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Environmental and Techno-Economic Assessment of Decarbonization Pathways for Ships Below 5,000 GT

Riina Otsason

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

Riina Otsason

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Kuni 5000 kogumahutavusega laevade dekarboniseerimisvõimaluste keskkonna- ja tehnilis-majanduslik hindamine

RIINA OTSASON

TALTECH KIRJASTUS

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List of Publications

The list of author's publications, on the basis of which the thesis has been prepared:

I **Otsason, R.**, Tapaninen, U. (2023). Decarbonizing City Water Traffic: Case of Comparing Electric and Diesel-Powered Ferries. Sustainability, 15(23),16170. https://doi.org/10.3390/su152316170

II **Otsason, R.**, Laasma, A., Gülmez, Y., Kotta, J., & Tapaninen, U. (2025). Comparative analysis of the alternative energy: Case of reducing GHG emissions of Estonian pilot fleet. Journal of Marine Science and Engineering, 13(2), 305. https://doi.org/10.3390/jmse13020305

III **Otsason, R.**, Thomasson, T., Rahikainen, J., & Tapaninen, U. (2025). Decarbonization of Estonian ferry lines – Challenges and opportunities. In NASE-MORE 2025 Conference Proceedings. https://www.nasemore.com/wp-content/uploads/2025/09/NASE-MORE-2025_Conference-proceedings-1.pdf

IV **Otsason, R.**, Tapaninen, U., Hilmola, O.-P., & Tovar, B. (2024). Business opportunities for a ground effect vehicle – Case of Canary Islands. Transportation Journal, 62(1), 34–52. https://doi.org/10.2478/ttj-2024-0034

Copies of the publications constituting the thesis are included in the appendix and marked in the text in Roman numbers as presented above.

Other related publications:

V Laasma, A., **Otsason, R.,** Tapaninen, U., Hilmola, O.-P. (2022). Evaluation of Alternative Fuels for Coastal Ferries. Sustainability, 14 (24), #16841. https://doi.org/10.3390/su142416841

VI Laasma, A, **Otsason, R.**, Tapaninen, U., Hilmola, O.-P. (2024). Decarbonising coastal ferries: case of the Estonian state fleet ferry. In: Ellen J. Eftestøl, Anu Bask Maximilian Huemer (Ed.). Towards a Zero-Emissions and Digitalized Transport Sector. (121−139). Edward Elgar Publishing. https://doi.org/10.4337/9781035321469.00014

Author’s Contribution to the Publications

The author is the first and corresponding author of the core four publications included in this dissertation. Contribution to the papers in this thesis are:

I Main author. The author was responsible for the conceptualization of the study, development of the processing workflow, performed the data collection and calculations of the comparative analysis, drafted the manuscript, figures, and tables, with co-author contributing to supervision and review.

II Main author. The author was responsible for the conceptualization of the study, development of the processing workflow, performed the data collection and calculations of the comparative analysis from greenhouse gas emissions, drafted the manuscript, with co-authors contributing to fuel alternative consumption assessment supervision and review.

III Main author. The author was responsible for the conceptualization of the study, development of the processing workflow, performing the data collection and analyzing greenhouse gas emissions, drafted the manuscript, with co-authors contributing to energy assessment modelling, supervision and review.

IV Main author. The author was responsible for the conceptualization of the study, development of the processing workflow, performing the data collection and route planning calculations, drafted the manuscript, with co-authors contributing to simulating business model related aspects, supervision and review.

All core publications reflect my original contributions as the principal investigator and doctoral candidate, with supervision, input and support from the co-authors. As an addition, contribution to other related publications:

V Second author. The author supported the conceptualization of the study, was responsible for the literature review and supported manuscript drafting.

VI Second author. The author supported mainly with background analysis and was responsible for the literature review, supported manuscript drafting and final review.

Introduction

Background and Motivation

Maritime transport is responsible for approximately 2.5-3% of global carbon dioxide (CO_2) emissions and it is estimated to grow (IMO, 2021; UNCTAD, 2025). As an addition maritime transport represents a significant source of air pollution and climate impact, particularly in coastal and port-adjacent regions (European Environment Agency (EEA), 2024; Fadaie et al., 2025; Issa-Zadeh & Garay-Rondero, 2025). While shipping is often described as one of the most energy-efficient transport modes per unit of freight or passenger carried (Bouman et al., 2017; Lindstad et al., 2023), its absolute emissions remain substantial due to the scale and intensity of global maritime operations (IMO, 2014; Mao et al., 2025).

In response to these challenges, international and regional bodies have articulated increasingly ambitious climate objectives for the maritime sector. The International Maritime Organization (IMO) has adopted a revised greenhouse gas (GHG) strategy and associated net-zero framework aimed at reducing CO_2 emissions per transport work by at least 40% by 2030 relative to 2008 levels, while achieving net-zero emissions by or around 2050 through the uptake of zero- and near-zero-emission technologies and fuel (IMO, 2023c).

