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Sustainable Ferries: Regulations, Innovation, and Business Cases

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Contents

Abstract

Decarbonizing the maritime sector has become imperative in the context of global climate change and increasing environmental concerns. This thesis provides a comprehensive analysis of alternative fuels in the ferry industry, exploring regulatory frameworks, technological innovations, and business cases that support the transition toward sustainable maritime transport. Emphasis is placed on alternative propulsion systems, including LNG, battery-electric, and hydrogen-powered solutions, which demonstrate the potential to significantly reduce greenhouse gas emissions and air pollutants. Through a critical evaluation of case studies such as the LNG-powered Hypatia de Alejandria and the battery-electric eFerry Ellen, the study identifies both the environmental benefits and the infrastructural and economic challenges associated with these technologies. Moreover, the research examines evolving international regulations and incentive schemes that foster innovation and guide industry practices. By integrating technological readiness with regulatory and economic perspectives, the thesis offers valuable insights for policymakers and industry stakeholders aiming to accelerate the decarbonization of maritime transport while ensuring operational efficiency and sustainability.

La decarbonizzazione del settore marittimo è diventata una necessità imprescindibile nel contesto del cambiamento climatico globale e delle crescenti preoccupazioni ambientali. Questa tesi offre un’analisi completa dei carburanti alternativi impiegati nel settore dei traghetti, esaminando quadri normativi, innovazioni tecnologiche e casi aziendali che supportano la transizione verso un trasporto marittimo sostenibile. L’attenzione è rivolta a sistemi di propulsione alternativi, quali soluzioni alimentate a LNG, a batteria elettrica e ad idrogeno, che evidenziano il potenziale di ridurre significativamente le emissioni di gas serra e gli inquinanti atmosferici. Mediante una valutazione critica di casi studio, come il traghetto a LNG “Hypatia de Alejandria” e il traghetto a batterie “eFerry Ellen”, lo studio individua benefici ambientali, unitamente alle sfide infrastrutturali ed economiche correlate. Inoltre, la ricerca analizza l’evoluzione delle normative internazionali e degli incentivi che promuovono l’innovazione e guidano le pratiche del settore. Integrando aspetti tecnologici, normativi ed economici, la tesi fornisce spunti preziosi per i decisori politici e gli operatori impegnati ad accelerare la decarbonizzazione del trasporto marittimo nel rispetto dell’efficienza operativa e della sostenibilità ambientale.

Chapter I: Decarbonisation in the Maritime Sector: Background & Regulatory Frameworks

This section establishes the contextual and regulatory foundation for addressing the environmental challenges in the maritime sector. It examines the global urgency to reduce greenhouse gas emissions and the critical role that decarbonization plays in mitigating climate change. An in-depth analysis is provided of the key international strategies and regulatory instruments, such as those developed by the International Maritime Organization and supported by the European Union’s climate initiatives. The discussion highlights how evolving policy frameworks are designed to steer the industry toward the adoption of low- and zero-carbon technologies. Furthermore, it considers the technical challenges inherent in retrofitting existing vessels and integrating alternative fuel systems. By combining theoretical insights with an evaluation of emerging standards and safety protocols, this section lays the groundwork for understanding the interplay between policy, technology, and operational practices, setting the stage for a comprehensive exploration of alternative fuels in maritime transport.

1.1. Introduction to Decarbonisation in the Maritime Sector

The decarbonization of economic systems stands as one of the most discussed topics in current literature, especially following the global pledge to limit the rise in global temperatures to 1.5°C. The transport industry contributes to the world green-house gas (GHG) by around 36% and the 12% is from the maritime sector, according to the analysis published by the International Maritime Organization (IMO).

The revised IMO GHG Strategy includes a checkpoint to reach the net-zero GHG emissions from international shipping industry around the 2050, a commitment to ensure an uptake of alternative zero and near-zero GHG fuels by 2030 and an indicative check-point of 20% - striving the 30% - for international shipping to reach the net-zero GHG emissions for 2030 and a more enhanced check-point of 70% - striving the 80% - for 2040.

Progress has been made in many sectors, however, despite the best efforts of the International Maritime Organization (IMO) to reduce greenhouse gas (GHG) emissions from ships, GHG emissions from the sector have continued to increase.

The mid-to-long-term legal environment in which the maritime sector will develop is yet to be fixed. However, much of the focus has been on technological solutions, with alternative fuels perceived as the low-hanging fruit in contributing to decarbonisation and can support an efficient regulatory framework to meet the purposed targets.

This revision Strategy states that the basket of candidate measures delivering the reduction targets should be developed comprising a technical element, namely a marine standard able to regulate the phased reduction of marine fuels' GHG intensity, and an economic one, based on a GHG emissions pricing mechanism in maritime. The alternative fuels, such as low- and zero-carbon fuels, are taken as one of the possible measures to achieve the decarbonization in shipping sector, but there is a grey zone around the rules to be applied to the use of these fuels and the regulatory map is still in work-in-progress.

The regulatory map developed by the IMO GreenVoyage2050 has identified that there are several gaps in safety requirements and there are currently few marine fuel quality standards for alternative fuels, but, to give a first solution to this regulatory limit, might be that there may not be a need for such standards specific for marine application, if available standards for land-based fuel can be used.

1.2. Importance of Decarbonisation in the Maritime Industry

Shipping is considered to be the most energy-efficient mode of transportation. It carries approximately 80 to 90% of global trade and the sheer amount of shipping has been increasing because of the accelerating pace of globalization and international population growth. Consequently, shipping has become one of the most energy-demanding industries in the world. In addition to these general reasons, there are other unique reasons why the shipping industry consumes such a significant amount of energy. Moreover, it is very difficult to economically renovate ships; thus, ships at sea and cargo onboard are considered to have very low substitution materials, providing the unique and crucial service of transport.

The International Maritime Organization (IMO) has been taking action to control GHG emissions of ships through the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI and the current target is to reduce GHG emissions by 50% by 2050[1]. So, MARPOL Annex VI is contextualized within the broader regulatory frameworks to reduce GHG emissions at the global level and it outlines a summary of the characteristics of future fuel technologies that will be used to comply with these regulations. This will provide a broader understanding of the policy and technological aspects of the IMO's regulatory activities associated with GHG emissions of ships. Together with the policies targeting a reduction in air pollutants, this study will set a clear and important scene that the modernization of the shipping industry should consider supporting.

1.3. IMO Regulatory Framework

The International Maritime Organization (IMO) has been a leading force in creating a regulatory framework to combat climate change and reduce greenhouse gas (GHG) emissions from ships. In 2018, the IMO adopted an Initial Strategy aimed at reducing GHG emissions from ships, with a vision to phase out these emissions from international shipping as soon as possible. This strategy was revised in 2023.

The 2023 IMO GHG Strategy[2] provides a framework for Member States, outlining the future vision for international shipping, ambitious GHG reduction targets, and guiding principles. It includes potential mid- and long-term measures with proposed timelines and their impacts on States. The strategy also addresses barriers and supportive measures such as capacity building, technical cooperation, and research and development (R&D).

The 2023 strategy aims to reduce the carbon intensity of international shipping (measured as CO2 emissions per transport work) by at least 40% by 2030, averaged across international shipping. Additionally, it introduces a new goal for adopting zero or near-

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[1] Comitato RINA per la Decarbonizzazione (2023), *"Da oggi al 2050: tra sfide e opportunità per l'industria marittima"*, State of the art and considerations by the RINA Italian Decarbonization Committee with the participation of Assarmatori and Confitarma.

[2] *2023 IMO Strategy on Reduction of GHG Emissions from Ships*

zero GHG emission technologies, fuels, and energy sources, targeting at least 5%, and striving for 10%, of the energy used by international shipping by 2030.

The IMO is also developing a potential outline for a maritime "net-zero framework." This framework includes regulations under the International Convention for the Prevention of Pollution from Ships (MARPOL), which will be adopted or amended to establish a new global fuel standard and a global pricing mechanism for maritime GHG emissions.

The FFT Project is a collaborative initiative between the Government of the Republic of Korea and the International Maritime Organization (IMO), carried out by the IMO's Marine Environment Division. The primary objective of this project is to support the development of new regulations within the potential IMO Net Zero Framework, aiming to meet the targets outlined in the 2023 IMO GHG Strategy.

In MEPC 80, IMO adopted the *"2023 IMO Strategy on Reduction of GHG Emissions from Ships"*, serves a framework for Member States, outlining the future vision for international shipping, the levels of ambition to reduce GHG emissions, and guiding principles. It also introduces potential mid- and long-term measures with suggested timelines and their impacts on States. Additionally, the strategy addresses barriers and supportive measures such as capacity building, technical cooperation, and research and development. A key aspect of the 2023 IMO GHG Strategy is the aim to reduce the carbon intensity of international shipping (CO_2 emissions per transport work) by at least 40% by 2030, averaged across international shipping. Additionally, the Strategy introduces a heightened ambition concerning the adoption of zero or near-zero GHG emission technologies, fuels, and/or energy sources, targeting them to constitute at least 5%, with a strive for 10%, of the energy utilized by international shipping by 2030[3].

Especially for existing vessels, is required the calculation and verification of the Energetic Efficiency Index (EEXI), a measure related to the technical design of a ship, and the Carbon Intensity Indicator (CII), an operational measure applicable to the ships with over or equal to 5.000 GT4 calculated in relation to the load carried and the distance travelled and that continuously expresses GHG emissions from a ship's operations.

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[3] IMO "*2023 IMO Strategy on Reduction of GHG Emissions from Ships*"

[4] GT: Gross Tonnage of a vessel measured according to international standards.

The strategy emphasizes the importance of aligning efforts with the long-term temperature goal outlined in Article 2 of the Paris Agreement, aiming to phase out GHG emissions in line with the agreed-upon vision. To achieve the 2050 targets, medium- and long-term measures are still under discussion[5] (they are expected to be adopted by 2025 and enter into force around 2027) resulting in a combination of technical (goal-based marine fuels standards) and economic (market-based) measures.

The FFT Project[6] aims to provide technical analysis and easy access to the latest information on zero- and near-zero marine fuels and technologies in support of the regulatory decision-making process at the Marine Environment Protection Committee (MEPC). The project includes technical analysis, e.g. conducting global studies and research to identify the state-of-play to promote the global uptake and dissemination of zero and near-zero marine fuels and technologies: an online information portal, providing easy and user-friendly access to the latest information on zero and near-zero marine fuels and technologies among IMO Member States and all the relevant organizations and institutions.

1.3.1. European Union’s Regulatory Framework

In parallel with the International Maritime Organisation (IMO) the European Union (EU) is developing its strategy and measures to effectively mitigate greenhouse gas (GHG) emissions and reduce effects of global warming.

Like the IMO, also the European Union has set itself two very challenging goals in two crucial time-points: the GHG emissions reduction by at least 55% compared to 1990 by 2030[7], and the 90% reduction (i.e. climate neutrality) in greenhouse gas emissions in the transport sector by 2050[8].

EU requirements have been included in the so-called “*Fit for 55 Package*” that is a rules package concerning all sectors of the EU economy, of course including maritime

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[5] IMO MEPC 80: *Shipping to reach net-zero GHG Emissions by 2050*

[6] IMO : *Future Fuels and Technology Project to inform GHG Strategy update (imo.org)*

[7] European Commission, *2030 Climate & Energy Framework*

[8] European Commission, *2050 long-term strategy*

transport. The package of proposals aims at providing a coherent and balanced framework for reaching the EU's climate objectives, which ensures a just and socially fair transition, maintains and strengthens innovation and competitiveness of EU industry while ensuring a level playing field with third country economic operators and underpins the EU's position as leading the way in the global fight against climate change[9].

1.3.2. The “Fit for 55” Package

The Fit for 55 package is crafted to pave the path towards EU climate neutrality by 2050, bearing substantial implications for EU environmental and climate policies.

As key proposals, the Package encompass the enhancement and extension of the emission trading system, elevation of targets concerning energy efficiency and renewable energy utilization, promotion of low-impact transport vehicle adoption, implementation of measures to curb carbon leakage, adjustments in taxation and fiscal policies, and initiatives aimed at safeguarding and augmenting natural carbon reservoirs like forests and ecosystems. Also entails potentially significant investment demands and costs, emphasizing the necessity of pursuing the most cost-effective of the current EU climate policies.

Among the changes proposed by the “Fit for 55”, the Energy Efficiency Directive[10] has been revised, setting national energy efficiency targets and according to Directives 2018/2002 and COM/2021/558 from the European Parliament and the Council, Member States are mandated to nearly double their annual energy savings[11]. Additionally, the Directive 2018/2001 on promoting energy use from renewable sources was revised according to the EC proposal COM/2021/557: this introduces a new objective of achieving 40% of the renewable energy resources in final energy consumption by 2030 entailing doubling the penetration of the renewable resources in the European energy mix. In the end, the Package proposes elevating emissions reduction targets identified by the

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[9] European Council, European Green Deal *“Fit for 55”- The EU Plan for a green transition*.

[10] Energy Efficiency Directive (EED) (2012) is one of the key elements of the EU climate and energy legislative package, mandating EU Member States to set 2020 indicative targets on energy efficiency and put in place several mandatory policy measures for energy supply, distribution and end-use sectors.

[11] Beccarello, M. et Di Foggia, G. (2023) *“Meeting decarbonization targets: Techno-economic insights from the Italian scenario”*, DeCarbon 2 (2023) 100022

Effort Sharing Regulation 2018/842 from 30% to 40% less compared to 2005 levels by 2030.

1.3.3. Emission Trading System reformed by EU Dir. 2023/959

Following the EU Directive 2023/959, which amends the Emission Trading System (ETS) Directive, from 2025 will be requested to each Shipping Company operating in Europe to report a verified aggregated emissions data for the previous year. If the Shipping Company is in a quota deficit, it will be fined for each issued tonnage which the quota has not been returned (€ 100/tons). At the extreme case, if the Shipping Company doesn't comply the ETS Directive for two consecutive years, its vessels may be denied entry into European ports until the Company fulfils its obligations.

The EU Directive, however, provides for certain derogations – which have to necessarily be requested by the Member State as not automatic – until the end of 2030 for passengers' ships (other than cruise ships) and Ro/Ro vessels sailing from/to European islands with population of less than 200.000 permanent residents[12]; for travel by passengers' ships and Ro/Ro vessels under a transnational public service contract[13]; and travel between a port located in the remote regions of a European State and a port of the same State[14].

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[12] Gazzetta Ufficiale dell'Unione Euopea, Direttiva (UE) 2023/959 del Parlamento europeo e del Consiglio del 10 Maggio 2023, *pt.24*

[13] Gazzetta Ufficiale dell'Unione Euopea, Direttiva (UE) 2023/959 del Parlamento europeo e del Consiglio del 10 Maggio 2023, *pt.25*

[14] Gazzetta Ufficiale dell'Unione Euopea, Direttiva (UE) 2023/959 del Parlamento europeo e del Consiglio del 10 Maggio 2023, *pt.26*

1.3.4. FuelEU Maritime

The FuelEU Maritime Regulation aims to reduce the intensity of the GHG in the maritime transport to reach 80% in 2050 in reference to the 2020's levels.

To achieve this challenging goal, the Regulation proposes a special incentive regime to support the uptake of the so-called renewable fuels of non-biological origin (RFNBO) with a high decarbonisation potential and the exclusion of fossil fuels from the regulation's certification process.

Moreover, it contains the provision of an obligation for passenger ships and containers to use onshore power supply for all electricity needs while moored at the quayside in major EU ports as of 2030, with a view to mitigating air pollution in ports, which are often close to densely populated areas.

Ships that have a higher GHG intensity than the requirement. must pay a penalty corresponding to its compliance deficit, this is the so called FuelEU penalties[15]. The revenues from the penalties should be used by member states to promote the distribution and use of renewable and low-carbon fuels in the maritime sector and help maritime operators to meet their climate and environmental goals.

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[15] European Council, *FuelEU maritime initiative*: Council adopts new law to decarbonise the maritime sector.

Chapter II: Navigating the Future of Maritime Fuels: Regulatory Frameworks, Technological Readiness, and Sustainability Assessment

This segment delves into the interplay between regulatory imperatives and technological innovation as it relates to maritime fuels. It provides a detailed examination of the dual challenges associated with both on-board fuel systems and onshore infrastructure for alternative fuel handling. The analysis covers a range of candidate fuels—including LNG, hydrogen, ammonia, and advanced biofuels—evaluating their technical feasibility, operational efficiency, and environmental sustainability. Emphasis is placed on the importance of aligning evolving international policies with technological advancements, as evidenced by recent updates in global emission reduction strategies. The discussion also incorporates sustainability assessments that account for life-cycle emissions, energy efficiency, and the potential for cost-effective deployment. By integrating a review of regulatory measures with critical insights into current and emerging technologies, this section underscores the necessity of a multifaceted approach to achieving long-term decarbonization in maritime transport.

2.1. Alternative Fuels Rules Framework for ships and yard: an on-board application and an onshore handling

The maritime industry's shift towards alternative fuels is driven by a combination of environmental regulations and the need for sustainable operations. The International Maritime Organization (IMO)[16] has set stringent emission standards that necessitate the use of cleaner fuels.

Alternative fuels such as LNG (Liquefied Natural Gas), biofuels, hydrogen, and electricity are being explored for their potential to reduce the carbon footprint of maritime operations. Each of these fuels has its own set of challenges and benefits when it comes to on-board applications and onshore handling[17].

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[16] International Maritime Organization (IMO). (2020). "*Reducing greenhouse gas emissions from ships.*"

[17] Z. Wan et al. (2018). "*Decarbonizing the international shipping industry: Solutions and policy recommendations*"

On-board applications involve the storage, distribution, and use of these fuels in the ship's engines. This requires significant modifications to the ship's design and operations. For instance, LNG requires cryogenic storage and special handling procedures to ensure safety.

Onshore handling involves the infrastructure needed to store and supply these fuels to the ships. This includes storage facilities, bunkering stations, and safety procedures. The lack of such infrastructure is one of the major hurdles in the widespread adoption of alternative fuels.

The regulatory framework for alternative fuels is still evolving, with rules varying by country and fuel type. Navigating this complex regulatory landscape is a significant challenge for ship operators[18].

2.2. 2023 IMO GHG Strategy - MEPC 80

The "2023 IMO GHG Strategy - MEPC 80"[19] is a pivotal development in the maritime industry's efforts to combat climate change. The strategy provides a comprehensive framework for reducing greenhouse gas (GHG) emissions from ships and it sets out a vision for the future of international shipping, levels of ambition to reduce GHG emissions, and guiding principles.

The strategy also identifies barriers and supportive measures including capacity building, technical cooperation, and research and development (R&D).

The main barriers identified are particularly relevant to the technological environment, as the use of alternative fuels is a relatively new concept: there are significant technological challenges to overcome, such as developing efficient engines that can run on these fuels, designing safe storage and distribution systems, and ensuring the reliability of them; to the lack of infrastructure (both onshore facilities and onboard systems) for the storage, distribution, and bunkering of alternative fuels; to the regulatory framework for alternative fuels is still evolving and the rules can vary by country and by fuel type, creating uncertainty for ship operators; at last to several economic factors due

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[18] Smith, T., et al. (2014). "*Third IMO GHG Study 2014.*" International Maritime Organization (IMO), London, UK.

[19] International Maritime Organization (IMO). (2023). "*Marine Environment Protection Committee (MEPC 80), 3-7 July 2023*"

to significant investment and the higher cost of these fuels compared to traditional marine fuels, coupled with the need for new infrastructure and technologies, can be a deterrent.

On the other hand, there are supportive measures such as training and education to equip maritime professionals with the necessary skills and knowledge to handle alternative fuels; major collaboration between different stakeholders, including ship operators, fuel suppliers, technology providers, and regulators, can help overcome the technological and infrastructural barriers and Governments and Regulatory bodies can introduce policies to incentivize the use of alternative fuels and this could include subsidies, tax breaks, or regulations that penalize the use of traditional marine fuels.

