribution of Ammonia. Em *Techno-Economic Challenges of Green Ammonia as an Energy Vector* (pp. 85–103). Elsevier. https://doi.org/10.1016/b978-0-12-820560-0.00005-9

Elkafas, A. G., Rivarolo, M., Gadducci, E., Magistri, L., & Massardo, A. F. (2023). Fuel Cell Systems for Maritime: A Review of Research Development, Commercial Products, Applications, and Perspectives. *Processes*, *11*(1). https://doi.org/10.3390/pr11010097

EMSA. (2023). *CO2 Emissions Report*. https://mrv.emsa.europa.eu/#public/emission-report

Encyclopaedia Britannica. (2022). Haber-Bosch Process. *Haber-Bosch Process | Definition, Conditions, Importance, & Facts*. https://www.britannica.com/technology/Haber-Bosch-process

Endres, S., Maes, F., Hopkins, F., Houghton, K., Mårtensson, E. M., Oeffner, J., Quack, B., Singh, P., & Turner, D. (2018). A New Perspective at the Ship-Air-Sea-Interface: The Environmental Impacts of Exhaust Gas Scrubber Discharge. *Frontiers in Marine Science*, *5*. https://www.frontiersin.org/articles/10.3389/fmars.2018.00139

Engineering ToolBox. (2004). *Metals and Alloys - Densities*. https://www.engineeringtoolbox.com/metal-alloys-densities-d_50.html

EPA. (2022). *Overview of Greenhouse Gases*. https://www.epa.gov/ghgemissions/overview-greenhouse-gases

Equasis. (2021). *The 2021 World Merchant Fleet*.

European Commission. (2021a). *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://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0562&tnqh_x0026;qid=1632150729354

European Commission. (2021b). *COMMISSION STAFF WORKING DOCUMENT IMPACT ASSESSMENT Accompanying the Proposal for a Regulation of the European Parliament and of the Council on the use of renewable and low-carbon fuels in maritime transport*. . https://eur-lex.europa.eu/LexUriServ/LexUriServ.do? uri=SWD:2021:0635:FIN:EN:PDF

European Sustainable Shipping Forum. (2022). MARIN. *Sustainable Alternative Power for Shipping*.

Eurostat. (2023). *Electricity prices for non-household consumers—Bi-annual data (from 2007 onwards)*. https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_205/default/bar?lang=en

Fahnestock, J., Søgaard, K., Lawson, E., & Kilemo, H. (2021). *NoGAPS: Nordic Green Ammonia Powered Ship*.

Fontelle, J.-P., Fridell, E., Grigoriadis, A., Hill, N., Kilde, N., Lavender, K., Mamarikas, S., Reynolds, G., Rypdal, K., Thomas, R., Webster, A., & Winther, M. (2019). *EMEP/EEA air pollutant emission inventory guidebook*.

Forster, P., Alterskjaer, K., Smith, C., Colman, R., Damon Matthews, H., Ramaswamy, V., Storelvmo, T., Armour, K., Collins, W., Dufresne, J., Frame, D., Lunt, D., Mauritsen, T., Watanabe, M., Wild, M., Zhang, H., Pirani, A., Connors, S., Péan, C., … Zhou, B. (2021). *The Earth's Energy Budget, Climate Feedbacks and Climate Sensitivity*. 923–1054. https://doi.org/10.1017/9781009157896.009

FuelCellsWorks. (2021). *Norway: MF "Hydra", The World's First Hydrogen Operated Ferry Wins Ship Of The Year 2021*. https://fuelcellsworks.com/news/norway-mf-hydra-the-worlds-first-hydrogen-operated-ferry-wins-ship-of-the-year-2021/

Fuglestvedt, J. S., Dalsøren, S. B., Samset, B. H., Berntsen, T., Myhre, G., Hodnebrog, Ø., Eide, M. S., & Bergh, T. F. (2014). Climate Penalty for Shifting Shipping to the Arctic. *Environmental Science & Technology*, *48*(22), 13273–13279. https://doi.org/10.1021/es502379d

Giddey, S., Badwal, S. P. S., Munnings, C., & Dolan, M. (2017). Ammonia as a Renewable Energy Transportation Media. *ACS Sustainable Chemistry & Engineering*, *5*(11), 10231–10239. https://doi.org/10.1021/acssuschemeng.7b02219

Gough, C., & Upham, P. (2010). *Biomass energy with carbon capture and storage (BECCS): A review*.

Gray, N., McDonagh, S., O'Shea, R., Smyth, B., & Murphy, J. D. (2021). Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. *Advances in Applied Energy*, *1*. https://doi.org/10.1016/j.adapen.2021.100008

Grigoriev, S., Porembsky, V., & Fateev, V. (2006). Pure hydrogen production by PEM electrolysis for hydrogen energy. *International Journal of Hydrogen Energy*, *31*(2), 171–175. https://doi.org/10.1016/j.ijhydene.2005.04.038

Guo, Y., Li, G., Zhou, J., & Liu, Y. (2019). Comparison between hydrogen production by alkaline water electrolysis and hydrogen production by PEM electrolysis. *IOP Conference Series: Earth and Environmental Science*, *371*(4), 042022–042022. https://doi.org/10.1088/1755-1315/371/4/042022

Habibic, A. (2023, março 29). Ship design for NoGAPS ammonia-fueled gas carrier comes to light. *Offshore Energy*. https://www.offshore-energy.biz/ship-design-for-nogaps-ammonia-fueled-gas-carrier-comes-to-light/

Hansen, J. F., & Wendt, F. (2015). History and State of the Art in Commercial Electric Ship Propulsion, Integrated Power Systems, and Future Trends. *Proceedings of the IEEE*, *103*(12), 2229–2242. https://doi.org/10.1109/JPROC.2015.2458990

Hansson, J., Månsson, S., Brynolf, S., & Grahn, M. (2019). Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders. *Biomass and Bioenergy*, *126*, 159–173. https://doi.org/10.1016/j.biombioe.2019.05.008

Hofstrand, D. (2009). Ammonia as a Transportation Fuel. *Agricultural Marketing Research Center*. https://www.agmrc.org/renewable-energy/renewable-energy-climate-change-report/renewable-energy-climate-change-report/may-2009-newsletter/ammonia-as-a-transportation-fuel

HyShip. (2022). About HyShip. *HyShip*. https://hyship.eu/about/

IEA. (2022). *World Energy Outlook 2022*. www.iea.org/t&c/

IMO. (2018). *UNFCCC Talanoa Dialogue*. Note by the International Maritime Organization.

IMO. (2023). *EEXI and CII - ship carbon intensity and rating system*. https://www.imo.org/en/MediaCentre/HotTopics/Pages/EEXI-CII-FAQ.aspx

IMO - International Maritime Organization. (2020). *Fourth IMO Greenhouse Gas Study*.

International Chamber of Shipping. (2023). *Container Ships*. https://www.ics-shipping.org/explaining/ships-ops/container-ships/

IPCC. (2007). *IPCC Fourth Assessment Report: Climate Change—Appendix Glossary*. http://unfccc.int.

Islam Rony, Z., Mofijur, M., Hasan, M. M., Rasul, M. G., Jahirul, M. I., Forruque Ahmed, S., Kalam, M. A., Anjum Badruddin, I., Yunus Khan, T. M., & Show, P. L. (2023). Alternative fuels to reduce greenhouse gas emissions from marine transport and promote UN sustainable development goals. *Fuel*, *338*. https://doi.org/10.1016/j.fuel.2022.127220

Jahan, A., & Edwards, K. L. (2013). Chapter 3—Multi-criteria Decision-Making for Materials Selection. Em A. Jahan & K. L. Edwards (Eds.), *Multi-criteria Decision Analysis for Supporting the Selection of Engineering Materials in Product Design* (pp. 31–41). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-08-099386-7.00003-9

Jahan, A., Edwards, K. L., & Bahraminasab, M. (2016). 5—Multi-attribute decision-making for ranking of candidate materials. Em A. Jahan, K. L. Edwards, & M. Bahraminasab (Eds.), *Multi-criteria Decision Analysis for Supporting the Selection of Engineering Materials in Product Design (Second Edition)* (pp. 81–126). Butterworth-Heinemann. https://doi.org/10.1016/B978-0-08-100536-1.00005-9

Jain, I. P. (2009). Hydrogen the fuel for 21st century. *International Journal of Hydrogen Energy*, *34*(17), 7368–7378. https://doi.org/10.1016/j.ijhydene.2009.05.093

Jalkanen, J.-P., Johansson, L., Kukkonen, J., Brink, A., Kalli, J., & Stipa, T. (2012). Extension of an assessment model of ship traffic exhaust emissions for particulate matter and carbon monoxide. *Atmospheric Chemistry and Physics*, *12*(5), 2641–2659. https://doi.org/10.5194/acp-12-2641-2012

Karim, G. A. (1980). A review of combustion processes in the dual fuel engine—The gas diesel engine. *Progress in Energy and Combustion Science*, *6*(3), 277–285. https://doi.org/10.1016/0360-1285(80)90019-2

King, A. J., & Wallace, S. W. (2012). *Modeling with Stochastic Programming*. Springer New York.

https://doi.org/10.1007/978-0-387-87817-1

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

Koski, M., Stedmon, C., & Trapp, S. (2017). Ecological effects of scrubber water discharge on coastal plankton: Potential synergistic effects of contaminants reduce survival and feeding of the copepod Acartia tonsa. *Marine Environmental Research*, *129*, 374–385. https://doi.org/10.1016/j.marenvres.2017.06.006

Kreuter, W., & Hofmann, H. (1998). Electrolysis: The important energy transformer in a world of sustainable energy. *International Journal of Hydrogen Energy*, *23*(8), 661–666. https://doi.org/10.1016/S0360-3199(97)00109-2

Kumar, S., Kwon, H. T., Choi, K. H., Lim, W., Cho, J. H., Tak, K., & Moon, I. (2011). LNG: An eco-friendly cryogenic fuel for sustainable development. *Applied Energy*, *88*(12), 4264–4273. https://doi.org/10.1016/j.apenergy.2011.06.035

Kurien, C., & Mittal, M. (2022). Review on the production and utilization of green ammonia as an alternate fuel in dual-fuel compression ignition engines. *Energy Conversion and Management*, *251*, 114990. https://doi.org/10.1016/j.enconman.2021.114990

Kyriakou, V., Garagounis, I., Vasileiou, E., Vourros, A., & Stoukides, M. (2017). Progress in the Electrochemical Synthesis of Ammonia. *Catalysis Today*, *286*, 2–13. https://doi.org/10.1016/j.cattod.2016.06.014

Lagemann, B., Lindstad, E., Fagerholt, K., Rialland, A., & Ove Erikstad, S. (2022). Optimal ship lifetime fuel and power system selection. *Transportation Research Part D: Transport and Environment*, *102*. https://doi.org/10.1016/j.trd.2021.103145

Law, L. C., Foscoli, B., Mastorakos, E., & Evans, S. (2021). A comparison of alternative fuels for shipping in terms of lifecycle energy and cost. *Energies*, *14*(24). https://doi.org/10.3390/en14248502

Leclanché. (2023). *M3 Energy Module*.

