SEAMLESS

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D4. 1 - PRELIMINARY ASSESSMENT OF ZERO-EMISSION POWER PLANT CONFIGURATIONS

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1.0	19.12.2024	Elias Kotsidis (ESI)	Final, review incorporated

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List of Abbreviations

Abbreviation	Description
AHP	Analytic Hierarchy Process
CapEx	Capital Expenditure
CFD	Computational Fluid Dynamics
CGH_2	Compressed Gaseous Hydrogen
CHP	Combined Heat and Power
ConOps	Concept of Operations
DS	Dempster-Shafer Theory
ELECTRE	ELimination Et Choix Traduisant la REalité (Decision-making method)
FMECA	Failure Mode, Effects and Critically Analysis
GHG	Greenhouse Gas
HELM	Helper for Energy Layouts in Maritime Applications
HFO	Heavy Fuel Oil
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
IMO	International Maritime Organization
IWT	Inland Waterway Transport
Kg	Kilogram
KPIs	Key Performance Indicators
KW	Kilowatt
L	Liter
LBG	Liquified Biogas
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Assessment
LH_2	Liquid Hydrogen
LNG	Liquified Natural Gas
LOHC	Liquid Organic Hydrogen Carriers
LPG	Liquified Petroleum Gas
MARCOS	Measurement of Alternatives and Ranking According to COmpromise Solution
MCDA	Multi-Criteria Decision Analysis
MGO	Marine Gas Oil
MJ	Mega Joules
MTF	Maritime Technologies Forum
NO_x	Nitrogen Oxides
OpEx	Operational Expenditure
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
PM	Particulate Matter
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluations
RCC	Remote Control Center
RoPax	Roll-on/Roll-off Passenger
SOFC	Solid Oxide Fuel Cell
SO_x	Sulfur Oxides
SSS	Short ship Shipping

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TFAHP	Trapezoidal Fuzzy Analytic Hierarchy Process
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
VIKOR	VIseKriterijumska Optimizacija I Kompromisno Resenje (Multi-criteria decision-making method)
Wh	Watt-hours
WtW	Well-to-Wake
ZE	Zero Emission

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EXECUTIVE SUMMARY

This document presents a study on the evaluation of alternative powertrains and their applications in the maritime sector, with a focus on zero-emission solutions. The work is structured around a multicriteria decision-making framework designed to assess and compare various energy technologies and fuel types suitable for marine vessels. The report aims to initiate guidance to decision-makers in selecting optimal powertrains based on performance criteria relevant to the maritime industry.

The document begins with an introduction outlining the background, purpose, scope, and structure of the report. It sets the context for the increasing importance of sustainability and emissions reduction in the maritime sector.

Then it introduces a multicriteria framework for assessing alternative powertrains. It includes a literature review of existing assessment frameworks specific to the maritime sector, followed by insights derived from these studies. The methodology for applying multicriteria decision analysis is then described, detailing the criteria and sub-criteria for evaluation, as well as the process of criteria weighting and prioritization.

Furthermore, it focuses on powertrains, with detailed discussions on various technologies, including battery-powered systems and fuel cells. The report covers PEM and SOFC fuel cells, and explores different fuel types used in fuel cells, such as hydrogen (H_2) in its various forms (CGH_2, LH_2, LOHC), ammonia, and methanol. The comparative performance of these fuels for use in fuel cells is also analyzed.

Finally, a vessel design process is described with two case studies, one for the Northern European and one for the Central European contexts. The performance parameters that will be assessed during the next phase of Task 4.1, including stability, resistance, seakeeping, and other relevant metrics are described.

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1 INTRODUCTION

1.1 BACKGROUND

The shipping industry is undergoing significant transformation, driven by increasing regulatory, environmental, and societal pressures to reduce greenhouse gas (GHG) emissions and transition to sustainable energy sources. This document addresses the urgent need to evaluate and implement zero-emission power plant configurations for short-sea shipping (SSS) and inland waterway transport (IWT) vessels. These transport modes face unique operational and logistical challenges, related to autonomy, fuel availability, and infrastructure constraints. Tailored approaches to decarbonization are, thus, required.

1.2 PURPOSE AND SCOPE

The purpose of this document is to provide a comprehensive preliminary assessment of zero-emission power plant configurations for SSS and IWT vessels. It focuses on methodologies and tools for evaluating alternative technologies, enabling stakeholders to make informed decisions that balance operational efficiency, cost, and environmental impact. This includes an exploration of key energy sources (batteries, fuel cells, and associated fuels) and their performance across criteria such as energy density, cost, and emissions. Additionally, the document aligns with the SEAMLESS project's goals by addressing use case requirements and supporting the development of sustainable maritime solutions. This deliverable is closely aligned with WP4 (Tasks 4.1 and 4.3) and WP6 (Tasks 6.2, 6.3, and 6.6). It lays the groundwork for establishing a multicriteria framework and initiates the development of two SEAMLESS design vessels, which will form a core part of Deliverable D4.3 (linked to Task 4.3). Additionally, the vessel designs produced in D4.3 will serve as inputs for simulations conducted within WP6 tasks, including T6.2, T6.3, and T6.6. The intended readership includes project stakeholders, policy makers, industry representatives and Academia and Research community interested in zero-emission shipping technologies and decarbonization targets.

1.3 STRUCTURE OF THE DOCUMENT

This document is structured in 5 chapters.

Chapter 2 introduces the multicriteria framework used to evaluate alternative powertrain solutions, including insights from the literature and a detailed assessment methodology.

Chapter 3 examines the key zero-emission powertrain technologies, with an emphasis on batteries and fuel cells, as well as the specific fuels powering these systems.

Chapter 4 focuses on the modeling and evaluation of ships for specific use cases, presenting case studies and performance metrics such as stability, resistance, and seakeeping.

Chapter 5 concludes the document, summarizing the findings

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2 MULTICRITERIA FRAMEWORK

2.1 OVERVIEW

The present study outlines the initial phase of a two-step process aimed at evaluating the available propulsion and energy supply systems based on alternative fuels and batteries tailored to the SEAMLESS short-sea shipping and inland shipping vessels. At the core of this process is a multi-criteria decision analysis framework developed and employed to assess combinations of energy carriers and associated energy conversions systems, based on their overall performance across multiple aspects.

In this first step, the fundamental strategy for the assessment was formulated. Specifically, the objective was to develop the basic methodology to explore the feasibility and performance of the alternatives. The outcome of this step sets the foundation for the second phase, which involves the meticulous evaluation and final ranking of energy carrier and systems alternatives for the two targeted shipping sectors.

2.2 LITERATURE REVIEW

Today, the shipping industry is undergoing a significant transformation as it faces the challenges of decarbonization and environmental sustainability. Driven by a combination of international, regional and national regulations, customer requirements, societal expectations and business dynamics, shipping companies are exploring and adopting various technical and operational measures to conduct greener operations and minimize their environmental impact. In fact, the transition to alternative fuels is at the forefront of these decarbonization efforts. Traditional marine fuels, such as heavy fuel oil (HFO), and even Liquefied Natural Gas (LNG), which is currently the most widely adopted alternative, are becoming unsuitable due to their high greenhouse gas (GHG) and air pollutants emissions. In response, the maritime sector is investigating and deploying various fuel alternatives, including methanol, ammonia, hydrogen and biofuels, as well as battery-electric solutions.

Shipping is a complex and diverse industry. It includes a wide range of vessel types, routes and operational profiles, each with unique characteristics, requirements, resources and challenges. Several green fuel technologies are currently under development, testing or deployment, each presenting distinct advantages and disadvantages in terms of availability, cost, environmental impact, short-term and long-term regulatory compliance, technological maturity, associated risks for health and safety, infrastructure needed, etc. The industry is in a phase of exploration to fully understanding the implications of adopting these alternatives. Large-scale adoption requires the establishment of new value chains at national, regional and international levels, based on collaborations and synergies among associated stakeholders, such as ship owners, engine manufacturers, fuel suppliers, authorities, industry organizations, shipyards, etc. Currently, these parties are closely observing each other for signals about the industry's direction, trying to navigate the associated uncertainty. This diversity of the industry and its associated uncertainty mean that a one-size-fits-all solution is highly unlikely or not even desirable. Each segment of the industry, even

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at a national or regional level, requires tailored solutions that match their specific needs and constraints.
Under these circumstances, it becomes apparent that determining the ideal combination of alternative fuel and energy conversion system for a new vessel can be a complex and challenging task. In fact, the solution to this multi-dimensional problem involves a multi-criteria decision making that needs to be optimized based on several parameters, including the ship- and route-specific operational requirements, the emerging energy landscape, the environmental initiatives at international, European and national levels, the available technologies, the existing and future regulatory framework, and the dynamic and evolving environment for each sector of the shipping industry.

One of the challenges in assessing alternative fuels for shipping is that relevant information is frequently missing or inadequately detailed. Furthermore, the reliability of the involved data is often questionable. In many cases, existing studies do not represent the latest developments or real-world conditions and operational practices, leading to potential misjudgment of a fuel's performance. These shortcomings make it difficult to perform accurate life cycle assessments (LCA) and life cycle cost assessments (LCCA), which are crucial for establishing the actual environmental and economic impacts of these fuels. In this regard, it is important to adopt a flexible and adaptive assessment framework that can accommodate new data as it becomes available. Moreover, engaging a wide range of stakeholders, including industry experts, researchers, and regulatory bodies, can help in gathering more comprehensive and up-to-date information. The use of digital modelling tools can further aid in filling information gaps and providing more accurate predictions of fuel performance.

Additionally, the accuracy of the evaluation of alternative maritime fuels depends on the availability of detailed ship- and region-specific data. This level of information is crucial for tailoring assessments of the unique operational profiles, environmental aspects and supply chain characteristics of different vessels and geographic regions. Ship-specific data includes parameters such as vessel type, size, propulsion and powering needs, typical routes and operational profiles. Incorporating these factors into the assessment allows for more precise modeling. For example, a fuel that is optimal for a large cargo ship operating on long international routes may not be suitable for a smaller vessel engaged in short-sea shipping. Region-specific data include regional regulatory requirements, fuel availability, infrastructure capabilities, such as bunkering facilities, and environmental conditions. These data significantly influence the feasibility and sustainability of adopting alternative fuels. For instance, the availability of refueling infrastructure for a particular alternative fuel can vary greatly between different ports and regions, affecting the logistics and overall viability of that fuel. Collecting and integrating this ship- and region-specific data into the evaluation process improves the credibility and the relevance of the assessments, ensures that the proposed fuels and technologies are not only theoretically but also practically viable and aligned with the operational realities, and facilitates more informed decision-making.

For assessing alternative marine fuel technology, the parameter of autonomy also needs to be thoroughly explored. The rapid evolution of sustainability targets is being significantly shaped by digitalization, which will have a transformative effect on the transportation and logistics industry in the foreseeable future. The development of autonomous ships is propelled by several key factors,

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such as cost reduction, safety levels that are (at minimum) the same as conventional ships, better working conditions, and the pursuit of environmental and sustainability goals through increased efficiency, reduced emissions (albeit automation is not necessarily intertwined with decarbonization), and the lack of qualified personnel (in inland waterway navigation). AI-powered autonomous navigation systems use data from various navigation equipment and sensors to steer a ship automatically at an optimized speed and route, thus minimizing fuel consumption and carbon emissions through route optimization. These systems also help adopt predictive maintenance policies and collision avoidance, thereby maintaining an acceptable level of safety at sea and mitigating the shortage of qualified seafarers. Additionally, they provide the ancillary benefits of freeing up space traditionally used for accommodation, machinery and human-centric functions. This facilitates the redesign of ship forms, structures and layouts, allowing for superior cargo stowage and transportation, and enabling the construction of lighter, more energy-efficient vessels with the same carrying capacity.

2.2.1 Assessment Frameworks in the Maritime Sector

In 2022, the Maritime Technologies Forum (MTF) (2022) presented a holistic framework to evaluate decarbonization technologies and energy carriers for the shipping industry. This framework was revised in 2024[1] to enhance its effectiveness. The purpose of the framework is to establish a common understanding and facilitate the assessment of alternatives by providing a systematic and standardized evaluation approach. It comprises eight categories of criteria: Greenhouse Gas Emission (GHG), technology, environmental sustainability, safety, economic viability, regulatory maturity, skills availability, and engineering. In total, there are thirty-three criteria within these categories. MTF recommends the evaluation of alternative technologies and energy carriers to be conducted in a workshop setting, with a team of specialists. Four grading levels are used to assess how well an alternative meets a criterion. Moreover, data availability and related epistemic uncertainty are considered for each criterion by employing a confidence level assessment, with four grading levels, to specify how confident the experts are regarding the accuracy of their evaluations.

Inal et al. (2022)[2] investigated two zero-carbon fuels, hydrogen and ammonia, specifically in fuel cell applications for powering ships. Their assessment was based on five criteria: safety (as the threat posed for personnel, equipment and environment), cost (referring to fuel cost and onboard storage cost), storage (consideration of storage methods and volumetric energy density), sustainability (depending on the global fuel availability and bunkering infrastructure) and environmental impact (emissions of the production phase). The importance (weighting) of the criteria was determined by using the AHP method, with the respective pairwise comparisons conducted with the help of experts from the maritime industry and academia. Notably, safety and environmental impact were identified as the most important criteria, having a major effect on the evaluation results. A semi-quantitative scale (performance points) was used to assess the two alternative fuels according to the established criteria. The study concluded that ammonia showed better performance than hydrogen. It should be

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[1] MTF. (2024). Revised framework for assessing decarbonization technologies and alternative energy carriers

[2] Inal, Omer & Zincir, Burak & Deniz, Cengiz. (2022). Investigation on the decarbonization of shipping: An approach to hydrogen and ammonia. International Journal of Hydrogen Energy. 10.1016/j.ijhydene.2022.01.189.

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mentioned that Inal et al. included a concise comparison of criteria used in previous works, from 2016 to 2021.
Perčić et al. (2020)[3] assessed alternative fuels for the Croatian short-sea shipping sector based on environmental and economic criteria to identify appropriate alternatives to diesel-fueled options. The study focused on three representative roll-on/roll-off passenger (RoPax) ships, operating on a short, medium and relatively long route respectively. The maritime fuels/energy sources considered in their analysis included, besides diesel, electricity (fully electrified, battery-powered ship), methanol (in a dual-fuel engine), dimethyl ether (in a dual-fuel engine), natural gas (in a dual-fuel engine), hydrogen (in a PEM fuel cell application) and biodiesel blend B20. The investigation of the environmental impact of these candidates was based on a Life-Cycle Assessment (LCA) approach, using the GREET 2019 software. A Life-Cycle Cost Assessment (LCCA) was performed for their economic evaluation, considering potential carbon allowance scenarios. According to the results, a fully electric configuration is both the most environmentally friendly and cost-effective option among the examined alternatives for all three RoPax ships, considering Croatia's 2018 electricity mix, which included 46% of renewable energy sources.