2.3. Study of the readiness and availability of low- and zero-carbon technologies and marine fuels.

Analysing the 80th Marine Environmental Protection Committee study[20], the Initial IMO GHG Strategy outlined objectives for reducing GHG emissions from international shipping using 2008 as reference year.

This study employs the voyage-based allocation method outlined in the 4th IMO GHG Study. Emission estimates in this study are based on Tank-To-Wake (TtW) emissions, as utilized in the 4th IMO GHG Study. Although the Initial IMO GHG Strategy does not explicitly address TtW or Well-To-Wake (WtW) emissions, because this study does not predetermine the discussions regarding their inclusion in the Revised IMO GHG Strategy. Instead, the focus is on demonstrating potential pathways for decarbonization to assess the feasibility of more stringent GHG reduction targets. For the purposes of this study, GHG emissions are calculated within a TtW framework, where CO_2 emissions resulting from the combustion of biogenic carbon or carbon sourced from direct air capture are considered zero.

This study includes CO_2, methane and nitrous oxide as GHG emissions, but does not include buying carbon credits from other sectors to meet targets, and this helps evaluating fuel pathways for reducing emissions.

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[20] Marine Environmental Protection Committee, 80th Session (2023), "*Reduction Of Ghg Emissions From Ships*"

Various types of fuels are being considered to reduce greenhouse gas emissions in international shipping, among other biofuels (such as biomethanol, biomethane, biodiesel), E-fuels or renewable fuels made from non-biological sources, primarily using hydrogen produced by electrolysis with renewable or nuclear electricity, Blue fuels utilize hydrogen produced from fossil energy sources, Electricity sourced from the grid, generated from a mix of fossil and renewable sources, Fossil fuels blended with advanced biofuels, sometimes paired with onboard carbon capture (e-fuels).

These candidate fuels aim to eliminate or significantly reduce Tank-To-Wake (TtW) greenhouse gas emissions, with potential reductions also in Well-To-Tank (WtT) and Wake-To-Wheel (WtW) emissions compared to traditional fossil fuels. However, depending on their primary energy source, production method, and energy conversion, they may still produce significant emissions.

Numerous energy efficiency technologies are already mature and poised for wider adoption, while others are on the brink of commercial availability or undergoing development expected to be commercialized by 2030, but these timelines represent maximum durations for commercialization. If demand increases, particularly due to a more ambitious Revised IMO GHG Strategy and supporting policies, technology development could accelerate.

In conclusion, the necessary technologies, and fuels to meet the demand for a more ambitious decarbonization scenario are expected to be technically and commercially ready on time. This assessment was confirmed by experts engaged to validate the literature review findings.

The current orderbook for methanol and hydrogen vessels is expected to stimulate demand for bunker facilities. Several port and bunkering investment projects are in the pipeline, including initiatives for green shipping corridors.

In one hand, bio- and e-diesel, as well as bio- and e-methane, can utilize existing bunkering infrastructure. In the other hand, new bunkering infrastructure will be required for ammonia, hydrogen, and methanol. Methanol already has some refuelling infrastructure in place, with ship-to-ship bunkering demonstrated, but ammonia will need to leverage its existing global network of storage terminals.

Assuming the availability of such fuels, the development of bunkering infrastructure, distribution networks, and storage capabilities is expected to be sufficient to facilitate their rollout without encountering potential constraints.

It’s clear that a signal of demand is essential to stimulate investments and achieve the higher ends of the projected availability ranges, so the availability in 2030 may increase with the emergence of more fuel production projects and shorter project lead-times, both in the planning and commissioning phases. But to meet the decarbonization targets by 2050, an average annual growth rate in fuel production of 6-12% from 2030 onwards is necessary, also if this rate is lower than historical growth rates observed in solar and wind power generation.

The availability of fuel for shipping hinges on the decarbonization efforts of other sectors in two ways: demand from other sectors drives production, but it also creates competition for the same fuels. This assessment of availability does not represent maximum potential availability but rather indicates a possible outcome if incentives and policies are implemented to scale up production and establish firm demand.

The increased capital costs associated with vessels using candidate fuels are not expected to be a significant barrier to adoption, then some alternatively fuelled vessels can already manage their upfront costs effectively. However, the high capital costs of onboard carbon capture systems may pose a barrier to adoption.

The main barrier to the uptake of candidate fuels in the shipping industry is not solely the higher prices of these fuels. Rather, it is the current uncertainty surrounding fuel price fluctuations in the absence of a clear demand signal. This uncertainty includes concerns about the timing and magnitude of fuel price changes, as well as the potential for unplanned and uneven price shifts across different segments and geographic regions.

Considering three decarbonization scenarios have been considered to outline potential bounds for the Revised IMO GHG Strategy: the initial IMO GHG Strategy is modelled as a 50% reduction by 2050; an 80% reduction by 2050; and complete decarbonization by 2050. The feasibility of a more ambitious decarbonization pathway is not hindered by the technical and commercial readiness of candidate fuels and technologies, nor infrastructure and shipyard readiness, but rather by the clarity provided to the sector by the ambition level and the policies in place to decarbonize the sector.

The expected availability of candidate fuels for the shipping sector is currently limited, and without action, will lead to insufficient availability to meet demand and as already anticipated, a clear signal of demand is required to enable sufficient availability of candidate fuels. This signal could come from the forthcoming Revised IMO Strategy, setting revised levels of ambition in combination with the necessary policies to drive the transition. Also, a clear signal of demand is needed soon to enable the sufficient availability of candidate fuels early enough to meet a steep transition pathway. Policies to achieve that ambition would need to come into effect by 2025 to meet the 2030 targets of the decarbonization scenarios.

All three decarbonization scenarios are expected to be feasible by 2040 and 2050 if policies to deliver an increased level of ambition are implemented in the short term. However, meeting the interim targets of the Decarbonization by 2050 scenario by 2030 appears challenging, considering the need to increase the uptake of candidate fuels well beyond currently announced projects.

While candidate fuels are and will be more expensive than currently used fuels, this is not a barrier to deployment if the demand signal is clear. Short-term cost changes can be planned for with a clear signal of demand over defined timescales.

2.4. Maritime Fuel Classification

Maritime fuel classification is a critical aspect of the shipping industry, ensuring the appropriate use of fuels for various marine applications. Technically, marine fuels are divided into two main categories: marine distillates and residual marine fuels.

The detailed classification is based on the main applications and characteristics of the products. Some of the most relevant marine fuel types include Liquid Natural Gas (LNG), Heavy Fuel Oil with a max Sulphur emission of 3.50%, Very-low Sulphur Fuel with a max Sulphur emission of 0.50%, Ultra-low Sulphur Fuel with a max Sulphur emission of 0.10%, and Biofuels.

The International Organization for Standardization (ISO) has a dedicated working group, ISO/TC 28/SC4/WG6, for the classification and specification of marine fuels. Furthermore, the FuelEU Maritime regulation, which will be in force from 2025, aims to increase the share of renewable and low-carbon fuels in the fuel mix of international maritime transport in the European Union.

2.5. The activity of analysis and reporting: an overview on the Tests for fuels quality specifications, following ASTM, ISO, and other standards

The activity of analysis and reporting in the context of fuel quality specifications is a comprehensive process that involves rigorous testing following established standards. These tests are designed to ensure the quality and performance of various fuel types, including petroleum refined fuels, biofuels, CNG, LPG, coal, pet-coke, and other fuel sources.

The testing process encompasses a wide range of parameters, such as acidity, density, sulphur content, viscosity, and more. These tests are conducted in specialized laboratories that support fuel quality control, research, and troubleshooting for various industries. The results of these tests are then reported, providing valuable insights into the fuel's quality and performance. This process is crucial for maintaining the safety, environmental standards, and efficiency of fuel-based operations.

ISO[21] and ASTM[22] are two organizations that provide standards for fuel testing, the most common are:

- ISO 8217:2017: This standard specifies the requirements for fuels for use in marine diesel engines and boilers. It covers a variety of tests, including density, sulphur content, flash point, hydrogen sulphide, acid number, oxidation stability, total sediment, fatty acid methyl ester (FAME), pour point/cloud point/cold filter plugging point, appearance/water, lubricity, vanadium, sodium, aluminium plus silicon, and used lubricating oil (ULO).
- ISO 12156-1: This standard is used for the assessment of lubricity using the high-frequency reciprocating rig.
- ISO 12185: This standard is used for the determination of density using the oscillating U-tube method.
- ASTM D396: This standard is used for the specification of fuel oils.
- ASTM D975: This standard is used for the specification of diesel fuel oils.

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[21] ISO Organization, *ISO Standards*

[22] ASTM International, *Petroleum Standards*

- ASTM D1655: This standard is used for the specification of aviation turbine fuels.
- ASTM D1835: This standard is used for the specification of liquified petroleum (LP) gases.
- ASTM D5800-21: This standard is used for the evaporation loss of lubricating oils by the Noack method.
- ASTM D6304-20: This standard is used for the determination of water in petroleum products, lubricating oils, and additives by Coulometric Karl Fischer Titration.

These tests are conducted in specialized laboratories that support fuel quality control, research, and troubleshooting for various industries. The results of these tests are then reported, providing valuable insights into the fuel's quality and performance. This process is crucial for maintaining the safety, environmental standards, and efficiency of fuel-based operations.

2.6. Major Vessel Routes and Their Possible Transformation with Alternative Fuels

As previously stated, the global maritime industry is instrumental in linking international markets, with major vessel routes acting as the lifelines of global trade. These routes are influenced by geopolitical factors, the distribution of essential resources, and the availability of traditional fuels. This section examines the current major vessel routes powered by traditional fossil fuels and investigates how these routes may evolve with the adoption of alternative fuels such as LNG, hydrogen, ammonia, and methanol[23].

Currently, the global maritime shipping network still relies heavily on fossil fuels, with bunker fuel (a byproduct of crude oil refining) being the predominant choice. Major routes can be categorized into three types based on their geographical and economic importance. Transoceanic routes, such as the Asia-Europe route via the Suez Canal, are among the busiest, facilitating trade between Asia's manufacturing hubs and Europe's consumer markets. The Trans-Pacific route links East Asia to North America and it is vital for trade between China, Japan, South Korea, and the United States. Similarly, Atlantic routes connect North America to Europe, forming the backbone of transatlantic trade.

Regional routes include the intra-Asia routes, which are among the densest in terms of shipping traffic, driven by trade between China, ASEAN countries[24], Japan, and India. Coastal and short-sea shipping in Europe, such as routes in the Baltic Sea and the Mediterranean, rely on proximity-based trade.

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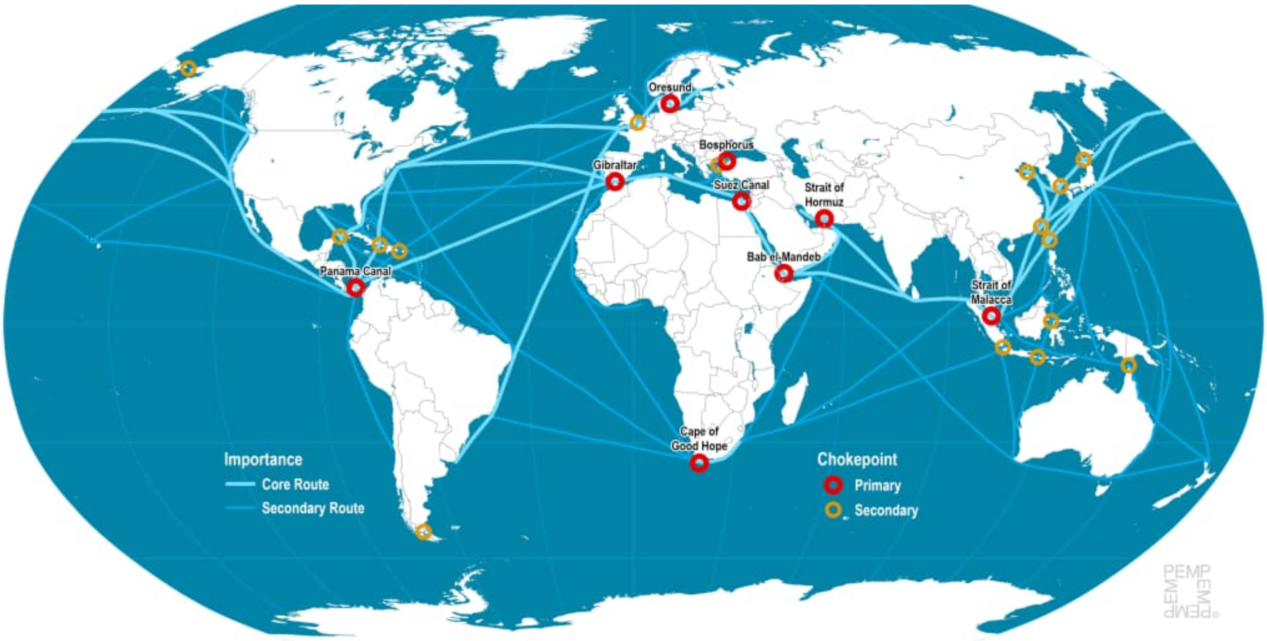
[23] Marrero, A., et al. (2023) *"Decarbonization of Short Sea Shipping in European Union: Impact of market and goal based measures"*, Journal of Cleaner Production 421 (2023) 138481

[24] Association of Southeast Asian Nations: Brunei Darussalam, Burma, Cambodia, Indonesia, Laos, Malaysia, Philippines, Singapore, Thailand, and Vietnam.

Figure 1: Main Maritime Shipping Routes.



Source: Theo Notteboom, Athanasios Pallis and Jean-Paul Rodrigue (2022) in "*Port Economics, Management and Policy*"

Strategic maritime passages also play a crucial role in global trade[25]. The Strait of Malacca, connecting the Indian and Pacific Oceans, is one of the world's busiest chokepoints for oil and container traffic[26]. An average of over 70.000 vessels transits this strait annually, highlighting its critical importance for energy and goods movement. The Panama Canal, with its dual-lock system and strategic location, facilitates approximately 14.000 ship transits annually[27], primarily connecting the Pacific and Atlantic Oceans without necessitating travel around South America. Similarly, the Suez Canal handles around 18.000 ships annually[28], providing a crucial link between Europe and Asia without the need to circumnavigate Africa. The Strait of Hormuz is pivotal in global energy trade,

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[25] *Chapter 1.3 – Interoceanic Passages | Port Economics, Management and Policy*, Theo Notteboom, Athanasios Pallis and Jean-Paul Rodrigue (2022).

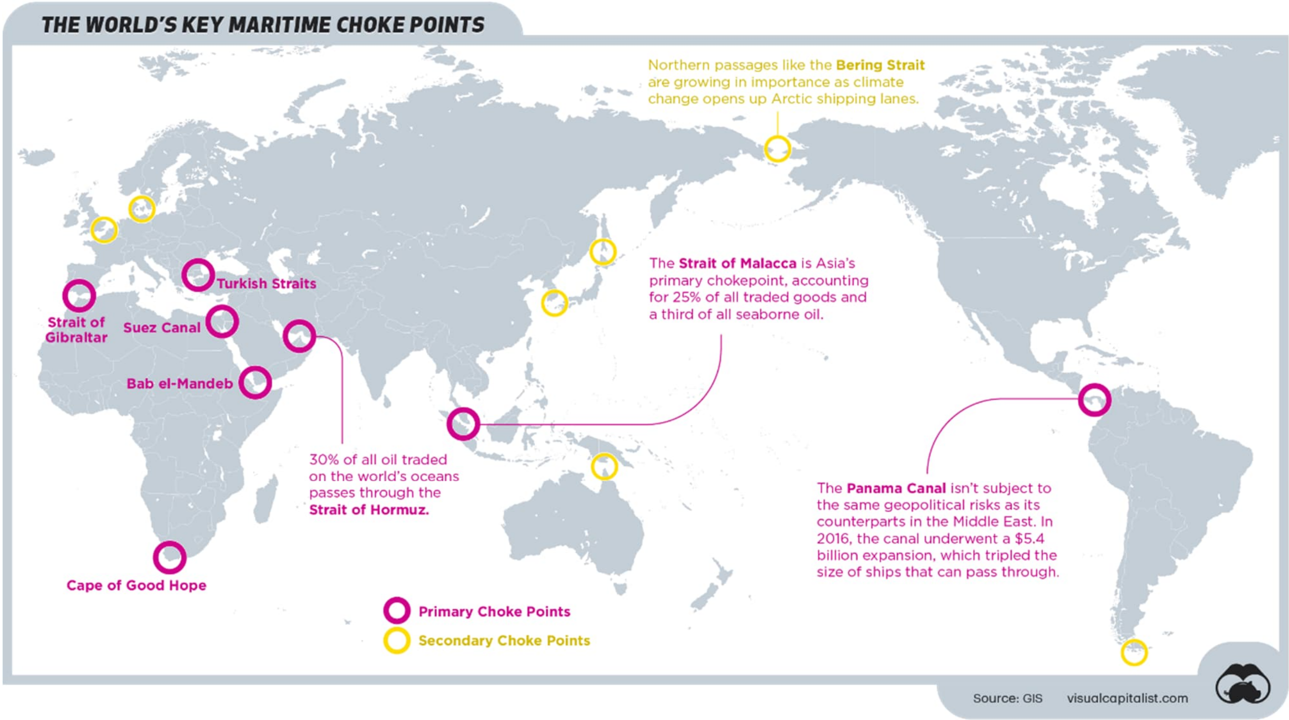
[26] *Capacity of Key Strategic Passages | Port Economics, Management and Policy*, Theo Notteboom, Athanasios Pallis and Jean-Paul Rodrigue (2022).

[27] *Capacity of Key Strategic Passages | Port Economics, Management and Policy*, Theo Notteboom, Athanasios Pallis and Jean-Paul Rodrigue (2022).

[28] *Capacity of Key Strategic Passages | Port Economics, Management and Policy*, Theo Notteboom, Athanasios Pallis and Jean-Paul Rodrigue (2022).

accounting for nearly 20% of the world’s crude oil transport, while the Bab-el-Mandeb [29]Strait ensures the connection between the Mediterranean and the Indian Ocean.

Figure 2: Maritime Choke Points



THE WORLD’S KEY MARITIME CHOKE POINTS

Northern passages like the **Bering Strait** are growing in importance as climate change opens up Arctic shipping lanes.

The **Strait of Malacca** is Asia’s primary chokepoint, accounting for 25% of all traded goods and a third of all seaborne oil.

30% of all oil traded on the world’s oceans passes through the **Strait of Hormuz.**

The **Panama Canal** isn’t subject to the same geopolitical risks as its counterparts in the Middle East. In 2016, the canal underwent a $5.4 billion expansion, which tripled the size of ships that can pass through.

Source: GIS visualcapitalist.com

The potential impacts of these interoceanic passages on global trade cannot be understated. Efficient connectivity provided by these routes significantly reduces transit times and costs, but they are also susceptible to vulnerabilities such as political instability, climate-induced disruptions, and the increasing scale of maritime traffic. For instance, congestion in these chokepoints can lead to delays, while their capacity limitations necessitate constant upgrades and technological advancements to accommodate growing demands. Furthermore, any closure or blockage, whether due to geopolitical tensions or environmental incidents, could have cascading effects on the global supply chain. Investments in alternative routes, technological enhancements like automated navigation systems, and infrastructure resilience are crucial to ensuring uninterrupted flow through these critical passages[30].

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[29] *Visualized: Mapping the World's Key Maritime Choke Points*

[30] *Potential Impacts of Interoceanic Passages and Canals | Port Economics, Management and Policy*
Theo Notteboom, Athanasios Pallis and Jean-Paul Rodrigue (2022)

While these passages enable efficient global trade, they face challenges such as congestion, capacity limitations, and security threats. These vulnerabilities underscore the importance of alternative routes or enhanced technological solutions to mitigate potential disruptions. These routes are dictated by factors such as fuel availability, infrastructure support for refuelling, and optimized paths to minimize costs. However, reliance on traditional fuels ties these routes to specific bunkering hubs that can accommodate large-scale storage and distribution.