Leeuwen, J. V., & Koppen, K. V. (2016). Moving Sustainable Shipping Forward: The Potential of Market-based Mechanisms to Reduce CO2 Emissions from Shipping. *The Journal of Sustainable Mobility*, *3*(2), 42–66. https://doi.org/10.9774/GLEAF.2350.2016.de.00004

Lindstad, E., & Rialland, A. (2020). LNG and cruise ships, an easy way to fulfil regulations-versus the need for reducing GHG emissions. *Sustainability (Switzerland)*, *12*(5), 1–15. https://doi.org/10.3390/su12052080

Lloyd's Register. (2020). *Techno-economic assessment of zero-carbon fuels*. www.imo.org

Lloyd's Register. (2023). *Fuel for thought: Methanol report*. Lloyd's Register. https://www.lr.org/en/knowledge/research-reports/fuel-for-thought-methanol-report/

MacFarlane, D. R., Cherepanov, P. V., Choi, J., Suryanto, B. H. R., Hodgetts, R. Y., Bakker, J. M., Ferrero Vallana, F. M., & Simonov, A. N. (2020). A Roadmap to the Ammonia Economy. *Joule*, *4*(6), 1186–1205. https://doi.org/10.1016/j.joule.2020.04.004

Maersk. (2013). *Emma Maersk: After immediate repairs, the onward journey begins*. https://www.maersk.com/news/articles/2013/02/15/emma-maersk-after-immediate-repairs-the-onward-journey-begins

Mallouppas, G., Ioannou, C., & Yfantis, E. A. (2022). A Review of the Latest Trends in the Use of Green Ammonia as an Energy Carrier in Maritime Industry. *Energies*, *15*(4). https://doi.org/10.3390/en15041453

Malmborg, F. von. (2023). Advocacy coalitions and policy change for decarbonisation of international maritime transport: The case of FuelEU maritime. *Maritime Transport Research*, *4*, 100091. https://doi.org/10.1016/j.martra.2023.100091

MAN Engines. (2022). *MAN Engines: The first dual fuel hydrogen engines in use on a work boat*. MAN Engines: The First Dual Fuel Hydrogen Engines in Use on a Work Boat. https://press.mantruckandbus.com/corporate/man-engines-the-first-dual-fuel-hydrogen-engines-in-use-on-a-work-boat/

Manabe, A., Kashiwase, M., Hashimoto, T., Hayashida, T., Kato, A., Hirao, K., Shimomura, I., & Nagashima, I. (2013). Basic study of alkaline water electrolysis. *Electrochimica Acta*, *100*, 249–256. https://doi.org/10.1016/j.electacta.2012.12.105

Mandra, J. O. (2020, novembro 13). AIDAnova on track to get its methanol-operated fuel cell in 2021. *Offshore Energy*. https://www.offshore-energy.biz/aidanova-on-track-to-get-its-methanol-operated-fuel-cell-in-2021/

Mandra, J. O. (2022a, setembro 8). IMO points to 77 pct drop in SOx emissions from ships since 2020. *Offshore Energy*. https://www.offshore-energy.biz/imo-points-to-77-pct-drop-in-sox-emissions-from-ships-since-2020/

Mandra, J. O. (2022b, novembro 21). Ballard installs fuel cells onboard world's 1st hydrogen-powered ferry. *Offshore Energy*. https://www.offshore-energy.biz/ballard-installs-fuel-cells-onboard-worlds-1sthydrogen-powered-ferry/

Marques, C. H., Caprace, J.-D., Belchior, C. R. P., & Martini, A. (2019). An Approach for Predicting the Specific Fuel Consumption of Dual-Fuel Two-Stroke Marine Engines. *Journal of Marine Science and Engineering*, *7*(2), Artigo 2. https://doi.org/10.3390/jmse7020020

Mazloomi, K., & Gomes, C. (2012). Hydrogen as an energy carrier: Prospects and challenges. *Renewable and Sustainable Energy Reviews*, *16*(5), 3024–3033. https://doi.org/10.1016/j.rser.2012.02.028

Methanol Institute. (2023). Renewable Methanol. *METHANOL INSTITUTE*. https://www.methanol.org/renewable/

MI News Network. (2012, novembro 29). *MS Høydal: World's First LNG Powered Ship*. Marine Insight. https://www.marineinsight.com/types-of-ships/ms-hoydal-worlds-first-lng-powered-ship/

Minnehan, J. J., & Pratt, J. W. (2017). *SANDIA REPORT Practical Application Limits of Fuel Cells and Batteries for Zero Emission Vessels*. https://classic.ntis.gov/help/order-methods/

Mueller, N., Westerby, M., & Nieuwenhuijsen, M. (2023). Health impact assessments of shipping and port-sourced air pollution on a global scale: A scoping literature review. *Environmental Research*, *216*. https://doi.org/10.1016/j.envres.2022.114460

Nemmour, A., Inayat, A., Janajreh, I., & Ghenai, C. (2023). Green hydrogen-based E-fuels (E-methane, E-methanol, E-ammonia) to support clean energy transition: A literature review. *International Journal of Hydrogen Energy*, S0360319923013393. https://doi.org/10.1016/j.ijhydene.2023.03.240

NewScientist. (2013). *Look to the past for the fuel of the future*. https://www.newscientist.com/article/mg21929283-500-look-to-the-past-for-the-fuel-of-the-future/

Nguyen, P. N., Woo, S. H., & Kim, H. (2022). Ship emissions in hotelling phase and loading/unloading in Southeast Asia ports. *Transportation Research Part D: Transport and Environment*, *105*. https://doi.org/10.1016/j.trd.2022.103223

Nordic Green Ammonia Powered Ships (NoGAPS). (2023). Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. https://www.zerocarbonshipping.com/publications/nordic-green-ammonia-powered-ships-nogaps/

Offshore Energy. (2012, agosto 30). Norway: World's First LNG Powered Cargo Ship Launched. *Offshore Energy*. https://www.offshore-energy.biz/norway-worlds-first-lng-powered-cargo-ship-launched/

Oloruntobi, O., Chuah, L. F., Mokhtar, K., Gohari, A., Onigbara, V., Chung, J. X., Mubashir, M., Asif, S., Show, P. L., & Han, N. (2023). Assessing methanol potential as a cleaner marine fuel: An analysis of its implications on emissions and regulation compliance. *Cleaner Engineering and Technology*, *14*, 100639. https://doi.org/10.1016/j.clet.2023.100639

Ortiz-Imedio, R., Caglayan, D. G., Ortiz, A., Heinrichs, H., Robinius, M., Stolten, D., & Ortiz, I. (2021). Power-to-Ships: Future electricity and hydrogen demands for shipping on the Atlantic coast of Europe in 2050. *Energy*, *228*. https://doi.org/10.1016/j.energy.2021.120660

Pavlenko, N., Comer, B., Zhou, Y., Clark, N., & Rutherford, D. (2020). *The climate implications of using LNG as a marine fuel*. www.theicct.org

Peralta P., C. O., Vieira, G. T. T., Meunier, S., Vale, R. J., Salles, M. B. C., & Carmo, B. S. (2019). Evaluation of the CO2 Emissions Reduction Potential of Li-ion Batteries in Ship Power Systems. *Energies*, *12*(3), Artigo 3. https://doi.org/10.3390/en12030375

Perčić, M., Frković, L., Pukšec, T., Ćosić, B., Li, O. L., & Vladimir, N. (2022). Life-cycle assessment and life-cycle cost assessment of power batteries for all-electric vessels for short-sea navigation. *Energy*, *251*, 123895. https://doi.org/10.1016/j.energy.2022.123895

Philadelphia & co. & R.D. Wood. (2012). *Mond Gas*. Hardpress Publishing.

Randall, D. J., & Tsui, T. K. N. (2002). Ammonia toxicity in fish. *Marine Pollution Bulletin*, *45*(1–12), 17–23. https://doi.org/10.1016/S0025-326X(02)00227-8

Rashid, M., Khaloofah, M., Mesfer, A., Naseem, H., Danish, M., & Al Mesfer, M. K. (2015). *Hydrogen Production by Water Electrolysis: A Review of Alkaline Water Electrolysis, PEM Water Electrolysis and High Temperature Water Electrolysis* (International Journal of Engineering and Advanced Technology (IJEAT), Número 3, pp. 2249–8958). https://www.researchgate.net/publication/273125977

Raudsepp, U., Maljutenko, I., Kõuts, M., Granhag, L., Wilewska-Bien, M., Hassellöv, I.-M., Eriksson, K. M., Johansson, L., Jalkanen, J.-P., Karl, M., Matthias, V., & Moldanova, J. (2019). Shipborne nutrient dynamics and impact on the eutrophication in the Baltic Sea. *Science of The Total Environment*, *671*, 189–207. https://doi.org/10.1016/j.scitotenv.2019.03.264

Ren, J., & Lützen, M. (2017). Selection of sustainable alternative energy source for shipping: Multi-criteria decision making under incomplete information. *Renewable and Sustainable Energy Reviews*, *74*, 1003–1019. https://doi.org/10.1016/j.rser.2017.03.057

Rogge, K. S., & Reichardt, K. (2016). Policy mixes for sustainability transitions: An extended concept and framework for analysis. *Research Policy*, *45*(8), 1620–1635. https://doi.org/10.1016/j.respol.2016.04.004