Ren and Liang (2017)[4] developed a methodology to address the multi-criteria decision-making problem of assessing the sustainability of alternative marine fuels. Three alternative marine fuels, methanol, LNG and hydrogen, were studied with the proposed method. First, a set of fourteen evaluation criteria in total was established, covering four aspects: environmental, economic, technological and social. The environmental dimension comprised four criteria: effect on CO2 emission reduction, effect on NOx emission reduction, effect on SOx emission reduction, and effect on PM emission reduction. The economic category included two criteria, "capital cost" and "operational cost". The technological aspect referred to the "maturity", "reliability" and "capacity" (i.e. global availability) of the technology. The social aspect included two criteria, which are "comply with emission regulations" and "social acceptance". Next, they utilized the fuzzy logarithmic least squares method to determine the significance (weights) of the criteria. At this stage, decision-makers/stakeholders were engaged to collect data regarding the relative importance of one criterion over another. The experts were asked to use linguistic variables, i.e. a qualitative approach, to determine the weight of each criterion, corresponding to specific fuzzy scales. Subsequently, the fuzzy Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) method was employed to determine the sustainability index of each alternative marine fuel. Finally, the sustainability order of the alternative marine fuels was determined based on the sustainability indices. The study concluded that hydrogen was the most sustainable option, followed by LNG.

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[3] Perčić, Maja & Vladimir, Nikola & Fan, Ailong. (2020). Life-cycle cost assessment of alternative marine fuels to reduce the carbon footprint in short-sea shipping: A case study of Croatia. Applied Energy, Volume 279, 2020, 115848, ISSN 0306-2619. https://doi.org/10.1016/j.apenergy.2020.115848.

[4] Ren, Jingzheng & Liang, Hanwei. (2017). Measuring the sustainability of marine fuels: A fuzzy group multi-criteria decision-making approach. Transportation Research Part D: Transport and Environment, Volume 54, 2017, Pages 12-29, ISSN 1361-9209. https://doi.org/10.1016/j.trd.2017.05.004.

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Hansson et al. (2019)[5] assessed the prospects for seven alternative marine fuels for the year 2030 using a multi-criteria decision analysis approach based on the AHP method, involving Swedish stakeholders. The fuel options examined were liquefied natural gas (LNG), liquefied biogas (LBG), methanol from natural gas, renewable methanol, hydrogen for fuel cells produced from natural gas or electrolysis based on renewable electricity, and hydrotreated vegetable oil (HVO), with heavy fuel oil (HFO) serving as a benchmark. Their assessment was based on ten sub-criteria, covering economic, technical, environmental and social aspects: investment cost for propulsion, operational cost, fuel price, available infrastructure, reliable supply of fuel, acidification, health impact, climate change, safety and upcoming legislation. These sub-criteria were elicited from twenty-three initial factors through a survey engaging Swedish maritime stakeholders. The performance of the fuels against these criteria was initially determined based on a literature review. Then, the fuels were compared via pairwise comparisons based on their performance across the selected criteria. The relative importance of the criteria and sub-criteria was also established through pairwise comparisons conducted at a dedicated workshop. This workshop included Swedish stakeholders, such as shipowners, fuel producers, engine manufacturers, governmental authorities' representatives and researchers. It is worth noting that the preferences varied across the stakeholder groups, which differentiated their ranking of the alternatives. Shipowners, fuel producers and engine manufacturers ranked the fuel price, i.e. an economic criterion, first. These groups also favored LNG and HFO, followed by fossil methanol and various biofuels (LBG, renewable methanol, and HVO). In contrast, the government representatives prioritized environmental and social criteria, particularly GHG emissions and regulatory compliance. In their fuels' ranking, renewable hydrogen ranked highest, followed by renewable methanol and HVO.

Fan et al. (2021)[6] examined alternative solutions for inland ship power systems, focusing on two case studies in China: canal ships using battery power and Yangtze River ships employing hybrid power. The Life Cycle Assessment (LCA) and Life Cycle Cost Assessment (LCCA) methods were utilized to evaluate the emissions and costs associated with each ship's life cycle. The results indicate that battery power and hybrid power systems significantly reduce lifetime CO_2 emissions and costs compared to traditional diesel power, across four considered carbon credit scenarios (no taxation scenario, current policies scenario, stated policies scenario, and sustainable development scenario).

Andersson et al. (2020)[7] performed a comprehensive review of the criteria utilized in current assessments of future marine fuels, to identify the most significant ones. In their study, they emphasize the importance of evaluating alternatives from both a life cycle and multi-criteria perspective. It is worth noting that they recommend a minimum set of criteria that differentiates between factors to be considered when assessing alternative fuels for existing ships and criteria for

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[5] Hansson, Julia & Månsson, Stima & Brynolf, Selma & Grahn, Maria. 2019. Alternative marine fuels: Prospects based on multi-criteria decision analysis involving Swedish stakeholders. Biomass and Bioenergy, Volume 126, 2019, Pages 159-173, ISSN 0961-9534. https://doi.org/10.1016/j.biombioe.2019.05.008.

[6] Fan, Ailong & Wang, Junteng & He, Yapeng & Perčić, Maja & Vladimir, Nikola & Yang, Liu. (2021). Decarbonising Inland Ship Power System: Alternative Solution and Assessment Method. Energy. 226. 10.1016/j.energy.2021.120266.

[7] Andersson, Karin & Brynolf, Selma & Hansson, Julia & Grahn, Maria. (2020). Criteria and Decision Support for A Sustainable Choice of Alternative Marine Fuels. Sustainability. 12. 3623. 10.3390/su12093623.

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cases of new types of propulsion systems not typically used in shipping. For each application, they propose four categories of criteria: "environmental", "technical", "economic" and "other", each comprising several sub-criteria. The sub-criteria vary depending on the application. For existing ships, the "modifications needed of the propulsion system", "retrofit costs" and "fuel price" are included in the sub-criteria. In contrast, "technology readiness', "technology complexity" and "total cost of ownership during the ship life cycle" are recommended instead for new propulsion types.

Mandić et al. (2021)[8] proposed a methodology based on a multicriteria analysis to be used as a decision-support tool for selecting alternative marine fuels in coastal marine traffic. Their study examined biofuels, LNG, hydrogen, LPG and batteries. These alternatives were assessed based on environmental criteria (climate change impact, acidification, exhaust emissions), technological criteria (available infrastructure, reliability of supply, adaptation of ship engines, safety of fuel), and economical criteria (investment, operational cost, fuel price). Different stakeholders, including shipowners as end users, government representatives, and academia as neutral experts, were involved in defining the importance of the criteria and evaluating the performance of each alternative with respect to these criteria. The final ranking of the alternatives was determined using the Simple Additive Weighting (SAW) method. Initially, the Analytic Hierarchy Process (AHP) was employed to establish the importance (weight) of each criterion, and a ranking score (0-10) was utilized to evaluate how well each alternative performed in each criterion. This methodology was demonstrated through a case study in Croatia. According to the results, the batteries were ranked as the best option by all stakeholders.

Xing et al. (2021)[9] conducted a review to explore the most promising alternative marine fuels from an environmental and sustainability perspective. They began by identifying potential alternatives, i.e. combinations of energy carriers and associated energy converters, through a literature review. To assess these alternatives, they created a set of criteria and appropriately subdivided the alternatives' life-cycle pathways, allowing for different treatment of the criteria as required. The criteria included in their decision-making framework were "technical availability", "safety", "available infrastructure", "reliable supply of fuel", "investment cost for infrastructure", "investment cost of plants", "operational cost", "climate change" and "air pollution". The performance of the alternatives was evaluated qualitatively by using a ranking scale from I (worst) to IV (best). According to their findings, hydrogen, ammonia, bioethanol and biodiesels derived from renewable energy are the recommended alternatives for domestic and short-sea shipping in general. In terms of emissions performance, renewable methanol, ammonia and hydrogen (compressed or liquefied) are the most promising options for inland (domestic), coastal (domestic) and short-sea (international) shipping. From technical and economic aspects, the combinations of hydrogen with a low-temperature fuel cell and ammonia with an internal combustion engine are the best alternatives for short-sea shipping.

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[8] Mandić, Nikola & Ukić Boljat, Helena & Kekez, Toni & Runko Luttenberger, Lidija. (2021). Multicriteria Analysis of Alternative Marine Fuels in Sustainable Coastal Marine Traffic. Applied Sciences. 11. 2600. 10.3390/app11062600.

[9] Xing, Hui & Stuart, Charles & Spence, Stephen & Chen, Hua. (2021). Alternative fuel options for low carbon maritime transportation: Pathways to 2050. Journal of Cleaner Production. 297. 126651. 10.1016/j.jclepro.2021.126651.

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Nazemian et al. (2024)[10] presented a decision-making tool utilizing the AHP and Measurement of Alternatives and Ranking according to COmpromise Solution (MARCOS) methods and demonstrated its application for the assessment of six alternative fuel power management systems (PMSs) of the ship propulsion of a particular vessel. The evaluation criteria included capital expenditures (CAPEX), operating expenditures, risk (assessed by using Failure Mode, Effects, and Criticality Analysis (FMECA), emissions, availability, bunkering infrastructure and weight. The PMSs i.e. combination of fuel and energy conversion system or hybrid systems, were conventional fuel and internal combustion engine (ICE), conventional fuel ICE and battery, ammonia ICE, ammonia ICE and battery, methanol ICE, and methanol ICE and battery. Initially, the AHP method was utilized to specify the priority weight of each criterion and produce an initial ranking of PMS systems. Then, the MARCOS method was employed to rank again the alternatives. For the MARCOS methodology the ammonia ICE ranked first and the ammonia ICE and battery second. Using the AHP method

Strantzali et al. (2023)[11] proposed a decision support model for the in-depth evaluation of alternative marine fuels utilizing the outranking multi-criteria methodology Preference Ranking Organization Method for Enrichment Evaluation (Promethee II). They included a concise review of multi-criteria applications for the assessment of marine fuels from 2015 to 2023, using the results as a base of comparison with their findings. Notably, while most similar studies utilized the AHP method, they point out that AHP may not be suitable for cases with many criteria. Their assessment included 16 marine fuels, including LNG, MGO and HFO, and utilized 11 criteria and 25 sub-criteria, covering economic, technical, environmental and social aspects. In particular, the selected criteria were capital cost, operational cost, fuel cost, fuel availability, adaptability, commercial effects, risk assessment, emissions reduction, fuel properties, regulation and job creation. The importance of each criterion was established by engaging stakeholder groups, such as shipowners, fuel suppliers, industry and engine manufacturers, academics, banks and the public, and using the revised Simos approach. According to their results, renewable options ranked highly in most categories, especially among academics, banks, the public, and in the combined case scenario. Drop-in biofuels, bio and e-LNG, fossils and bio methanol were the preferred alternatives.

Ren and Lützen (2017)[12] developed a multi-criteria decision-making method combining Dempster-Shafer (DS) theory with a trapezoidal fuzzy analytic hierarchy process (TFAHP) to select alternative energy sources for shipping. Their methodology was specifically designed to facilitate decision making under uncertainty due to the lack of information. In this regard, they opted for the TFAHP method over the traditional AHP method because it handles better incomplete information. For their assessment, they selected 15 criteria covering four aspects: technological, economic, environmental, and social-political. The criteria for the technological aspect included maturity, reliability, and energy storage efficiency. The economic criteria comprised infrastructure, capital cost,

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[10] Nazemian, Amin & Boulougouris, Evangelos & Melemadom, Sarath. (2024). Hybrid and Alternative Fuel Power Management Systems in Ships – Multi-Criteria Decision-Making Assessment. International Marine Design Conference. 10.59490/imdc.2024.861.

[11] Strantzali, Eleni & Livanos, Georgios & Aravossis, Konstantin. (2023). A Comprehensive Multicriteria Evaluation Approach for Alternative Marine Fuels. Energies. 16. 7498. 10.3390/en16227498.

[12] Ren, Jingzheng & Lützen, Marie. (2017). Selection of sustainable alternative energy source for shipping: Multi-criteria decision making under incomplete information. Renewable and Sustainable Energy Reviews, Volume 74, 2017, Pages 1003-1019, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2017.03.057.

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bunker price, repair and maintenance cost, training cost and crew wage. The environmental parameters focused on SO_x reduction, NO_x reduction, GHG emissions reduction, and PM reduction. Lastly, the social-political criteria involved social acceptability, governmental support, and safety. To illustrate the functionality of their method, Ren and Lützen conducted a case study evaluating LNG, nuclear power and wind power to identify the most sustainable alternative. It should be mentioned that they determined the importance of the four aspects and the 10 criteria using both TFAHP and traditional AHP. The resulting weights were comparable, but they found TFAHP to be more accurate, and therefore, the weights determined by TFAHP were used in their case study.

Malmegren et al. (2021)[13] investigated the feasibility of adopting alternative marine fuels and propulsion technologies for the various shipping segments in Sweden, focusing on both domestic shipping and international shipping to and from the country. Their study utilized data from the Shipair module to estimate and analyze the routing and fuel consumption of different ship categories. These estimates were based on vessel movements and characteristics cross-referenced with vessel databases. The researchers identified ship categories and analyzed their operational characteristics, considering critical parameters such as function, typical route length, bunkering time requirements, energy requirements, and vessel age. These characteristics were then mapped against the performance profiles of selected alternative propulsion technologies and fuels. The energy carriers considered included electricity, hybrid electric, diesel, ammonia, methane, methanol, ethanol, and hydrogen. To determine the constraints for the Swedish shipping segments, the performance of the alternatives was examined based on technical, environmental and economic aspects through expert input from project partners and a literature review. Each alternative was matched with the ship categories, analyzed within the Swedish context, and the identified constraints.

Rattazzi et al. (2020)[14] developed the software Helper for Energy Layouts in Maritime applications (HELM) for the preliminary assessment of various energy systems onboard ships, aimed at identifying the most promising alternatives for specific applications. The digital tool utilizes maps that report main indicators, such as weight, volume, cost and emissions, for each component, relative to the installed power and operational hours required. Then, HELM compares the results to provide the best solution for the application considered. The maps were built from a comprehensive database developed through an extensive analysis of available market solutions in terms of fuels, energy conversion systems and storage technologies. The developers emphasize HELM's flexibility, noting that the tool can be easily updated to include more fuel technologies and can be applied to various typologies and sizes of ships.

Law et al. (2021)[15] reviewed 22 potential pathways for shipping by comparing them across six quantifiable parameters: fuel mass, fuel volume, life cycle (Well-To-Wake—WTW) energy intensity, WTW cost, WTW greenhouse gas (GHG) emission, and non-GHG emissions. They utilized simulations conducted with the ASPEN HYSYS modelling software and available literature (where

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[13] Malmgren, Elin & Hansson, Julia & Brynolf, Selma & Grahn, Maria. (2021). The feasibility of alternative fuels and propulsion concepts for various shipping segments in Sweden.

[14] Rattazzi, Diego & Rivarolo, M. & Massardo, Aristide. (2020). An innovative tool for the evaluation and comparison of different fuels and technologies onboard ships.

[15] Law, Li & Foscoli, Beatrice & Mastorakos, Epaminondas & Evans, Stephen. (2021). A Comparison of Alternative Fuels for Shipping in Terms of Lifecycle Energy and Cost. Energies. 14. 8502. 10.3390/en14248502.

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simulations were not possible) to obtain energy and cost data considering the entire life cycle of the alternative fuels, from the production phase to the final energy conversion phase. In the final part of their study, Law et al. ranked the alternative pathways based on the results of their quantitative analysis and additional qualitative criteria, including fuel scalability, fuel safety, regulations and guidelines, and technology readiness level.