At the European level, the Fit for 55 climate package and the FuelEU Maritime Regulation introduce binding measures designed to reduce the carbon intensity of maritime transport within EU waters (European Commission, 2021; European Union, 2023b).
These initiatives include the extension of the EU Emissions Trading System (EU ETS) to parts of maritime transport, progressive GHG intensity reduction requirements for marine energy use, and the Alternative Fuels Infrastructure Regulation (AFIR), which supports shore-side electricity and renewable fuel infrastructure, alongside broader climate measures such as the Carbon Border Adjustment Mechanism (EMSA, n.d.).

However, these regulatory instruments have primarily been designed with large (above 5000 GT), ocean-going vessels in mind, which account for the majority of global shipping emissions (Fadaie et al., 2025; Lu et al., 2023; Robalo-Cabrera et al., 2025). As a result, smaller vessels operating in short-sea and coastal transport systems (such as ferries, pilot boats, and other service crafts) have received comparatively limited attention in both academic research and policy-oriented analyses (Vakili et al., 2025).

Although vessels below 5,000 gross tonnage (GT) are often outside the formal scope of major international regulatory instruments, they play a critical role in regional mobility, island connectivity, and port operations. Moreover, their operational profiles that are characterized by frequent manoeuvring, idling, and short-distance voyages mean that they can contribute disproportionately to local air pollution in populated coastal areas. Despite this, empirical evidence on their decarbonization potential, technical constraints, and economic feasibility remains fragmented.

Decarbonizing smaller vessels presents a distinct set of technical and operational challenges. Limited onboard space constrains the installation of large batteries or alternative fuel storage systems, thereby restricting range and endurance (Ahmed et al., 2025). At the same time, charging and refuelling infrastructure for low-emission technologies (such as electrification, hydrogen, or renewable fuels) remains unevenly distributed across smaller ports, in contrast to major maritime hubs (Wingrove, 2023).

Retrofitting existing vessels often involves high upfront investment costs, and economic viability can be uncertain for operators working within narrow financial margins (Liang et al., 2024).

In addition, small-vessel operations are highly heterogeneous. Pilot boats are characterized by intensive manoeuvring and irregular duty cycles, while ferries often operate continuous shuttle services on fixed routes. These differences complicate the transferability of generic decarbonization solutions and underline the importance of vessel- and route-specific analysis(Fadaie et al., 2025; Kanchiralla et al., 2023; Ziakas & Boile, 2025).

The upper boundary of 5,000 gross tonnage (GT) is selected as a relevant threshold in maritime regulation, as many International Maritime Organization (IMO) measures (including energy efficiency and emission reporting requirements) apply primarily to vessels above this size (Hellström et al., 2024; Kotzampasakis, 2025; Malmgren et al., 2025). Consequently, vessels below 5,000 GT are often less directly regulated, despite their operational significance. This makes them a distinct and relevant category for focused decarbonization analysis.

Recent doctoral research (Laasma, 2025) has contributed significantly to the understanding of maritime decarbonization in small-scale and coastal shipping contexts, particularly through the development of an integrated decarbonization framework for Estonian coastal ferries that combines technological options, economic considerations, and regulatory structures. That work provides a high-level, strategic perspective on how different decarbonization pathways can be assessed and compared within a national ferry system. Building on this foundation, the present dissertation adopts a complementary and more application-oriented approach by focusing on vessel- and fleet-level techno-economic and environmental feasibility analyses. This research extends the empirical evidence base by examining how specific propulsion technologies and energy solutions perform under real operational constraints, thereby contributing practical insights that support and operationalize earlier framework-level findings.

Against this background and building on earlier framework-level research, the current dissertation focuses on the technical and economic feasibility of decarbonization pathways for vessels below 5,000 GT operating in short-sea and coastal transport systems. The study examines how evolving regulatory ambitions and energy-transition objectives form the operational context within which technology adoption decisions are made. Estonia serves as a relevant empirical setting due to its dense network of island ferry routes, coastal service vessels, and centralized pilotage operations, and additional case studies broaden the geographical and operational scope of the analysis.

Research Gap and Research Questions

Despite growing academic and policy attention to maritime decarbonization, the existing literature remains unevenly distributed across vessel segments and operational contexts. Most research has concentrated on large ocean-going vessels (DNV, 2025b; Issa-Zadeh & Garay-Rondero, 2025; Zis et al., 2020), global fuel transitions (Law et al., 2022; Liang et al., 2024; Shangguan et al., 2024; Y. Wang & Wright, 2021; X. Zhou et al., 2024), and deep-sea trade corridors (Farrukh et al., 2023; Grzelakowski et al., 2022; Law et al., 2022). In contrast, vessels operating below 5,000 GT in short-sea and coastal environments have received comparatively limited empirical attention.

This imbalance is significant because this vessel segment operated under distinct technical and operational constraints. Limited onboard space, high manoeuvring demand, short but frequent duty cycles, proximity to ports, and dependence on local infrastructure create boundary conditions that differ fundamentally from those of deep-sea shipping. Consequently, decarbonization solutions developed for large vessels cannot be directly transferred to small-scale maritime operations without careful contextual evaluation (G. N. Lee et al., 2022; Rauca et al., 2025; UK GOV, 2025).