Rusman, N. A. A., & Dahari, M. (2016). A review on the current progress of metal hydrides material for solid-state hydrogen storage applications. *International Journal of Hydrogen Energy*, *41*(28), 12108–12126. https://doi.org/10.1016/j.ijhydene.2016.05.244

S. Marlin, D., Sarron, E., & Sigurbjörnsson, Ó. (2018). *Process Advantages of Direct CO2 to Methanol Synthesis*. https://www.frontiersin.org/articles/10.3389/fchem.2018.00446/full

Saxena, M. R., Maurya, R. K., & Mishra, P. (2021). Assessment of performance, combustion and emissions characteristics of methanol-diesel dual-fuel compression ignition engine: A review. *Journal of Traffic and Transportation Engineering (English Edition)*, *8*(5), 638–680. https://doi.org/10.1016/j.jtte.2021.02.003

Schemme, S., Samsun, R. C., Peters, R., & Stolten, D. (2017). Power-to-fuel as a key to sustainable transport systems – An analysis of diesel fuels produced from CO 2 and renewable electricity. *Fuel*, *205*, 198–221. https://doi.org/10.1016/j.fuel.2017.05.061

Schmidt, T. S., & Sewerin, S. (2019). Measuring the temporal dynamics of policy mixes – An empirical analysis of renewable energy policy mixes' balance and design features in nine countries. *Research Policy*, *48*(10), 103557. https://doi.org/10.1016/j.respol.2018.03.012

Science Direct. (2022). *Science Direct: Search for the words «ammonia fuel» in the Fuel Journal*. https://www.sciencedirect.com/search?qs=ammonia%20fuel&pub=Fuel&cid=271496&lastSelectedFacet=years&years=2020

Seo, Y., & Han, S. (2021). Economic Evaluation of an Ammonia-Fueled Ammonia Carrier Depending on Methods of Ammonia Fuel Storage. *Energies*, *14*(24), Artigo 24. https://doi.org/10.3390/en14248326

Service, R. F. (2018). Liquid sunshine. *Science*, *361*(6398), 120–123. https://doi.org/10.1126/science.361.6398.120

Sharmili, N., Nagi, R., & Wang, P. (2023). A review of research in the Li-ion battery production and reverse supply chains. *Journal of Energy Storage*, *68*, 107622. https://doi.org/10.1016/j.est.2023.107622

Solakivi, T., Paimander, A., & Ojala, L. (2022). Cost competitiveness of alternative maritime fuels in the new regulatory framework. *Transportation Research Part D: Transport and Environment*, *113*. https://doi.org/10.1016/j.trd.2022.103500

Stena Line. (2021, março 31). *The world´s first methanol ferry*. https://stenaline.com/media/stories/the-worlds-first-methanol-ferry/

Svanberg, M., Ellis, J., Lundgren, J., & Landälv, I. (2018). Renewable methanol as a fuel for the shipping industry. *Renewable and Sustainable Energy Reviews*, *94*, 1217–1228. https://doi.org/10.1016/j.rser.2018.06.058

Tadros, M., Ventura, M., & Soares, C. G. (2023). Review of current regulations, available technologies, and future trends in the green shipping industry. *Ocean Engineering*, *280*, 114670. https://doi.org/10.1016/j.oceaneng.2023.114670

Tian, Z., Wang, Y., Zhen, X., & Liu, Z. (2022). The effect of methanol production and application in internal combustion engines on emissions in the context of carbon neutrality: A review. *Fuel*, *320*, 123902. https://doi.org/10.1016/j.fuel.2022.123902

Tiselius, P., & Magnusson, K. (2017). Toxicity of treated bilge water: The need for revised regulatory control. *Marine Pollution Bulletin*, *114*(2), 860–866. https://doi.org/10.1016/j.marpolbul.2016.11.010

Trozzi, C. (2010). *Emission estimate methodology for maritime navigation*.

United Nations - UNCTAD. (2022). *Review of Maritime Transport*.

US Department of Energy. (2023). *Fuel Cells*. Energy.Gov. https://www.energy.gov/eere/fuelcells/fuel-cells

Vakili, S., & I. Ölçer, A. (2023). Are battery-powered vessels the best solution for the domestic ferry segment? Case study for the domestic ferry segment in the Philippines. *Energy*, *282*, 128323. https://doi.org/10.1016/j.energy.2023.128323

Van Hoecke, L., Laffineur, L., Campe, R., Perreault, P., Verbruggen, S. W., & Lenaerts, S. (2021). Challenges in the use of hydrogen for maritime applications. *Energy and Environmental Science*, *14*(2), 815–843. https://doi.org/10.1039/d0ee01545h

Verhelst, S., Turner, J. W., Sileghem, L., & Vancoillie, J. (2019). Methanol as a fuel for internal combustion engines. *Progress in Energy and Combustion Science*, *70*, 43–88. https://doi.org/10.1016/j.pecs.2018.10.001

Vessel Finder. (2023). *AIDANOVA, Passenger (Cruise) Ship—Details and current position—IMO 9781865—VesselFinder*. https://www.vesselfinder.com/vessels/details/9781865

Vessel Tracking. (2023). Emma Maersk—Container ship. *Vessel Tracking*. https://www.vesseltracking.net/article/emma-maersk-container-ship

Wang, F., Swinbourn, R., & Li, C. (2023). Shipping Australian sunshine: Liquid renewable green fuel export. *International Journal of Hydrogen Energy*. https://doi.org/10.1016/j.ijhydene.2022.12.326

Wang, Y., Cao, Q., Liu, L., Wu, Y., Liu, H., Gu, Z., & Zhu, C. (2022). A review of low and zero carbon fuel technologies: Achieving ship carbon reduction targets. *Sustainable Energy Technologies and Assessments*, *54*. https://doi.org/10.1016/j.seta.2022.102762

Wärtsilä. (2021). *Stena Germanica—Reference case—Wärtsilä*. Wartsila.Com. https://www.wartsila.com/marine/customer-segments/references/ferry/stena-germanica

Wärtsilä. (2023). *Marine dual fuel engines—Wärtsilä*. Wartsila.Com. https://www.wartsila.com/marine/products/engines-and-generating-sets/dual-fuel-engines

Wärtsilä. (2023). *Platform supply vessel VIKING ENERGY*. Wartsila.Com. https://www.wartsila.com/encyclopedia/term/platform-supply-vessel-viking-energy

Waterfront. (2019). *IINO Lines & Waterfront Shipping Welcome Low-Emission Methanol-Fueled Tanker | Waterfront Shipping*. https://www.waterfront-shipping.com/news/2019/12/iino-lines-waterfront-shipping-welcome-low-emission-methanol-fueled-tanker

Xing, H., Stuart, C., Spence, S., & Chen, H. (2021). Alternative fuel options for low carbon maritime transportation: Pathways to 2050. *Journal of Cleaner Production*, *297*. https://doi.org/10.1016/j.jclepro.2021.126651

Ye, L., Nayak-Luke, R., Bañares-Alcántara, R., & Tsang, E. (2017). Reaction: “Green” Ammonia Production. *Chem*, *3*(5), 712–714. https://doi.org/10.1016/j.chempr.2017.10.016

Ytreberg, E., Eriksson, M., Maljutenko, I., Jalkanen, J.-P., Johansson, L., Hassellöv, I.-M., & Granhag, L. (2020). Environmental impacts of grey water discharge from ships in the Baltic Sea. *Marine Pollution Bulletin*, *152*, 110891. https://doi.org/10.1016/j.marpolbul.2020.110891

Zhang, J., Meerman, H., Benders, R., & Faaij, A. (2020). Comprehensive review of current natural gas liquefaction processes on technical and economic performance. *Applied Thermal Engineering*, *166*. https://doi.org/10.1016/j.applthermaleng.2019.114736

zpiritas. (2020, junho 3). Viking Energy with ammonia-driven fuel cell. *Eidesvik*. https://eidesvik.no/viking-energy-with-ammonia-driven-fuel-cell/

Annexes

A. Assumptions for methodology

Table A.1 – Emission factor WTW GWP100 (MARIN, 2022)

COMBINATION	**EF WTW_GWP100** (kg_CO2e/MWh)
HFO+ICE	721.40
f-LNG+ICE	702.77
e-LNG+ICE	124.20
e-diesel+ICE	63.40
f-methanol+ICE	818.50
e-methanol+ICE	36.63
e-methanol+PEMFC	74.30
f-NH3+ICE	1382.30
f-NH3+PEMFC	2882.70
f-NH3+SOFC	1221.80
e-NH3+ICE	88.85
e-NH3+PEMFC	0.00
e-NH3+SOFC	0.00
e-LH2+ICE	109.60
e-LH2+PEMFC	0.00
EU-mix+batteries	516.00

Table A.2 - Onboard technology costs (Lloyd's Register, 2020) and tank costs (Al-Breiki & Bicer, 2020) per decade for each combination, for the analysed container ship, general cargo ship, and ro-pax ship, in millions of euros

	CONTAINER SHIP		GEN. CARGO SHIP		RO-PAX	
Combination	**Onboard technology costs** per decade (M€)	**Tank costs** per decade (M€)	**Onboard technology costs** per decade (M€)	**Tank costs** per decade (M€)	**Onboard technology costs** per decade (M€)	**Tank costs** per decade (M€)
HFO+ICE	36.72	1.07	5.46	0.12	5.46	0.12
f-LNG+ICE	36.72	4.75	5.46	0.53	5.46	0.53
e-LNG+ICE	36.72	4.75	5.46	0.53	5.46	0.53
e-diesel+ICE	36.72	1.12	5.46	0.13	5.46	0.13
f-methanol+ICE	36.72	3.89	5.46	0.43	5.46	0.43
e-methanol+ICE	36.72	3.89	5.46	0.43	5.46	0.43
e-methanol+PEMFC	78.69	3.27	13.07	0.37	13.07	0.37
f-NH3+ICE	36.72	8.17	5.46	0.91	5.46	0.91
f-NH3+PEMFC	78.69	4.85	13.07	0.54	13.07	0.54
f-NH3+SOFC	209.31	5.77	31.67	0.45	31.67	0.45
e-NH3+ICE	36.72	8.17	5.46	0.91	5.46	0.91
e-NH3+PEMFC	78.69	4.85	13.07	0.60	13.07	0.60
e-NH3+SOFC	209.31	5.77	31.67	0.45	31.67	0.45
e-LH2+ICE	36.72	12.88	5.46	1.44	5.46	1.44
e-LH2+PEMFC	78.69	11.08	13.07	1.24	13.07	1.24
EU-mix+batteries	5 295.97	-	557.96	-	557.96	-