Zamboni et al. (2024)[16] investigated the emission performance of various alternative marine fuels for ship propulsion from a well-to-wake (WtW) perspective. They performed a comparative analysis of LNG (fossil and bio-), methanol (grey and green) and ammonia (grey and green) on a case study involving a specific cruise ship operating under two different operational profiles. They evaluated the WtW CO_2 equivalent emission factors and employed the Carbon Intensity Indicator (CII) as a metric to evaluate emission performance. An extensive literature review was conducted to identify the WtW GHG emissions of alternative fuels in perspective.

Lloyd's Register (2024)[17] has developed the Zero Carbon Fuel Monitor, an online digital tool designed to provide a regularly updated assessment of the readiness of zero-carbon fuels for the maritime industry. The monitored energy carriers are ammonia, biodiesel, methane, batteries, hydrogen, methanol and nuclear. The platform presents in a tabulated format the readiness level of each alternative across three main aspects: technology (Technology Readiness Level - TRL, indicating maturity to become application-ready, on a 9-level scale), investment (Investment Readiness Level - IRL, indicating commercial maturity, on a 6-level scale) and community (Community Readiness Level - CRL, indicating social acceptability/adoption, on a 6-level scale). Additionally, it provides the readiness level of each fuel's supply chain in terms of resources/feedstocks, production (processing), bunkering and ports integration, ship-on-board handling and storage and ship-propulsion.

DNV-GL (2019)[18] conducted a study to assess the commercial and operational viability of alternative marine fuels. They examined the performance of six alternative fuels compared to LNG across sixteen discrete pathways and evaluated them based on a set of eleven criteria. These criteria covered four main categories: applicability (including energy density, technological maturity, flammability and toxicity, and regulations and guidelines (including the existence of bunkering/fuel loading guidelines and regulations)), economics (including energy costs and capital costs), environment (including GHG emissions (well-to-wake), and local emissions (SOx, NOx and PM) and scalability (including main current usages, availability, and global production capacity and locations). Data on the key assessment parameters were collected from academic and industry literature, processed, and graphically illustrated. The results for each pathway were then evaluated and compared to provide relevant insights. It must be pointed out that DNV-GL's conclusions focus on ammonia, hydrogen and electric options originating from renewable pathways. They explain that

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[16] Zamboni, Giorgio & Scamardella, Filippo & Gualeni, Paola & Canepa, Edward. (2024). Comparative analysis among different alternative fuels for ship propulsion in a well-to-wake perspective. Heliyon. 10. e26016. 10.1016/j.heliyon. 2024.e26016.

[17] Zero Carbon Fuel Monitor, The Lloyd's Register Maritime Decarbonisation Hub, July 2022 update. Available at https://www.lr.org/en/marine-shipping/maritime-decarbonisation-hub/zcfm/

[18] DNV-GL. (2019). Comparison of Alternative Marine Fuels. SEA\LNG Ltd, Report No. 2019-0567 Rev. 3.

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these alternatives can only effectively contribute to the decarbonization of the shipping industry in the long term if they are produced from renewable sources.

2.2.2 Key Insights from Literature

Based on the above literature review on assessment methodologies and evaluation criteria for alternative fuels in the maritime sector, several key conclusions can be drawn. These insights were utilized to develop the alternative fuel assessment framework for Task 4.1 of the SEAMLESS project. Firstly, there are diverse methodological approaches that can be used for the systematic evaluation of alternatives. Various multi-criteria decision-making methods, such as AHP, TOPSIS, VIKOR, PROMETHEE, ELECTRE, etc. have been employed in previous studies. The assessment framework needs to be flexible to handle uncertainties and incomplete information. It should also be adaptable to accommodate new data, emerging technologies, and shifting regulatory constraints.

Additionally, an extensive range of criteria and sub-criteria have been used to evaluate alternatives. It should be noted that no single criterion can provide a comprehensive assessment, highlighting the necessity for multi-criteria methodologies. The evaluation criteria are generally categorized into four main aspects: technological, economic, environmental, and social-political. Technological criteria often include technology maturity, reliability, and energy storage efficiency. Economic criteria involve capital costs, operational costs and infrastructure costs. Environmental criteria focus on GHG emissions and emissions of air pollutants (SOx, NOx, and particulate matter, PM). Social-political criteria assess factors such as social acceptability, governmental support, and safety. Given the project's focus on specific use cases, the criteria must be carefully chosen to reflect their unique characteristics. The number of criteria is also an important factor. There should be enough criteria to ensure an effective and reliable assessment and at the same time facilitate the engagement of the decision makers, decrease their logical or comprehension misjudgments and reduce as far as possible the overall complexity of the evaluation process.

Moreover, involving stakeholders in the assessment process ensures the evaluation is realistic, captures the challenges and reflects actual priorities. This engagement is also essential for the credibility of the evaluation process. Normally, stakeholders have diverse views regarding the ranking of the candidate schemes. Engaging stakeholders from different sectors (e.g., shipowners, fuel suppliers, engine manufacturers, governmental authorities, researchers/academia, public, etc.) using appropriate methods is crucial in determining the criteria to be used, their relative importance, and the final evaluation of the alternatives. This strategy helps produce a mapping of the preferences and provides valuable insights into their choices. Thus, an efficient and effective method must be chosen to engage stakeholders and capture their preferences and priorities.

Life cycle assessment (LCA) and life cycle cost assessment (LCCA) are often employed to evaluate the environmental and economic impacts of alternative fuels. Such an approach ensures that all stages, from production to consumption (well-to-wake), are considered, providing a holistic view of the alternative fuel performance.

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Digital tools (e.g., NAPA[19], TRANSYS[20], ANSYS[21]) can be valuable in conducting a detailed analysis and predicting the performance of alternative fuel systems. These tools facilitate the modelling of energy consumption, which can be transformed into emissions and energy costs, providing a more accurate and robust data set for the evaluation and subsequent decision-making.

Finally, in terms of alternative energy carriers, fuels produced from renewable sources such as biofuels, green hydrogen, and green ammonia often rank high in assessments due to their better environmental performance when compared with other alternative fuels. However, their feasibility heavily depends on developing the relevant energy sources and supporting infrastructure. Nevertheless, the focus of the shipping industry should be placed on renewable fuels to align with the decarbonization goals and achieve long-term sustainability.

2.3 ASSESSMENT METHODOLOGY

This section outlines the approach that will be employed to assess the alternative fuel technologies for the short-sea and inland shipping use cases. The selection of this specific methodology is based on the results of the review of academic and industry literature, which was conducted for this Deliverable. The approach is designed to be comprehensive to ensure that the evaluation process will be thorough, inclusive of stakeholder perspectives, and supported by robust modeling techniques and data.

In the final phase of the task, a rigorous and robust implementation of a multi-criteria decision analysis framework will be undertaken. In particular, the following steps outlined below will be followed. However, it should be noted that the methodology may be revised as the task (T4.1) progresses. Although the methodology as described is generic, some steps may still be revised.

- Review maritime industry literature to identify potential combinations of energy carriers and associated energy conversion systems suitable for propulsion in short-sea and inland shipping vessels.
- Iterate the review of academic and industry literature to explore proposed or utilized methodologies and criteria for assessing alternatives within the maritime transportation sector.
- Develop the evaluation methodology of the candidates based on the review findings, supplemented by the expertise and insights of the research team.
- The review results and the expert opinions of the advisory board members will be used to establish a set of criteria and sub-criteria that will form the basis of the evaluation process. The project’s advisory board will participate through an appropriate survey.
- Organize a workshop to engage key stakeholders in determining the importance (weight) of each criterion/sub-criterion and assessing the performance of the alternatives against these criteria using appropriate methods. The engaged stakeholders should represent various sectors, such as shipowners, fuel producers, engine manufacturers, governmental authorities and academia/researchers, particularly those affiliated with short-sea and inland shipping. The

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[19] https://www.napa.fi/
[20] https://www.trnsys.com/
[21] https://www.ansys.com/

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stakeholders could be divided into working groups based on the stakeholder sector they represent to explore each sector's priorities.

- Employ a digital tool[22] to model the candidate propulsion/power generation schemes and specify each alternative's fuel/energy consumption. Efforts will be made to acquire and use ship-specific technical and operational data.
- Update the developed model to include the autonomy parameter to explore the potential consequences of introducing autonomy.
- Conduct a literature review to collect economic (fuel/energy cost) and emission data regarding the candidates. If available, area-specific data can be used.
- Use the calculated and collected data to perform a Life Cycle Assessment (LCA) and Life Cycle Cost Assessment (LCCA) of the alternatives to establish their environmental and economic impact.
- Conduct the final evaluation and ranking of the alternatives for the two use cases.

Figure 1 presents the methodology to be applied for the assessment of the alternatives.

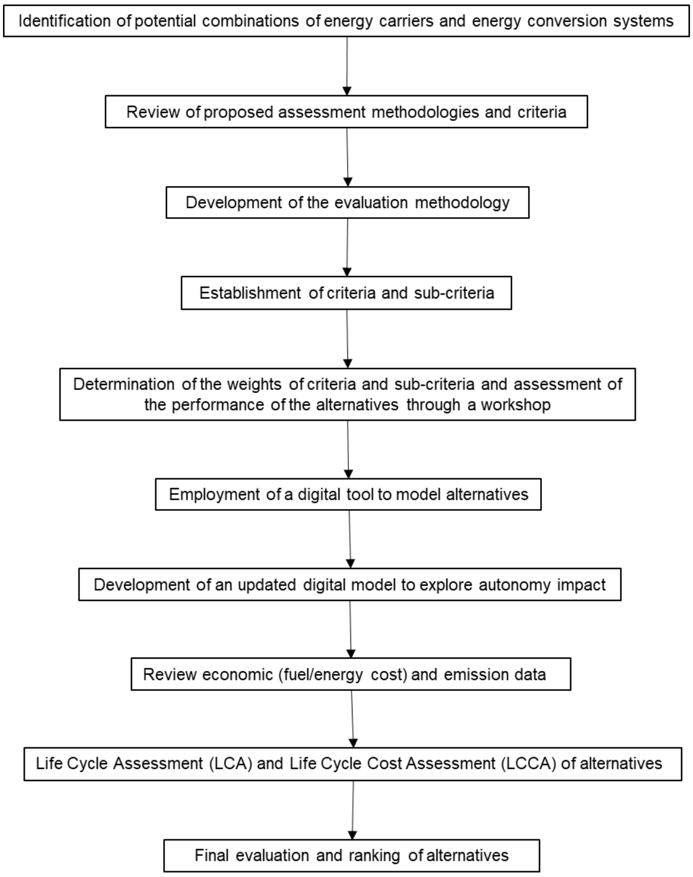

Figure 1 Methodology for the assessment of alternatives

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[22] This will be further elaborated on in T4.1 subsequent deliverable, i.e., D4.3.

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2.4 MULTI-CRITERIA DECISION ANALYSIS (MCDA)

The evaluation of the candidate combinations of energy carrier and energy conversion system, to derive a ranking of the most suitable options, will be performed through the application of a multi-criteria analysis. An overview of this analysis is briefly presented in the following paragraphs.

2.4.1 Evaluation Criteria and Sub-Criteria

The assessment of the alternative marine fuel options will be conducted by utilizing a specific set of main criteria and associated sub-criteria. The primary division between criteria and sub-criteria and the respective grouping of sub-criteria will be carefully established to assist in the development and execution of the evaluation process and aid the engaged decision-makers in their assessments. This structuring will also facilitate the consistency of the results of the comparisons to be conducted for the weighting of the criteria, which is a critical factor for the reliability of the applied technique.

The selection of the criteria and sub-criteria will be based on a comprehensive review of the pertinent literature, including studies conducted by relevant organizations and authorities, and various scientific publications. Additionally, the expertise and insights of the SEAMLESS advisory board will also be exploited. An indicative set of criteria and sub-criteria are outlined in Table 1, along with a concise explanation of each of them. Figure 2 provides an overview of these criteria. It should also be noted that the criteria mentioned on Table 1 will be updated in D4.3, according to the KPIs that were defined in the context of T6.1/D6.1.

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Table 1 Potential evaluation criteria and sub-criteria of candidate scenarios (combinations of alternative fuel with power conversion system).

Criterion	Sub-criterion	Definition
1. Economic	1.1 Capital expenditure	It refers to the initial investment cost for acquiring the new ship (Capital Expenditure - CapEx).
	1.2 Operational expenditure (excluding energy costs)	It includes the costs associated with the maintenance and operation of the ship (Operational Expenditure - OpEx).
	1.3 Fuel/Energy cost	It refers to the cost of supplying alternative fuel or electricity.
	1.4 Shore Infrastructure Cost	It is the cost (CapEx) for developing the necessary onshore infrastructure, including storage and supply facilities.
	1.5 Resale value	It refers to the resale value of the ship.
2. Environmental	2.1 GHG emissions	Greenhouse Gases (GHG) emissions refer to the quantity of greenhouse gases (CO_2, CH_4, N_2O, etc.) produced by the operation of the ship's propulsion and electric generation system.
	2.2 Emissions of air pollutants	It refers to the quantity of emissions of NO_X, SO_X, particulate matter (PM), etc., produced by the operation of the ship's propulsion and electric generation system. In addition to the general pollution of the atmosphere, these emissions also impact air quality in the areas where the ship is docked and in the coastal areas it traverses.
	2.3 Noise emissions	It refers to the noise generated during the operation of the ship's propulsion and electric generation system.
3. Technical	3.1 Endurance	It refers to the ship's ability to remain operational without the need for refueling. Also, this criterion is linked to the possibility of covering other routes of longer distances/duration if deemed necessary.
	3.2 Technological maturity	It refers to the maturity/technological readiness of the alternative fuel combined with the associated energy conversion technology.
	3.3 Safety	It refers to the risks associated with the safe operation of the system over time, including fire, explosion, and human health risks. It is also related to the existence/maturity of the appropriate regulatory framework for the safe use of each alternative as a marine fuel.
	3.4 Adaptability	It refers to the propulsion system's capacity to be modified to meet future developments (technological, energy, regulatory, etc.).
4. Energy	4.1 Availability of Fuel/Electric Power	It refers to the long-term availability of fuel and energy. It is related to energy security concerning the future stability and capacity of supply and distribution.
	4.2 Shore Infrastructure Compatibility	It assesses the compatibility with existing infrastructure, including ports and fuel/energy supply infrastructure/networks, and the availability of storage, distribution, and supply facilities upon the ship's delivery.
	4.3 Refueling time	It is the time required for the refueling of the ship or the full charging of its battery (in the case of a battery-equipped ship)
5. Social	5.1 Public Image	It refers to the effect on the public image and prestige of the ship-owning company.
	5.2 Passenger comfort	It refers to the passengers' voyage experience, encompassing factors such as noise, vibrations, and odors generated during the ship's operation.