2.6.1. Potential Changes in Vessel Routes with LNG Adoption

Liquefied Natural Gas (LNG) is seen as a transition fuel in the shift toward greener alternatives. LNG's adoption could influence vessel routes due to the specific infrastructure required for its storage and bunkering.

The enhanced role of LNG bunkering hubs is expected to increase traffic at major ports such as Rotterdam, Singapore, and Shanghai, which have established LNG bunkering facilities. Secondary ports might develop LNG infrastructure to cater to local demands and short-sea shipping, reshaping regional routes. Geographical constraints associated with LNG, such as its need for cryogenic tanks for storage, make smaller ports less likely to adopt it without significant investment. Routes could consolidate around ports with LNG facilities, altering traditional shipping lanes. Environmental considerations also come into play. Emission control areas (ECAs) in the Baltic Sea, North Sea, and North America could encourage more LNG-fueled shipping within these zones.

Economic benefits are another driving force behind LNG adoption. Its potential to lower operating costs and meet regulatory compliance makes LNG an attractive option for shipowners. The International Maritime Organization's (IMO) sulphur cap regulations have incentivized a transition to cleaner fuels, and LNG stands out as a cost-effective alternative. Emerging LNG corridors, particularly in the Asia-Pacific region and between the Middle East and Europe, could redefine traditional maritime routes. For instance, ports in Australia and Qatar are investing heavily in LNG infrastructure to cater to

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growing demands. Similarly, Japan, South Korea, and China are expected to become pivotal LNG hubs, reshaping intra-Asia trade routes.

Additionally, LNG bunkering is likely to expand in traditionally underserved areas. Ports in Africa and South America are beginning to develop LNG capabilities to capitalize on regional trade growth. For example, Brazil's Santos Port[31] and South Africa's Durban Port[32] are exploring LNG projects to enhance their competitive edge. These developments not only create new opportunities for LNG-powered vessels but also diversify the maritime network, reducing dependence on a few established hubs.

Technological advancements are expected to further accelerate LNG adoption. Innovations in dual-fuel engines, which allow ships to switch between LNG and conventional fuels, provide flexibility and reduce risks associated with fuel availability[33]. Retrofitting older ships with LNG-compatible systems is another avenue being explored to speed up the transition. However, challenges remain, including the high initial investment costs for LNG infrastructure and geopolitical uncertainties that may affect supply chains.

Forecasts for 2025[34] highlight that LNG-powered shipping will likely dominate emission control zones and high-density trade lanes, particularly those connecting Asia, Europe, and North America. The shift is expected to bring about a more environmentally sustainable and economically viable global shipping network, albeit with some adjustments to established routes.

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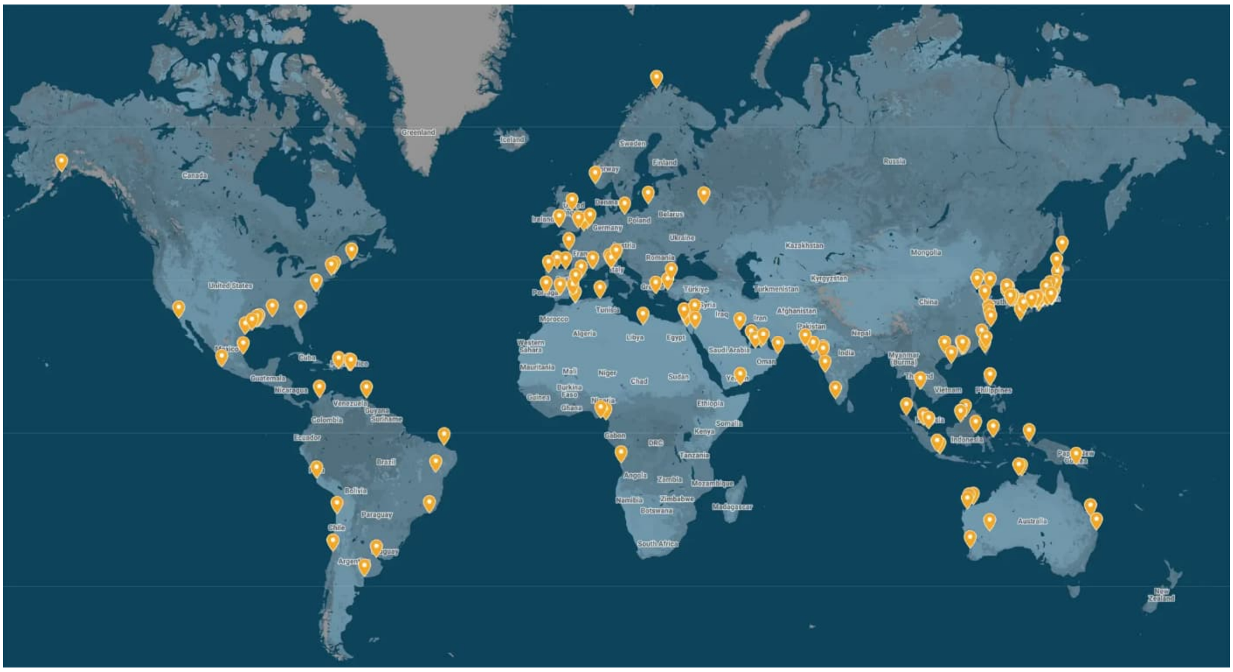
[31] *Port of Santos' First LNG Tanker Ship Docks Amid Legal Disputes - DatamarNews*

[32] *Vopak Terminal Durban | Royal Vopak*

[33] "A comprehensive feasibility analysis of dual-fuel engines and solid oxide fuel cells on a tanker ship considering environmental, economic, and regulation aspects", Onur Yuksel in "Sustainable Production and Consumption", 42 (2023), 103-124

[34] *2025 Shipping Routes Forecast: Opportunities, Risks, and Trends – Ship Universe*, January 2025.

Figure 3: LNG Terminals over the world: Complete list and map 2025.



Source: Analytical Solution and Products

2.6.2.Hydrogen-Powered Shipping and Its Route Dynamics

Hydrogen is a promising zero-emission fuel for maritime applications but faces challenges related to production, storage, and distribution. These challenges stem largely from hydrogen’s physical properties, which require specialized infrastructure and careful planning for its use in global shipping.

A recent study highlights the role of hydrogen as a potential game-changer in decarbonizing the maritime sector. It suggests that advancements in hydrogen liquefaction technologies and high-pressure storage methods could significantly improve its viability as a maritime fuel. The development of hydrogen-powered fuel cells, combined with hybrid propulsion systems, offers the potential to improve fuel efficiency and reduce greenhouse gas emissions. Hydrogen supply hubs are likely to be localized near renewable energy sources or industrial hubs, such as the North Sea (offshore wind power) or Middle Eastern regions with abundant solar energy. These regions offer optimal conditions for producing green hydrogen, which is created using renewable electricity and water electrolysis. Shipping routes may gravitate toward these supply hubs, shifting traditional patterns and potentially creating new regional trade hubs. This would necessitate a re-evaluation of long-established trade corridors.

One significant challenge is the low energy density of hydrogen compared to traditional fuels, which means ships would require larger storage capacities or more frequent refuelling stops. This could result in a network of strategically placed hydrogen bunkering stations along key trade routes[35], increasing port calls and influencing maritime logistics. For transoceanic voyages, where refuelling opportunities are limited, hydrogen-powered ships might require additional innovations such as hybrid propulsion systems or onboard hydrogen production technologies. Coastal regions with stringent emission regulations, such as California or Scandinavia, are expected to become early adopters of hydrogen bunkering infrastructure. These areas may pioneer hydrogen use, both due to regulatory incentives and the proximity to renewable energy sources. Over time, these early adoption zones could serve as models for other regions, accelerating hydrogen adoption worldwide.

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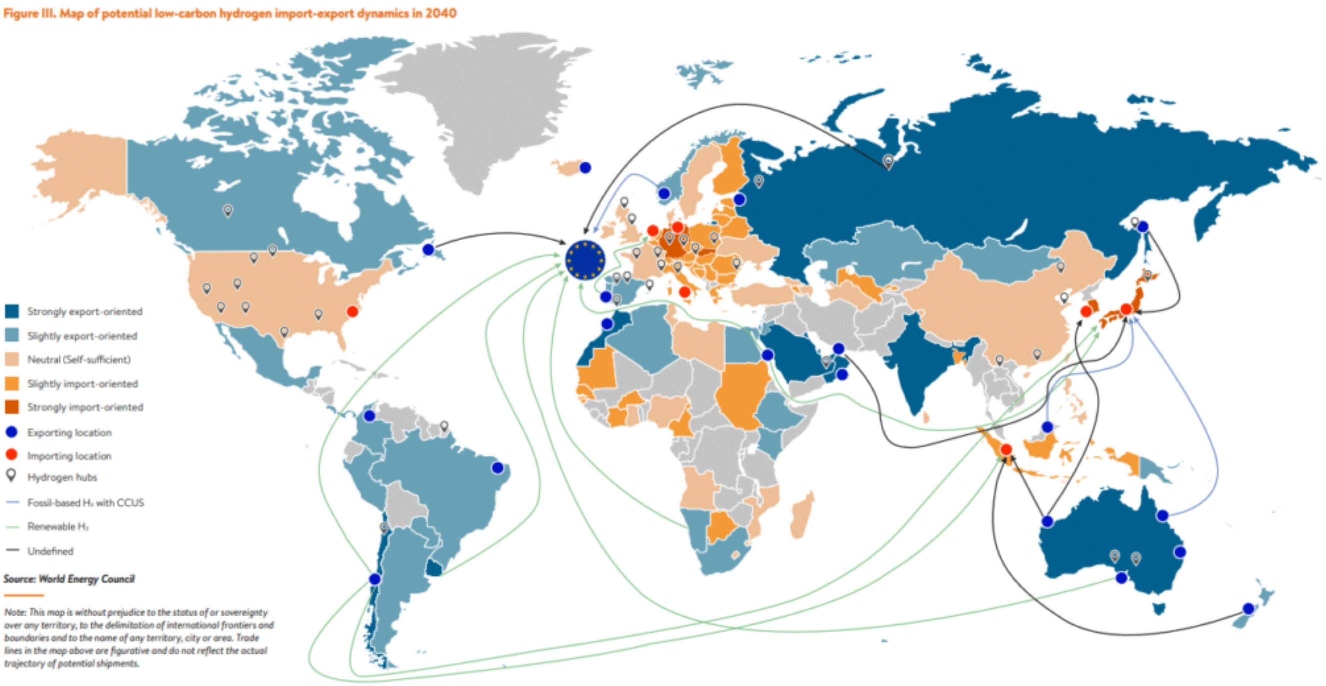
[35] “*Developing hydrogen energy hubs: The role of H_2 prices, wind power and infrastructure investments in Northern Norway*”, Svendsmark E. et al (2024) in “*Applied Energy*”, Vol. 376, Part A.

Additionally, hydrogen's potential extends beyond direct use as a fuel. It could serve as a precursor for other alternative fuels, such as ammonia or synthetic hydrocarbons, which might offer better storage and transport characteristics. The development of a hydrogen-based maritime economy would require international collaboration to standardize safety protocols, optimize supply chains, and establish consistent pricing mechanisms. If successfully implemented, hydrogen could redefine global shipping, leading to a more sustainable and diversified network of maritime routes[36].

[37]

Figure 4 Map of potential low-carbon hydrogen import-export dynamics in 2040



Source: WORLD ENERGY INSIGHTS: WORKING PAPER

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[36] "Developing hydrogen energy hubs: The role of H_2 prices, wind power and infrastructure investments in Northern Norway", Svendsmark E. et al (2024) in "*Applied Energy*", Vol. 376, Part A.

[37] World_Energy_Insights_Working_Paper_Regional_insights_into_low-carbon_hydrogen_scale_up.pdf

Governments and international organizations must incentivize research and development while establishing global standards for hydrogen infrastructure. These efforts will be instrumental in overcoming barriers such as high costs and the lack of a robust hydrogen supply chain.

2.6.3.Ammonia as a Maritime Fuel and Its Impacts on Routes

Ammonia offers significant promise due to its high energy density and ease of storage compared to hydrogen. Its adoption could influence vessel routes in several ways, reshaping the maritime industry as it becomes a viable alternative fuel for large-scale operations[38].

The potential of ammonia as a maritime fuel is underpinned by its ability to be produced from renewable energy sources, such as wind or solar power, resulting in green ammonia. This renewable production capability aligns well with decarbonization efforts and provides an opportunity to diversify global energy sources. Proximity to ammonia production centres, currently aligned with fertilizer production, could transform these centres into key bunkering hubs. Regions like the Middle East and North Africa (MENA), with their low-cost ammonia production capabilities, may see increased maritime traffic as they develop the necessary infrastructure to support ammonia-fuelled vessels.

According to the IEA’s Ammonia Technology Roadmap, ammonia is identified as a cornerstone for achieving net-zero emissions in the maritime industry. The roadmap highlights that transitioning to ammonia-powered vessels could reduce carbon dioxide emissions by up to 70% by 2050 compared to conventional marine fuels[39][40]. Additionally, innovations in ammonia cracking technologies, which allow for the extraction of hydrogen from ammonia, can enhance its versatility and use as a dual-purpose fuel. Logistical adjustments will be necessary as ammonia’s toxicity requires specialized handling facilities and safety protocols. This requirement limits its adoption to ports

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[38] Jang, H., et al. (2023) *“Regulatory gap analysis for risk assessment of ammonia-fuelled ships”*, Ocean Engineering 287 (2023) 115751

[39] *Executive Summary – Ammonia Technology Roadmap – Analysis - IEA*

[40] Chen, M., et al. (2024) *“Bunkering for change: Knowledge preparedness on the environmental aspect of ammonia as a marine fuel”*, Science of the Total Environment 907 (2024) 167677

capable of managing these challenges, centralizing shipping routes around advanced ports while potentially bypassing smaller ones. Nevertheless, these ports could benefit from substantial investments in ammonia-specific storage and refuelling systems, fostering regional economic growth.

A report by Lloyd's Register highlights that ammonia-fuelled ships are particularly well-suited for long-haul and bulk cargo operations, given ammonia's energy density and storage benefits compared to hydrogen[41]. This suitability could lead to shifts in major global shipping lanes, with ammonia bunkering hubs becoming central nodes in the maritime network. Additionally, ammonia's capacity to be stored as a liquid at relatively low pressures makes it attractive for large tankers, enabling significant economies of scale. The alignment with renewable energy sources could also shape ammonia's adoption. Green ammonia, produced using renewable energy, might create new hubs near wind or solar farms, diversifying traditional maritime networks. For example, countries like Australia and Chile, with abundant renewable energy resources, are investing heavily in green ammonia production, which could lead to new shipping routes emerging to connect these production hubs with global markets.

However, challenges persist, including the need for international collaboration to establish safety standards, optimize production and distribution networks, and address the higher upfront costs associated with ammonia adoption. Policy interventions and incentives will be critical to overcome these barriers, fostering the development of a robust ammonia-powered maritime ecosystem. If successfully implemented, ammonia could play a transformative role in achieving a sustainable and efficient global shipping network.

Proximity to ammonia production centres, currently aligned with fertilizer production, could transform these centres into key bunkering hubs. Regions like the Middle East and North Africa (MENA), with their low-cost ammonia production capabilities, may see increased maritime traffic. Logistical adjustments will be necessary as ammonia's toxicity requires specialized handling facilities[42], limiting its adoption to

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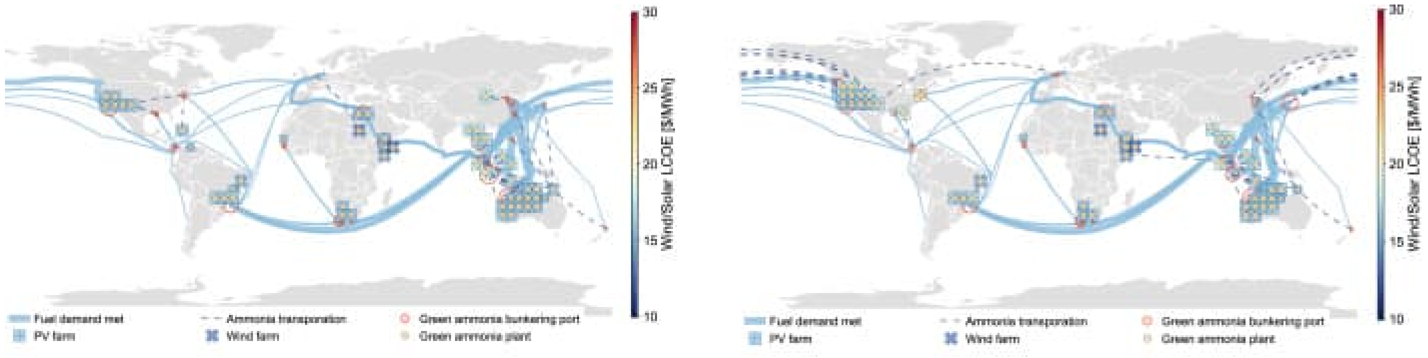
[41] *Ammonia - Compare zero carbon fuels | LR*

[42] Leng Ng C. K., et al. (2023). "Accidental release of ammonia during ammonia bunkering: Dispersion behaviour under the influence of operational and weather conditions in Singapore", Journal of Hazardous Materials 452 (2023) 131281

ports capable of managing these requirements. This constraint may centralize shipping routes around advanced ports while bypassing smaller ones. The alignment with renewable energy sources could also shape ammonia's adoption. Green ammonia, produced using renewable energy, might create new hubs near wind or solar farms, diversifying traditional maritime networks.

Figure 5: Ammonia-based green corridors for sustainable maritime transportation



(a) 5% cost reduction in the U.S.

(b) 20% cost reduction in the U.S.

Wang H. et al, Vol. 6 (2023)

2.6.4.Methanol-Fuelled Shipping and Route Transformations

Methanol is gaining traction as a viable alternative fuel due to its liquid state under ambient conditions, making storage and transport relatively simple[43]. This characteristic, combined with its lower carbon intensity compared to traditional fuels, positions methanol as an important option in the maritime sector's decarbonization efforts[44].

Emerging bunkering ports for methanol could include locations compatible with existing liquid fuel infrastructure, allowing for quicker integration at existing ports[45]. These locations benefit from methanol's ability to utilize much of the current liquid fuel distribution systems with minimal modifications, lowering infrastructure costs and accelerating adoption. Regions such as the Caribbean, with their growing interest in methanol production from renewable sources, may emerge as significant bunkering hubs. This could turn ports, like in Trinidad and Tobago[46], into critical nodes in the methanol supply chain.