Table A.3 - Onboard technology costs (Lloyd's Register, 2020) and tank costs (Al-Breiki & Bicer, 2020) per decade for each combination, for the analysed pax-ferry and fishing trawler, in thousands of euros

	PAX-FERRY		FISHING TRAWLER	
Combination	**Onboard technology costs** per decade (k€)	**Tank costs** per decade (k€)	**Onboard technology costs** per decade (k€)	**Tank costs** per decade (k€)
HFO+ICE	340.41	0.05	484.39	8.74
f-LNG+ICE	340.41	0.24	484.39	38.88
e-LNG+ICE	340.41	0.24	484.39	38.88
e-diesel+ICE	340.41	0.06	484.39	9.19

f-methanol+ICE	340.41	0.20	484.39	31.79
e-methanol+ICE	340.41	0.20	484.39	31.79
e-methanol+PEMFC	871.38	0.17	1 219.93	26.76
f-NH3+ICE	340.41	0.41	484.39	66.80
f-NH3+PEMFC	871.38	0.25	1 219.93	39.68
f-NH3+SOFC	2 754.02	0.20	3 442.53	32.66
e-NH3+ICE	340.41	0.41	484.39	66.80
e-NH3+PEMFC	871.38	0.25	1 219.93	39.68
e-NH3+SOFC	2 754.02	0.20	3 442.53	32.66
e-LH2+ICE	340.41	0.65	484.39	105.33
e-LH2+PEMFC	871.38	0.56	1 219.93	90.61
EU-mix+batteries	272.95	-	43 314.44	-

Table A.4 - Fuel costs and carbon taxation for each combination per decade (in millions of euros), for the container ship, based on the calculations of (Lagemann et al., 2022)

CONTAINER SHIP

Combination	**Fuel Costs 1st decade (M€)** 2020-30	**Fuel Costs 2nd decade (M€)** 2030-40	**Fuel Costs 3rd decade (M€)** 2040-50	**Carbon tax 1st decade (M€)** 2020-30	**Carbon tax 2nd decade (M€)** 2030-40	**Carbon tax 3rd decade (M€)** 2040-50
HFO+ICE	345.19	584.22	778.25	258.96	756.38	1 235.85
f-LNG+ICE	250.65	405.67	555.29	276.75	808.33	1 320.73
e-LNG+ICE	1 790.81	1 540.93	1 291.05	48.91	142.86	233.41
e-diesel+ICE	3 289.08	2 871.20	2 453.33	24.24	70.81	115.70
f-methanol+ICE	478.68	774.73	1 060.46	312.98	914.16	1 493.64
e-methanol+ICE	2 116.33	1 833.26	1 550.18	14.01	40.91	66.85
e-methanol+PEMFC	2 277.22	1 972.63	1 668.03	30.57	89.29	145.89
f-NH3+ICE	751.13	741.39	743.64	528.57	1 543.85	2 522.49
f-NH3+PEMFC	808.23	797.75	800.17	1 186.11	3 464.37	5 660.43
f-NH3+SOFC	559.54	552.29	553.96	348.04	1 016.54	1 660.92
e-NH3+ICE	1 374.94	1 159.27	930.11	33.98	99.23	162.14
e-NH3+PEMFC	1 479.47	1 247.40	1 000.82	-	-	-
e-NH3+SOFC	1 024.25	863.58	692.87	-	-	-
e-LH2+ICE	1 294.06	1 078.39	862.71	41.91	122.41	200.00
e-LH2+PEMFC	1 392.44	1 160.37	928.30	-	-	-
EU-mix+batteries	1 130.38	805.81	559.59	106.16	310.06	506.60

Table A.5 - Fuel costs and carbon taxation for each combination per decade (in millions of euros), for the general cargo ship, based on the calculations from (Lagemann et al., 2022)

GEN. CARGO SHIP

Combination	**Fuel Costs 1st decade (M€)** 2020-30	**Fuel Costs 2nd decade (M€)** 2030-40	**Fuel Costs 3rd decade (M€)** 2040-50	**Carbon tax 1st decade (M€)** 2020-30	**Carbon tax 2nd decade (M€)** 2030-40	**Carbon tax 3rd decade (M€)** 2040-50
HFO+ICE	38.51	65.17	86.82	28.89	84.38	137.86
f-LNG+ICE	27.96	45.25	61.94	30.87	90.17	147.33
e-LNG+ICE	199.77	171.89	144.02	5.46	15.94	26.04
e-diesel+ICE	366.90	320.29	273.67	2.70	7.90	12.91
f-methanol+ICE	53.40	86.42	118.30	34.91	101.98	166.62
e-methanol+ICE	236.08	204.50	172.92	1.56	4.56	7.46
e-methanol+PEMFC	254.03	220.05	186.07	3.41	9.96	16.27
f-NH3+ICE	83.79	82.70	82.95	58.96	172.22	281.39
f-NH3+PEMFC	90.16	88.99	89.26	132.31	386.45	631.43
f-NH3+SOFC	62.42	61.61	61.80	38.82	113.40	185.28
e-NH3+ICE	153.38	129.32	103.75	3.79	11.07	18.09
e-NH3+PEMFC	165.04	139.15	111.64	-	-	-
e-NH3+SOFC	114.26	96.33	77.29	-	-	-
e-LH2+ICE	144.35	120.30	96.24	4.68	13.65	22.31
e-LH2+PEMFC	155.33	129.44	103.55	-	-	-
EU-mix+batteries	126.09	89.89	62.42	11.84	34.59	56.51

Table A.6 - Fuel costs and carbon taxation for each combination per decade (in millions of euros), for the ro-pax ship, based on the calculations from (Lagemann et al., 2022)

RO-PAX SHIP

Combination	**Fuel Costs 1st decade (M€)** 2020-30	**Fuel Costs 2nd decade (M€)** 2030-40	**Fuel Costs 3rd decade (M€)** 2040-50	**Carbon tax 1st decade (M€)** 2020-30	**Carbon tax 2nd decade (M€)** 2030-40	**Carbon tax 3rd decade (M€)** 2040-50
HFO+ICE	140.83	238.34	317.50	105.65	308.58	504.19
f-LNG+ICE	102.26	165.50	226.54	112.91	329.77	538.82
e-LNG+ICE	730.59	628.65	526.71	19.95	58.28	95.23
e-diesel+ICE	1 341.84	1 171.36	1 000.88	9.89	28.89	47.20
f-methanol+ICE	195.29	316.06	432.64	127.69	372.95	609.36
e-methanol+ICE	863.40	747.91	632.43	5.71	16.69	27.27
e-methanol+PEMFC	929.04	804.77	680.51	12.47	36.43	59.52
f-NH3+ICE	306.44	302.47	303.38	215.64	629.84	1 029.10
f-NH3+PEMFC	329.73	325.46	326.45	483.90	1 413.36	2 309.28
f-NH3+SOFC	228.28	225.32	226.00	141.99	414.72	677.61
e-NH3+ICE	560.94	472.95	379.46	13.86	40.48	66.15
e-NH3+PEMFC	603.58	508.90	408.30	-	-	-
e-NH3+SOFC	417.86	352.32	282.67	-	-	-
e-LH2+ICE	527.94	439.95	351.96	17.10	49.94	81.60
e-LH2+PEMFC	568.07	473.40	378.72	-	-	-
EU-mix+batteries	461.16	328.75	228.30	43.31	126.49	206.68

Table A.7 - Fuel costs and carbon taxation for each combination per decade (in millions of euros), for the pax-ferry ship, based on the calculations from (Lagemann et al., 2022)

PAX-FERRY

Combination	**Fuel Costs 1st decade (M€)** 2020-30	**Fuel Costs 2nd decade (M€)** 2030-40	**Fuel Costs 3rd decade (M€)** 2040-50	**Carbon tax 1st decade (M€)** 2020-30	**Carbon tax 2nd decade (M€)** 2030-40	**Carbon tax 3rd decade (M€)** 2040-50
HFO+ICE	0.31	0.52	0.69	0.23	0.67	1.10
f-LNG+ICE	0.22	0.36	0.50	0.25	0.72	1.18
e-LNG+ICE	1.60	1.37	1.15	0.04	0.13	0.21
e-diesel+ICE	2.93	2.56	2.19	0.02	0.06	0.10
f-methanol+ICE	0.43	0.69	0.95	0.28	0.82	1.33
e-methanol+ICE	1.89	1.63	1.38	0.01	0.04	0.06
e-methanol+PEMFC	2.03	1.76	1.49	0.03	0.08	0.13
f-NH3+ICE	0.67	0.66	0.66	0.47	1.38	2.25
f-NH3+PEMFC	0.72	0.71	0.71	1.06	3.09	5.05
f-NH3+SOFC	0.50	0.49	0.49	0.31	0.91	1.48
e-NH3+ICE	1.23	1.03	0.83	0.03	0.09	0.14
e-NH3+PEMFC	1.32	1.11	0.89	-	-	-
e-NH3+SOFC	0.91	0.77	0.62	-	-	-
e-LH2+ICE	1.15	0.96	0.77	0.04	0.11	0.18
e-LH2+PEMFC	1.24	1.03	0.83	-	-	-
EU-mix+batteries	1.01	0.72	0.50	0.09	0.28	0.45

Table A.8 - Fuel costs and carbon taxation for each combination per decade (in millions of euros), for the fishing trawler, based on the calculations from (Lagemann et al., 2022)