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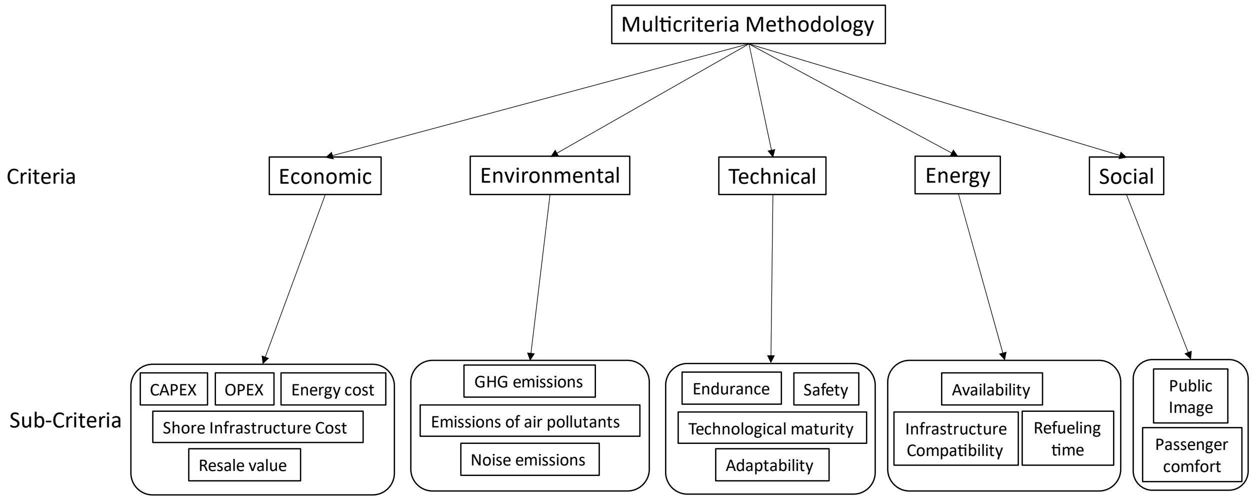

Figure 2 Overview of indicative set of criteria and sub-criteria for the assessment of alternative marine fuel technologies.

2.4.2 Criteria Weighting and Prioritization

The evaluation criteria and sub-criteria may have different levels of importance (weights) for each decision-maker or stakeholder. These weights reflect the impact of each criterion on their overall decision. If the environmental footprint is a major concern for a particular stakeholder, it should be weighted accordingly to influence the decision proportionately. By applying appropriate weights, all relevant factors are considered in a balanced manner. Without weighting, lesser criteria could disproportionately affect the evaluation outcome, leading to suboptimal decisions.

For example, ship owners may prioritize fuel cost, fuel availability, operational cost, reliability and regulatory compliance. Fuel suppliers might focus on the scalability and marketability of fuels. Authorities and regulatory bodies may emphasize environmental impact and safety. Crews may be concerned with safety and ease of handling. In terms of operational context, the short-sea shipping sector might prioritize fuel availability and cost due to shorter, more frequent routes. Inland shipping could focus on emissions and environmental regulations due to proximity to populated areas. Long-distance shipping would likely emphasize fuel efficiency and energy density for extended voyages.

Therefore, a method for determining their weight is necessary to evaluate the candidate scenarios effectively. This approach ensures that the diverse priorities and perspectives of different stakeholders are accurately reflected in the decision-making process, leading to more balanced and informed outcomes.

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3 POWERTRAINS

In this chapter the different Zero Emission (ZE) power plants will be explored for candidate power plants of short sea shipping and inland waterway vessels. The information provided will be used to quantify the criteria in the MCDA at a later stage of the task. Among the candidate technologies, batteries and fuel cells stand out as promising options, offering truly ZE solutions that align with environmental goals and operational requirements for these vessel types.

Before presenting the various ZE power plants configurations a distinction should be made of the key differences and considerations when applying ZE power plants, on SSS versus IW vessels, as each operates under distinct conditions and has unique operational needs.

Concerning range and energy demand, SSS vessels typically cover longer distances and spend more time at sea, resulting in higher energy demands. This calls for energy-dense power solutions to ensure that vessels can meet longer-range requirements without frequent refueling. Lower density solutions in this case might be more practical, especially given the proximity to refuelling infrastructure.

About refuelling infrastructure, ports of SSS may lack ZE fuel infrastructure as they're traditionally geared towards conventional fuels. Therefore, deploying ZE technology for these vessels may require significant investment in port infrastructure to accommodate fuel cells and hydrogen storage, adding to operational costs and requiring regulatory support. For IW, due to the smaller geographic scope, it is more feasible to set up refuelling infrastructure along major inland waterways. This makes it easier to implement fuel cells and battery-based solutions that can be recharged frequently, enhancing their practicality and cost-effectiveness. In any case, the exact infrastructure solution depends on the specific of the use case and operational requirements. More specifically, on the distance of the trip, speed resistance characteristics, etc. which are planned to be studied and evaluated during the design of the power plant and the size and characteristics of the ship.

Regarding environmental and safety constraints, SSS vessels operate in open seas and occasionally close to populated areas whereas safe handling of hazardous fuels is critical. Emission regulations are stringent, but there is more leeway for infrastructure development and fuel storage modifications to meet these requirements. For IW vessels, safety considerations are paramount as they operate near urban centres and sensitive ecosystems.

Finally, concerning the storage space, SSS vessels can afford to allocate more space for fuel storage to accommodate energy-dense options, which can support extended operations. IW vessels with limited space and typically lower energy demands (compared to SSS), compact solutions are often better suited, balancing storage constraints with the power needed for shorter, regulated routes.

In summary, short-sea shipping ZE applications benefit from energy-dense, reliable, and longer-range fuel sources, albeit with higher infrastructure demands and safety requirements. In contrast, inland waterway vessels align better with solutions that favour safety, refuelling flexibility, and lower operational complexity, even if it means sacrificing some energy density.

Lastly it is noteworthy to mention that in the next chapters alternative energy generation technologies are described and discussed, such as battery and Fuel Cell technologies. While other might exist,

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the aforementioned present the most promising ones, in terms of availability, and overall energy efficiency. According to recent research, the optimal selection of clean energy technologies for maritime applications varies significantly based on vessel type and operational profile. DNV GL[23] indicates that battery systems demonstrate high energy efficiency (around 90%) but remain limited by energy density (0.2-0.5 kWh/kg), making them ideal for short-sea shipping and ferry operations. Van Biert et al.[24] shows that hydrogen fuel cells achieve 45-55% efficiency and sometimes 80-85% (SOFC with cogeneration) while offering zero emissions, though infrastructure remains a challenge. Hydrogen-fueled ICEs[25], maintain approximately 40% efficiency with simpler storage requirements than fuel cells but produce NOx emissions. On the other hand, ammonia[26] as an alternative fuel carrier, with fuel cells achieving from 45% efficiency up to 65% and more, depending on FC and cogeneration and better storage characteristics than hydrogen. For practical applications[27], hybrid systems combining batteries with fuel cells present the most viable near-term solution for decarbonization. Based on these studies, the best options emerge as: 1) Battery-electric systems for short-sea shipping and ferry operations (<100 nautical miles); 2) Hydrogen fuel cell-battery hybrids for medium-range vessels (100-1000 nautical miles); and 3) Ammonia-based systems (Fuel cells) for long-range shipping (>1000 nautical miles). ICE power plants are also considered but have lower efficiency compared to FCs and potential NOx emissions. This conclusion is supported by the IMO[28], which emphasizes the importance of matching technology selection to specific operational profiles for optimal efficiency and commercial viability.

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[23] DNV GL. (2023). "Maritime Forecast to 2050: Energy Transition Outlook." DNV GL Technical Report, Oslo, Norway

[24] van Biert, L., Godjevac, M., Visser, K., & Aravind, P. V. (2021). "A review of fuel cell systems for maritime applications." Journal of Power Sources, 381(2), 156-172

[25] 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

[26] Kim, J. H., Ryu, J., Kang, S., & Kim, H. J. (2022). "Ammonia as an environmentally benign energy carrier: Overview and new perspectives." Progress in Energy and Combustion Science, 88, 100957.

[27] Minnehan, J. J., & Pratt, J. W. (2021). "Practical Application Limits of Fuel Cells and Batteries for Zero Emission Vessels." Sandia National Laboratories Technical Report, SAND2021-1098.

[28] IMO. (2022). "Fourth IMO GHG Study." International Maritime Organization, London, UK

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3.1 BATTERY POWERED

Types of Batteries

Ships currently use several types of batteries, each suited for specific applications due to their distinct characteristics[29]. The primary types include lithium-ion batteries, lead-acid batteries, nickel-cadmium batteries, and sodium-nickel chloride batteries[30].

- **Lithium-ion batteries** are the most widely adopted due to their high energy density, long cycle life, and relatively low self-discharge rate. These batteries are favored in modern electric and hybrid ships, including ferries and short-sea vessels, because they provide a good balance between energy storage capacity and weight, allowing for efficient propulsion and auxiliary power systems[2].
- **Lead-acid batteries** have been traditionally used in marine applications due to their robustness and cost-effectiveness. Despite their lower energy density and shorter cycle life compared to lithium-ion batteries, they remain popular in smaller vessels and for backup power due to their reliability and simplicity[31].
- **Nickel-cadmium batteries** offer excellent durability and the ability to perform under extreme temperatures, which makes them suitable for emergency power systems and applications where environmental conditions are challenging. However, their use has declined due to environmental concerns associated with cadmium[32].
- **Sodium-nickel chloride batteries**, also known as ZEBRA batteries, are emerging as a viable option for marine applications due to their high energy density, safety, and operational efficiency at high temperatures. They are being explored for larger vessels and long-duration applications[33].

In recent years the most prevailing option for electrical ships is the Lithium-ion batteries. Offering increased storage capacity both in terms of volume and weight compared to the other battery technologies, it's used for short-sea shipping and inland waterways. One notable example is the MS Roald Amundsen[34], a hybrid cruise ship operated by Hurtigruten, which uses a combination of lithium-ion batteries and traditional marine fuel. This ship can sail for short periods using only its battery power, significantly reducing emissions and fuel consumption during its voyages in environmentally sensitive areas such as the Arctic and Antarctic regions. Another prominent example is the E-ferry Ellen[35], operating in Denmark. This fully electric ferry is powered exclusively by lithium-ion batteries, boasting one of the longest ranges for a battery-electric ferry, covering approximately 22 nautical miles between charges. The ferry's battery system, provided by Leclanché, has a total

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[29] International Maritime Organization (IMO). "Energy Efficiency Technologies for Ships." 2021

[30] DNV GL. "Batteries in Ships: An Introduction to Battery Systems and Their Integration into Ship Design." 2019

[31] Maritime Battery Forum. "Lead-Acid Batteries for Marine Applications." 2020

[32] ABS (American Bureau of Shipping). "Guide for Use of Supercapacitors and Nickel-Cadmium Batteries in the Marine Industry." 2018

[33] Lloyd's Register. "Sodium Nickel Chloride Batteries for Marine Use." 2021

[34] Hurtigruten. "MS Roald Amundsen - World's First Hybrid Cruise Ship"

[35] Danish Maritime Authority. "E-ferry Ellen – a Showcase for Electric Ferries"

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capacity of 4.3 MWh. Additionally, the Yara Birkeland[36], a fully autonomous electric container ship, utilizes lithium-ion batteries supplied by Swiss company Leclanché. Operating in Norway, this vessel aims to eliminate the need for diesel-powered trucking in the transport of goods between inland facilities and coastal ports, further showcasing the capabilities and environmental benefits of large-scale battery-powered maritime operations.

Characteristics

As mentioned, the Lithium-ion batteries are the best choice for ships due to their inherent advantages in power density, both volumetric and gravimetric:

Lithium-Ion Batteries:

- The size of lithium-ion battery systems can vary significantly depending on the application. For large ships like the MS Roald Amundsen[6] and E-ferry Ellen[7], the battery systems are extensive and integrated into the vessel's design. For instance, the E-ferry Ellen's battery system has a total capacity of 4.3 MWh, which is housed in large battery rooms within the ferry.
- Typical volumetric energy density for lithium-ion batteries ranges from 250 to 700 Wh/L, depending on the specific chemistry and design of the battery.
- Gravimetric energy density for lithium-ion batteries usually ranges from 150 to 250 Wh/kg, again depending on the chemistry and design of the battery.
- Charging times for lithium-ion batteries can vary based on the charging infrastructure and the battery's capacity. Typically, it can take anywhere from 1 to 4 hours to fully charge a large marine lithium-ion battery system, depending on the power of the charging station. For example, the E-ferry Ellen can recharge in about 30 minutes at its dedicated high-power charging station.

Lead-Acid Batteries[37]:

- Lead-acid batteries are bulkier compared to lithium-ion batteries for the same capacity. They are typically used in smaller vessels or as backup power sources. The size of a lead-acid battery system in marine applications can vary, but it generally takes up more space than modern alternatives.
- The volumetric energy density of lead-acid batteries is relatively low, typically around 50 to 90 Wh/L.
- Gravimetric energy density for lead-acid batteries ranges from 30 to 50 Wh/kg.
- Lead-acid batteries have longer charging times compared to lithium-ion batteries. It can take anywhere from 6 to 12 hours to fully charge, depending on the battery's state of charge and the charging infrastructure.

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[36] Yara. "Yara Birkeland – The World's First Autonomous and Zero Emission Container Vessel."
[37] Maritime Battery Forum. "Lead-Acid Batteries for Marine Applications." 2020

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Nickel-Cadmium Batteries[4]:

- Nickel-cadmium (NiCd) batteries are more compact than lead-acid batteries but less energy-dense than lithium-ion batteries. They are used in specific marine applications requiring high reliability and durability under extreme conditions.
- Volumetric energy density of NiCd batteries is typically around 50 to 150 Wh/L.
- Gravimetric energy density for NiCd batteries ranges from 40 to 60 Wh/kg.
- NiCd batteries generally charge faster than lead-acid batteries but slower than lithium-ion batteries. Charging times can range from 3 to 8 hours depending on the battery and charger specifications.

Sodium-Nickel Chloride (ZEBRA) Batteries[5]:

- Sodium-nickel chloride batteries are relatively compact and are being increasingly considered for marine applications due to their high energy density and safety characteristics.
- The volumetric energy density of ZEBRA batteries is typically around 150 to 300 Wh/L.
- Gravimetric energy density for ZEBRA batteries ranges from 90 to 120 Wh/kg.
- ZEBRA batteries have moderate charging times, typically ranging from 4 to 6 hours depending on the charging infrastructure and battery capacity.

As seen the Lithium-ion battery technology offers the best volumetric and gravimetric density, compared to alternatives and charging times better or comparable to alternatives.

Battery cost

A significant consideration is the cost of these battery technologies, in terms of acquisition, installation, operation as well as maintenance. For the Lithium-ion batteries cost has been decreasing over the years due to advancements in technology and increased production scale. As of recent estimates, the cost for marine applications ranges from $200 to $600 per kWh. For Lead-acid batteries are relatively inexpensive compared to lithium-ion batteries. The cost typically ranges from $100 to $150 per kWh. For Nickel-cadmium (NiCd) batteries are more expensive than lead-acid batteries but less so than lithium-ion batteries. The cost generally ranges from $300 to $500 per kWh. Finally, for Sodium-nickel chloride batteries (ZEBRA) are priced competitively with other advanced battery technologies, generally ranging from $300 to $500 per kWh. In terms of operational and maintenance costs, the Lithium-Ion batteries generally have lower maintenance costs compared to lead-acid and NiCd batteries.

Below, Table 2 summarizing the key characteristics of each battery type for marine applications.