The reduced dependency on traditional oil hubs stems from methanol's versatile production methods. It can be derived from natural gas, coal, or increasingly from biomass and captured carbon dioxide through green methanol synthesis. This flexibility enables countries with renewable energy capacities, such as Denmark and Iceland, to lead in producing and exporting green methanol. Consequently, these nations could transform their ports into global bunkering hubs, further diversifying shipping routes. Sustainability incentives play a critical role in methanol's growing popularity. Ports in countries with aggressive decarbonization policies, such as Denmark or New Zealand, are prioritizing methanol bunkering, reshaping regional maritime networks. For example, the Port of Auckland[47] is investing in methanol fueling facilities to support its green shipping

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[43] *Marine Fuel|Methanol Institute|www.methanol.org*

[44] Oloruntobi, O., et al. (2023) *"Assessing methanol potential as a cleaner marine fuel: An analysis of its implications on emissions and regulation compliance"*, Cleaner Engineering and Technology 14 (2023) 100639

[45] *Methanol as fuel heads for the mainstream in shipping*, DNV

[46] *Proman scales up methanol bunkering in Trinidad and Tobago - Offshore Energy*

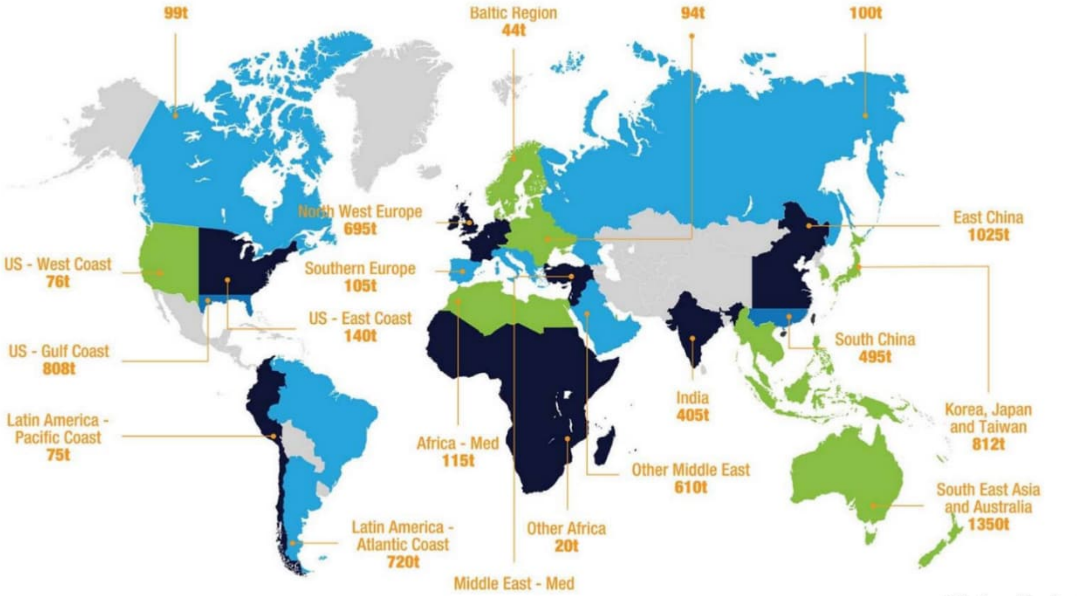
[47] *Ports of Auckland – Zero Emissions 2040 – World Port Sustainability Program*

initiatives. Such advancements not only reduce carbon emissions but also encourage vessels to alter their routes to take advantage of methanol-ready ports.

Moreover, methanol's simplicity in storage and transport reduces logistical complexities compared to cryogenic fuels like LNG or hydrogen. This simplicity enables smaller and medium-sized ports to adopt methanol bunkering more easily, potentially decentralizing maritime networks and reducing congestion at major hubs. In turn, this decentralization could open up new trade routes and enhance regional connectivity.

Technological advancements further bolster methanol's viability as a maritime fuel. The development of dual-fuel engines, capable of switching between methanol and conventional fuels, provides flexibility for vessel operators. Retrofitting older fleets to run on methanol is also becoming a feasible option, helping to lower the entry barriers for its adoption. However, challenges such as the need for global standards in methanol production, storage, and pricing mechanisms remain, requiring international collaboration and policy support. If successfully implemented, methanol could play a transformative role in reshaping the global shipping industry. Its adoption has the potential to reduce carbon emissions significantly, expand the scope of maritime routes, and establish a more sustainable and economically viable future for global trade.

Figure 6: Worldwide Methanol ports



©Methanol Institute

2.7. Life Cycle Assessment (LCA) case study

To better understand what the Life Cycle Assessment (LCA) is, I have deepened the subject thanks to the study published by Hyun Yong Lee et al. (2024)[48].

As first milestone, the carbon pricing is emerging as a key measure to facilitate the maritime sector's transition to alternative fuels and achieve emission reductions. Several proposals have been submitted for a Carbon Tax to the IMO (such as the Japanese one of USD 56 per ton of CO_2 beginning in 2025, and as high as USD 673 per ton in 2040 [49]), but many times these proposals see only Tank-to-Wake emissions, not covering the ones produces from Well-to-Wake.

The Life Cycle Assessment (LCA) Guidelines adopted by the International Maritime Organization (IMO) provide a comprehensive methodology for calculating the greenhouse gas (GHG) emissions associated with the production, transport, and use of marine fuels. This "Well-to-Wake" (WtW) approach ensures that all stages of a fuel's life cycle are considered, from extraction or production ("Well") to combustion in the ship's engine ("Wake").

The inclusion of the upstream emission of ship fuels can help in conducting a more comprehensive assessment of emissions in the sector and prevent the miscalculation of overall emissions. By implementing Life Cycle Assessments (LCAs) of marine fuel, it's possible to measure GHG emissions from various stages including feedstock extraction, fuel conversion or synthesis, transportation, bunkering, and onboard combustion.

This comprehensive approach can guide shipowners in choosing environmentally sustainable marine fuels. The development of these LCA Guidelines, which cover all relevant fuel types, was a topic of discussion at the 76th session of the Marine Environment Protection Committee (MEPC) in 2021.

The Life Cycle Assessment (LCA) comprises four main phases: goal and scope definition, which involves determining the functional unit and system boundary; inventory analysis; impact assessment; and interpretation. The objective of the LCAs conducted in this study was to assess the environmental impact of marine fuels to identify

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[48] Hyun Yong Lee et al. (2024), "*Comparative Life Cycle Assessments and Economic Analyses of Alternative Marine Fuels: Insights for Practical Strategies*"

[49] Climate Leadership Council (2023), "*Carbon Pricing in the Shipping Industry*"

those that are relatively viable. The assessment scope encompassed various stages, including feedstock extraction, conversion and transportation, storage, and combustion in the ship engine.

To conduct LCA, is employed the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) model, this counts two primary stages: Well-to-Tank, which evaluates energy consumption and emissions related to production and delivery, and Tank-to-Wake, which focuses on fuel combustion. The GREET model facilitates the calculation of emissions of pollutants (such as CO_2, CH_4 and N_2O) released throughout the fuel life cycle. Various studies have utilized GREET for assessing the environmental impacts of marine fuels and any data not available within the GREET inventory were computed externally and incorporated into the calculation of Well-to-Wake emissions.

Focusing on the Tank-to-Wake phase, there is the specific fuel consumption, i.e. a measure of how much fuel is required to generate a unit of power. For each fuel type in the analysis (HFO, MGO, LNG, Methanol, and Ammonia), both main engines and auxiliary engines are considered: the first ones are the primary source of propulsion for the vessel, while the second ones typically provide power for auxiliary functions such as electricity generation and onboard services. The specific fuel consumption values vary depending on the engine type and the fuel being used and for both Ammonia and Methanol, the specific fuel consumption values for auxiliary engines were assumed based on the corresponding main engine values. This assumption simplifies the estimation process, given that auxiliary engines typically have similar performance characteristics to the main engines they support.

As conclusion, the Life Cycle Assessment (LCA) analysis compares the greenhouse gas (GHG) emissions of different fuels, divided into Well-to-Tank and Tank-to-Wake stages. LNG, ammonia, and methanol emissions include pilot fuel emissions. Among the fuels analysed, NG-based ammonia exhibits the highest GHG emissions, emitting approximately 48.7% more than HFO, but with CCS (Carbon Capture and Storage) reduces CO2-eq emissions by 79.9%, affected by uncaptured CH4 and N2O emissions and pilot fuel combustion.

Well-to-Tank emissions contribute 95.8% of the life cycle CO2-eq emissions, while Tank-to-Wake emissions are minor, mostly from pilot fuel combustion. NG-based methanol follows NG-based ammonia in GHG emissions, with 3.2% more emissions than HFO. Ammonia and methanol from natural gas are deemed less viable alternatives.

Auxiliary engines generally emit slightly more than main engines due to efficiency differences. LNG shows 19.5% lower CO2-eq emissions in the main engine compared to HFO, but similar emissions in the auxiliary engine due to methane slip. NG-based ammonia's Tank-to-Wake emissions account for only 4.3% of the life cycle emissions. Bio-based fuels' emission reduction potential significantly decreases if Well-to-Tank emissions are excluded.

Summarising the analysis of the proposed study, they suggest several considerations for fuel choices in mid-2020’s ship orders: firstly, LNG raised as a viable economic option, subject to carbon pricing and CO2-eq emission limits. While e-fuels become more cost and environmentally competitive over time, their adoption for mid-2020s ships is not currently cost-effective. Thus, biofuels or CCS-connected fuels are preferable alternatives. Moreover, fuel blending offers a practical solution, utilizing existing engines to meet environmental regulations and reduce overall costs. To conclude, even if not discussed in detail, ordering ships as 'ready' for future fuel transitions, such as LNG-fuelled ships that could be modified for ammonia in the future.

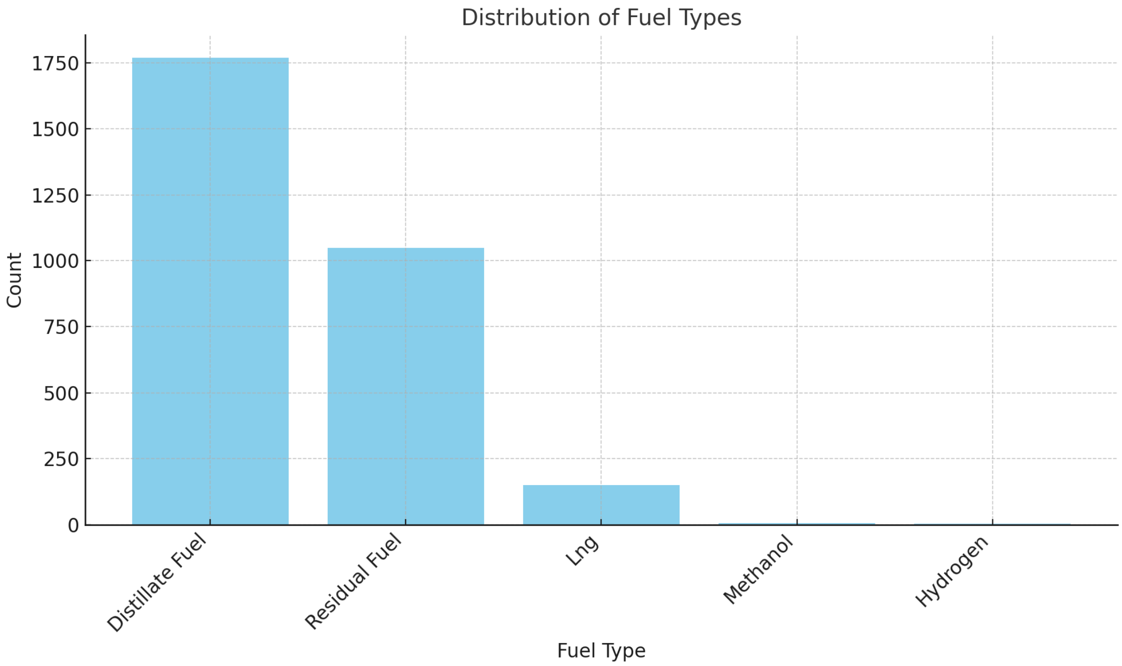
Chapter III: Analysis of the European Ferry Fleet Using Alternative Fuels

This portion of the thesis presents a comprehensive evaluation of the European ferry fleet's transition from conventional fossil fuels to alternative energy sources. It analyses historical reliance on marine diesel and heavy fuel oil while contrasting these with emerging trends that incorporate LNG, hydrogen, biofuels, and other sustainable options. The analysis examines environmental performance, operational efficiency, and the dual-fuel strategies currently being implemented to meet stringent emission regulations. Particular attention is given to the regional dynamics within Europe and the progressive initiatives observed in key maritime hubs. Data-driven insights illuminate the benefits and challenges of adopting alternative fuels, highlighting improvements in energy efficiency and reductions in greenhouse gas emissions. By synthesizing fleet composition, performance metrics, and case-specific outcomes, this section provides a critical understanding of how innovative fuel technologies are reshaping the operational landscape of European ferry services.

3.1. Traditional and Alternative Fuels: Transforming the European Ferry Industry

The European ferry industry has long played a pivotal role in connecting nations, fostering economic activities, and promoting tourism across the continent. For decades, the sector predominantly relied on conventional fossil fuels, particularly marine diesel and heavy fuel oil (HFO), to power its fleet. While these fuels were instrumental in facilitating the industry's growth, they also brought challenges, including environmental concerns and compliance with evolving regulatory standards.

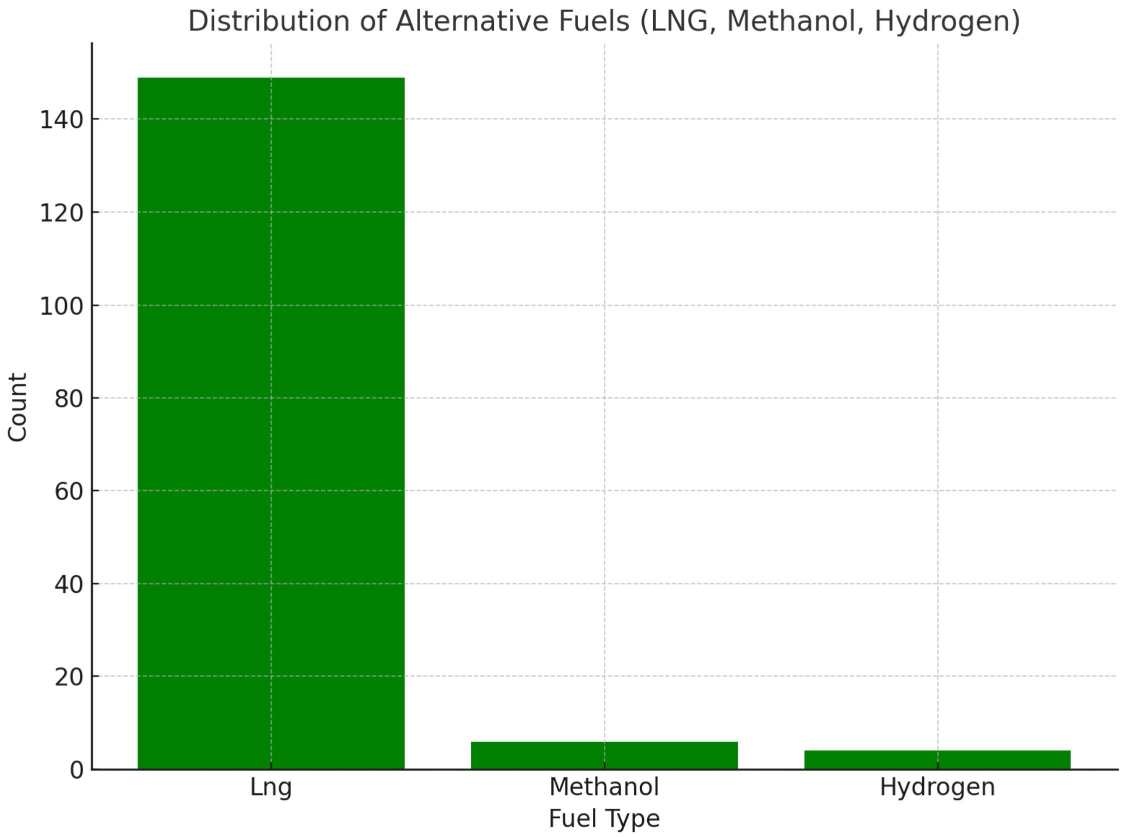
Figure 7: Distribution of fuel types in the European Ferry fleet



Marine diesel and heavy fuel oil (HFO) are still the conventional energy sources that powered ferries industry. These fuels, though cost-effective and energy-dense, are associated with significant environmental drawbacks. Combustion of traditional fuels releases large quantities of greenhouse gases (GHGs), particulate matter, and sulphur oxides (SOx), contributing to air pollution and climate change. The adoption of stringent environmental regulations, such as the International Maritime Organization's (IMO) 2020 sulphur cap, has further highlighted the need for a transition away from these fuels.

As the ferry industry seeks to align with global sustainability goals, alternative fuels have emerged as viable options. Liquefied natural gas (LNG), biofuels, hydrogen, and ammonia are among the most promising alternatives being explored[50]. These fuels offer substantial reductions in GHG emissions and air pollutants, with some options like hydrogen and ammonia producing zero carbon emissions when used in fuel cells or combustion engines[51].

Figure 8: Distribution of Alternative fuels



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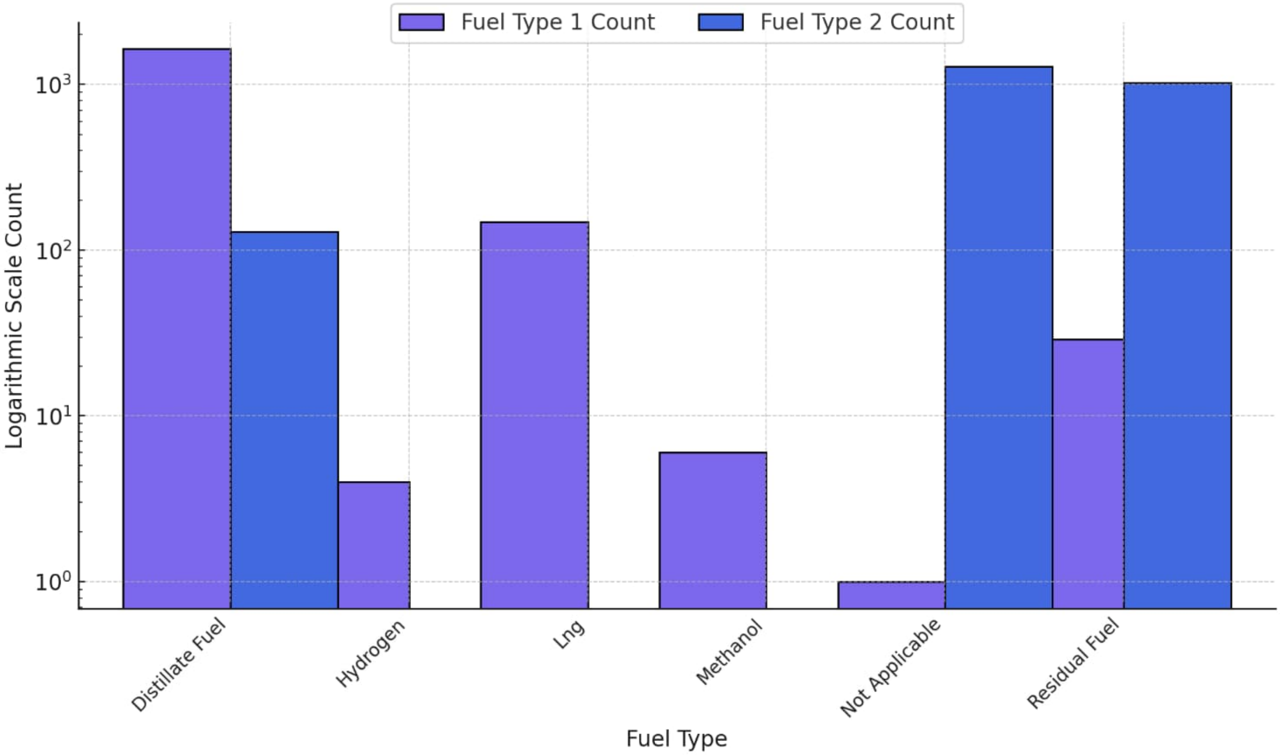
[50] Dotto, A., et al. (2023) *"Energy, environmental and economic investigations of cruise ships powered by alternative fuels"*, Energy Conversion and Management 285 (2023) 117011

[51] Solakivi, T., et al. (2022) *"Cost competitiveness of alternative maritime fuels in the new regulatory framework"*, Transportation Research Part D 113 (2022) 103500

Figure 9: Dual Fuels Type in European Ferry fleet



LNG has gained significant traction due to its lower carbon intensity compared to marine diesel. It is particularly effective in reducing SOx and particulate matter emissions. However, its use requires specialized infrastructure, including LNG bunkering facilities, which limits its adoption in regions lacking such resources[52].

Biofuels, derived from organic materials such as plant oils, algae, and waste products, offer a renewable and versatile energy source. Their compatibility with existing engine technologies makes them an attractive option for retrofitting existing fleets. Despite their advantages, the sustainability of feedstock sourcing and competition with food production remain critical concerns.

Hydrogen and ammonia represent the forefront of innovation in maritime fuels. Hydrogen, when used in fuel cells, produces only water vapor as a byproduct, making it a zero-emission fuel. Ammonia, a derivative of hydrogen, has similar environmental benefits but poses challenges related to toxicity and safe handling. Both fuels require substantial investment in new technologies and supply chains to become mainstream.