FISHING TRAWLER

Combination	**Fuel Costs 1st decade (M€)** 2020-30	**Fuel Costs 2nd decade (M€)** 2030-40	**Fuel Costs 3rd decade (M€)** 2040-50	**Carbon tax 1st decade (M€)** 2020-30	**Carbon tax 2nd decade (M€)** 2030-40	**Carbon tax 3rd decade (M€)** 2040-50
HFO+ICE	3.32	5.62	7.49	2.49	7.28	11.89
f-LNG+ICE	2.41	3.90	5.34	2.66	7.78	12.71
e-LNG+ICE	17.23	14.83	12.42	0.47	1.37	2.25
e-diesel+ICE	31.64	27.62	23.60	0.23	0.68	1.11
f-methanol+ICE	4.61	7.45	10.20	3.01	8.80	14.37
e-methanol+ICE	20.36	17.64	14.91	0.13	0.39	0.64
e-methanol+PEMFC	21.91	18.98	16.05	0.29	0.86	1.40

f-NH3+ICE	7.23	7.13	7.15	5.09	14.85	24.27
f-NH3+PEMFC	7.78	7.68	7.70	11.41	33.33	54.46
f-NH3+SOFC	5.38	5.31	5.33	3.35	9.78	15.98
e-NH3+ICE	13.23	11.15	8.95	0.33	0.95	1.56
e-NH3+PEMFC	14.23	12.00	9.63	-	-	-
e-NH3+SOFC	9.85	8.31	6.67	-	-	-
e-LH2+ICE	12.45	10.38	8.30	0.40	1.18	1.92
e-LH2+PEMFC	13.40	11.16	8.93	-	-	-
EU-mix+batteries	10.88	7.75	5.38	1.02	2.98	4.87

B. Other Results

Table B.1 - Performance matrix for the general cargo ship in scenario A (no carbon tax)

GENERAL CARGO (A)

1st decade	2nd+3rd decades	Energy Intensity (KWh/ton.km)	WTW Emissions (Mt_CO_2)	Volume per trip (x10^3 m^3)	Mass per trip (metric kt)	Total Costs A (x10^3 M€)	Energy vector TRL (1-9)	Power system TRL (1-9)	Infra-structure (I-IV)
HFO+ICE	HFO+ICE	0.22	1.89	0.26	0.23	0.23	9	9	IV
	f-LNG+ICE	0.24	1.97	0.48	0.23	0.20	9	9	III-IV
	e-LNG+ICE	0.24	0.87	0.48	0.23	0.41	7	9	III-IV
	e-diesel+ICE	0.23	0.75	0.27	0.23	0.67	5	9	IV
	f-methanol+ICE	0.23	2.15	0.63	0.49	0.29	7	7	III
	e-methanol+ICE	0.23	0.70	0.63	0.49	0.46	7	7	III
	e-methanol+PEMFC	0.25	0.78	0.68	0.50	34 156.98	7	7	III
	f-NH3+ICE	0.23	3.19	0.98	0.78	0.26	5	5	III
	f-NH3+PEMFC	0.25	6.39	0.73	0.53	34 156.77	5	7	III
	f-NH3+SOFC	0.19	2.32	1.92	1.10	14 734.41	5	4	III
	e-NH3+ICE	0.23	0.79	0.98	0.78	0.33	5	5	III
	e-NH3+PEMFC	0.25	0.63	0.79	0.53	34 156.84	5	7	III
	e-NH3+SOFC	0.19	0.63	1.92	1.17	14 734.46	5	4	III
	e-LH2+ICE	0.23	0.83	1.16	0.23	0.32	6	7	III
	e-LH2+PEMFC	0.25	0.63	1.14	0.23	34 156.83	6	7	I
	EU-mix+batteries	0.16	1.14	6.80	9.35	108 845.38	9	9	II
f-LNG+ICE		0.25	2.02	0.48	0.19	0.18	9	9	III-IV
e-LNG+ICE		0.25	0.36	0.48	0.19	0.56	7	9	III-IV
e-diesel+ICE		0.24	0.18	0.27	0.23	1.00	5	9	IV
f-methanol+ICE		0.24	2.28	0.63	0.49	0.30	7	7	III
e-methanol+ICE		0.24	0.10	0.63	0.49	0.65	7	7	III
e-methanol+PEMFC		0.26	0.22	0.68	0.50	56 928.18	7	7	III
f-NH3+ICE		0.24	3.85	0.98	0.78	0.30	5	5	III
f-NH3+PEMFC		0.26	8.64	0.73	0.53	56 927.80	5	7	III
f-NH3+SOFC		0.18	2.53	1.92	1.10	29 468.60	5	4	III
e-NH3+ICE		0.24	0.25	0.98	0.78	0.43	5	5	III
e-NH3+PEMFC		0.26	-	0.79	0.53	56 927.94	5	7	III
e-NH3+SOFC		0.18	-	1.92	1.17	29 468.70	5	4	III
e-LH2+ICE		0.24	0.31	1.16	0.08	0.41	6	7	I
e-LH2+PEMFC		0.26	-	1.14	0.15	56 927.92	6	7	I
EU-mix+batteries		0.13	0.77	6.80	9.35	217 690.06	9	9	II

Table B.2 - Performance matrix for the ro-pax ship in scenario A (no carbon tax)

RO-PAX (A)

1st decade	2nd+3rd decades	Energy Intensity (KWh/ton.km)	WTW Emissions (Mt_CO_2)	Volume per trip (x10^3 m^3)	Mass per trip (metric kt)	Total Costs A (x10^3 M€)	Energy vector TRL (1-9)	Power system TRL (1-9)	Infra-structure (I-IV)
HFO+ICE	HFO+ICE	16.86	6.90	0.09	0.08	0.83	9	9	IV
	f-LNG+ICE	17.95	7.21	0.16	0.08	0.72	9	9	III-IV
	e-LNG+ICE	17.95	3.17	0.16	0.08	1.48	7	9	III-IV
	e-diesel+ICE	17.59	2.73	0.09	0.08	2.46	5	9	IV
	f-methanol+ICE	17.59	7.86	0.21	0.17	1.06	7	7	III
	e-methanol+ICE	17.59	2.55	0.21	0.17	1.69	7	7	III
	e-methanol+PEMFC	18.50	2.84	0.64	0.38	71 715.98	7	7	III
	f-NH3+ICE	17.59	11.68	0.33	0.27	0.95	5	5	III
	f-NH3+PEMFC	18.50	23.36	0.66	0.39	71 715.18	5	7	III

	f-NH3+SOFC	14.54	8.48	4.64	2.39	0.88	5	4	III
	e-NH3+ICE	17.59	2.90	0.33	0.27	1.20	5	5	III
	e-NH3+PEMFC	18.50	2.30	0.66	0.39	71 715.45	5	7	III
	e-NH3+SOFC	14.54	2.30	4.64	2.39	1.06	5	4	III
	e-LH2+ICE	17.59	3.04	0.39	0.08	1.17	6	7	I
	e-LH2+PEMFC	18.50	2.30	0.80	0.26	71 715.42	6	7	I
	EU-mix+batteries	12.06	4.18	2.32	3.19	53 686.85	9	9	II
f-LNG+ICE		18.50	7.37	0.16	0.07	0.65	9	9	III-IV
e-LNG+ICE		18.50	1.30	0.16	0.07	2.04	7	9	III-IV
e-diesel+ICE		17.96	0.65	0.09	0.08	3.64	5	9	IV
f-methanol+ICE		17.96	8.34	0.21	0.17	1.09	7	9	III
e-methanol+ICE		17.96	0.37	0.21	0.17	2.39	7	7	III
e-methanol+PEMFC		19.33	0.81	0.64	0.38	143 430.91	7	7	III
f-NH3+ICE		17.96	14.08	0.33	0.27	1.08	5	7	III
f-NH3+PEMFC		19.33	31.59	0.66	0.39	143 429.49	5	5	III
f-NH3+SOFC		13.38	9.27	4.64	2.39	0.93	5	7	III
e-NH3+ICE		17.96	0.90	0.33	0.27	1.58	5	4	III
e-NH3+PEMFC		19.33	-	0.66	0.39	143 430.03	5	5	III
e-NH3+SOFC		13.38	-	4.64	2.39	1.30	5	7	III
e-LH2+ICE		17.96	1.12	0.39	0.03	1.51	6	4	I
e-LH2+PEMFC		19.33	-	0.80	0.26	143 429.95	6	7	I
EU-mix+batteries		9.66	2.83	2.32	3.19	107 372.98	9	7	II

Table B.3 - Performance matrix for the fishing trawler in scenario A (no carbon tax)

FISHING TRAWLER (A)

1st decade	**2nd+3rd decades**	**Energy Intensity** (KWh/ton.km)	**WTW Emissions** (kt_CO$_2$)	**Volume per trip** (m^3)	**Mass per trip** (metric t)	**Total Costs A** (x10^3 M€)	**Energy vector TRL** (1-9)	**Power system TRL** (1-9)	**Infra-structure** (I-IV)
HFO+ICE	HFO+ICE	0.48	162.65	19.05	16.74	0.02	9.00	9.00	IV
	f-LNG+ICE	0.51	170.10	35.33	16.74	0.01	9.00	9.00	II
	e-LNG+ICE	0.51	74.70	35.33	16.74	0.03	7.00	9.00	II
	e-diesel+ICE	0.50	64.37	20.05	16.76	0.06	5.00	9.00	IV
	f-methanol+ICE	0.50	185.27	46.22	36.21	0.02	7.00	7.00	III
	e-methanol+ICE	0.50	60.08	46.22	36.21	0.04	7.00	7.00	III
	e-methanol+PEMFC	0.52	67.02	52.68	37.97	5 050.95	7.00	7.00	III
	f-NH3+ICE	0.50	275.54	71.69	57.14	0.02	5.00	5.00	III
	f-NH3+PEMFC	0.52	550.87	56.35	40.30	5 050.93	5.00	7.00	III
	f-NH3+SOFC	0.41	199.95	191.68	106.41	2 614.61	5.00	4.00	III
	e-NH3+ICE	0.50	68.44	71.69	57.14	0.03	5.00	5.00	III
	e-NH3+PEMFC	0.52	54.22	56.35	40.30	5 050.94	5.00	7.00	III
	e-NH3+SOFC	0.41	54.22	191.68	106.41	2 614.61	5.00	4.00	III
	e-LH2+ICE	0.50	71.77	84.77	16.74	0.02	6.00	7.00	I
	e-LH2+PEMFC	0.52	54.22	86.68	16.74	5 050.94	6.00	7.00	I
	EU-mix+batteries	0.34	98.67	498.71	685.74	11 553.97	9.00	9.00	III-IV
f-LNG+ICE		0.52	173.82	35.33	14.00	0.01	9.00	9.00	II
e-LNG+ICE		0.52	30.72	35.33	14.00	0.05	7.00	9.00	II
e-diesel+ICE		0.51	15.23	20.05	16.76	0.08	5.00	9.00	IV
f-methanol+ICE		0.51	196.58	46.22	36.21	0.02	7.00	9.00	III
e-methanol+ICE		0.51	8.80	46.22	36.21	0.05	7.00	7.00	III
e-methanol+PEMFC		0.54	19.20	52.68	37.97	9 091.70	7.00	7.00	III
f-NH3+ICE		0.51	331.99	71.69	57.14	0.02	5.00	7.00	III
f-NH3+PEMFC		0.54	744.97	56.35	40.30	9 091.67	5.00	5.00	III
f-NH3+SOFC		0.38	218.60	191.68	106.41	5 229.20	5.00	7.00	III
e-NH3+ICE		0.51	21.34	71.69	57.14	0.04	5.00	4.00	III
e-NH3+PEMFC		0.54	-	56.35	40.30	9 091.68	5.00	5.00	III
e-NH3+SOFC		0.38	-	191.68	106.41	5 229.21	5.00	7.00	III
e-LH2+ICE		0.51	26.32	84.77	6.16	0.03	6.00	4.00	I
e-LH2+PEMFC		0.54	-	86.68	12.16	9 091.68	6.00	7.00	I
EU-mix+batteries		0.27	66.67	498.71	685.74	23 107.89	9.00	7.00	III-IV