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Table 2 Comparison of battery types characteristics

Battery Type	Size	Volumetric Energy Density	Gravimetric Energy Density	Charging Times	Cost (per kWh)
Lithium-Ion	Variable: large systems (e.g., E-ferry Ellen) can reach capacities of 4.3 MWh in dedicated battery rooms	250-700 Wh/L	150-250 Wh/kg	1-4 hours (e.g., 30 mins for high-power)	\$200-\$600
Lead-Acid	Bulkier than lithium-ion; typically for smaller vessels or backup systems	50-90 Wh/L	30-50 Wh/kg	6-12 hours	\$100-\$150
Nickel-Cadmium (NiCd)	More compact than lead-acid but less energy-dense than lithium-ion, suited for high-durability applications	50-150 Wh/L	40-60 Wh/kg	3-8 hours	\$300-\$500
Sodium-Nickel Chloride (ZEBRA)	Relatively compact; used in marine applications for high energy density and safety	150-300 Wh/L	90-120 Wh/kg	4-6 hours	\$300-\$500

3.2 FUEL CELLS

Fuel cells are the most energy-efficient systems for generating power from fuels. Fuel cells, which may run on a range of fuels such as hydrogen, natural gas, and biogas, can produce clean power for applications ranging from less than a watt to several megawatts[38].

They are already in use for transportation purposes (buses, cars and tramways). Fuel cells may also be an appealing option for ship power. However, the development of fuel cell systems for marine vessels is still not widespread[39].

Fuel cells efficiently extract the chemical energy that hydrogen has to electricity, with the only waste being clean water and possibly useful heat. Hydrogen-powered fuel cells are not only pollution-free, but they can also outperform existing combustion technologies in terms of efficiency. A normal combustion-based power plant generally generates electricity at 33 to 35 percent efficiency, but fuel cell systems may create energy at up to 60 percent efficiency (and even higher with cogeneration)[11]. Cogeneration in fuel cell powertrains involves the simultaneous production of electrical power and useful heat from the same energy source. In fuel cell systems, in particular PEMFC and SOFC, the electrochemical reaction generates both electricity and heat as byproducts[40].

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[38] Fuel Cells, 2015

[39] Han et al., State of the art of fuel cells for ship applications, 2012

[40] Khzouz, M., & Gkanas, E. I. (2018). "Comprehensive review of the water-gas shift reaction for hydrogen production." Renewable and Sustainable Energy Reviews, 82, 1, 420-450

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The best candidate FCs for powering ships are the PEMFC (Proton Exchange Membrane) and the SOFC (Solid Oxide FC), the first one due to its technology maturity and the second one due to its very high efficiency (80-85%) achieved through cogeneration.

PEM

The PEMFC utilizes an electrolyte composed of a polymer matrix linked to functional groups that can exchange cations and anions (see Figure 3). In general, the electrolyte is an acid with a sulphonic group inserted in the matrix capable of transporting H+ ions, while the anion is blocked by the polymer structure. As a result, identical processes occur in both these cells and those with acid electrolytes[41].

They have the benefit of being simpler and more compact than other types of cells, as well as not requiring electrolyte reserves or recirculation. The working temperature varies between 60 and 130 degrees Celsius[42].

Nonetheless, the PEMFC's operation at low temperatures impedes the kinetics of the electrochemical process. As a result, the use of electrocatalyst materials is required. Most of them are valuable metals, such as platinum or ruthenium. As a result, the battery's price rises. Furthermore, its fuel is virtually entirely made up of high pure hydrogen. If another fuel, like gasoline or natural gas, is chosen, the fuel must first go through a reforming phase to create hydrogen[43].

Although these cells are typically utilized in automobiles, the PEMFC has a wide range of applications. This technique is used in almost all automobile prototypes that use fuel cells. Another use that is becoming increasingly common is the generation of electricity and the heating of water in home and commercial settings[44].

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[41] López Sastre et al., 2004

[43] Hurtado & Soria, El hidrógeno y la energía, 2007

[44] López Sastre et al., 2004

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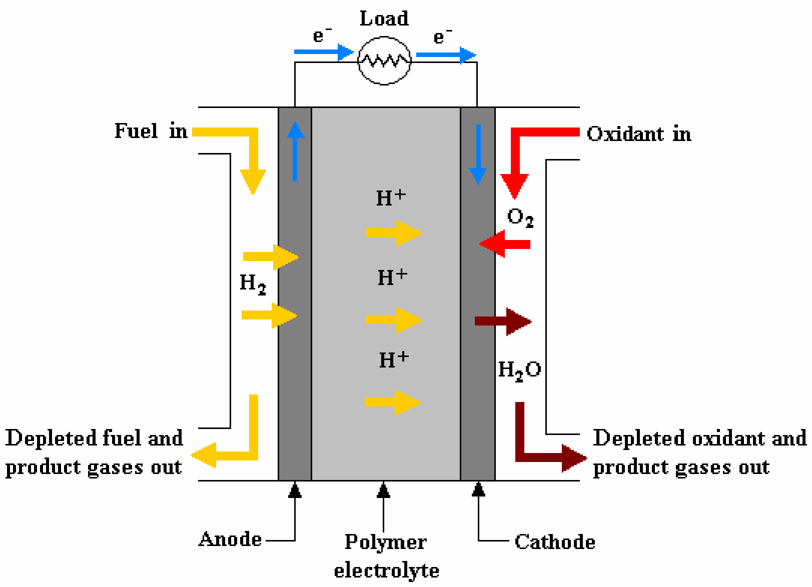

Figure 3 Proton Exchange Membrane Fuel Cell diagram[45]

The Performance Characteristics of PEMFC are listed below:

- PEM fuel cells can achieve efficiencies of around 40-60% for converting chemical energy in hydrogen to electrical energy. When waste heat is utilized, overall efficiency can be higher.
- High power density (up to 2 kW/L) makes them suitable for compact applications., i.e. relatively small vehicles (automobiles, trucks, etc.)
- Typically, between 60°C and 80°C, allowing for rapid start-up and operation in various environments.
- PEM fuel cells can operate for thousands of hours, though lifetime can be affected by factors such as catalyst degradation and membrane durability.

Advantages of PEMFC

A PEMFC arrangement offers several advantages, for use as the primary energy generator in a marine power plant system. These are:

- Converts hydrogen to electricity with high efficiency.
- Only water and heat are produced as by-products, resulting in zero greenhouse gas emissions.
- Operates quietly, making it suitable for residential and urban environments.
- Can start up quickly, which is beneficial for transportation and portable applications

Challenges of PEMFC

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[45] Wang, Y., Chen, K. S., Mishler, J., Cho, S. C., & Adroher, X. C. (2011). "A review of polymer electrolyte membrane fuel cells: Technology, applications, and needs on fundamental research." Applied Energy, 88(4), 981-1007

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Nevertheless, there are some challenges in using PEMFC for marine use. These are:

- High cost of platinum catalyst and PEM materials.
- Requires a reliable hydrogen supply infrastructure.
- Performance degradation over time due to catalyst poisoning and membrane wear.
- It requires high purity H2 to operate (>99%)

3.2.1 SOFC

The SOFC exploits solid oxides as electrolytes, which are impermeable ceramics capable of conducting an electrical charge by transferring oxygen ions oxygen (O_2) over a crystalline network at a suitable high temperature (see Figure 4). This ranges from 800 ºC to 1000 ºC, while attempts have been made to produce systems that function at 700 C (López Sastre et al., 2004). The primary material is zirconium oxide (ZrO_2), which is cubically stabilized with tiny amounts of calcium oxides (CaO), yttrium (Y_2O_3), ytterbium (Yb_2O_3), or a blend of heavier rare earths. Their attractiveness can be explained by the fact that they are solid-state, as well as their ability to reconstruct gaseous fuels in the fuel cell[46].

Solid oxide fuel cells are classified into two types: flat SOFCs and tubular SOFCs[16.] Sulzer Hexis, with the flat SOFC, and Siemens Westinghouse, with the tubular SOFC, are the two businesses who pioneered these two technologies. They have the same applicability as carbonate cells, with experimental systems capable of producing hundreds of kW[47].

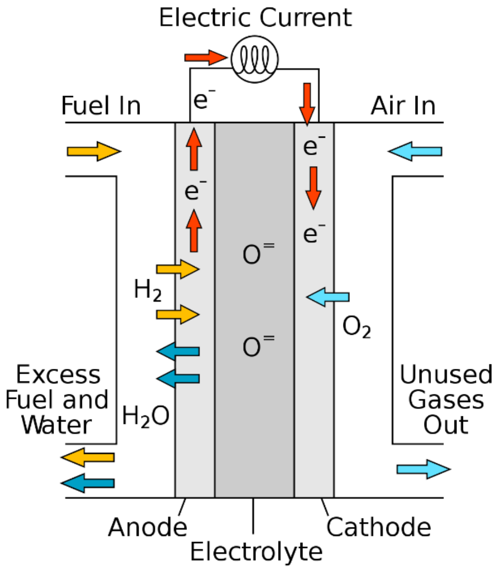

Figure 4 Solid Oxide Fuel Cell diagram

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[46] De-Troya et al., 2016a

[47] López Sastre et al., 2004

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The Performance characteristics of SOFC are:

- SOFCs can achieve electrical efficiencies of 45-60%. When combined with a gas turbine in a hybrid system, overall efficiencies can exceed 80%.
- High power density (around 0.5-2 W/cm² at the cell level).
- Typically, between 600°C and 1000°C, which allows for internal reforming of hydrocarbons and cogeneration of heat.
- Can operate for tens of thousands of hours, although high temperatures can lead to material degradation over time

Advantages of SOFC

A SOFC arrangement offers several advantages, for use as the primary energy generator in a marine power plant system. These are:

- It can operate on a variety of fuels including natural gas, biogas, and liquid hydrocarbons.
- High electrical efficiency and potential for even higher total efficiency in CHP applications.
- High-grade heat by-product can be used for heating or industrial processes.
- Produces fewer pollutants compared to combustion-based power generation

Challenges of SOFC

The SOFC has also some challenges, in terms of using it as a power source for marine purposes. These are:

- Requires high-temperature materials and insulation, leading to longer start-up times and thermal cycling issues.
- Material degradation over time due to high operating temperatures and thermal cycling.
- High initial costs for materials and manufacturing.
- Requires access to hydrogen or reforming systems for hydrocarbon fuels

3.3 FUEL TYPES FOR FUEL CELLS

3.3.1 Hydrogen (H_2)

Hydrogen is one of the most promising fuels for powering fuel cells in the marine sector, offering a zero-emission solution with high energy efficiency and scalability[48]. As the maritime industry shifts

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[48] de-Troya, J. J., Álvarez, C., Fernández-Garrido, C., & Carral, L. (2016). "Analysing the possibilities of using fuel cells in ships." International Journal of Hydrogen Energy, 41(4), 2853-2866. This paper specifically examines hydrogen fuel cells' energy efficiency and scalability potential in marine applications.

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toward sustainable energy sources, hydrogen-based fuel cells present a viable alternative to traditional fossil fuels, particularly for vessels aiming to minimize carbon emissions and environmental impact. This section examines hydrogen in three primary forms: Compressed Gaseous Hydrogen (CGH_2), Liquid Hydrogen (LH_2), and Liquid Organic Hydrogen Carriers (LOHC). Each form has distinct characteristics in terms of energy density, storage requirements, and applicability, making hydrogen adaptable to different vessel types and operational needs.

3.3.1.1 CGH_2 (Compressed Gaseous Hydrogen)

Compressed Gaseous Hydrogen (CGH_2) is emerging as a potential marine fuel, particularly in the context of decarbonizing the shipping industry. CGH_2, unlike traditional marine fuels such as heavy fuel oil, does not produce carbon dioxide during combustion, thus offering a path towards reducing greenhouse gas emissions from maritime operations. This, as in the case of LH2, also aligns with the International Maritime Organization's (IMO) targets for decarbonization by 2030.

One of the primary benefits of CGH_2 is its environmental impact. When used in fuel cells, hydrogen combines with oxygen from the air to produce electricity, with water and heat as the only byproducts. This zero-emission output makes CGH_2 an attractive alternative to traditional fossil fuels. Additionally, hydrogen can be produced using renewable energy sources, resulting in green hydrogen that has no associated carbon emissions during its lifecycle. However, the widespread adoption of CGH_2 in the maritime industry faces several challenges, particularly regarding storage, distribution, and the economics of hydrogen production.

The volumetric energy density of CGH_2 is significantly lower than that of liquid fuels. This necessitates the use of high-pressure storage tanks[49], typically rated between 350 to 700 bars, to store the gas at a density sufficient for practical use on board vessels. These tanks are larger and heavier than those required for liquid fuels, leading to increased space and weight considerations on ships. The infrastructure required for refueling and handling CGH_2 is also complex and costly, involving specialized equipment and facilities to safely compress, store, and transfer the gas[50].

Safety is another critical aspect in the adoption of CGH_2 as a marine fuel[51]. Hydrogen is highly flammable, and its storage in compressed form requires stringent safety measures to prevent leaks and mitigate the risks of fire and explosion. The development of international safety standards and regulations for hydrogen storage and handling is essential to ensure safe operations in the maritime context.

Economic factors also play a significant role in the adoption of CGH_2. The current cost of hydrogen production, especially green hydrogen, is relatively high compared to traditional marine fuels. However, advances in electrolysis technology and economies of scale are expected to reduce these costs over time. Furthermore, government incentives and carbon pricing mechanisms may enhance the competitiveness of CGH_2 in the future.

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[49] DNV GL, "Hydrogen as a Fuel in the Shipping Industry," 2020
[50] Hydrogen Council, "Hydrogen Insights 2021," 2021
[51] Lloyd’s Register, "Safety Considerations for Hydrogen Use in Shipping," 2022

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Pilot projects and feasibility studies are exploring the use of CGH_2 in various types of vessels[52], from ferries to commercial cargo ships. These initiatives aim to test the technical feasibility, safety, and economic viability of CGH_2, while also demonstrating its potential to meet stringent environmental regulations. The transition to CGH_2 in maritime applications is likely to be gradual, with hybrid systems and dual-fuel engines serving as transitional solutions

Operational characteristics of CGH2 are:

- Storage and handling: Stored at high pressures (350-700 bar) in robust composite tanks
- Fuel: Directly supplied to the SOFC anode at required pressure
- Efficiency: Good efficiency with well-established refueling infrastructure

For the performance characteristics CGH2 offers:

- Volumetric density: Lower than LH2 due to gaseous state, around 5-6 MJ/L at 700 bar
- Gravimetric density: Approximately 120-150 MJ/kg
- Storage: High-pressure systems (350-700 bar) require robust safety protocols (see Figure 5)

CGH2 offers advantages in terms of simpler and handling compared to LH2, and also it has established infrastructure, especially for transportation applications. On the other hand, it offers lower volumetric density than LH2 and high-pressure storage adds weight and complexity.