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[52] Ha, M-H., et al. (2023), *"Understanding core determinants in LNG bunkering port selection: Policy implications for the maritime industry"*, Marine Policy 152 (2023) 105608

The transition to alternative fuels in the European ferry industry is not without challenges[53]. High initial costs, infrastructure limitations, and the need for technological advancements are significant barriers. Moreover, regulatory uncertainties and the slow pace of policy harmonization across countries add complexity to this shift. Despite these challenges, the opportunities presented by alternative fuels are immense. They enable the industry to reduce its environmental footprint, comply with stringent regulations, and enhance its competitiveness in an increasingly eco-conscious market. Moreover, investments in alternative fuel technologies can spur innovation and create new economic opportunities in related sectors.

3.2. Overview of the European Ferry Fleet

Ferries often utilize two types of fuel for a variety of practical, technical and economic reasons. This dual-fuel approach allows operators to optimize vessels operations under varied condition, such as cost management, fuel efficiency and engine performance. Different fuels can be more suitable for specific operational modes. For instance, during low-speed operations, a cleaner-burning fuels is preferable as it helps prevent engine fouling. Conversely, during high-speed or fully loaded operations, heavier fuels can provide better energy efficiency and cost savings. When managed properly, switching[54] to a heavier fuel for extended operations can yield significant cost advantages without imposing undue strain on the engine.

The dual-fuel approach also offers environmental and regulatory flexibility. Operators may choose to use the cleaner fuel (commonly referred to as Fuel Type 1) near ports or environmentally sensitive areas, either as part of voluntary sustainability initiatives or to comply with local policies or regulations.

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[53] Understanding Energy Density Of Future Fuels Could Be Key To Clearer Decarbonisation Decision-Making - Sea-Lng

[54] There are Fuel Switching Protocols that ensured smooth transitions between fuels to avoid engine damage or operational issues. These Protocols may be found in Ship-specific Manuals, such as Engine Manufacturer’s Guidelines or Vessel Operational Manuals (developed by the shipowner or operator), international guidelines or regulation, such as MARPOL Annex VI, Classification Societies requirements, Port State Control requirements and Fuel Suppliers’ recommendations.

As illustrated in *Figure 3*, distillate fuels[55] are often the dominant choice for Fuel Type 1: MGO, being cleaner and lighter, is a suitable choice for operations requiring low emissions even if it is typically expensive due to these characteristics. In contrast Fuel Type 2 is often a residual fuel, such as Heavy Fuel Oil (HFO) or blended fuels. These are more economical and commonly used during long-haul or high-load operations in international waters, where emissions limits are less stringent. This cost-effective use of residual fuels balances operational costs while meeting engine demands during extended voyages.

The use of distillate fuels supports compliance with international maritime environmental regulations, such as the above-mentioned IMO 2020 Sulphur Cap, which mandates a maximum sulphur content of 0,5% globally and 0,1% in ECAs[56]. These regulations aim to mitigate the environmental and health impacts of ship emissions in ecologically sensitive or high-traffic areas. Moreover, ECAs drive innovation in maritime technologies, encouraging the adoption of alternative cleaner fuels like liquefied natural gas (LNG) or advanced emissions control systems, such as scrubbers.

3.3. Transforming the Ferry Industry: Global and Regional Efforts Toward Environmental Sustainability

The ferry industry is on brink of a substantial transformation as international and regional efforts converge to address the pressing need for decarbonization and environmental stewardship. With ambitious goals set by the IMO, the next few years and decades will witness substantial changes in how ferries operate, particularly concerning fuel use and emissions. Among the IMO's pivotal regulatory milestones are the IMO 2020 Sulphur Cap and the IMO 2050 target[57] to reduce GHG emissions by 50% relative to

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[55] These include Marine Gas Oil (MGO), a high-quality distillate fuel preferred for its low sulphur and compatibility with smaller ships as ferries, and Marine Diesel Oil (MDO), a blend of distillate and residual fuels. However, MDO is less commonly used in ferries due to stricter environmental regulations.

[56] Emission Control Areas: are maritime zones where stricter regulations on air pollution from ships apply. These regulations are established in Annex VI of MARPOL (International Convention for the Prevention of Pollution from Ships) and adopted by IMO. Ships operating in ECAs must use fuel with a sulphur content of 0.10% or less by mass. Alternatively, vessels can use exhaust gas cleaning systems (scrubbers) to meet equivalent emissions standards.

[57] Reference to Chapter 1, par 4.5.

2008 levels. These goals highlight the critical role of the maritime industry, including ferries, in fighting climate change.

Ferries, which frequently operate in environmentally sensitive coastal and urban areas, are central to these global efforts. Their unique operational context makes them a prime focus for decarbonization initiatives, as their emissions directly impact ait quality and ecosystems in high-traffic areas.

Transitioning from conventional fuels to alternative energy sources is therefore imperative. In this context, the dual-fuel system will serve as a critical interim solution, bridging the gap between current practices a fully sustainable future. Across the globe, regulatory frameworks and incentive programs are catalysing the shift toward cleaner maritime fuels and technologies. These efforts are underpinned by IMO regulations, which serve as a benchmark for global maritime emissions standards. Beyond regulatory mandates, initiatives such as the Poseidon Principles[58] play a key role in fostering environmentally sustainable practices. By aligning ship financing with climate goals, the Poseidon Principles encourage financial institutions[59] to support investments in greener technologies, incentivizing shipowners to adopt sustainable practices.

National governments have also taken significant steps to accelerate the transition to greener ferry operations. Norway, a global leader in zero-emission ferry operations, has pioneered the use of fully electric ferries[60], supported by substantial government grants and an emphasis on renewable energy. In the Far East, Japan is investing heavily in the development of hydrogen-fuelled vessels, with significant exploration of ammonia as a viable alternative, while the U.S. Government has allocated funds to retrofit vessels with cleaner technologies through the EPA's Clean Ports Program[61].

Europe stands at the forefront of global efforts to decarbonize the maritime industry, as well as the ferry ones, driven by stringent environmental policies and substantial financial support for green technologies. Key initiatives, such as the European Green Deal

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[58] Poseidon Principles: *A global framework for responsible ship finance*

[59] Major banks, financial institutions, and insurers involved in shipping finance commit to the principles. As of now, over 30 global financial institutions representing a significant portion of the global ship finance portfolio are signatories.

[60] Corvus Energy "*Case Study*: Norled AS, MF Ampere, Ferry"

[61] United States Environmental Protection Agency, "*Clean Ports Program*"

and the EU's “Fit for 55”[62] package, establish ambitious targets, aiming to reduce GHG emissions by at least 55% by 2030 and achieve full climate neutrality by 2050. These frameworks not only set the agenda for decarbonization but also provide the necessary funding and regulatory mechanisms to ensure their implementation: the Horizon Europe and the Connecting Europe Facility (CEF) allocates significant resources to the development of alternative fuel infrastructure, such as bunkering facilities, and the construction of zero-emission vessels[63]. While the FuelEU Maritime Regulation, aims to accelerate the adoption of sustainable alternative fuels by imposing strict carbon intensity limits on ships, creating a market-driven incentive for ferry operators to transition away from conventional fuels. Moreover, Europe’s strategic ports are preparing for the future of maritime fuel: the Port of Rotterdam, the largest in Europe, is investing heavily in LNG bunkering infrastructures and exploring capabilities for hydrogen and ammonia storage as well; and the Port of Antwerp is similarly advancing its alternative fuel infrastructure, contributing to the EU’s broader goals of a sustainable maritime ecosystem.

European ferry operators are increasingly investing in greener vessels, prioritizing the adoption of alternative fuels to replace conventional options like marine gas oil (MGO) and heavy fuel oil (HFO). These alternative fuels offer promising pathways for decarbonizing ferry operations while complying with strict regional and global regulations.

3.3.1. Focus on Italy

As mentioned, our Country is proactively preparing both in regulation and infrastructure development. Additionally, Italy’s adoption of the European Green Deal aligns with LNG's potential to reduce the maritime sector's carbon footprint by meeting the EU’s goal of cutting greenhouse gas emissions by 55% by 2030.

Italy has made significant strides in establishing LNG bunkering facilities, which are essential for supporting LNG-powered vessels. Ports across the Mediterranean are being upgraded to accommodate LNG storage and refuelling capabilities: the Port of

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[62] Reference to Ch.1, par 4.2.

[63] Mayanti, B., et al. (2024) *“Assessing the decarbonization roadmap of a RoPax ferry”*, Maritime Economics & Logistics

Livorno[64] is playing a critical role in supplying LNG to ferries operating in the Tyrrhenian Sea, while the Port of Venice[65] is emerging as a strategic LNG hub in the Adriatic Sea, offering refuelling services for ferries and other vessels operating in this region and the Port of Civitavecchia[66] serves as central point for LNG bunkering for both cruises and ferries. To promote LNG adoption, Italian ferry operators benefit from state incentives and EU grants, such as funding under the "Connecting Europe Facility (CEF)" for LNG infrastructure projects and Regional grants for ship retrofitting, as what's happening in Liguria and Sicily.

Italy's ferry operators, such as GNV, Caronte & Tourist, and Grimaldi Lines, have successfully adopted LNG technology, proving its viability in both economic and operational terms.

3.4. Future Outlook

As the ferry industry transition toward decarbonization, a multi-fuel approach is emerging as the most pragmatic way. This strategy allows operators to adapt to varying regulatory requirements and technological advancements while mitigating the risks associated with reliance on a single fuel type.

Europe's leadership in innovation, supported by robust funding and regulatory frameworks, positions the region as a global model for sustainable ferry operations. By embracing alternative fuels like LNG, hydrogen and ammonia, alongside the development of supporting infrastructure, the European ferry fleet is set to play a crucial role in achieving global climate goals.

The adoption of dual-fuel systems and gradual integration of zero-carbon technologies, ensure that the industry remains resilient during this transformative period, contributing meaningfully to a greener and more sustainable maritime future. This shift not only aligns the ferry industry with environmental objectives but also demonstrates the

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[64] Ministry of Infrastructure and Transport, Autorità di Sistema Portuale del Mar Tirreno Settentrionale "*GNL Italia: tra sfide ed opportunità*"

[65] Ministry of Infrastructure and Transport, Autorità di Sistema Portuale del Mar Adriatico Settentrionale "*TEN-T/CEF Programme*"

[66] Port Mobility Civitavecchia "*Green Port: first ship fed to LNG arrives at Civitavecchia*"

potential for collaborative global action in addressing one of the most significant challenges of our time: climate change. Thanks to innovation and determination, the maritime sector is charting a course toward a sustainable horizon, with ferries leading the way.

The outlook for the Italian ferry industry is influenced by a combination of environmental pressures, technological innovation, and a rapidly evolving regulatory landscape. As the sector seeks to reduce its environmental footprint, especially in light of the EU's Green Deal and decarbonization goals, several trends and challenges are emerging that will shape the future of ferry services in Italy.

One of the most significant drivers is the push toward sustainability. Like other European countries, Italy is seeing a strong shift towards alternative fuels in maritime transport. LNG (liquefied natural gas) is currently the most popular alternative fuel, as it provides a notable reduction in CO2 emissions compared to traditional marine fuels. However, LNG’s role is expected to be transitional, with biofuels, green hydrogen, and ammonia emerging as potential long-term solutions. Ferries operating in Italy, particularly those along the busy Mediterranean routes, are increasingly adopting hybrid and LNG-powered vessels as part of their sustainability strategies. These vessels combine both battery and conventional fuel systems, allowing for reduced emissions and operational flexibility.

The Italian ferry sector is also embracing electrification, with several projects underway to introduce electric ferries on shorter routes, particularly in regions like Sardinia, Sicily, and along the Italian mainland. While full electrification is still in its infancy due to the significant infrastructure investments required, hybrid vessels are proving to be a practical interim solution. Hybrid ferries use both electric power and fuel, which helps ferry operators reduce their carbon footprint while maintaining the operational capacity needed for longer routes.

In addition to fuel and vessel changes, Italy’s ferry industry is seeing a significant investment in port infrastructure[67]. Many of the country’s key ports are upgrading their facilities to accommodate the storage and refuelling of alternative fuels. For instance, ports such as Genoa and Naples are building LNG refuelling stations, while others are exploring the installation of green hydrogen facilities. This shift is crucial as ferry

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[67] LNG Journal: *Italian LNG infrastructure drives energy mix shift*, November 2023

operators will need reliable access to these fuels to ensure the continued operation of greener fleets.

Looking further ahead, the Italian ferry industry is likely to experience more regulatory pressures. The European Union's stringent emissions targets mean that ferry operators will be required to invest in technologies that reduce emissions further. For example, new regulations are expected to promote the adoption of zero-emission vessels and could incentivize the use of biofuels, hydrogen, and ammonia. Additionally, ferry companies will need to keep pace with technological advancements such as wind-assisted propulsion, which is gaining traction for large ferries and could help reduce fuel consumption.

Overall, the future of Italy’s ferry industry will be shaped by a combination of environmental regulations, technological innovation, and investments in alternative fuels. Operators are under increasing pressure to balance operational efficiency with sustainability, but with the development of new fuel types and the gradual implementation of hybrid and electric systems, the industry is well-positioned to transition towards greener maritime transport solutions. However, full decarbonization will require significant investments in both ships and port infrastructure, which may challenge the industry's competitiveness unless coordinated with sufficient government support and global collaboration.

Chapter IV: Business Cases: Comparison of three Ferries using different Alternative Fuels

This section offers an in-depth comparative analysis of practical implementations of alternative fuel technologies within ferry operations. It scrutinizes three distinct cases involving LNG-powered, battery-electric, and hydrogen-powered vessels, with special emphasis on their technical configurations, financial performance, and environmental impacts. Detailed assessments of capital expenditures, operational costs, break-even points, and return on investment reveal the economic viability of each fuel alternative. In addition, the discussion highlights pioneering projects such as the innovative hybrid ferry, which integrates dual-fuel systems to enhance operational flexibility and reduce emissions. By drawing on empirical data and expert insights, this segment illustrates the transformative potential of alternative fuels in reducing the maritime sector's carbon footprint while maintaining competitive economic performance. The comparative approach provides a nuanced understanding of the trade-offs and synergies among different technological pathways, thereby informing strategic decision-making for future investments in sustainable maritime transport.

4.1. Business Case for LNG-Powered Ferry: *"Hypatia de Alejandría"*

The *Hypatia de Alejandría*, an LNG-powered ferry operated by Baleària, represents a significant leap in maritime transportation within the Mediterranean region. Launched in 2019 and constructed by Cantiere Navale Visentini in Italy[68], this vessel combines cutting-edge LNG propulsion technology with advanced operational features. From a technical standpoint, the ferry spans 186 meters in length, accommodating up to 880 passengers and 166 vehicles. Its dual-fuel engine, designed for flexibility, enables seamless switching between LNG and traditional marine fuels, providing resilience in fuel supply disruptions. Cruising at a speed of 22 knots, the *Hypatia de Alejandría* is

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[68] *Visentini verso la consegna del primo ferry a Gnl - The MediTelegraph* , 19/12/2019

optimized for efficiency and safety on routes between mainland Spain and the Balearic Islands.

The advanced propulsion systems of the *Hypatia de Alejandría* are powered by LNG, a fuel celebrated for its cleaner-burning properties. This technological choice not only enhances engine performance but also extends maintenance intervals due to the reduced buildup of particulates and residues[69]. The ferry is designed to operate at a cruising speed of 22 knots, which is optimized for fuel efficiency while meeting the schedule requirements of its Mediterranean routes. Environmentally, the vessel stands as a benchmark for sustainability in maritime operations. Utilizing LNG as its primary fuel, it achieves a 25% reduction in CO_2 emissions, as reported by Baleària[70][71] and corroborated by studies on LNG emissions reduction in maritime transportation, aligning with global decarbonization targets. There is also an 85% reduction in NO_x emissions, mitigating harmful effects on air quality. Additionally, the virtual elimination of sulphur oxides (SOx) and particulate matter ensures compliance with IMO 2020 sulphur regulations.

4.1.1 Technical and Environmental Context

One of the ferry's most noteworthy features is its state-of-the-art waste heat recovery system. This system captures and repurposes thermal energy generated during engine operations, converting it into usable power for onboard systems[72]. This innovation not only reduces fuel consumption but also contributes to the vessel's overall energy efficiency. Coupled with energy-saving hull designs that minimize drag, the *Hypatia de Alejandría* represents a holistic approach to sustainability.

From a regulatory perspective, the ferry's compliance with international environmental standards underscores its role as a model for the industry. The IMO Tier III NO_x[73] regulations, which impose strict limits on nitrogen oxide emissions, are met

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[69] *LNG as fuel for ships: Expert answers to 17 important questions* – Wartsila, 'Insights', 19/06/2024

[70] *Baleària plans to stop emitting almost 80,000 tonnes of CO2* – Ferry Shipping News, 07/07/2023

[71] *Environmental performance* - DNV

[72] *The total cost of using natural gas engines | Cummins Inc.*, 19/09/2023

[73] *Nitrogen Oxides (NOx) – Regulation 13,* IMO

through advanced engine technologies and exhaust treatment systems. The vessel’s operations align with the European Union’s Fit for 55 initiatives, aimed at reducing greenhouse gas emissions by at least 55% by 2030. This regulatory adherence positions the *Hypatia de Alejandría* as a leader in environmentally conscious shipping.

The operational context of the *Hypatia de Alejandría* is equally significant. The ferry serves high-traffic routes between mainland Spain and the Balearic Islands, providing a vital link for passengers and freight. The consistent demand on these routes allows the ferry to maximize its operational efficiency and showcase the scalability of LNG technology in high-capacity scenarios. Baleària’s investment in dedicated LNG bunkering facilities at key ports has ensured uninterrupted operations, further solidifying the ferry’s reliability. Baleària has also prioritized crew training to manage the unique requirements of LNG-powered vessels. Specialized courses in LNG handling, safety protocols, and emergency response procedures have been integrated into the company’s training programs. This proactive approach ensures that the *Hypatia de Alejandría* operates with the highest standards of safety and efficiency, setting a benchmark for other operators considering LNG adoption.

The ferry’s operational excellence is complemented by its passenger experience. The *Hypatia de Alejandría* features modern amenities designed to enhance comfort and convenience. Spacious seating areas, advanced climate control systems, and reduced engine noise contribute to a superior travel experience. The vessel’s commitment to sustainability is also evident in its onboard waste management systems, which are designed to minimize environmental impact and align with Baleària’s broader sustainability goals.

4.1.2.Financial Overview

The construction cost of the *Hypatia de Alejandría*, estimated at approximately Euro 120 million, represents a strategic investment by Baleària. This capital expenditure covers state-of-the-art LNG storage and handling systems, dual-fuel engines, and advanced environmental technologies integrated into the vessel’s design. While the initial investment is higher compared to traditional ferries, financial incentives such as grants and subsidies offered by the European Union and Spanish government significantly offset the costs. Programs like the EU's Connecting Europe Facility (CEF)[74] and the Spanish national grants for LNG infrastructure development have been pivotal in reducing the financial burden.

Operational savings provide long-term financial stability for LNG-powered vessels. LNG, as a marine fuel, is known for its cost advantage compared to conventional marine diesel or heavy fuel oil (HFO). The *Hypatia de Alejandría* benefits from lower per-unit energy costs of LNG. Moreover, LNG's cleaner combustion process reduces maintenance expenses by extending the lifespan of engine components and minimizing downtime for repairs. This dual benefit strengthens the vessel's financial sustainability over its operational lifespan.

The Break-even Point (BEP) of the *Hypatia de Alejandría* is a pivotal metric that demonstrates the financial feasibility of LNG technology in maritime applications. The calculation for BEP incorporates both fixed costs, such as the initial capital investment of Euro 120 million, and variable costs like fuel and maintenance. The ferry's robust annual revenue, estimated at Euro 50 million, is generated through its dual passenger and freight transport services. Complementing this revenue stream are the operational savings facilitated by LNG's cost efficiency, which amount to approximately Euro 3 million annually. These savings arise from LNG's lower per-unit cost compared to traditional marine fuels and its ability to reduce engine wear and maintenance expenses. As a result, the *Hypatia de Alejandría* achieves BEP within six years of operation, a timeframe that underscores the financial prudence of its design and deployment.