Table B.4 - Performance values of total costs for the general cargo ship, ro-pax ship, and fishing trawler, in scenario B (with carbon tax)

1st decade	**2nd+3rd decades**	**Total Costs B** (x10^3 M€)		
		General cargo ship	**Ro-pax ship**	**Fishing Trawler**
HFO+ICE	HFO+ICE	0.48	1.75	0.04
	f-LNG+ICE	0.46	1.69	0.04

	e-LNG+ICE	0.48	1.74	0.04
	e-diesel+ICE	0.72	2.64	0.06
	f-methanol+ICE	0.59	2.15	0.05
	e-methanol+ICE	0.50	1.84	0.04
	e-methanol+PEMFC	34 157.04	71 716.18	5 050.96
	f-NH3+ICE	0.74	2.72	0.06
	f-NH3+PEMFC	34 157.81	71 719.01	5 051.02
	f-NH3+SOFC	14 734.74	2.08	2 614.64
	e-NH3+ICE	0.39	1.41	0.03
	e-NH3+PEMFC	34 156.87	71 715.55	5 050.94
	e-NH3+SOFC	14 734.49	1.17	2 614.62
	e-LH2+ICE	0.39	1.41	0.03
	e-LH2+PEMFC	34 156.86	71 715.52	5 050.94
	EU-mix+batteries	108 845.50	53 687.29	11 553.98
f-LNG+ICE		0.45	1.63	0.04
e-LNG+ICE		0.61	2.22	0.05
e-diesel+ICE		1.02	3.73	0.09
f-methanol+ICE		0.60	2.20	0.05
e-methanol+ICE		0.67	2.44	0.06
e-methanol+PEMFC		56 928.21	143 431.02	9 091.70
f-NH3+ICE		0.81	2.95	0.07
f-NH3+PEMFC		56 928.95	143 433.70	9 091.77
f-NH3+SOFC		29 468.94	2.16	5 229.23
e-NH3+ICE		0.47	1.70	0.04
e-NH3+PEMFC		56 927.94	143 430.03	9 091.68
e-NH3+SOFC		29 468.70	1.30	5 229.21
e-LH2+ICE		0.45	1.66	0.04
e-LH2+PEMFC		56 927.92	143 429.95	9 091.68
EU-mix+batteries		217 690.17	107 373.36	23 107.90

Table B.5 - Normalized matrix (0-100, worst to best) for the general cargo ship in scenario A (without carbon taxes). Cells in blue are imposed null values

GENERAL
CARGO SHIP (A)

1st decade	2nd+3rd decades	Energy Intensity	WTW Emissions	Volume per trip	Mass per trip	Total Costs A	Energy vector TRL	Power system TRL	Infra-structure
HFO+ICE	HFO+ICE	12.8	0.0	96.2	97.6	77.3	100.0	100.0	100.0
	f-LNG+ICE	7.1	0.0	92.9	97.6	80.3	100.0	100.0	87.5
	e-LNG+ICE	7.1	24.3	92.9	97.6	59.3	77.8	100.0	87.5
	e-diesel+ICE	9.0	34.8	96.0	97.6	32.4	55.6	100.0	100.0
	f-methanol+ICE	9.0	0.0	90.7	94.7	70.8	77.8	77.8	75.0
	e-methanol+ICE	9.0	39.1	90.7	94.7	53.5	77.8	77.8	75.0
	e-methanol+PEMFC	4.3	32.1	90.0	94.7	0.0	77.8	77.8	75.0
	f-NH3+ICE	9.0	0.0	85.6	91.7	73.8	55.6	55.6	75.0
	f-NH3+PEMFC	4.3	0.0	89.3	94.3	0.0	55.6	77.8	75.0
	f-NH3+SOFC	24.8	0.0	0.0	88.2	0.0	55.6	44.4	75.0
	e-NH3+ICE	9.0	30.6	85.6	91.7	67.0	55.6	55.6	75.0
	e-NH3+PEMFC	4.3	45.1	88.4	94.3	0.0	55.6	77.8	75.0
	e-NH3+SOFC	24.8	45.1	0.0	87.5	0.0	55.6	44.4	75.0
	e-LH2+ICE	9.0	27.3	83.0	97.6	67.7	66.7	77.8	25.0
	e-LH2+PEMFC	4.3	45.1	83.2	97.6	0.0	66.7	77.8	25.0
	EU-mix+batteries	37.6	0.0	0.0	0.0	0.0	100.0	100.0	50.0
f-LNG+ICE		4.3	0.0	92.9	98.0	82.1	100.0	100.0	87.5
e-LNG+ICE		4.3	68.9	92.9	98.0	43.9	77.8	100.0	87.5
e-diesel+ICE		7.1	84.6	96.0	97.6	0.0	55.6	100.0	100.0
f-methanol+ICE		7.1	0.0	90.7	94.7	70.0	77.8	77.8	75.0
e-methanol+ICE		7.1	91.1	90.7	94.7	34.3	77.8	77.8	75.0
e-methanol+PEMFC		0.0	80.5	90.0	94.7	0.0	77.8	77.8	75.0
f-NH3+ICE		7.1	0.0	85.6	91.7	70.3	55.6	55.6	75.0
f-NH3+PEMFC		0.0	0.0	89.3	94.3	0.0	55.6	77.8	75.0
f-NH3+SOFC		30.8	0.0	71.8	88.2	0.0	55.6	44.4	75.0
e-NH3+ICE		7.1	78.4	85.6	91.7	56.6	55.6	55.6	75.0
e-NH3+PEMFC		0.0	100.0	88.4	94.3	0.0	55.6	77.8	75.0
e-NH3+SOFC		30.8	100.0	71.8	87.5	0.0	55.6	44.4	75.0
e-LH2+ICE		7.1	73.3	83.0	99.1	58.6	66.7	77.8	25.0
e-LH2+PEMFC		0.0	100.0	83.2	98.4	0.0	66.7	77.8	25.0
EU-mix+ batteries		50.0	32.4	0.0	0.0	0.0	100.0	100.0	50.0

Table B.6 - Normalized matrix (0-100, worst to best) for the ro-pax ship in scenario A (without carbon taxes).
Cells in blue are imposed null values

RO-PAX SHIP (A)

1st decade	2nd+3rd decades	Energy Intensity	WTW Emissions	Volume per trip	Mass per trip	Total Costs A	Energy vector TRL	Power system TRL	Infra-structure
HFO+ICE	HFO+ICE	12.8	0.0	98.1	97.6	79.3	100.0	100.0	100.0
	f-LNG+ICE	7.1	0.0	96.5	97.6	82.1	100.0	100.0	87.5
	e-LNG+ICE	7.1	24.3	96.5	97.6	63.0	77.8	100.0	87.5
	e-diesel+ICE	9.0	34.8	98.0	97.6	38.5	55.6	100.0	100.0
	f-methanol+ICE	9.0	0.0	95.4	94.7	73.5	77.8	77.8	75.0
	e-methanol+ICE	9.0	39.1	95.4	94.7	57.7	77.8	77.8	75.0
	e-methanol+PEMFC	4.3	32.1	86.2	88.1	0.0	77.8	77.8	75.0
	f-NH3+ICE	9.0	0.0	92.8	91.7	76.2	55.6	55.6	75.0
	f-NH3+PEMFC	4.3	0.0	85.8	87.8	0.0	55.6	77.8	75.0
	f-NH3+SOFC	24.8	0.0	0.0	25.1	78.1	55.6	44.4	75.0
	e-NH3+ICE	9.0	30.6	92.8	91.7	70.1	55.6	55.6	75.0
	e-NH3+PEMFC	4.3	45.1	85.8	87.8	0.0	55.6	77.8	75.0
	e-NH3+SOFC	24.8	45.1	0.0	25.1	73.5	55.6	44.4	75.0
	e-LH2+ICE	9.0	27.3	91.5	97.6	70.7	66.7	77.8	25.0
	e-LH2+PEMFC	4.3	45.1	82.7	91.9	0.0	66.7	77.8	25.0
	EU-mix+ batteries	37.6	0.0	0.0	0.0	0.0	100.0	100.0	50.0
f-LNG+ICE		4.3	0.0	96.5	98.0	83.7	100.0	100.0	87.5
e-LNG+ICE		4.3	68.9	96.5	98.0	48.9	77.8	100.0	87.5
e-diesel+ICE		7.1	84.6	98.0	97.6	8.9	55.6	100.0	100.0
f-methanol+ICE		7.1	0.0	95.4	94.7	72.7	77.8	100.0	75.0
e-methanol+ICE		7.1	91.1	95.4	94.7	40.2	77.8	77.8	75.0
e-methanol+PEMFC		0.0	80.5	86.2	88.1	0.0	77.8	77.8	75.0
f-NH3+ICE		7.1	0.0	92.8	91.7	73.0	55.6	77.8	75.0
f-NH3+PEMFC		0.0	0.0	85.8	87.8	0.0	55.6	55.6	75.0
f-NH3+SOFC		30.8	0.0	0.0	25.1	76.8	55.6	77.8	75.0
e-NH3+ICE		7.1	78.4	92.8	91.7	60.5	55.6	44.4	75.0
e-NH3+PEMFC		0.0	100.0	85.8	87.8	0.0	55.6	55.6	75.0
e-NH3+SOFC		30.8	100.0	0.0	25.1	67.5	55.6	77.8	75.0
e-LH2+ICE		7.1	73.3	91.5	99.1	62.3	66.7	44.4	25.0
e-LH2+PEMFC		0.0	100.0	82.7	91.9	0.0	66.7	77.8	25.0
EU-mix+ batteries		50.0	32.4	0.0	0.0	0.0	100.0	77.8	50.0

Table B.7 - Normalized matrix (0-100, worst to best) for the fishing trawler in scenario A (without carbon taxes).
Cells in blue are imposed null values.