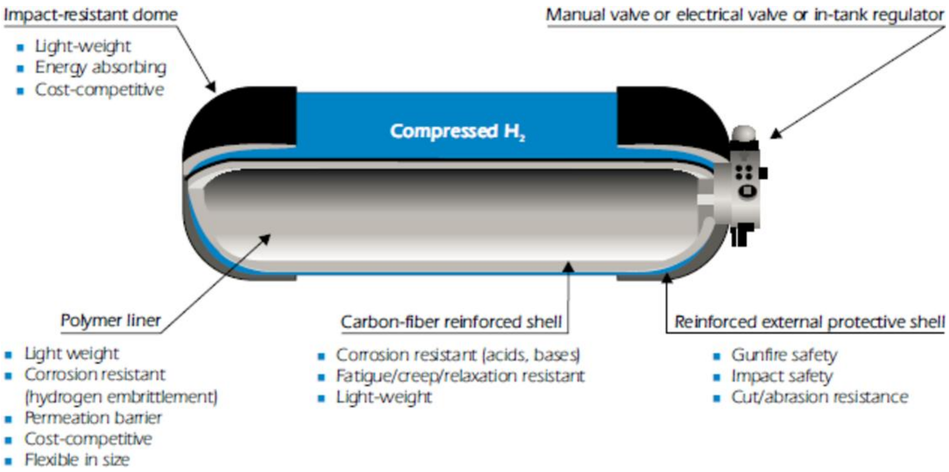

Figure 5 CGH2 pressure vessel section[53]

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[52] Maritime Executive, "Hydrogen-Fueled Ships: Feasibility and Challenges," 2023

[53] Gupta, Apoorv. “Hydrogen Storage, Distribution and Cleaning Study in collaboration with AGA AB.” (2017).

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3.3.1.2 LH2 (Liquid Hydrogen)

The use of LH_2 in maritime applications is driven by the global push towards decarbonization and the International Maritime Organization's (IMO)[54] goal to reduce the shipping industry's carbon intensity by at least 40% by 2030, compared to 2008 levels.

One of the main advantages of LH_2 is its high energy density by mass, which is nearly three times that of traditional fossil fuels. However, its energy density by volume is lower, necessitating larger storage tanks. This poses significant challenges for ship design, as LH_2 must be stored at extremely low temperatures (-253°C) to remain in liquid form. The cryogenic storage and handling infrastructure required for LH_2 is technologically advanced and costly, potentially limiting its immediate widespread adoption. Additionally, the energy-intensive process of liquefying hydrogen, along with its current high production costs, adds to the economic challenges. However, as the production of green hydrogen—derived from renewable energy sources—scales up, costs are expected to decrease, making LH_2 more competitive[55].

In terms of safety[56], LH_2 is highly flammable and requires stringent safety measures to prevent leaks and manage risks associated with its use. The maritime industry needs to develop comprehensive safety standards and protocols for the adoption of LH_2 as a fuel. Despite these challenges, LH_2 offers significant environmental benefits, as it can potentially be produced from renewable sources, thus contributing to a closed carbon cycle. Additionally, the advancements in hydrogen technology, such as improved fuel cells, are making LH_2 a more viable option for marine propulsion.

Pilot projects and feasibility studies[57] are underway to explore the use of LH_2 in different types of vessels, from small ferries to large cargo ships. These projects aim to demonstrate the practical and economic feasibility of LH_2 as a marine fuel, while also addressing the technical and regulatory challenges[58]. The transition to LH_2 in the maritime sector is expected to be gradual, with hybrid systems and dual-fuel engines serving as intermediate steps towards fully hydrogen-powered vessels.

The operational characteristics of LH2 are:

- Storage and Handling: LH2 is stored at cryogenic temperatures (-253°C) and requires insulated tanks to prevent boil-off.
- Fuel Delivery: Hydrogen is vaporized and supplied as gas to SOFC.
- Efficiency: High energy density and purity lead to efficient operation with minimal impurities affecting the anode

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[54] International Maritime Organization (IMO) Strategy on Reduction of GHG Emissions, IMO, 2021
[55] Hydrogen Economy Outlook." Bloomberg NEF, 2021
[56] Safety and Operational Considerations for LH_2, Lloyd's Register, 2022
[57] Pilot Projects in Hydrogen-Powered Shipping, The Maritime Executive, 2023
[58] Liquid Hydrogen as a Marine Fuel, DNV GL Report, 2020

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The performance Characteristics are:

- Volumetric density: 8.49 MJ/L
- Gravimetric density: 120 MJ/kg, high energy content
- Storage: Requires stringent safety protocols for handling and storage (see Figure 6)

LH2 offers advantages in terms of high storage capacity and high H2 purity which in turn enhances cell efficiency. On the other hand, it requires complex and high-cost storage infrastructure and there are boil off losses during storage and transportation.

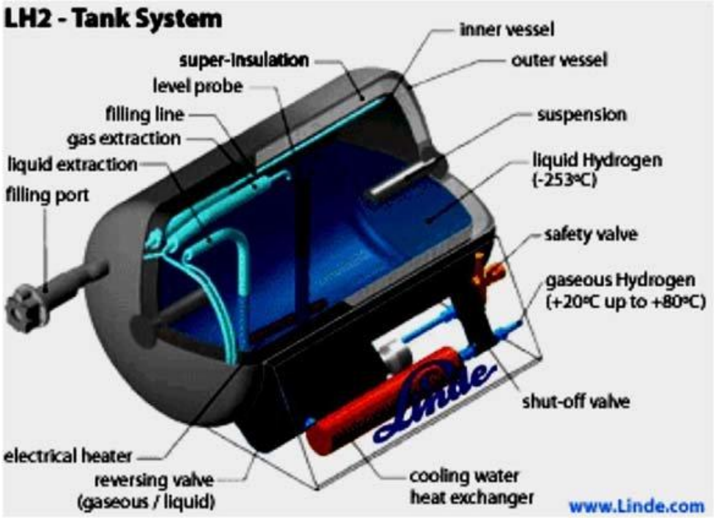

Figure 6 Section of an LH2 storage tank[59]

3.3.1.3 LOHC (Liquid Organic Hydrogen Carriers)

Liquid Organic Hydrogen Carriers (LOHCs) are an emerging technology in the marine fuel sector, offering a novel method for storing and transporting hydrogen, which can be used to decarbonize maritime operations. LOHCs work by chemically binding hydrogen to a liquid organic compound, which can be stored and transported under ambient conditions, unlike cryogenic liquid hydrogen or compressed hydrogen gas. This makes LOHCs a practical and versatile option for marine applications[60], where storage and safety are significant concerns.

One of the primary advantages of using LOHCs as a marine fuel is their ability to store hydrogen in a safe and stable manner[61]. Hydrogen is chemically bound within the LOHC molecule, making it non-explosive and safe to handle, reducing the risk of leaks or fire compared to traditional hydrogen storage methods. This is particularly important in the maritime environment, where safety standards are stringent, and the consequences of accidents can be severe. LOHCs can be transported using

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[59] Suyamburajan, Vijayananth & Kumar, R. & P, SenthamaraiKannan & Saravanakumar, S.S & Khan, Anish & Ganesh, K. (2021). Nanomaterials for Hydrogen Storage Applications.

[60] The Potential of Liquid Organic Hydrogen Carriers (LOHCs) for Hydrogen Storage and Transport," International Energy Agency (IEA), 2020

[61] Safety and Efficiency Considerations for LOHCs in Marine Applications," Lloyd's Register, 2023

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conventional liquid fuel infrastructure, including pipelines and tankers, which offers a significant logistical advantage.

From an environmental perspective[62], the use of LOHCs can significantly reduce greenhouse gas emissions if the hydrogen used is produced from renewable sources, known as green hydrogen. The primary emissions associated with LOHCs are the result of the hydrogenation and dehydrogenation processes, which involve adding hydrogen to or removing hydrogen from the LOHC compound, respectively. These processes require energy, which, if sourced from renewable electricity, can lead to a low-carbon fuel cycle. Additionally, the dehydrogenation process, where hydrogen is released from the LOHC for use in fuel cells or combustion engines, produces no carbon emissions if the LOHCs themselves are made from non-fossil-based feedstocks.

However, there are several challenges associated with LOHCs in maritime applications. The energy efficiency of the LOHC system can be a concern, as the processes of hydrogenation and dehydrogenation are energy intensive. The round-trip efficiency, or the total energy efficiency from hydrogen loading to unloading, can be lower compared to direct hydrogen use, which may affect the overall energy efficiency of the vessel. Furthermore, the development of efficient and economically viable catalysts for these chemical reactions is crucial to improving the system's overall efficiency and cost-effectiveness.

The economic feasibility of LOHCs as a marine fuel also depends on the development of the necessary infrastructure and technology[63]. This includes onboard dehydrogenation units and systems for handling and storing the LOHCs. While the existing infrastructure for liquid fuels can be adapted for LOHCs, significant investment and research are required to optimize these systems for maritime use.

The operational characteristics of LOHC are:

- Storage and handling: Hydrogen is chemically bonded to a carrier liquid (e.g., dibenzyl toluene) and stored in ambient conditions
- Fuel delivery: Hydrogen is released via a dehydrogenation process before or within the SOFC Dehydrogenation Reaction: LOHC + Heat → LOHC (dehydrogenated) + H_2
- Efficiency: Moderate efficiency due to the energy required for dehydrogenation

The performance characteristics of LOHC are:

- Volumetric density: typically ranges from approximately 2 to 3 megajoules per liter (MJ/L)
- Gravimetric density: typically ranges from approximately 1 to 2 megajoules per kilogram (MJ/kg)
- Safety: Generally safer due to ambient temperature and pressure storage

LOHC offers advantages in terms of simplified storage and transportation compared to pure H2. It also offers safer handling compared to cryogenic and high-pressure hydrogen. On the other hand, it

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[62] LOHCs: A Promising Hydrogen Carrier for Shipping," Hydrogen Council, 2022
[63] Decarbonizing Maritime Transport with Hydrogen Technologies," Maritime Executive, 2023

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requires additional energy for hydrogen release and lower overall efficiency due to chemical processes involved.

3.3.2 Ammonia (NH_3)

Ammonia (NH_3) is gaining attention as a potential marine fuel, driven by the global maritime industry's push towards decarbonization. As a hydrogen-rich compound, ammonia offers a promising pathway to significantly reduce greenhouse gas emissions from ships, aligning with the International Maritime Organization's (IMO) ambitious targets.

One of the key advantages of using ammonia as a marine fuel[64] is its relatively high energy density compared to other hydrogen carriers. Ammonia has an energy density of about 12.7 megajoules per Liter (MJ/L), which, although lower than conventional marine fuels, is higher than other alternatives like liquid hydrogen. This makes it more practical for storage and transportation in terms of volume, crucial for long-distance shipping where fuel storage space and range are significant concerns. Ammonia can be stored as a liquid under relatively mild conditions of -33°C, at atmospheric pressure or under slight pressurization at ambient temperature, making its storage and handling less challenging than those of cryogenic hydrogen.

From a safety perspective, ammonia presents certain challenges[65]. It is toxic and poses health risks if inhaled, requiring stringent safety protocols to protect crew and port workers. Additionally, while ammonia does not produce CO_2 when burned, its combustion can lead to the formation of nitrogen oxides (NO_x), which are pollutants harmful to human health and the environment. However, advancements in combustion technology, such as selective catalytic reduction (SCR) systems, can help mitigate NO_x emissions. Moreover, ammonia can be used in fuel cells to generate electricity, where the process can be controlled to minimize or eliminate NO_x emissions entirely.

The production of ammonia is another critical aspect to consider. Currently, most ammonia is produced from natural gas via the Haber-Bosch process, which emits CO_2. However, green ammonia production, using renewable energy sources to produce hydrogen through electrolysis, followed by synthesis into ammonia, is being developed. This green ammonia can offer a fully renewable and low-carbon fuel option, although its production is currently more expensive than conventional methods. Scaling up green ammonia production and improving cost-efficiency will be essential for its widespread adoption as a marine fuel.

Economically, the adoption of ammonia as a marine fuel requires significant investment[66] in new infrastructure, including storage facilities, bunkering stations, and retrofitting ships with compatible engines or fuel cells. The existing global ammonia infrastructure, primarily used for fertilizers, could potentially be adapted for fuel purposes, which may help reduce some costs. Furthermore, regulatory

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[64] Ammonia as a Marine Fuel: Potential and Challenges, DNV GL Report, 2021

[65] Lloyd's Register, "Safety and Environmental Considerations for Ammonia as a Marine Fuel, 2022

[66] The Role of Ammonia in Decarbonizing Maritime Transport, Maritime Executive, 2023

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frameworks and standards for ammonia bunkering and safety will need to be established to support its use in maritime operations.

The operational characteristics of Ammonia are:

- Storage and handling: Stored as a liquid under moderate pressure or refrigeration
- Fuel delivery: Ammonia is cracked (decomposed) to produce hydrogen and nitrogen before or within the FC; Cracking Reaction: 2NH3→3H2+N22NH3→3H2+N2
- Efficiency: Ammonia cracking requires energy but provides a convenient hydrogen source

The performance characteristics of Ammonia are:

- Volumetric density: 11.5 MJ/L (liquid state)
- Gravimetric density: Approximately 18.6 MJ/kg
- Safety: Requires careful handling due to toxicity and potential for environmental harm

Ammonia offers advantages in terms of easier storage and transportation compared to pure H2. It also offers higher energy compared to CGH2. On the other hand, it requires an efficient ammonia cracker to produce H2 and there is the possibility of catalyst poisoning and reduced efficiency due to impurities.

3.3.3 Methanol (CH_3OH)

When evaluated for use as marine fuels, methanol (CH_3OH) and hydrogen (H_2) have their own pros and cons. However, methanol's biggest boon is the fact that it is a liquid at ambient temperatures and pressures, so it can be stored and transported easily via the existing infrastructure designed for conventional fuels. That is significantly less expensive, and indeed less complex to adopt then hydrogen (which generally needs cryogenic storage as liquid hydrogen) or high pressure tanks for compressed hydrogen. Because it is less volatile than hydrogen, leaks or explosions are no longer safety concerns with methanol. Moreover, methanol can be synthesized from renewable energy (green methanol) equaling net-zero emissions.

A key advantage of methanol as a marine fuel is the reduction in harmful emissions. On combustion methanol results in less Sulphur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter as compared to conventional marine fuels like heavy fuel oil (HFO) or marine diesel oil (MDO). Methanol has the virtue of producing less CO_2 per energy unit and, if sourced from renewables at least close to net-zero emissions. This tie into the International Maritime Organization's (IMO) goals to combat shipping's carbon intensity.

Methanol stands out as an appealing fuel when it comes to logistics. It stays liquid at room temperature allowing it to be kept in existing fuel tanks and moved around using the same systems as other liquid fuels. This means you don't need special cold storage like you do for LNG, which makes it much easier and cheaper to adapt current infrastructure. What's more, methanol breaks down and mixes with water. So, if it spills, it's not as harmful to the environment as oil-based fuels.

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When it comes to safety, methanol isn't as dangerous as some other fuels, like hydrogen and LNG. That said, it can still catch fire and hurt you if you drink it. One tricky thing about methanol is that it burns without a visible flame, which means you need special systems to spot it and handle it . The good news is that lots of other industries already use methanol, so we can take their safety rules and tweak them for ships.

From an economic standpoint, using methanol as fuel for ships might be easier than other options. It works with current systems and doesn't cost as much to store or move around. But changing old ships or building new ones to run on methanol is still expensive at first. Engines that can use both methanol and regular ship fuels give ship owners more choices. This lets them start using methanol as it becomes more available worldwide.

Methanol is also compatible with fuel cells, which convert chemical energy into electrical energy with higher efficiency than internal combustion engines. This makes it an appealing option for next-generation marine vessels, as fuel cells are quieter and produce fewer emissions.