Delving deeper into the factors influencing BEP, it is important to consider the ferry's high-demand routes between mainland Spain and the Balearic Islands. These routes, characterized by consistent passenger volumes and freight requirements, provide a reliable revenue foundation. The integration of LNG technology further strengthens this foundation by mitigating risks associated with fluctuating fuel costs and tightening environmental regulations. The vessel's dual-fuel capability also ensures operational flexibility, allowing it to maintain service even under challenging market conditions. This adaptability reduces financial volatility and supports steady progress toward achieving BEP.

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[74] 2019-ES-TM-0082-W.pdf – "LNGHIVE 2" Vessels Demand2: Completing green links; European Commission

The Return on Investment (ROI) for the *Hypatia de Alejandría* offers a comprehensive view of its long-term financial performance. With an annual ROI of 8%, the ferry demonstrates its ability to generate consistent and sustainable returns. This ROI is calculated by comparing the annual net income generated by the ferry against its initial capital investment. Key contributors to this positive ROI include the vessel's operational cost savings, revenue-generating capacity, and competitive market positioning as an eco-friendly transport solution. Furthermore, the ROI metric reflects the ferry's alignment with evolving consumer preferences, which increasingly prioritize sustainability and environmental responsibility.

A more granular analysis of ROI highlights additional economic benefits associated with LNG adoption. The ferry's compliance with stringent environmental standards, such as the IMO 2020 regulations, avoids costly penalties and enhances its reputation among stakeholders. This reputational advantage not only attracts environmentally conscious passengers but also facilitates access to government subsidies and grants designed to promote green shipping practices. By leveraging these incentives, Baleària strengthens the financial case for the *Hypatia de Alejandría* while reinforcing its leadership in sustainable maritime transport.

In conclusion, the BEP and ROI metrics of the Hypatia de Alejandría indicate the financial feasibility of investing in LNG-powered ferries[75]. These metrics, supported by revenue streams, operational efficiencies, and regulatory incentives, show the potential value of LNG technology in the maritime sector. The vessel's performance provides an example for future investments in sustainable shipping solutions, illustrating that environmental responsibility and economic profitability can be aligned.

4.1.3.Operational and Technical Considerations

One of the most important aspects of operating an LNG-powered ferry is access to reliable bunkering infrastructure. The *Hypatia de Alejandría* benefits from Baleària's strategic investments in LNG facilities at key Mediterranean ports, including Valencia and Barcelona. These ports are equipped with dedicated LNG storage and bunkering systems, ensuring efficient and safe refueling operations. The vessel's dual-fuel capability

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[75] *What RoPax ferry owners must be doing right now to address decarbonization* - DNV

further enhances operational flexibility, allowing it to switch to conventional fuels when LNG is unavailable. This feature mitigates risks related to supply chain disruptions, providing an additional layer of reliability.

The transition to LNG propulsion requires specialized training for the vessel's crew. Baleària has implemented comprehensive training programs to equip crew members with the knowledge and skills needed to handle LNG systems safely. These programs cover a wide range of topics, including LNG handling procedures, emergency response protocols, and the operation of dual-fuel engines. Regular drills and simulations ensure that the crew remains prepared to address any operational challenges, thereby enhancing the vessel's safety profile.

LNG propulsion technology offers several advantages in terms of maintenance and efficiency. The cleaner combustion of LNG reduces the buildup of carbon deposits in engines, extending the lifespan of critical components and lowering maintenance costs. The *Hypatia de Alejandría* is equipped with advanced monitoring systems that provide real-time data on engine performance and fuel consumption, enabling predictive maintenance and optimizing operational efficiency. These systems also support compliance with environmental regulations by continuously monitoring emissions levels.

Operating an LNG-powered ferry requires adherence to stringent regulatory standards. The *Hypatia de Alejandría* complies with the International Maritime Organization's (IMO) Tier III standards, which mandate significant reductions in nitrogen oxide emissions. The vessel has also received certifications for its LNG storage and handling systems, ensuring that all safety and environmental requirements are met. Regular inspections and audits by maritime authorities further validate the vessel's compliance with international standards.

Moreover, the *Hypatia de Alejandría*'s design prioritizes passenger comfort while maintaining its commitment to sustainability. The vessel's LNG propulsion system significantly reduces engine noise and vibrations, creating a quieter and more enjoyable onboard experience. Spacious seating areas, advanced climate control systems, and state-of-the-art facilities contribute to passenger satisfaction. Additionally, the ferry's waste management systems are designed to minimize environmental impact, aligning with Baleària's broader sustainability objectives.

While LNG technology offers numerous benefits, it also presents certain challenges. The initial cost of LNG infrastructure development is high, requiring substantial investment in storage facilities, bunkering stations, and retrofitting of existing ports. Moreover, the availability of LNG bunkering facilities is still limited in some regions, necessitating careful route planning to ensure refueling capabilities. As the maritime industry continues to adopt LNG, addressing these challenges will be crucial for the long-term success of LNG-powered vessels.

4.2. Business Case for Battery-Electric Ferry: *“eFerry Ellen”*

The global push for sustainable transportation has driven innovations across various sectors, including maritime transport. As the world faces intensifying climate change and pollution challenges, the need for eco-friendly solutions has become urgent. Battery-electric ferries represent a transformative leap in maritime sustainability, offering a cleaner, quieter, and more efficient alternative to conventional diesel-powered vessels. This case study explores the implementation, performance, and implications of a specific battery-electric ferry project, shedding light on its potential to revolutionize maritime transport.

Battery-electric ferries operate using electric propulsion systems powered by rechargeable batteries rather than internal combustion engines. This technology eliminates the direct emissions of greenhouse gases (GHGs) and other pollutants, making it a critical tool for reducing the maritime sector’s environmental footprint. There are clear advantages using battery-electric ferries, including the non-production of CO_2, nitrogen or sulphur oxides with relevant results reducing both air and water pollution; the costs of the electricity that’s typically cheaper than marine diesel, requiring less maintenance than typical fuel engines; also, electric propulsion significantly decreases noise pollution, benefiting marine life and coastal communities. Despite their advantages, adoption is hindered by challenges such as high initial costs, limited battery range, and the need for robust charging infrastructure. Advances in battery technology and supportive policies are essential for overcoming these barriers.

This case study focuses on the implementation of the "*eFerry Ellen*[76]," a pioneering battery-electric ferry operating in Denmark. The *eFerry Ellen* connects the islands of Ærø and Als, showcasing the potential of battery-electric technology in maritime transport. The *eFerry Ellen* was developed as part of the EU's Horizon 2020 initiative, aimed at fostering innovation in sustainable transport. The ferry was designed to address rising environmental concerns, particularly the need to reduce CO_2 emissions from regional ferry services. Prior to its deployment, the route was serviced by diesel-powered vessels, which contributed significantly to local air pollution and noise.

4.2.1.Implementation of Battery-Electric Technology

The *eFerry Ellen* project involved building a fully electric vessel from the ground up. The process encompassed extensive planning, collaboration, and integration of cutting-edge technologies.

The ferry was constructed at the Søby Shipyard[77] in Denmark, and required innovative solutions, including the construction of substantial onshore facilities. These facilities are situated in Søby, where a brand-new ferry berth has been specially designed for the electric ferry, along with a larger power building, consists of four large transformers delivering 1.2 MW to the ferry and inverters that convert power from alternating current to direct current, that's the type of current Ellen's batteries is charged with. To support operations, a fast-charging station was installed at the harbour, enabling quick and reliable energy replenishment between trips.

The Ellen design emphasized energy efficiency, with lightweight materials and streamlined features to optimize battery performance. The vessel uses a 4.3 MWh lithium-ion battery pack, one of the largest ever installed on a ship. These batteries provide sufficient energy for a 22-nautical-mile round trip without recharging.

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[76] The E-ferry - European Commission was a European featured project (above 70% of the overall budget) for prototype and full-scale demonstration of next generation 100% electrically powered ferry for passengers and vehicles. The project has been carried out from June 2015 to May 2020.

[77] Søby Shipyard has an extremely central location in the southwestern part of the Baltic Sea, on the island Ærø. The Shipyard was the scene of Ellen's construction and had to undergo some changes to proceed with it. *ref. A Shipyard in Denmark | Søby Shipyard*

4.2.1. Operational Performance: pros and cons of Battery-Electric Ferry

Since its launch, the *eFerry Ellen* has demonstrated remarkable operational performance, setting new benchmarks for battery-electric ferry systems. In this section the analysis delves deeper into key performance indicators and insights from its operation.

First advantage is the Energy Efficiency: the ferry’s energy consumption is significantly lower than that of traditional diesel ferries, achieving remarkable efficiency in power usage. Advanced energy management systems onboard ensure optimal battery utilization, extending battery life while maintaining consistent performance.

As alluded, the *eFerry Ellen*’s 22-nautical-mile range is a testament to the feasibility of electric ferries for short to medium routes. The ferry has completed numerous voyages under varying conditions, demonstrating reliability and resilience. Enhanced battery capacity and thermal management systems help maintain operational consistency even under high demand or colder climates. Moreover, unlike the diesel engines, the electric propulsion system has fewer mechanical components, reducing wear and tear. Operators have reported a substantial decrease in routine maintenance tasks, leading to lower long-term maintenance costs and less downtime.

The fast-charging infrastructure ensures efficient turnaround times between trips. The charging process, typically completed in under 30 minutes, seamlessly integrates with the ferry’s schedule. However, operators remain vigilant about the reliability of grid power and have contingency measures to address potential outages. The batteries are designed to maintain spare capacity for emergencies and typically use no more than 45% of their energy during normal operations. Approximately one-third of the electric ferry's daily energy consumption is recharged overnight, with additional charging occurring during the day while Ellen is docked at Søby Harbor.

The transition to battery-electric propulsion has involved diverse stakeholders, each with unique experiences and perspectives: at first place, operators and crew member that report improved working conditions due to reduce noise, vibration and air pollution onboard. Also, travellers enjoy quieter, smoother rides with the added benefit of supporting an environmentally friendly initiative. Lastly, residents of Ærø and Als have expressed pride in hosting a groundbreaking project, alongside appreciation for reduced local air and noise pollution.

Despite the appreciable positive aspects highlighted, there are still some major challenges. First, the infrastructure dependence: the ferry's operations are closely tied to the availability and reliability of charging infrastructure: unplanned power outages or equipment failures can disrupt schedules, emphasizing the need for backup systems and robust infrastructure planning. Then, operational insights and adaptation: over time, the ferry's operators have refined procedures to optimize energy usage, including route planning adjustments and real-time performance monitoring. Data collected during operations provides valuable insights for improving future electric ferry designs and operations. Lastly, adverse weather conditions that can affect battery performance and energy consumption rates. Continuous monitoring and adaptive energy management strategies are employed to mitigate these effects.

4.2.2.Economic Metrics

The *eFerry Ellen*'s economic impact is multifaceted, encompassing cost savings, job creation, regional economic stimulation, and long-term financial sustainability for operators.

While the upfront cost of building a battery-electric ferry like the *eFerry Ellen* is higher than that of traditional diesel vessels, the return on investment (ROI) becomes evident over time. Savings on fuel and maintenance accrue rapidly, often achieving cost parity within 4-8 years of operation[78]. Additionally, subsidies and incentives for green technology adoption, such as those provided under the EU's Horizon 2020 program, significantly offset initial expenses, making such projects financially viable for operators and municipalities.

In terms of general cost savings, the ferry's operational expenses are significantly reduced due to the lower cost of electricity compared to marine diesel. On average, electricity costs can be 50-70% lower than fossil fuels, depending on energy prices. As already mentioned, another critical factor is maintenance costs saving with fewer moving parts and no reliance on complex combustion engines, maintenance costs are reduced by

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[78] Ellen ferry operator, *interview* *Ellen, Denmark's First Electric Ferry, Passes All Tests With Flying Colors - CleanTechnica*

approximately 30-40% annually, minimizing downtime and ensures reliable service. Indirect economic benefits have been recorded linked to this project: cleaner air and reduced noise pollution contribute to improved quality of life and could be helpful in long-term solutions to reallocate resources of government or local communities to developmental initiatives.

The delivery of the *eFerry Ellen*, has also sparked interest among global stakeholders, leading to increased investments in battery-electric ferry technologies. Manufacturers, engineers, and policymakers view the project as a model for future applications, ensuring that the technological and economic lessons learned continue to influence the maritime sector. Scaling similar initiatives globally could generate a multi-billion-dollar market for electric marine propulsion systems, creating substantial economic opportunities while driving sustainability.

The construction of the *eFerry Ellen* generated employment in shipbuilding, engineering, and related sectors. The demand for skilled labour in designing and integrating advanced battery systems has spurred regional workforce development. Maintenance of the ferry and its charging infrastructure requires ongoing support, creating long-term job opportunities in green technology sectors. Moreover, improved ferry operations enhance connectivity between islands and mainland areas, boosting tourism and commerce. This has a ripple effect, increasing revenues for local businesses and fostering economic resilience in remote areas. The deployment of green technology positions regions as pioneers in sustainable innovation, attracting investment and encouraging further advancements in clean energy solutions.

The *eFerry Ellen* provides a valuable blueprint for scaling battery-electric ferry technology globally, especially in technology advancement and continuous improvement in battery energy density and charging infrastructures, that will help to expand the viability of electric ferries for longer routes. In this scenario, it’s remarkable that the *eFerry Ellen* sailed 50 nautical miles[79] (around 90 kilometres) on a single battery charge.

All government incentives and international regulations shall promote zero-emission vessels, to accelerate adoption of carbon-free solutions in maritime sector and

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[79] Danfoss to apply for Guinness World Record after e-ferry Ellen sails more than 90 kilometres on single battery charge | Danfoss

possibly improve with combination of battery-electric and other renewable energy sources to further reduce lifecycle emissions.

The *eFerry Ellen* exemplifies the transformative potential of battery-electric ferries in achieving sustainable maritime transport. By addressing environmental challenges and demonstrating economic feasibility, this project sets the stage for wider adoption of green technologies in the maritime sector. As technology advances and policy support grows, battery-electric ferries are poised to play a pivotal role in decarbonizing global transport networks.

4.3. Business Case for Hydrogen-Powered Ferry

The maritime industry is under increasing pressure to decarbonize, with traditional fossil-fuel-powered vessels contributing significantly to greenhouse gas emissions. Hydrogen-powered ferries offer a clean alternative, utilizing hydrogen fuel cells to produce electricity for propulsion. This business case focuses on deploying a hydrogen-powered ferry as part of the European Union's Green Deal objectives, supported by a grant from the “Innovation Fund”[80]. The EU Emissions Trading System revenues launched the Innovation Fund as a key financial instrument of the European Union aimed at fostering innovation and sustainability in the maritime sector. The “Innovation Fund” provides grants, subsidies, and funding mechanisms to support projects that align with the EU’s environmental and technological goals. Key focus areas include decarbonization, renewable energy integration, and advancements in maritime safety and efficiency.

The program has been instrumental in various projects across Europe, such as in Norway, supporting research and development for the “*MF Hydra*”[81] the world’s

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[80] Thanks to the revenue generated from greenhouse gas emissions through the EU Emissions Trading System (ETS), the “Innovation Fund” receives reinvestments. This has made the “Innovation Fund” one of the largest funding programs for innovative low-carbon technologies. The program supports various projects across Europe, with a strong focus on hydrogen initiatives aimed at advancing its production, storage, and applications as a powerful energy source.

[81] The “MF Hydra” is the world's first ferry powered by zero-emission liquid hydrogen, representing a groundbreaking achievement in maritime transportation. The project involved extensive efforts to establish regulations allowing Norwegian passenger ships to operate on hydrogen. Norway has long been a leader in green ferry innovation, beginning in the 2000s with the launch of the first car ferry running on LNG and the first battery-operated ferry.

first liquid hydrogen-powered ferry; in Germany, funding the "*ZEM Ship*" project[82], which operates a hydrogen-powered ferry for inland waters; and in Portugal, financing the hydrogen integration efforts under the H2Ports initiative in Lisbon.

4.3.1.Exploring the *HySeas III* Initiative

The *HySeas III* project provides a compelling example of a real-world business case for a hydrogen-powered ferry. This initiative, supported by "Innovation Fund", focuses on connecting the Orkney Islands in Scotland using a hydrogen-powered vessel. The project leverages locally produced green hydrogen generated from wind and tidal energy, creating a fully circular and sustainable energy system. This local hydrogen generation ensures a closed-loop, environmentally sustainable system, reducing reliance on external fuel sources and mitigating supply chain challenges.

With a focus on reducing carbon emissions, the ferry is expected to serve as a model for other island communities heavily dependent on marine transport. The economic viability is enhanced by integrating renewable energy sources into the hydrogen production process, significantly lowering operational costs. Additionally, the project has spurred local job creation and infrastructure development, highlighting the broader economic and social benefits of hydrogen technology.

4.3.2.Pros and Cons of Hydrogen-Powered Ferries

Hydrogen-powered ferries offer numerous environmental benefits: they produce zero emissions, with water vapor being the only byproduct, and significantly reduce air pollution by eliminating NOx, SOx, and particulate matter emissions. In terms of energy efficiency, hydrogen has a high energy density, enabling extended operations, and the technology ensures quiet operation, reducing noise pollution in marine environments.

Additionally, there is significant economic potential, as the adoption of hydrogen technology creates opportunities for new industries, such as green hydrogen production and related supply chains. It also aligns with regulatory incentives, granting access to subsidies and funding under green energy initiatives. Hydrogen-powered ferries are

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[82] Acronym for "*Zero Emissions Ships*", the project aimed to develop and realise the first hydrogen-powered passenger ship with capacity of over 100 persons and power-assisted by an electric motor.

highly scalable and versatile, suitable for various vessel sizes and types, and can be seamlessly integrated with renewable energy sources for hydrogen production[83].

Despite their benefits, hydrogen-powered ferries face several challenges[84]. High initial costs are a significant barrier, with expensive hydrogen fuel cells, storage systems, and retrofitting requirements, along with the need for dedicated hydrogen production, also considering that the green hydrogen produced via electrolysis using renewable energy is currently more expensive than hydrogen derived from fossil fuels and requires significant investment is needed for infrastructure and technology development.

Technological challenges[85]also persist, including the safe storage and handling of hydrogen, which is highly flammable, and limited operational range compared to diesel-powered vessels. Market limitations further complicate adoption, as the technology relies on a limited number of suppliers and immature supply chains. The maritime sector plays a crucial role in enabling international hydrogen trade. However, for hydrogen to become a viable alternative and drive the transition to clean energy, it is essential to develop supply chain logistics, supporting infrastructure, and new port facilities. Globally, hydrogen import, and export hubs are expected to emerge in areas that align with countries' decarbonization strategies and leverage existing trade connections through port terminals.

Moreover, hydrogen fuel costs can be volatile, depending on production methods and energy market dynamics.