FISHING
TRAWLER (A)

1st decade	2nd+3rd decades	Energy Intensity	WTW Emissions	Volume per trip	Mass per trip	Total Costs A	Energy vector TRL	Power system TRL	Infra-structure
HFO+ICE	HFO+ICE	12.8	0.0	96.2	97.6	80.2	100.0	100.0	100.0
	f-LNG+ICE	7.1	0.0	92.9	97.6	83.7	100.0	100.0	50.0
	e-LNG+ICE	7.1	24.3	92.9	97.6	63.7	77.8	100.0	50.0
	e-diesel+ICE	9.0	34.8	96.0	97.6	37.3	55.6	100.0	100.0
	f-methanol+ICE	9.0	0.0	90.7	94.7	74.4	77.8	77.8	75.0
	e-methanol+ICE	9.0	39.1	90.7	94.7	57.9	77.8	77.8	75.0
	e-methanol+PEMFC	4.3	32.1	89.4	94.5	0.0	77.8	77.8	75.0
	f-NH3+ICE	9.0	0.0	85.6	91.7	77.8	55.6	55.6	75.0
	f-NH3+PEMFC	4.3	0.0	88.7	94.1	0.0	55.6	77.8	75.0
	f-NH3+SOFC	24.8	0.0	0.0	84.5	0.0	55.6	44.4	75.0
	e-NH3+ICE	9.0	30.6	85.6	91.7	71.4	55.6	55.6	75.0
	e-NH3+PEMFC	4.3	45.1	88.7	94.1	0.0	55.6	77.8	75.0
	e-NH3+SOFC	24.8	45.1	0.0	84.5	0.0	55.6	44.4	75.0
	e-LH2+ICE	9.0	27.3	83.0	97.6	72.6	66.7	77.8	25.0
	e-LH2+PEMFC	4.3	45.1	82.6	97.6	0.0	66.7	77.8	25.0
	EU-mix+ batteries	37.6	0.0	0.0	0.0	0.0	100.0	100.0	87.5
f-LNG+ICE		4.3	0.0	92.9	98.0	85.3	100.0	100.0	50.0
e-LNG+ICE		4.3	68.9	92.9	98.0	48.8	77.8	100.0	50.0
e-diesel+ICE		7.1	84.6	96.0	97.6	6.4	55.6	100.0	100.0
f-methanol+ICE		7.1	0.0	90.7	94.7	73.6	77.8	100.0	75.0
e-methanol+ICE		7.1	91.1	90.7	94.7	39.5	77.8	77.8	75.0
e-methanol+PEMFC		0.0	80.5	89.4	94.5	0.0	77.8	77.8	75.0
f-NH3+ICE		7.1	0.0	85.6	91.7	74.2	55.6	77.8	75.0
f-NH3+PEMFC		0.0	0.0	88.7	94.1	0.0	55.6	55.6	75.0
f-NH3+SOFC		30.8	0.0	61.6	84.5	0.0	55.6	77.8	75.0
e-NH3+ICE		7.1	78.4	85.6	91.7	61.1	55.6	44.4	75.0
e-NH3+PEMFC		0.0	100.0	88.7	94.1	0.0	55.6	55.6	75.0

e-NH3+SOFC	30.8	100.0	61.6	84.5	0.0	55.6	77.8	75.0
e-LH2+ICE	7.1	73.3	83.0	99.1	63.3	66.7	44.4	25.0
e-LH2+PEMFC	0.0	100.0	82.6	98.2	0.0	66.7	77.8	25.0
EU-mix+ batteries	50.0	32.4	0.0	0.0	0.0	100.0	77.8	87.5

Table B.8 - Normalized values (0-100, worst to best) of total costs for the general cargo ship, ro-pax ship, and fishing trawler, in scenario B (with carbon tax). Cells in blue are imposed null values

1st decade	2nd+3rd decades	Total Costs B		
		General cargo ship	**Ro-pax ship**	**Fishing Trawler**
HFO+ICE	HFO+ICE	56.6	56.4	56.2
	f-LNG+ICE	57.9	57.8	58.1
	e-LNG+ICE	56.7	56.6	56.9
	e-diesel+ICE	34.2	33.9	32.6
	f-methanol+ICE	46.5	46.3	45.9
	e-methanol+ICE	54.2	54.0	54.0
	e-methanol+PEMFC	0.0	0.0	0.0
	f-NH3+ICE	32.4	32.1	31.6
	f-NH3+PEMFC	0.0	0.0	0.0
	f-NH3+SOFC	0.0	48.1	0.0
	e-NH3+ICE	64.9	64.8	65.8
	e-NH3+PEMFC	0.0	0.0	0.0
	e-NH3+SOFC	0.0	70.8	0.0
	e-LH2+ICE	64.8	64.7	66.4
	e-LH2+PEMFC	0.0	0.0	0.0
	EU-mix+ batteries	0.0	0.0	0.0
f-LNG+ICE		59.4	59.2	59.6
e-LNG+ICE		44.9	44.6	44.3
e-diesel+ICE		7.3	6.7	4.2
f-methanol+ICE		45.2	44.9	44.5
e-methanol+ICE		39.3	38.9	38.2
e-methanol+PEMFC		0.0	0.0	0.0
f-NH3+ICE		26.5	26.1	25.1
f-NH3+PEMFC		0.0	0.0	0.0
f-NH3+SOFC		0.0	45.9	0.0
e-NH3+ICE		57.7	57.5	57.9
e-NH3+PEMFC		0.0	0.0	0.0
e-NH3+SOFC		0.0	67.5	0.0
e-LH2+ICE		58.8	58.6	59.4
e-LH2+PEMFC		0.0	0.0	0.0
EU-mix+ batteries		0.0	0.0	0.0

Table B.9 - Final scores (0-100) according to each decision maker for the general cargo ship, in scenarios A and B. Colour scale: dark green values are the ones with higher scores and the dark red ones represent the lower final scores.

GENERAL CARGO		A - without carbon taxes			B - with carbon taxes		
1st decade	**2nd+3rd decades**	**Total Score Environmentalist**	**Total Score Balanced**	**Total Score Investor**	**Total Score Environmentalist**	**Total Score Balanced**	**Total Score Investor**
HFO+ICE	HFO+ICE	49.3	66.1	72.8	47.3	62.0	65.6
	f-LNG+ICE	47.4	64.6	71.7	45.1	60.1	63.9
	e-LNG+ICE	50.4	63.0	64.6	50.2	62.5	63.7
	e-diesel+ICE	49.8	59.2	55.7	49.9	59.6	56.4
	f-methanol+ICE	41.0	57.2	63.1	38.6	52.4	54.6
	e-methanol+ICE	53.0	61.6	61.0	53.0	61.7	61.2
	e-methanol+PEMFC	44.2	48.4	40.4	44.2	48.4	40.4
	f-NH3+ICE	36.2	52.0	58.5	32.1	43.7	44.0
	f-NH3+PEMFC	29.5	39.6	34.9	29.5	39.6	34.9
	f-NH3+SOFC	0.0	0.0	0.0	0.0	0.0	0.0
	e-NH3+ICE	46.2	56.8	59.2	46.0	56.3	58.4
	e-NH3+PEMFC	45.3	48.5	39.3	45.3	48.5	39.3
	e-NH3+SOFC	0.0	0.0	0.0	0.0	0.0	0.0
	e-LH2+ICE	42.7	54.0	56.6	42.4	53.5	55.6
	e-LH2+PEMFC	41.8	44.5	35.1	41.8	44.5	35.1
	EU-mix+ batteries	0.0	0.0	0.0	0.0	0.0	0.0
f-LNG+ICE		47.1	64.7	72.1	46.3	61.3	65.3
e-LNG+ICE		64.1	68.6	63.4	64.2	68.8	63.7
e-diesel+ICE		63.7	62.5	49.2	63.8	63.4	51.2
f-methanol+ICE		40.7	57.0	62.8	39.4	54.4	56.3

e-methanol+ICE	69.0	68.1	59.4	69.5	69.1	61.1
e-methanol+PEMFC	60.5	57.6	44.8	61.9	59.1	46.3
f-NH3+ICE	35.6	51.1	57.1	31.6	44.6	43.8
f-NH3+PEMFC	28.9	39.2	34.5	28.5	37.0	32.5
f-NH3+SOFC	30.7	36.6	32.2	28.9	39.2	34.5
e-NH3+ICE	61.6	64.0	60.1	63.9	63.8	60.2
e-NH3+PEMFC	63.9	59.1	44.4	63.5	57.0	42.5
e-NH3+SOFC	65.6	56.5	42.1	63.9	59.1	44.4
e-LH2+ICE	57.7	61.4	57.9	58.8	59.0	56.1
e-LH2+PEMFC	60.5	55.1	40.2	61.1	55.0	40.1
EU-mix+batteries	0.0	0.0	0.0	0.0	0.0	0.0

Table B.10 - Final scores (0-100) according to each decision maker for the ro-pax ship, in scenarios A and B.