The operational characteristics of methanol are:

- Reduces SO_x, NO_x, and particulate matter emissions.
- Produces less CO_2 than conventional fuels, especially when sourced from renewable feedstocks.
- Stored as a liquid at ambient temperature, simplifying infrastructure needs compared to LNG or hydrogen.
- It can be used in existing fuel systems with relatively minimal retrofitting.
- Methanol is toxic if ingested and burns with an invisible flame, requiring special safety measures.
- Compatible with dual-fuel engines, allowing vessels to switch between methanol and traditional marine fuels.
- Can be used in fuel cells, offering higher efficiency and fewer emissions than combustion engines.
- Utilizes existing liquid fuel storage and transportation infrastructure, reducing the need for new facilities.

The performance characteristics of methanol are:

- Volumetric density: Approximately 15.6 MJ/L
- Gravimetric density: Approximately 19.9 MJ/kg
- Storage condition: Stored as a liquid at ambient temperature and pressure
- Fuel Purity: Typically high, with purity levels of 99.85% for fuel-grade methanol
- Safety: Generally safer due to ambient temperature and pressure storage
- Infrastructure cost: Moderate, due to compatibility with existing liquid fuel storage and transport systems; lower than LNG or hydrogen infrastructure costs
- Operational Complexity: Lower complexity compared to LNG or hydrogen; existing fuel systems can be retrofitted with minimal changes

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- Efficiency (for use with Fuel Cells): High efficiency, especially in fuel cells; offers quiet operation and fewer emissions than traditional engines

Methanol and hydrogen (H_2) offer distinct advantages and disadvantages when considered as marine fuels. Methanol has the key advantage of being a liquid at ambient temperatures and pressures, making it much easier to store and transport using existing infrastructure designed for conventional fuels. This reduces the cost and complexity of adoption compared to hydrogen, which typically requires either cryogenic storage as liquid hydrogen (LH_2) or high-pressure tanks for compressed hydrogen (CH_2). Methanol is also less volatile than hydrogen, reducing safety concerns related to leaks or explosions. Additionally, methanol can be produced from renewable sources (green methanol), providing a pathway to net-zero emissions.

However, hydrogen offers a higher energy density per unit mass, making it more efficient for long-range or high-power applications in terms of fuel weight. Hydrogen, especially when used in fuel cells, also offers higher operational efficiency with zero emissions at the point of use, producing only water as a byproduct. Despite these benefits, hydrogen infrastructure is less developed and more expensive to implement, particularly due to the need for cryogenic or high-pressure storage systems. Hydrogen's storage challenges, along with its flammability and handling risks, make methanol a more practical near-term solution for decarbonizing marine transport, especially for smaller vessels or short-range routes.

3.3.4 Comparison of different fuels for use in FCs

When comparing different fuels for use in zero-emission powertrains (see Table 3), each fuel option offers unique characteristics that influence its suitability. Liquid Hydrogen (LH_2) has a high gravimetric energy density, reaching around 120 MJ/kg, with a moderate volumetric density between 8-9 MJ/L. However, its storage requires cryogenic conditions at -253°C, necessitating complex insulation and making it costly and challenging to handle. Due to its high purity requirements, LH_2 is efficient, though its operational complexity and high infrastructure cost remain significant barriers.

Compressed Gaseous Hydrogen (CGH_2) offers a similar gravimetric density to LH_2, ranging from 120 to 150 MJ/kg, but its volumetric density is lower, around 5-6 MJ/L at 700 bar. This fuel requires high-pressure containment (typically between 350-700 bar), which adds a layer of safety and storage complexity, although it is somewhat easier to manage than cryogenic LH_2. CGH_2 demands high fuel purity and offers high efficiency, with moderate infrastructure costs and operational complexity.

In contrast, Ammonia (NH_3) provides a different balance with a gravimetric density of 18.6 MJ/kg and a higher volumetric density of 11.5 MJ/L. It can be stored in liquid form under moderate pressure or mild refrigeration, making it less demanding than hydrogen in terms of storage conditions. However, ammonia is toxic and requires careful handling, especially when used as a hydrogen carrier, as it requires cracking to release the hydrogen, adding complexity to its operation. Despite these challenges, ammonia infrastructure costs remain moderate, though its efficiency is only moderate.

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Liquid Organic Hydrogen Carriers (LOHC**)** present a safer storage alternative, operating at ambient temperature and pressure, and are generally safer to handle. However, LOHC has low energy density, with gravimetric values between 1-2 MJ/kg and volumetric density at 2-3 MJ/L. It requires moderate fuel purity after dehydrogenation, which slightly impacts its efficiency. LOHC is advantageous for its low-to-moderate infrastructure cost and low operational complexity, though it may not achieve the same efficiency levels as other options.

Finally, Methanol provides the highest volumetric density among these options at 15.6 MJ/L, with a gravimetric density of 19.9 MJ/kg, making it a dense and efficient choice. Stored at ambient conditions, it requires 99.85% purity, and although toxic, it remains one of the easier fuels to manage operationally. Methanol has a moderate infrastructure cost and is simpler to operate than other fuels, with high efficiency, making it a compelling choice for zero-emission applications where safety and simplicity are priorities.

Table 3 Comparison of different fuels for use in FCs

Aspect	LH2	CGH2	Ammonia (NH3)	LOHC	**Methanol**
Volumetric density **(MJ/L)**	8-9	5-6 at 700 bar	11.5	2-3	15.6
Gravimetric density (MJ/kg)	120	120-150	18.6	1-2	19.9
Storage condition	Cryogenic (-253°C)	High Pressure (350-700 bar)	Liquid under moderate pressure or refrigeration	Ambient Temp and Pressure	Ambient Temp and Pressure
Fuel purity	High	High	Moderate (post-cracking)	Moderate (post-dehydrogenation)	99%
Safety	Complex requires insulation	High-pressure safety	Toxic, careful handling required	Generally safer	Toxic, careful handling required
Infrastructure cost	High	Medium	Medium	Low to Medium	Medium
Operational complexity	High	Medium	High (due to cracking)	Low	Low
Efficiency	High	High	Moderate	Moderate	High

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4 MODELLING OF SHIP FOR SPECIFIC USE CASES

To prove the project's wide impact throughout its ambitious demos and transferability use cases, it is imperative that SEAMLESS utilises credible simulation methods and approaches (e.g., SIMPACT,[67] agent-based models, operations research). These simulations will be designed to produce outcomes relevant to the project's scope (e.g., logistical KPIs, energy needs for specific use case scenarios) as well as its technological innovations (building blocks).

As part of the work outlined in T4.1, a methodology will be developed for designing the conceptual SEAMLESS ships to enable their use in simulations required for various project tasks (e.g., T6.2, T6.3, and T6.6). The following paragraphs provide an initial outline of the rationale and approach to be employed. The description below is based on the work carried out in the context of T2.1/D2.1 that includes an initial dataset of operational parameters and constraints, for the project's Northern European use case: the Bergen-Ågotnes route (see Figure 7) and the Central European use case: the Dourges – Duisburg route (see Figure 8). However, the scope of this work pertains to developing concept vessels pertinent to every use case of SEAMLESS. Thus, the aim is to give a preliminary sense of the work which will follow in the context of T4.1 and will be included in D4.3.

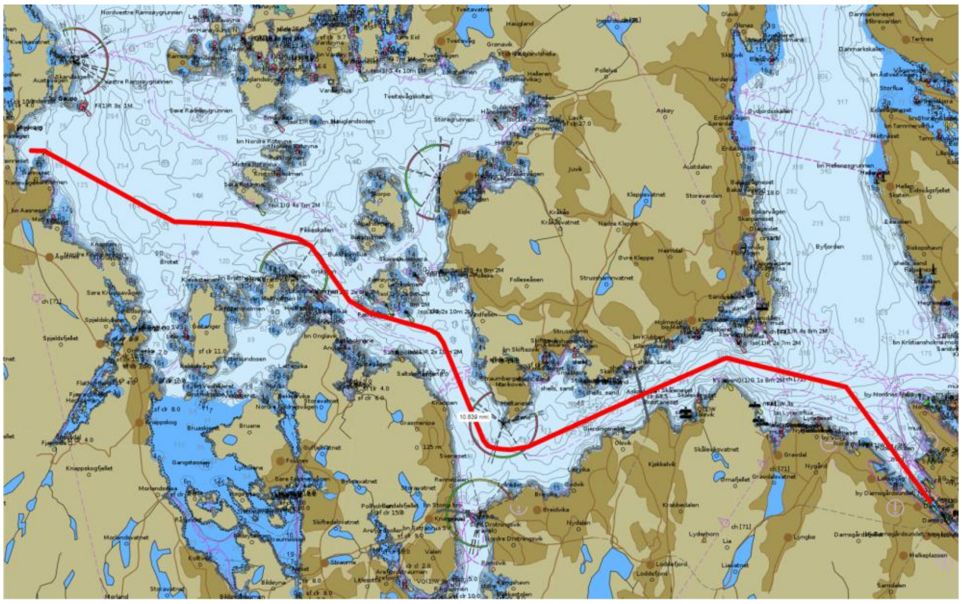

Figure 7 Route between Ågotnes and Bergen.

Source: ISL based on Norwegian Mapping Authority (2023)

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[67] https://www.sintef.no/en/publications/publication/2152220/

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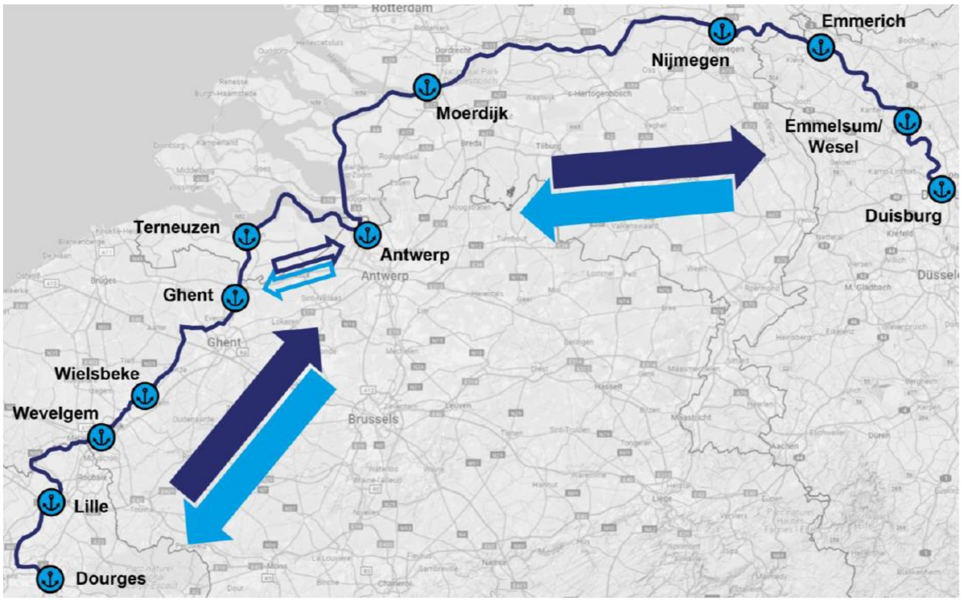

Figure 8 Envisioned Central European route and ports.

Source: Google LLC

This section addresses the modelling of SSS and IWT ships that will be assessed during the next period. Modelling will consider ships operating for specific use cases, with detailed analysis, for ship design and arrangement, such as power plant arrangement and placement on board, storage of alternative fuels, stability, resistance and seakeeping. The MAXSURF naval architecture software package will be used to model the ship (power plant arrangement, storage of alternative fuels). The design, as well as the operational characteristics will also be dictated by the specific use cases envisaged in the SEAMLESS use cases, such as travel distance, speed, sea state and wave characteristics.

4.1 CASE STUDY 1: NORTHERN EUROPEAN USE CASE

The study case will provide the operational conditions for applying the SEAMLESS concept to autonomous small feeder shuttles operating between a container terminal and smaller ports in the Bergen region. The objective is to replace truck transport with an efficient and cost competitive waterborne option. Considering also, the ConOps and requirements determined in T2.5/D2.3, the following parameters are taken into consideration for identifying the initial ship design concept.

- The area of operation was selected to be between Ågotnes and Bergen (short sea trade, SSS). The route is 11nm, estimated to approximately 1.5 hours in each direction that is considering for the feeder loop service between the two ports and the transported cargo is containers of TEU size.
- The vessel will have a capacity of 100-120 TEU and is fully electric powered by rechargeable batteries.
- The feeder loop service will be operated by autonomous vessels without onboard crew, supervised through a Remote Operation Centre (ROC).

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- Main engine configuration and type of propulsion: fully electric powered by rechargeable batteries.
- Mooring arrangements: onboard automated mooring (T3.2: SEAMLESS autonomous mooring system) shall be included

The initial ship design concept and logistic concept evaluation method enables trade-offs between costs, emissions, and logistical performance, based on design choices related to the specific ship concept and the logistic system capacities, so that one can iterate the design towards an optimal design for the particular study case.

4.2 CASE STUDY 2: CENTRAL EUROPEAN CASE

Building on the approach used for the Northern European Use Case, SEAMLESS will also develop concept vessels tailored to the requirements of the Central European Use Case. This involves considering a range of operational parameters that will influence vessel design. The Central European Use Case envisions a self-propelled inland vessel designed for remote-controlled and highly autonomous operationsThe goal is for the vessel to operate unmanned, supervised remotely by a dedicated Remote Control and Operations Centre.

Key design priorities include adaptability to ensure efficient operation under diverse nautical and market conditions, as well as enhanced availability to maximize operational uptime. This entails minimizing crew dependencies, reducing energy recharge times, and overcoming range limitations to support continuous and efficient operations.

The design concept for this use case will be heavily inspired by the X-Barge, developed by ZULU Associates (see Figure 9). The X-Barge is a 1,500-dwt CEMT IV vessel featuring the following amin particulars: 85 meters in length, 9.6 meters in beam, and a 2.5-3-meter draft when fully loaded, with a carrying capacity of 90 TEU. Further developments on this topic will be conducted in the coming months under T4.1 and will be detailed in Deliverable D4.3.

Figure 9 Rendering of ZULU X-Barge

Source: ZULU associates

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4.3 PERFORMANCE COMPONENTS TO BE STUDIED

4.3.1 Stability

The assessment of stability revolves around ensuring a vessel can remain upright and handle various environmental conditions. For zero-emission vessels, the placement and weight distribution of new technology systems significantly impacts stability characteristics. For instance, liquid hydrogen fuel storage tanks [68], with their necessary insulation and structural support, can affect the vessel's center of gravity in ways that differ substantially from conventional fuel arrangements. Their research demonstrates that the lower density of hydrogen requires larger storage volumes, potentially leading to stability considerations not present in conventional vessels. The stability assessment methodology should specifically address how different power plant configurations affect both initial and damage stability. For instance, battery-powered vessels[69] require particular attention to weight distribution due to the high density of battery installations, which can significantly impact the vessel's metacentric height. Their work shows that strategic placement of battery rooms can actually enhance stability when properly integrated into the design process.

For inland vessels specifically, the stability criteria should align with ES-TRIN technical requirements (2021/23 edition), which provides specific stability standards for inland navigation vessels. These requirements differ significantly from IMO standards and are tailored to inland waterway conditions. The stability analysis should incorporate loading conditions specific to the intended routes, including considerations for varying water depths and lock operations[70].