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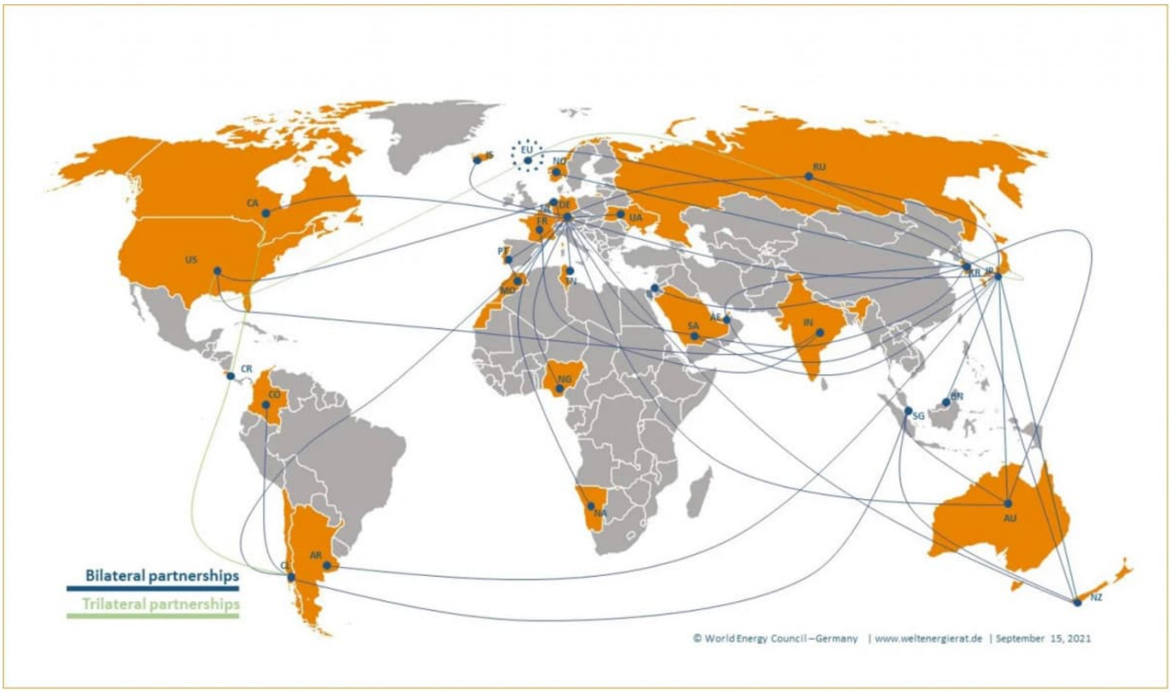
[83] Mojarrad, M., et al. (2023*) "Techno-economic modeling of zero-emission marine transport with hydrogen fuel and superconducting propulsion system: Case study of a passenger ferry"*, International Journal of Hydrogen Energy 48 (2023), 27427-27440.

[84] "*Overcoming barriers to hydrogen adoption in maritime: A path to a cleaner future*", Aug. 2024 in Offshore Energy

[85] "*Hydrogen In Maritime: Opportunities and Challenges*", in WSP

Figure 10: Hydrogen import-export partnerships “booming” around the wo*rld*



[86]

Source: World Energy Council – Germany, www.weltenergierat.de

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[86] *Hydrogen import-export partnerships “booming” around the world | Clean Energy Wire*

4.3.3.Economic Metrics

The BEP for the *HySeas III* project depends heavily on initial capital costs, operational costs and savings from reduced fuel expenses.

The project includes expenses for the hydrogen ferry, retrofitting ports for hydrogen storage and refuelling infrastructure, and integrating renewable energy system for hydrogen production. Early estimates suggest capital expenditures in the range of 20-30 million euros for the pilot phase. Using green hydrogen, significantly reduces fuel costs over time compared to diesel, particularly as renewable energy scales and hydrogen production becomes cheaper. Hydrogen's price stability further mitigates fuel costs volatility.

Additionally, ticket sales subsidies under the European fundings and investments, and potential carbon credit trading add revenue streams, enhancing financial sustainability.

Considering the above information, and based on similar projects, a 5-to-7-year timeline is projected for achieving the BEP, contingent on efficient operations and growing passengers' adoption. Long-term ROI is promising, driven by reduced operational expenses, subsidies, and the monetization of environmental benefits: projections suggest a potential ROI of 10% to 15% annually after reaching BEP, depending on continued policy support and market conditions.

These financial dynamics of hydrogen-powered ferries, including BEP and ROI, can be better understood by examining projects like *HySeas III* project. The first project analysed is the *MF Hydra* in Norway: as mentioned above, supported by grants from Innovation Norway and aligned with the Norwegian government's ambitious decarbonization targets, the *MF Hydra* project demonstrates the financial viability of the hydrogen technology in region with strong renewable energy integration. The project highlights how subsidies and local energy production can offset high capital costs and enable the BEP within 5 to 7 years, indeed.

Analysing the *Havyard's Hydrogen Ferry*, located in Norway too, we may see how this project illustrates the potential for hydrogen ferries to serve not only short, commuter routes but also medium-distance travel. Its business model integrates hydrogen production facilities near ferry terminals, reducing the logistics costs and accelerating BEP achievement.

Lastly, we may analyse the *Green Hydrogen Ferry* in Brittany (France), that integrates renewable energy sources for hydrogen production to power ferries in coastal regions. The focus on green hydrogen underscores the environmental and economic benefits of localizing fuel production, cutting logistics and transport costs, and creating a closed-loop energy system. This approach has been pivotal in achieving operational costs reductions.

In conclusion, the BEP and ROI for hydrogen ferries are closely tied to factors such as subsidies, local renewable energy production, and the scale of deployments. Collaborative financing models, like public-private partnerships, further enhance economic viability. By analysing these projects, the BEP for hydrogen ferries generally ranges from 5 to 7 years, with ROIs potentially reaching 10–15% annually after the BEP. These examples underscore the importance of subsidies, renewable energy integration, and economies of scale in enhancing financial outcomes.

4.3.4.Future of Hydrogen-Powered Ferries

The future of hydrogen-powered ferries is marked by advancements in technology, supportive policies and regulations, and expanding market opportunities. Technological innovations will play a crucial role in shaping the efficiency and cost-effectiveness of hydrogen-powered ferries. Research and development are driving significant improvements in hydrogen fuel cells, with a focus on increasing their efficiency, durability, and scalability[87].

Additionally, advancements in green hydrogen production, particularly through renewable energy sources like wind and solar, will significantly reduce production costs and enhance the environmental benefits of hydrogen technology.

Policy and regulatory frameworks are also pivotal in promoting the adoption of hydrogen-powered ferries. The European Union’s Fit for 55 Package exemplifies the strong policy push toward maritime decarbonization. This legislative initiative aims to reduce greenhouse gas emissions by at least 55% by 2030, offering subsidies, grants, and

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[87] Melideo, D. e Desideri, U., *International Journal of Hydrogen Energy*, https://doi.org/10.1016/j.ijhydene.2023.10.142

other incentives for adopting hydrogen technologies. Furthermore, the introduction of carbon pricing mechanisms encourages the shift from fossil fuels to cleaner alternatives, making hydrogen-powered solutions economically attractive.

The market for hydrogen-powered ferries is poised for substantial growth, driven by expanding infrastructure and integration with other energy sectors. As hydrogen refuelling networks develop across ports, ferry operators will find it increasingly feasible to transition to hydrogen-powered vessels. Additionally, hydrogen ferries have the potential to function as energy storage and grid-balancing tools, integrating seamlessly with renewable energy systems. This dual utility positions hydrogen ferries not only as transportation assets but also as critical components of a sustainable energy ecosystem.

The hydrogen-powered ferry represents a transformative step towards sustainable maritime transport. While high initial costs and technological challenges persist, ongoing investments and advancements promise to overcome these barriers. Supported by organizations such as EMIF, the adoption of hydrogen ferries across Europe demonstrates the potential to scale this technology globally.

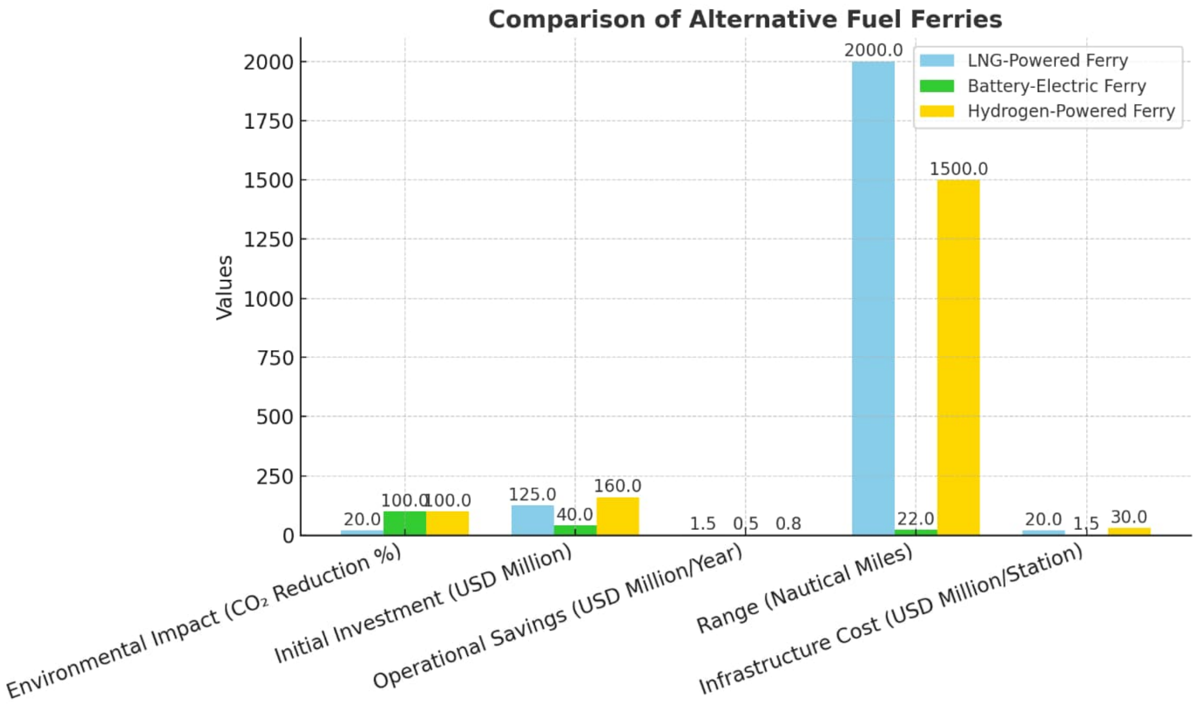
The future of hydrogen-powered ferries is bright, driven by regulatory support, technological innovation, and a growing market for green hydrogen solutions. Investing in this technology not only aligns with environmental objectives but also positions stakeholders as leaders in the transition to a low-carbon economy.

4.4. Comparative Analysis of the Three Cases

In the LNG-powered Ferry case, the alternative fuel reduces CO_2 by around 20%, NOx by 85% and SOx is eliminated, helping ferries comply with IMO Tier III standards. This equates to approximately 50 thousand tons fewer CO_2 emissions annually for a medium-sized ferry. As mentioned in the business case, the initial investment (CAPEX) is around 20% to 30% higher than conventional ferries, like USD 100-to-150 million for new buildings and USD 10-to-30 million for retrofits. On the other hand, considering the operational costs (OPEX) the LNG is around 30% to 50% cheaper than MDO, saving USD 1-to-2 million annually in fuel costs, and around 15% to 30% as maintenance savings due to cleaner-burning properties. The LNG-powered new buildings are ideal for operators aiming for long-term cost and emissions savings, instead of the retrofits that are practical for fleets operating in Emission Control Area (ECA). As regulatory compliance, the LNG-powered ferries align with IMO 2030 goals and EU Emissions Trading Scheme (ETS) starting 2025.

In the Battery-electric Ferry business case, the environmental benefits are the highest, fully eliminating the direct emissions (CO_2, SOx and NOx) cutting around 2 thousand tons of CO_2 annually and cuts noise pollution, benefiting marine life and local communities. This kind of ferries utilize advanced lithium-ion batteries with around 4.3 MWh capacity, for short-medium routes and emerging solid-state batteries promise extended ranges. Crucial point for battery-electric ferries is the infrastructure need to ensure fast-charging stations (~USD 1-2M per port). Reliability of the grid is critical for uninterrupted service. Initial CAPEX is higher (~USD 30-50M), but lower OPEX (~30-40% maintenance savings). Break-even within 4-8 years, supported by subsidies.

In the Hydrogen-powered ferry business case, it has been highlighted that the hydrogen produces zero emissions when burned or used in fuel cells. However, green hydrogen production is energy-intensive and costlier. Infrastructure & Costs: Fuel: USD 6-10/kg for green hydrogen; Infrastructure: Hydrogen bunkering facilities cost ~USD 10-50M. this kind of ferries is Ideal for long-distance ferries due to scalability. Hydrogen adoption requires coordinated global efforts to address infrastructure and technology gaps.



Factor	LNG-Powered Ferry	Battery-Electric Ferry	Hydrogen-Powered Ferry
Environmental Impact	Reduces CO_2 (~20%), SOx (100%), and NOx (85%).	Zero direct emissions of CO_2, SOx, or NOx.	Zero direct emissions; depends on green hydrogen production.
Initial Investment	High: USD 100-150M for new builds; retrofits ~USD 10-30M.	High: USD 30-50M due to battery and vessel design.	Very High: USD 120-200M, mostly for new builds.
Operational Costs	~30-50% fuel savings compared to diesel; 15-30% reduced maintenance costs.	Low fuel cost (electricity) and 30-40% reduced maintenance costs.	High fuel costs due to hydrogen price volatility; maintenance costs moderate.
Range	Long-range, suitable for international routes.	Short-to-medium routes (22 nautical miles typical).	Long-range, scalable for heavy-duty and international routes.
Infrastructure Needs	LNG bunkering stations (~USD 10-30M per station).	Fast-charging stations (~USD 1-2M per port); grid dependency.	Hydrogen bunkering facilities (~USD 10-50M per port).

Factor	LNG-Powered Ferry	Battery-Electric Ferry	Hydrogen-Powered Ferry
Technological Readiness	Mature and widely adopted.	Rapidly evolving; depends on battery advancements.	Emerging; infrastructure and supply chains under development.
Regulatory Compliance	Meets IMO 2030 and EU ETS standards.	Fully aligns with zero-emission regulations.	Aligns if green hydrogen is used; depends on future policies.
Economic Viability	Break-even ~10-15 years for new builds; ~5 years for retrofits.	Break-even ~4-8 years with subsidies and incentives.	Long-term viability uncertain; relies on green hydrogen scaling.
Key Advantages	Cost-effective for operators; significant emissions reduction.	Zero emissions; reduced noise and air pollution.	Potential for complete decarbonization with scalability.
Key Challenges	High upfront costs; methane leakage concerns.	Limited range; dependency on charging infrastructure.	High cost of fuel and infrastructure; immature technology.
Example Use Case	Ferries on long-haul routes or ECAs (Emission Control Areas).	Short-distance commuter ferries (e.g., *eFerry Ellen*).	Long-distance international ferries (future potential).

4.5. Conclusion on Business Cases

In the context of this thesis, the exploration and evaluation of various business cases within the realm of alternative fuels have underscored the transformative potential of sustainable energy solutions. The findings elucidate not only the economic viability but also the environmental imperative of adopting cleaner and more efficient energy systems. This chapter consolidates the insights derived from the analysed business models, outlining the critical factors contributing to their success and identifying areas that require further attention to achieve broader market integration.

One of the key takeaways from the analysis is the increasing alignment between regulatory frameworks and the operational models of businesses adopting alternative fuels. Governments and international organizations are playing pivotal roles in fostering environments conducive to innovation and investment[88][89]. Subsidies, tax incentives, and stringent emissions regulations have been instrumental in driving the adoption of technologies such as hydrogen fuel cells, biofuels, and batteries. This supportive ecosystem significantly reduces the financial barriers that traditionally hindered the commercialization of alternative fuels, making them a feasible option for large-scale deployment.

Market dynamics and consumer behaviour also emerged as critical determinants of success in the examined business cases. There is a discernible shift in consumer preferences towards environmentally responsible products and services[90], driven by heightened awareness of climate change and environmental degradation. Businesses that have effectively capitalized on this trend by positioning themselves as eco-conscious innovators have not only achieved competitive advantages but have also contributed meaningfully to the broader sustainability agenda. However, this transition is not without its challenges. High initial costs, coupled with limited infrastructure for distribution and storage, remain significant hurdles that need to be addressed through collaborative efforts between the public and private sectors.

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[88] International Energy Agency. (2022). *Global Hydrogen Review 2022*.

[89] European Union *Alternative fuels | European Alternative Fuels Observatory*

[90] *Awareness increases acceptance and willingness to pay for low-carbon fuels amongst marine passengers – Nyari J. et al.*, Helyon, Vol. 10, issue 3 (2024)

Technological advancements have played an equally vital role in shaping the landscape of alternative fuels. Innovations in production processes, energy storage solutions, and distribution networks have enhanced the efficiency and scalability of alternative fuel technologies[91]. For instance, advancements in electrolysis and carbon capture technologies have significantly reduced the production costs of green hydrogen, making it a more attractive option for industries and consumers alike. Similarly, the development of advanced biofuels from non-food biomass has mitigated some of the ethical concerns associated with first-generation biofuels, such as competition with food supply chains.

The financial analysis of the business cases revealed a complex interplay between cost structures, revenue models, and investment requirements. While many alternative fuel businesses exhibit strong long-term growth potential, the short-term financial viability often hinges on external support mechanisms[92]. Venture capital, government funding, and strategic partnerships have emerged as crucial enablers for these businesses to scale their operations and achieve profitability. Furthermore, innovative business models, such as pay-as-you-go energy systems and subscription-based services, have demonstrated the potential to bridge affordability gaps and enhance accessibility for end-users.

Reductions in greenhouse gas emissions, improvements in air quality, and the minimization of ecological footprints were consistently observed across the studied models. These outcomes underscore the integral role of alternative fuels in achieving global sustainability targets, however, it is equally important to acknowledge the trade-offs and unintended consequences associated with certain alternative fuel technologies, such as the energy intensity of production processes and the lifecycle environmental impacts of battery technologies.

The integration of alternative fuels into existing energy systems poses significant logistical and technical challenges, as evidenced by the analysed business cases. Compatibility with existing infrastructure, interoperability of new technologies, and the need for robust supply chains are some of the critical areas requiring attention. The

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[91] Bilgili L. (2023) "A systematic review on the acceptance of alternative marine fuels", Renewable and Sustainable Energy Reviews 182, 113367

[92] *International Shipping | Climate Action Tracker*

development of integrated energy systems that seamlessly incorporate alternative fuels alongside conventional energy sources is imperative for ensuring a smooth transition. Moreover, cross-sectoral collaboration and stakeholder engagement are essential for addressing these challenges effectively.

Policy and regulatory landscapes emerged as both enablers and barriers in the context of alternative fuel business cases. While progressive policies have accelerated the adoption of alternative fuels, inconsistencies and uncertainties in regulatory frameworks can impede progress. Harmonization of policies across regions, coupled with clear and predictable regulatory guidelines, is essential for fostering investor confidence and facilitating market growth. Additionally, the role of international cooperation in establishing global standards and best practices cannot be overstated.

In conclusion, the analysis of business cases within the alternative fuels sector highlights a multifaceted landscape characterized by opportunities, challenges, and transformative potential. The success of these business cases hinges on a synergistic interplay between technological innovation, supportive policies, market dynamics, and stakeholder collaboration. By addressing the identified challenges and leveraging the demonstrated opportunities, alternative fuels can play a pivotal role in shaping a sustainable and resilient energy future. This chapter underscores the importance of a holistic approach that integrates economic, environmental, and social dimensions to unlock the full potential of alternative fuels.

4.6. Italian Pioneering: the “*Elio*” Hybrid Ferry

The transition to sustainable maritime operations is exemplified by the "*Elio*," a hybrid ferry operated by Caronte & Tourist. This ferry represents a significant step toward reducing emissions and advancing green technology within the maritime sector. The "*Elio*" serves the Strait of Messina, connecting the ports of Villa San Giovanni and Messina, a high-traffic area where environmental concerns are paramount. This analysis explores the vessel’s technology, environmental impact, and operational advantages.

The "*Elio*" employs a dual-fuel hybrid system combining Liquefied Natural Gas (LNG) and electric propulsion. The primary engine runs on LNG, reducing CO_2 emissions by approximately 20%, while eliminating sulfur oxides (SOx) and significantly reducing nitrogen oxides (NOx). The onboard batteries enable zero-emission operations while manoeuvring in ports, reducing local air pollution and noise levels and advanced technologies recover energy during braking and deceleration, further enhancing fuel efficiency. These systems are integrated with state-of-the-art monitoring tools to optimize fuel consumption and ensure compliance with environmental regulations.