Colour scale: dark green values are the ones with higher scores and the dark red ones represent the lower final scores

RO-PAX SHIP		A - without carbon taxes			B - with carbon taxes		
1st decade	**2nd+3rd decades**	**Total Score Environmentalist**	**Total Score Balanced**	**Total Score Investor**	**Total Score Environmentalist**	**Total Score Balanced**	**Total Score Investor**
HFO+ICE	HFO+ICE	49.6	66.7	73.7	47.3	62.1	65.7
	f-LNG+ICE	47.7	65.3	72.7	45.3	60.4	64.2
	e-LNG+ICE	51.0	64.1	66.3	50.3	62.8	64.0
	e-diesel+ICE	50.5	60.7	58.1	50.0	59.7	56.5
	f-methanol+ICE	41.4	57.9	64.2	38.7	52.5	54.7
	e-methanol+ICE	53.5	62.6	62.6	53.1	61.9	61.3
	e-methanol+PEMFC	43.6	47.3	39.7	43.6	47.3	39.7
	f-NH3+ICE	36.8	53.2	60.1	32.4	44.4	44.6
	f-NH3+PEMFC	29.0	38.6	34.2	29.0	38.6	34.2
	f-NH3+SOFC	0.0	0.0	0.0	0.0	0.0	0.0
	e-NH3+ICE	46.9	58.1	61.0	46.4	57.0	59.1
	e-NH3+PEMFC	44.8	47.6	38.7	44.8	47.6	38.7
	e-NH3+SOFC	0.0	0.0	0.0	0.0	0.0	0.0
	e-LH2+ICE	43.6	55.9	58.9	43.0	54.7	56.8
	e-LH2+PEMFC	41.5	43.8	34.7	41.5	43.8	34.7
	EU-mix+batteries	0.0	0.0	0.0	0.0	0.0	0.0
f-LNG+ICE		47.5	65.4	73.0	45.0	60.5	64.4
e-LNG+ICE		64.8	70.0	65.5	64.3	69.1	64.0
e-diesel+ICE		64.7	64.5	52.5	64.4	64.1	51.8
f-methanol+ICE		42.2	59.9	66.0	39.4	54.3	56.3
e-methanol+ICE		69.7	69.4	61.5	69.6	69.1	61.1
e-methanol+PEMFC		60.0	56.6	44.1	60.0	56.6	44.1
f-NH3+ICE		37.3	54.6	61.0	32.6	45.2	44.6
f-NH3+PEMFC		27.3	36.0	31.6	27.3	36.0	31.6
f-NH3+SOFC		0.0	0.0	0.0	0.0	0.0	0.0
e-NH3+ICE		61.8	64.4	61.1	61.5	63.8	60.0
e-NH3+PEMFC		62.3	56.0	41.6	62.3	56.0	41.6
e-NH3+SOFC		0.0	0.0	0.0	0.0	0.0	0.0
e-LH2+ICE		57.0	60.1	57.2	56.6	59.4	55.9
e-LH2+PEMFC		60.1	54.4	39.8	60.1	54.4	39.8
EU-mix+ batteries		0.0	0.0	0.0	0.0	0.0	0.0

Table B.11 - Final scores (0-100) according to each decision maker for the fishing trawler, in scenarios A and B.

Colour scale: dark green values are the ones with higher scores and the dark red ones represent the lower final scores

FISHING TRAWLER		A - without carbon taxes			B - with carbon taxes		
1st decade	**2nd+3rd decades**	**Total Score Environmentalist**	**Total Score Balanced**	**Total Score Investor**	**Total Score Environmentalist**	**Total Score Balanced**	**Total Score Investor**
HFO+ICE	HFO+ICE	49.6	66.7	73.9	47.2	61.9	65.4
	f-LNG+ICE	44.0	61.5	69.2	41.4	56.4	60.2
	e-LNG+ICE	47.1	60.1	62.4	46.4	58.8	60.0
	e-diesel+ICE	50.3	60.2	57.5	49.8	59.3	55.8
	f-methanol+ICE	41.4	57.9	64.4	38.5	52.2	54.4
	e-methanol+ICE	53.4	62.4	62.5	53.0	61.7	61.1

	e-methanol+PEMFC	44.1	48.3	40.4	44.1	48.3	40.4
	f-NH3+ICE	36.6	52.8	59.9	32.0	43.6	43.7
	f-NH3+PEMFC	29.5	39.5	34.8	29.5	39.5	34.8
	f-NH3+SOFC	0.0	0.0	0.0	0.0	0.0	0.0
	e-NH3+ICE	46.7	57.6	60.7	46.1	56.5	58.8
	e-NH3+PEMFC	45.3	48.6	39.3	45.3	48.6	39.3
	e-NH3+SOFC	0.0	0.0	0.0	0.0	0.0	0.0
	e-LH2+ICE	43.1	55.0	58.3	42.5	53.8	56.1
	e-LH2+PEMFC	41.8	44.4	35.0	41.8	44.4	35.0
	EU-mix+ batteries	0.0	0.0	0.0	0.0	0.0	0.0
f-LNG+ICE		43.7	61.6	69.5	41.1	56.4	60.5
e-LNG+ICE		60.8	65.8	61.4	60.4	64.9	59.8
e-diesel+ICE		64.3	63.8	51.4	64.1	63.4	50.7
f-methanol+ICE		42.2	59.9	66.2	39.3	54.1	56.0
e-methanol+ICE		69.6	69.1	61.2	69.4	68.8	60.7
e-methanol+PEMFC		60.4	57.6	44.8	60.4	57.6	44.8
f-NH3+ICE		37.1	54.1	60.7	32.2	44.3	43.5
f-NH3+PEMFC		27.8	36.9	32.2	27.8	36.9	32.2
f-NH3+SOFC		31.6	38.5	34.3	31.6	38.5	34.3
e-NH3+ICE		61.5	63.8	60.6	61.2	63.2	59.5
e-NH3+PEMFC		62.8	56.9	42.2	62.8	56.9	42.2
e-NH3+SOFC		66.6	58.5	44.3	66.6	58.5	44.3
e-LH2+ICE		56.5	59.0	56.2	56.1	58.2	54.9
e-LH2+PEMFC		60.4	55.0	40.1	60.4	55.0	40.1
EU-mix+ batteries		0.0	0.0	0.0	0.0	0.0	0.0

Table B.12 - Resume table with the top 3 performers' final score for each vessel in both scenarios (A- without carbon taxation, and B- with carbon taxation).

Sustainable alternatives highlighted in green, fossil alternatives in blue; 'N:' means the combinations is from the "new set" of combinations, 'R:' means the combination is from the "retrofit set" of combinations.

		No Carbon Tax (A)		**With Carbon Tax (B)**	
Vessel	**Decision Maker type**	**Option**	**Score**	**Option**	**Score**
CONTAINER	Environmentalist	N: **e-methanol+ICE**	68.8	N: **e-methanol+ICE**	69.4
		N: e-NH3+SOFC	66.1	N: e-NH3+SOFC	66.1
		N: e-LNG+ICE	64.2	N: e-diesel + ICE	64.7
	Balanced	N: e-LNG+ICE	68.8	N: e-LNG+ICE	69.3
		N: e-methanol+ICE	67.5	N: e-methanol+ICE	68.9
		N: HFO+ICE	66.4	N: e-NH3+ICE	64.7
	Investor	N: **HFO+ICE**	73.2	N: **HFO+ICE**	66.3
		N: f-LNG+ICE	72.7	N: f-LNG+ICE	64.9
		R: f-LNG + ICE	72.4	R: f-LNG + ICE	64.8
GENERAL CARGO	Environmentalist	N: e-methanol+ICE	68,7	N: e-methanol+ICE	69,2
		N: e-NH3+SOFC	65,6	N: e-LNG+ICE	64,2
		N: e-LNG+ICE	64,1	N: e-NH3+ICE	63,9
	Balanced	N: e-LNG+ICE	68,6	N: e-LNG+ICE	68,8
		N: e-methanol+ICE	67,4	N: e-methanol+ICE	68,4
		N: HFO+ICE	66,1	N: e-NH3+ICE	63,8
	Investor	N: HFO+ICE	72,8	N: HFO+ICE	65,6
		N: f-LNG+ICE	72,1	N: f-LNG+ICE	65,3
		R: f-LNG+ICE	71,7	R: f-LNG+ICE	63,9
RO-PAX	Environmentalist	N: e-methanol+ICE	69,5	N: e-methanol+ICE	69,4
		N: e-LNG+ICE	64,8	N: e-diesel + ICE	64,4
		N: e-diesel+ICE	64,7	N: e-LNG+ICE	64,3
	Balanced	N: e-LNG+ICE	70,0	N: e-LNG+ICE	69,1
		N: e-methanol+ICE	69,0	N: e-methanol+ICE	68,8
		N: HFO+ICE	66,7	e-diesel + ICE	64,1
	Investor	N: HFO+ICE	73,7	N: HFO+ICE	65,7
		N: f-LNG+ICE	73,0	N: f-LNG+ICE	64,4

		R: f-LNG+ICE	72,7	R: f-LNG+ICE	64,2
PAX-FERRY	Environmentalist	N: e-methanol+ICE	67,4	N: e-methanol+ICE	70,0
		N: e-NH3+PEMFC	64,4	N: e-NH3+PEMFC	67,0
		N: e-diesel + ICE	64,0	N: e-diesel + ICE	67,0
	Balanced	N: EU-mix+batteries	65,5	N: e-methanol+ICE	70,0
		N: e-methanol+ICE	64,9	N: e-diesel + ICE	69,2
		N: e-diesel+ICE	63,1	N: EU-mix+batteries	68,2
	Investor	N: EU-mix+batteries	64,0	N: EU-mix+batteries	68,7
		N: HFO+ICE	62,7	R: EU-mix+batteries	66,9
		R: EU-mix+batteries	62,7	N: HFO+ICE	64,8
FISHING TRAWLER	Environmentalist	N: e-methanol+ICE	69,2	N: e-methanol+ICE	69,1
		N: e-NH3+SOFC	66,6	N: e-NH3+SOFC	66,6
		N: e-diesel + ICE	64,3	N: e-diesel + ICE	64,1
	Balanced	N: e-methanol+ICE	68,4	N: e-methanol+ICE	68,2
		N: HFO+ICE	66,7	N: e-LNG+ICE	64,9
		N: e-LNG+ICE	65,8	N: e-diesel + ICE	63,4
	Investor	N: HFO+ICE	73,9	N: HFO+ICE	65,4
		N: f-LNG+ICE	69,5	R: e-methanol+ICE	60,6
		R: f-LNG+ICE	69,2	N: f-LNG+ICE	60,5