In the aforementioned context, once a design has been displayed utilizing the Modeler, its stability and strength characteristics can be evaluated utilizing the MAXSURF Stability examination module, which can handle a wide range of stability and strength calculations. Exact calculations are performed specifically from the trimmed NURB surface model without the requirement for offsets.

All operations inside the Stability module are performed employing a graphical multi-window environment, interacting with all other modules. All information is displayed concurrently in graphical and tabular shape and is consequently upgraded when changes are made and as the analysis advances.

Loading cases will be implemented concurrently in the modelling environment of MAXSURF, thus setting up any number of loading conditions without discretizing the loading cases to one-by-one cases. In this manner, complex loading schedules can be prepared and loaded to and from other design software, using spreadsheets. These in turn can be used and run in the Stability module. Loading cases can also be saved and reused with different design arrangements as well as different power plants and fuel storage configurations.

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[68] Minnehan, J. J., & Pratt, J. W. (2017). "Practical Application Limits of Fuel Cells and Batteries for Zero Emission Vessels." Sandia National Labs Report SAND2017-12665

[69] Kim, H., et al. (2021). "Stability Analysis for Battery-Powered Ships: A Case Study of Norwegian Coastal Vessels." Journal of Marine Science and Engineering, 9(5), 527

[70] Rusche, H. (2023). "Modern Approaches to Stability Assessment in Inland Navigation." International Journal of Maritime Engineering, 165(A3), 123-138

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Tank and compartment modelling is integrated in the stability module offering simple vessel's tank and compartment design and layout. More complex compartments can be designed utilizing surface and volume modeling. Tanks are designed in a parametric manner, and they are automatically included within the weight plan and their parametric definition offers automatic update in the off chance that hull shape or internal arrangement of ship design is changed.

In the context of assessing the stability requirements of the SSS and IWT ships the following evaluations will be made:

- Calculate the upright hydrostatic properties of the vessel at a range of prescribed drafts or displacements at specified trim. Computed data include, volumetric properties (volume, centre of buoyancy), waterplane properties (area, moments of area, centre of floatation), coefficients of form etc.
- Produce calibration tables for tanks and compartments. These may be computed for a range of trims and heels or for the vessel in the upright condition only. The data presented in the sounding tables and graphs will be customized from a wide range of properties (sounding, ullage, %full, volume, mass, centre of gravity, volumetric moments of inertia, free surface area and area moments, etc).
- Comprehensive intact stability analysis. GZ curves are calculated from first principles for the specified loading condition. The GZ is calculated at each of the specified heel angles with the vessel free to trim or at specified fixed trim. Provision of a comprehensive range of fundamental stability calculations which can be performed on the resulting GZ curve (eg: max and mini values and the angles at which these occur, intersections with heeling arms etc). These calculations form the basis of stability criteria where the result of the calculation is compared with a required value. These calculations include integration of the area under the GZ curve between fixed limits and limits which depend on other parameters of the GZ curve; furthermore, IMO criteria (such as the OSV rules in MSC.267(85) and HSC rules in MSC.96(73) where the required area under the GZ curve depends on the angle at which max GZ is achieved). For IWT ships, the European Standard laying down Technical Requirements for Inland Navigation vessels (ES-TRIN) and similar regional regulations, will be used to evaluate intact stability[71].
- Comprehensive deterministic damage stability analysis, with parametric damage cases. Several damage cases will be specified in addition to the “intact condition”. The damage will be specified by selecting which tanks or compartments will be flooded. Damage will be computed using the “lost buoyancy method”. Damage may be “full” where the lost buoyancy level in the flooded tank is up to the external sea level; or “partial” where the lost buoyancy is limited to a max percentage of the tank volume. A “conditional flooding” option may be specified whereby a tank is only considered as damaged if a specified inflow point, linked to the tank, is immersed. For IWT ships, the European Standard laying down Technical Requirements for Inland Navigation vessels (ES-TRIN) and similar regional regulations, will be used to evaluate damage stability[54].

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[71] https://www.cesni.eu/wp-content/uploads/2016/06/ES_TRIN_en.pdf

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- Probabilistic damage stability analysis as specified in IMO MSC.421(98) and MSC.429(98). The analysis will be performed by specifying; a) General parameters, including 3 load cases which define the deepest, partial and light draft conditions for the analysis as well as vessel type, etc., b) Longitudinal subdivision into zones; transverse subdivision by longitudinal bulkheads and vertical subdivision due to decks (for which the various probability factors are computed automatically), c) Which compartments will be breached in each damage space; the final damage and any intermediate stages of damage that will be considered.

4.3.2 Resistance

The evaluation of hull resistance components, including frictional resistance, wave-making resistance, and appendage resistance, for SSS and IWT ships operating in different water conditions. Resistance calculations will be performed using empirical formulas and Computational Fluid Dynamics (CFD) simulations.

Empirical methods:

- For SSS ships, Holtrop and Mennen[72,73] which approximate open water resistance. Holtrop and Mennen's method is arguably the most popular method to estimate resistance and powering of displacement type ships. It is based on the regression analysis of a vast range of model tests and trial data which give it a wide applicability. The Holtrop method computes a dimensional total resistance which is broken down into several components: frictional resistance, appendage resistance, wave resistance, resistance due to bulbous bow near the water surface, pressure resistance due to immersed transom, model-ship correlation resistance, and air resistance. This chapter explains the resistance estimate for the container ship and describes an estimate for the powering requirements. The powering estimate starts with the computation of thrust deduction fraction and relative rotative efficiency. The chapter shows the results for wake fraction estimates and the self-propulsion point analysis based on the propeller characteristics
- For IWT ships, Schlichting's shallow water resistance[74] method focuses on modification factors applied to deep water resistance components. The method begins by calculating the deep-water resistance and then applies specific correction factors that account for the influence of shallow water. These corrections consider the critical depth Froude number and the water depth to draft ratio. The method introduces specific correction factors for different depth-draft ratios and speed ranges. These corrections become particularly significant as the vessel approaches the critical speed in shallow water, where resistance increases can be substantial. For practical application, Schlichting provided a series of curves and tables that allow designers to determine the appropriate correction factors based on:

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[72] *J. Holtrop & G.G.J. Mennen "An approximate power prediction method" International Shipbuilding Progress, 1982*

[73] *J. Holtrop "A Statistical re-analysis of resistance and propulsion data", International Shipbuilding Progress, 1984, pp.272–276*

[74] Lars Larsson & Hoyte C. Raven, SHIP RESISTANCE & FLOW, PRINCIPLES OF NAVAL ARCHITECTURE, SNAME, edited by J. Randolph Paulling (2010)

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  - Depth-draft ratio (h/T)
  - Depth Froude number (Fnh)
  - Hull form parameters
  - Speed range

  The method's limitations should be noted:
  - Most accurate for conventional displacement vessels
  - May require modification for modern hull forms
  - Best suited for preliminary design stages
  - Accuracy decreases near critical speed

Later interpretations and applications of Schlichting's method can be found in[75].

- For SSS there is also another options, such as the Wyman method for displacement and semi-displacement hulls. This numerical method of power prediction contains universal formulation for calculating the resistance of both planning and displacement hulls. The calculations result in an effective power being estimated, and hence, considerations must be made for losses that occur between the brake power and effective power. An overall efficiency value needs to be input, which considers the loss of power between engine and propeller shaft. The module assumes that the hull form is proper, of normal form for the intended use and optimized for best performance. It also considers that the running gear (propeller, strut, shaft, rudder) are of proper size to ensure best performance.

CFD (Computational Fluid Dynamics) using ANSYS FLUENT:

Analysis using CFD involves solving the governing equations of fluid flow numerically. The three governing equations of fluid flow are the continuity equation or the mass conservation equation, the momentum conservation equation or the Navier-Stokes equations, and the energy conservation equation. Every CFD code solves the mass and momentum conservation equations in the background as these form the basis of any fluid calculations. The CFD numerical simulations will be performed using the true 3D designs (see Figure 10) of the assessed ships, the RANS (Reynolds Averaged Navier Stokes) k-ε Model, which is used for external flows with complex geometry. The parameters of the k and ε are calculated by solving transport equations for each of these quantities along with equations describing mean flow. The ships is modeled as a rigid body and the fluid is modelled as moving around the rigid object. The ship (rigid body) will be constrained to allow pitching movement along the axis perpendicular to the water surface.

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[75] Schneekluth, H., & Bertram, V. (1998). "Ship Design for Efficiency and Economy." Butterworth-Heinemann, Oxford

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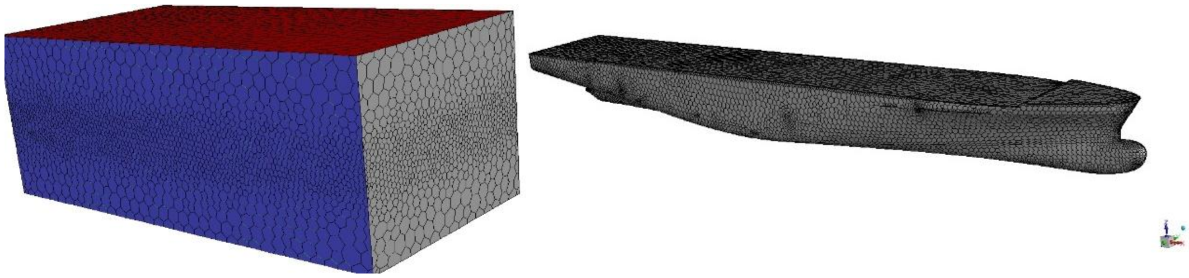

Figure 10 Ship model meshing, a) full CFD domain (left), b) mesh of the whole ship model (right).

4.3.3 Seakeeping

The assessment of a ship's motion responses, including roll, pitch, heave, and yaw is a critical aspect of the modeling process, especially when evaluating performance in various sea states and operating conditions. This analysis is conducted in alignment with the specifications and requirements outlined in the use cases. The primary objective is to design a vessel that achieves low accelerations in these motion responses, ensuring enhanced stability and operational reliability. Ships with minimized motion accelerations can maintain normal operations at sea more effectively, reducing the likelihood of accidental or unscheduled shifts in cargo or equipment. This not only enhances safety but also helps to safeguard crew comfort, optimize performance, and mitigate the risk of structural degradation over time.

The seakeeping analysis approach for Short Sea Ships and Inland Waterway vessels using MAXSURF and ANSYS CFD software packages, will focus on their specific capabilities and integration.

MAXSURF Seakeeping Module provides an efficient initial analysis platform for both vessel types. The software utilizes strip theory calculations, particularly effective for inland vessels and short sea ships. The process begins with importing or creating the hull form in MAXSURF Modeler, ensuring accurate representation of the underwater geometry. For inland vessels, particular attention must be paid to the shallow draft and fuller hull forms typical of these designs. The Seakeeping module allows direct input of the loading conditions, including cargo distribution and tank conditions, which significantly affect the vessel's response characteristics.

For environmental conditions, MAXSURF allows the definition of custom wave spectra. For short sea ships, the software can implement JONSWAP spectra with user-defined significant wave heights and peak periods representative of coastal conditions. For inland waterways, the wave spectrum can be modified to reflect the limited fetch conditions typical of rivers and canals. The software's ability to handle different water depths is particularly valuable for inland vessels, where shallow water effects significantly influence vessel behavior.

ANSYS CFD provides more detailed analysis capabilities, particularly valuable for complex hydrodynamic phenomena not fully captured by potential flow methods. The workflow typically begins with importing the geometry from MAXSURF into ANSYS Design Modeler or SpaceClaim for

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preparation and mesh generation. For both vessel types, careful attention must be paid to the mesh refinement around the free surface and near the hull, particularly in areas where accurate pressure prediction is crucial.

The ANSYS setup for short sea ships focuses on simulating regular waves of varying frequencies to generate Response Amplitude Operators (RAOs). The analysis typically includes heave, pitch, and roll motions, with particular attention to relative motion at the bow for slamming assessment. The CFD analysis can capture non-linear effects such as green water on deck and wave breaking, which are particularly important for short sea ships operating in coastal waters.

For inland vessels, ANSYS CFD simulations focus on shallow water effects and bank interaction. The domain setup must accurately represent the restricted water depth and channel width. The analysis typically emphasizes steady-state conditions with current effects, though dynamic simulations can be performed for passing vessel scenarios. The CFD results provide detailed information about pressure distribution along the hull and flow patterns, particularly valuable for assessing bank effects and squat.

Integration between MAXSURF and ANSYS creates a comprehensive analysis approach. Initial seakeeping predictions from MAXSURF guide the selection of critical conditions for detailed CFD analysis. MAXSURF's rapid analysis capabilities allow exploration of multiple operating conditions, while ANSYS CFD provides detailed verification of critical scenarios. The hydrostatic and stability calculations from MAXSURF also inform the setup of CFD simulations, ensuring consistent mass distribution and inertial properties.

For operational limits, MAXSURF's post-processing capabilities allow evaluation of motions against standard criteria. Results can be presented as polar plots showing operational envelopes for different wave conditions. The software can generate tables of limiting significant wave heights for different heading angles and operating speeds. These results can be verified through targeted ANSYS CFD simulations of critical conditions.

Validation of numerical predictions should combine results from both software packages. MAXSURF provides global response characteristics and statistical predictions, while ANSYS CFD offers detailed flow visualization and pressure distributions. For inland vessels, particular attention should be paid to shallow water effects and bank interaction, where ANSYS CFD can provide valuable insights into local flow phenomena not captured by potential flow methods.

The combined use of these software packages allows for comprehensive documentation of vessel performance. MAXSURF generates standard seakeeping reports including RAO data, motion statistics, and operational limits. ANSYS CFD provides detailed visualization of flow patterns and pressure distributions, particularly valuable for understanding complex hydrodynamic phenomena.

4.3.4 Other

In the design and analysis of SSS and IWT vessels, additional assessments and evaluations may be required, particularly when integrating alternative fuel storage systems. For instance, evaluating structural integrity becomes critical when storing fuels that demand elevated pressures or extremely low temperatures. Alternative storage designs can provide enhanced conditions and ensure greater structural integrity.

For example, storing Compressed Gaseous Hydrogen (CGH_2) may require cylindrical storage tanks capable of withstanding pressures of up to 700 bars, while Liquid Hydrogen (LH_2) storage necessitates the development of cryogenic tanks designed to maintain ultra-low temperatures. These considerations not only influence the ship's design but also ensure safety, efficiency, and compliance with technical and operational requirements.

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5 SUMMARY

This document presents a comprehensive evaluation of zero-emission power plant configurations for short-sea shipping and inland waterway transport vessels. It introduces a multicriteria decision-making framework to assess various technologies and fuels, offering guidance for selecting optimal powertrain solutions. Key findings include:

- **Technological Feasibility**: Batteries and fuel cells (PEM and SOFC) are identified as leading options, with distinct advantages depending on vessel type and operational context.
- **Energy Source Analysis**: Hydrogen (in forms such as CGH_2, LH_2, and LOHC), ammonia, and methanol are explored as fuels, with detailed comparisons of their energy densities, costs, and infrastructure requirements.
- **Use Case Modeling**: Two case studies highlight specific scenarios for implementing zero-emission solutions, focusing on performance metrics such as stability, resistance, and seakeeping.

The document underscores the importance of aligning technological solutions with regulatory, operational, and environmental requirements. Recommendations include further refinement of the evaluation framework, increased stakeholder engagement, and continued research into infrastructure development and fuel scalability to support the transition to zero-emission maritime operations.

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