The "*Elio*" was designed to address the unique ecological challenges of the Strait of Messina. By utilizing LNG and electric propulsion, the ferry achieves near-zero emissions during port operations, reduces greenhouse gas emissions by up to 20% compared to traditional marine fuels and eliminates particulate matter, benefiting local air quality. These features make the "*Elio*" a benchmark for sustainability in short-distance maritime transport.

The "*Elio*" holds the distinction of being the first LNG-powered ferry to operate in the Mediterranean Sea, marking a significant achievement for Italy in advancing sustainable maritime transport. This milestone underscores Italy's leadership in adopting alternative fuels and aligns with the European Union's environmental objectives. By being the first to implement LNG technology in this region, Caronte & Tourist[93] has set a precedent for other Mediterranean operators.

Caronte & Tourist has reported significant benefits since deploying the "*Elio*": despite higher upfront costs, operational savings from reduced fuel consumption and maintenance have made the investment economically viable. The hybrid system ensures uninterrupted operations, even under challenging weather conditions. Passengers have noted the quieter operation and reduced vibrations, enhancing overall travel experience.

The "*Elio*" aligns with the European Union's "Fit for 55" strategy and contributes to Italy's decarbonization goals. Caronte & Tourist's investment demonstrates how regional ferry operators can lead in adopting innovative technologies to meet environmental and economic challenges. By spearheading the use of LNG in the Mediterranean, Italy positions itself as a leader in the sustainable transformation of the maritime sector.

The "*Elio*" serves as a model for integrating alternative fuels and hybrid systems, balancing ecological responsibility with operational efficiency. This case underlines the importance of continued innovation and investment in green maritime technologies, particularly in environmentally sensitive regions like the Strait of Messina. Furthermore,

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[93] Elio | Caronte & Tourist

Italy’s pioneering role in operating the first LNG-powered ferry in the Mediterranean cements its reputation as a forerunner in sustainable maritime practices, paving the way for broader adoption of green technologies across the region.

Chapter V: Advancing Sustainable Maritime Fuels

This segment focuses on the strategic vision and future trends necessary for the widespread adoption of sustainable maritime fuels. It discusses the evolution of fuel technologies—ranging from traditional LNG to emerging solutions such as hydrogen, ammonia, methanol, and advanced biofuels—while addressing the transitional role of each in the pathway toward a decarbonized shipping industry. A detailed roadmap is outlined for the preparation and modernization of port infrastructures, emphasizing the development of bunkering facilities and the integration of digital monitoring systems. The analysis also highlights the leadership roles played by industry stakeholders, exemplified by initiatives that prepare vessels for future fuel conversions and support collaborative research networks. By linking technological innovation with policy support and infrastructural readiness, this section offers a robust vision for transforming maritime transport into a more sustainable and resilient system, ensuring that both environmental and economic objectives are met.

5.1. The future of fuels

The maritime industry is undergoing a significant transformation, driven by a concerted effort to decarbonize shipping and meet global sustainability goals. The implementation of alternative fuels is critical for reducing greenhouse gas emissions and decreasing the environmental impact of maritime transport. Among the promising alternatives are hydrogen, ammonia, methanol, biofuels, and liquefied natural gas (LNG), which are increasingly being considered as feasible substitutes for conventional fossil fuels.

Hydrogen and ammonia are particularly promising due to their zero-carbon emissions potential[94] when used in fuel cells or advanced combustion systems. While the infrastructure and production costs pose challenges[95], innovations in green hydrogen

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[94] *Emission reduction and cost-benefit analysis of the use of ammonia and green hydrogen as fuel for marine applications* , Wu Y., Chen A. et al. in *'Green Energy and Resources'*, vol. 1, issue 4. December 2023

[95] Cloete, S., et al. (2023*) "The future of fuels: Uncertainty quantification study of mid-century ammonia and methanol production costs"*, Energy Conversion and Management 297 (2023), 117701

production[96] and ammonia synthesis[97] are expected to drive costs down[98] over the coming decades. Methanol, derived from renewable sources, presents another attractive option due to its compatibility with existing engines and bunkering infrastructure, though it emits carbon dioxide when combusted. Advanced biofuels, on the other hand, offer a near-term solution by leveraging existing feedstocks and processing technologies, though scalability remains a concern.

Liquefied Natural Gas (LNG) has emerged as a transitional fuel, providing significant emissions reductions compared to heavy fuel oil (HFO). LNG reduces sulphur oxides (SOx) emissions by nearly 100% and nitrogen oxides (NOx) by up to 85%, while also lowering carbon dioxide emissions by 20-30%. The adoption of LNG has been driven by International Maritime Organization (IMO) regulations mandating lower sulphur content in fuels and encouraging innovation in cleaner propulsion systems. However, the methane slip - unburned methane emissions during LNG combustion - remains a critical issue that the industry must address to maximize its environmental benefits. The future trajectory of LNG as an alternative fuel is linked to technological advancements aimed at minimizing methane slip, such as enhanced engine designs and methane oxidation catalysts. Moreover, the development of bio-LNG, derived from organic waste, represents a pathway to making LNG a carbon-neutral fuel option. As global LNG bunkering infrastructure continues to expand, it reinforces LNG's role as a bridge fuel toward more sustainable alternatives like hydrogen and ammonia.

As technology matures and policies tighten, the future of maritime fuels will likely depend on a multi-fuel strategy, with different options serving distinct segments of the industry. Collaborative efforts among governments, industry stakeholders, and technology providers will be crucial to accelerating this transition and overcoming technical, economic, and regulatory hurdles. The interplay between established fuels like LNG and emerging solutions will define the next chapter of maritime energy

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[96] *Sustainable green hydrogen production: Trading off costs and environmental impacts* , Rangel G.P. et al. in '*International Journal of Hydrogen Energy*', vol 100, pp. 994-1009. January 2025

[97] *Towards the decarbonization of ammonia synthesis – A techno-economic assessment of hybrid-green process alternatives* , Isella A. et al in '*Chemical Engineering Journal*', vol. 486, April 2024

[98] *Economic viability and CO2 emissions of hydrogen production for ammonia synthesis: A comparative analysis across Europe* , Mangino A., Marocco P. et al. in '*Advances in Applied Energy*', vol. 17. March 2025

transformation, ensuring a balanced approach to sustainability, economic viability, and operational efficiency.

5.2. Roadmap for port preparation of alternative fuel bunkering

Ports play a pivotal role in enabling the adoption of alternative fuels by providing the necessary bunkering infrastructure and operational frameworks. A structured roadmap for port preparation includes key phases: assessment, planning, implementation, and continuous improvement.

In the assessment phase, ports must evaluate the potential demand for alternative fuels, considering regional trade patterns, vessel traffic, and regulatory trends. Environmental and safety impact assessments are essential to identify risks associated with handling and storing fuels like hydrogen and ammonia.

The planning phase involves designing bunkering infrastructure tailored to the specific fuel type. This includes storage tanks, pipelines, and refuelling stations. Collaboration with local governments and regulatory bodies ensures compliance with safety and environmental standards. Equally important is workforce training to handle alternative fuels safely.

Implementation entails constructing infrastructure and integrating it into existing port operations. Investments in digital solutions, such as fuel quality monitoring systems and predictive maintenance tools, enhance operational efficiency. Partnerships with technology providers and energy companies can expedite this process.

Finally, continuous improvement ensures that port facilities evolve alongside advancements in fuel technologies and regulatory changes. Regular audits and feedback mechanisms are vital to maintaining high standards of safety, efficiency, and environmental performance.

5.3. RINA as roadmap leader in *Hydrogen Europe*

Hydrogen Europe is a leading European association that represents a diverse group of stakeholders in the hydrogen industry, including producers, distributors, technology providers, and research organizations. The association's primary objective is to promote hydrogen as a pivotal solution for achieving Europe's decarbonization goals by providing clean and sustainable energy across various sectors, such as energy, mobility, and industry[99].

In line with its commitment to spearheading the energy transition towards a zero-carbon future, RINA joined *Hydrogen Europe* in March 2021[100]. This membership has enabled RINA to actively participate in collaborative projects and research initiatives aimed at advancing hydrogen-based solutions for maritime applications.

Demonstrating its leadership within the association, RINA has seen several of its experts appointed to key positions. Notably, in June 2023, four RINA professionals were designated as Roadmap Leaders in Hydrogen Europe leading the Electrolysis roadmap[101] under the technical committee of Hydrogen Production, considering that electrolysis is crucial for a decarbonized energy system, enabling higher proportions of intermittent renewable generation while promoting hydrogen as an energy vector; the Chair of the Skills Working Group, dedicated to addressing the challenges of upskilling and reskilling in response to the rapid deployment of the hydrogen ecosystem as outlined by the EU Hydrogen Strategy; and RM 14 Rail Technical Committee and Roadmap, focusing on supporting the rollout of fuel cell regional passenger trains on European rail networks, aiming for hydrogen to be recognized as the leading option for trains on non-electrified routes by 2030[102].

RINA's active involvement in Hydrogen Europe encompasses several strategic areas. RINA contributes to the development of comprehensive guidelines that address the design, installation, and operation of hydrogen systems, ensuring safety and reliability

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[99] *RINA as roadmap leader in Hydrogen Europe - RINA.org*

[100] *RINA joins Hydrogen Europe - RINA.org*

[101] see reference 63

[102] *RINA people elected as chairs of Hydrogen Europe Working Groups and Technical Committees - RINA.org*

across various applications and by collaborating with industry stakeholders, RINA aims to bridge gaps in production, distribution, and storage, creating a seamless supply chain from producers to end-users. RINA advocates for aligning international regulations and standards related to hydrogen technologies, facilitating broader acceptance and implementation across different regions.

A notable example of RINA's commitment to hydrogen-based solutions is the *Hydra* Project[103]. Funded by the European Commission's *NextGenerationEU* plan and backed by the Italian Ministry of Enterprises and Made in Italy through RINA's Centro Sviluppo Materiali (CSM), the Euro 88 million R&D project aims to develop a hydrogen-fuelled pilot plant for near-zero-emissions steel production. As part of *Hydra*, RINA will establish a training centre to gather and disseminate knowledge related to the design, implementation, and deployment of hydrogen-based decarbonization technologies.

Through these concerted efforts, RINA plays a pivotal role in advancing hydrogen technologies, positioning itself as a key enabler of the maritime sector's decarbonization journey.

5.4. RINA Class notation “Ammonia Ready”

Ammonia has emerged as a promising alternative fuel for the maritime industry, primarily due to its carbon-free composition, which allows for zero CO_2 emissions during combustion. Recognizing its potential, RINA has undertaken significant initiatives to facilitate the adoption of ammonia as a marine fuel.

In May 2021, RINA published the first edition of its rules for the use of "*Ammonia as Fuel*", providing a comprehensive regulatory framework to address the technical challenges associated with ammonia utilization in shipping. These rules encompass critical aspects such as material compatibility, containment systems, and safety protocols, ensuring that vessels can safely handle ammonia fuel[104].

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[103] *European Commission backs RINA’s Hydra Project to Drive 100% Hydrogen fuelled Steel Production - RINA.org*

[104] *RINA publishes new rules for the use of “ammonia as a fuel” and the class notation “Ammonia Ready” - RINA.org*

To further support shipowners in transitioning to ammonia fuel, RINA introduced the "*Ammonia Ready*" class notation. This notation is designed for traditionally fuelled ships that are constructed or retrofitted to be prepared for future conversion to ammonia fuelling. By obtaining the "*Ammonia Ready*" notation, shipowners can demonstrate that their vessels meet the stringent requirements for ammonia handling, thereby reducing the risks and costs associated with future retrofitting.

RINA's commitment to ammonia as a marine fuel extends beyond regulatory frameworks. The organization actively engages in research and development projects to explore the practical applications of ammonia in shipping. For instance, RINA has participated in joint development projects with designers, marine equipment manufacturers, and shipowners to gather information and expertise on ammonia as a fuel. These collaborations aim to address the challenges related to ammonia's toxic characteristics and to develop preventive measures to ensure safe usage. Moreover, RINA has been involved in projects like ENGIMMONIA[105], which focuses on integrating ammonia as a fuel in the shipping sector. Such initiatives highlight RINA's proactive approach in supporting the industry's decarbonization efforts through innovative solutions.

By providing a clear pathway for the adoption of ammonia as a marine fuel, RINA reinforces its role as a leader in sustainable shipping solutions, contributing significantly to the global efforts in reducing greenhouse gas emissions.

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[105] *ENGIMMONIA: verso la decarbonizzazione del settore marittimo - RINA Italy*

Chapter VI: Comments and conclusions

This concluding segment synthesizes the research findings and reflects on the broader implications of adopting alternative fuels in maritime transport. It integrates the technical, economic, and regulatory insights developed throughout the study, offering a critical evaluation of the contributions made toward reducing the sector's carbon footprint. Key policy recommendations are presented, emphasizing the need for enhanced investment in research and development, clearer regulatory frameworks, and coordinated international efforts to standardize best practices. The discussion also addresses the limitations of current technologies and data, proposing areas for future research that include integrated energy system models and deeper assessments of socio-economic impacts. Ultimately, this synthesis reinforces the conclusion that a diversified and technology-driven approach to alternative fuels is essential for achieving sustainable maritime transport, thereby providing a strategic roadmap for future innovations and policy initiatives aimed at fostering a low-carbon maritime future.

6.1. Summary of Finding

The research presented in this thesis underscores the critical importance of transitioning to alternative fuels in mitigating the global challenges associated with climate change and resource depletion. Chapter 2 discussed the scientific foundations of alternative fuels, detailing their chemical properties and potential applications. This groundwork was essential for comprehending the practical implications explored in Chapter 3, which focused on technological advancements in the production and distribution of these fuels. Chapter 4 provided a detailed assessment of environmental impacts, while Chapter 5 evaluated economic and policy factors influencing the adoption of alternative energy solutions. Together, these chapters built a comprehensive understanding of the multifaceted nature of energy transitions.

The findings reveal that alternative fuels, such as biofuels, hydrogen, and renewable electricity, offer significant potential for reducing greenhouse gas (GHG) emissions, enhancing energy security, and fostering technological innovation. For example, the case studies analyzed in Chapter 3 demonstrated that biofuels derived from non-food crops and waste materials present a promising avenue for decarbonizing the transportation sector. However, their sustainability hinges on the development of efficient production methods and robust policy frameworks, as emphasized in Chapter 5. Similarly, hydrogen, particularly when produced through green methods such as electrolysis powered by renewable energy, has shown substantial promise in decarbonizing industrial processes and heavy transportation sectors, which were key areas of focus in Chapter 4. Renewable electricity, augmented by energy storage technologies, has proven instrumental in accelerating the electrification of personal vehicles and urban transit systems, linking directly to the broader environmental benefits discussed in Chapter 4.

6.2. Contributions to the Field

This thesis offering a comprehensive evaluation of alternative fuels across technological, economic, and environmental dimensions. Chapter 2’s exploration of the science of alternative fuels provided a solid theoretical foundation, which informed the analysis of technological innovations and challenges in Chapter 3. Furthermore, the economic modelling conducted in Chapter 5 enriched the understanding of market dynamics, shedding light on the cost structures and investment trends associated with alternative fuel technologies.

The research emphasizes that no single alternative fuel can serve as a panacea; rather, a diversified energy portfolio tailored to specific regional, sectoral, and resource constraints is necessary. Chapter 5’s discussion of policy interventions highlighted the critical role of government and industry collaboration in achieving this diversification. The thesis also underscores the importance of community engagement, as detailed in Chapter 4, to foster public acceptance and ensure that energy transitions are inclusive and equitable.

Another significant contribution lies in the methodology adopted, which combines quantitative modelling with qualitative assessments. This holistic approach enabled the exploration of nuanced dynamics such as the socio-economic implications of alternative fuel adoption and the role of government policy and public acceptance in shaping energy transitions. Chapters 3 and 5, in particular, demonstrated the value of integrating empirical data with theoretical insights to address complex energy challenges.

6.3. Policy Implications

The findings of this research carry several policy implications, which were elaborated in Chapter 5. Governments should prioritize investments in research and development (R&D) to enhance the efficiency and cost-competitiveness of alternative fuel technologies. Establishing clear regulatory frameworks and incentivizing private-sector participation will be crucial in fostering innovation and market adoption. Chapter 5’s analysis of case studies revealed that targeted subsidies and tax incentives can significantly accelerate the deployment of alternative fuels.

Moreover, policies must address potential socio-economic disparities by ensuring equitable access to alternative energy solutions, particularly in developing regions. Chapter 4 highlighted the environmental justice implications of energy transitions, emphasizing the need for policies that mitigate adverse impacts on vulnerable populations. International collaboration is essential for standardizing technologies and sharing best practices to accelerate global progress towards sustainability goals. This theme was explored in Chapter 3, which detailed the role of international agreements and partnerships in advancing renewable energy deployment.

6.4. Limitations of the Study and Future Research Directions

While this thesis provides a robust foundation for understanding the potential of alternative fuels, it is not without limitations. Chapter 3’s discussion of technological challenges highlighted the rapid pace of innovation in the energy sector, which means that some findings may become outdated as new technologies emerge. Additionally, the analysis is constrained by the availability and accuracy of data, particularly regarding emerging technologies and nascent markets. Chapter 5’s economic modelling faced limitations due to uncertainties in long-term market trends and policy developments. Future studies could benefit from longitudinal analyses and the inclusion of broader geographic and demographic datasets, as recommended in Chapter 4.

Future research in the domain of alternative fuels should develop integrated models that assess the combined impact of various alternative fuels on global energy systems, as

Chapter 3 highlighted the importance of systems-level thinking in addressing energy challenges. Investigations should also focus on exploring the social dimensions of energy transitions, including public perceptions and behavioral shifts associated with adopting alternative fuels, which was a prominent theme in Chapter 4. Moreover, the role of circular economy principles in enhancing the sustainability of biofuel production, as introduced in Chapter 2 and expanded in Chapter 4, warrants further exploration. Additionally, advanced materials and nanotechnologies hold significant potential to improve the performance of energy storage systems, a critical enabler of renewable electricity discussed extensively in Chapter 3. These avenues represent promising directions for advancing the understanding and application of alternative fuels within a holistic framework.

6.5. Final Considerations

The transition to alternative fuels represents not merely a technological shift but a profound reimagining of the relationship between society and energy systems. It embodies the collective aspiration to address the pressing challenges of climate change, resource depletion, and environmental degradation while simultaneously advancing human development and economic resilience. The findings of this thesis underscore the critical role of innovation, collaboration, and policy alignment in fostering a sustainable energy future.

Alternative fuels present an unparalleled opportunity to bridge the gap between environmental imperatives and economic progress. As illustrated in this research, technologies such as biofuels, hydrogen, and renewable electricity offer transformative potential when integrated thoughtfully into existing energy systems. However, their success requires a concerted effort that transcends individual disciplines, bringing together stakeholders from government, industry, academia, and civil society.

This thesis has highlighted the multifaceted benefits of alternative fuels, ranging from emissions reductions and enhanced energy security to economic diversification and social inclusion. Yet, it has also revealed the complexities and trade-offs inherent in energy transitions, emphasizing the need for adaptive strategies and iterative learning.

The lessons drawn from this research suggest that the path to a sustainable energy future is neither linear nor singular but dynamic and context dependent.

Looking ahead, the transition to alternative fuels should be guided by principles of equity, innovation, and resilience. Policymakers must prioritize inclusive approaches that ensure the benefits of energy transitions are shared widely and equitably. Researchers and practitioners must continue to push the boundaries of knowledge and technology, addressing emerging challenges with creativity and rigor. Communities and individuals must be empowered to participate actively in shaping energy futures that reflect their values and aspirations.

The journey toward sustainable energy is a shared endeavor, demanding a spirit of cooperation and a commitment to long-term vision. The conclusions of this thesis affirm that while the challenges are formidable, the opportunities for positive change are boundless. By embracing the promise of alternative fuels, society can unlock new pathways to sustainability, resilience, and prosperity, leaving a legacy of innovation and stewardship for future generations.

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