The first research gap therefore concerns the limited empirical evidence on the environmental performance of alternative propulsion systems in small-vessel applications. While electrification, biofuels, hydrogen, ammonia, and hybrid systems are widely discussed in conceptual and scenario-based studies (European Commission, 2023; IMO, 2011; Laasma et al., 2022), detailed vessel-level measurements and comparative life-cycle assessments for sub-5,000 GT fleets remain relatively scarce. In particular, high-manoeuvrability service vessels such as pilot boats and short-route passenger ferries are underrepresented in empirical life-cycle studies.

The second gap relates to the integration of environmental and economic assessment in real operational settings. Many studies examine environmental impacts using life-cycle assessment (Ahmed et al., 2025; Andrade & Estévez-Pérez, 2024; Nykiel et al., 2025; Y. Wang et al., 2025), while others focus on techno-economic modelling and cost analysis (Aspelund et al., 2006; Perčić et al., 2021). However, fewer studies combine measured operational data, well-to-wake (WTW) GHG assessment, and life-cycle cost evaluation within the same empirical cases. For small fleets operating under tight financial margins and high investment sensitivity, understanding this interaction between emissions performance and cost feasibility is essential.

The third gap concerns the context dependency of decarbonization pathways. The suitability of electrification, alternative fuels, or hybrid systems depends not only on technical fuel characteristics, but also on route length, charging availability, storage constraints, electricity carbon intensity, port infrastructure readiness, and operational patterns (Caprace et al., 2025; Farrukh et al., 2023; Shi et al., 2023). Empirical research that systematically evaluates these interacting dimensions in small-vessel contexts remains limited.

This dissertation addresses these gaps through four empirical case studies covering passenger ferries, pilot vessels, regional ferry systems, and an emerging transport concept (ground-effect vehicles). The study does not analyse regulatory instruments as such; rather, it evaluates the environmental performance, economic feasibility, and operational suitability of alternative decarbonization pathways under real-world maritime conditions. In this dissertation, the lower bound of vessel size is not defined by a strict gross tonnage threshold, but rather by operational characteristics typical of small and medium-sized vessels, including pilot boats, service vessels, and short-route ferries. These typically range from small craft below 100 GT to vessels approaching 5,000 GT, thereby capturing a heterogeneous segment characterized by limited onboard space, high manoeuvrability, and strong dependence on port-based infrastructure.

Based on these identified gaps, the dissertation is guided by the following research questions:

Research Question 1 (**RQ1**): What is the environmental performance of alternative propulsion and fuel solutions for vessels below 5,000 GT?

Research Question 2 (**RQ2**): What is the economic feasibility of these decarbonization pathways under real operational conditions?

Research Question 3 (**RQ3**): How do operational characteristics and infrastructure constraints affect the suitability of different decarbonization options for small vessels?

These research questions provide a focused structure for evaluating smaller vessel decarbonization from environmental, economic, and operational perspectives. By grounding the analysis in measured case study data while maintaining comparability across vessel types and regions, the dissertation contributes empirical evidence to a segment of maritime transport that remains comparatively underrepresented in decarbonization research.

Overview of Methodology and Case Studies

This dissertation employs a multi-method case study approach to investigate decarbonization pathways for small and medium-sized maritime vessels operating primarily in short-sea shipping. The research combines quantitative methods, including life-cycle assessment (LCA) and techno-economic evaluation, with qualitative examination of operational and contextual factors related to vessel operation and market conditions. Each of the four peer-reviewed articles constitutes a distinct yet interrelated case study, collectively contributing to an empirical understanding of the technical and economic feasibility of alternative propulsion and energy solutions in small-vessel maritime transport.

The overall research design is comparative and application oriented. The selected case studies reflect a deliberate progression in analytical scope, moving from individual vessel-level assessment to fleet-level evaluation and, finally, to the exploration of new transport concepts and business opportunities. This structure enables the examination of decarbonization challenges across different operational contexts while maintaining consistency in core analytical methods and key performance indicators.

Article I, Decarbonizing City Water Traffic: Case of Comparing Electric and Diesel-Powered Ferries, presents a comparative analysis of an electric ferry and its diesel-powered sister vessel operating in an urban inland waterway environment. A well-to-wake (WTW) LCA is applied to quantify GHG emissions, supported by operational data such as energy consumption, service hours, and route-specific operating conditions. In addition, a techno-economic analysis evaluates investment and operational costs, including the influence of the electricity grid composition on emission outcomes. This case provides empirical evidence on the technical and economic performance of battery-electric propulsion in short-distance waterborne transport.

Article II, Comparative Analysis of the Alternative Energy: Case of Reducing GHG Emissions of Estonian Pilot Fleet, extends the analysis to a national state-owned pilot fleet characterized by highly variable operational profiles. The study evaluates the GHG reduction potential of alternative fuels, including biomethane, hydrotreated vegetable oil (HVO), hydrogen, and e-methanol, using a WTW LCA complemented by sensitivity analysis under different energy scenarios. The results highlight how fuel substitution and hybrid solutions can offer feasible emission reductions for small but energy-intensive vessels, where full electrification may be operationally constrained. This observation is consistent with broader marine sector analyses, which demonstrate that propulsion system suitability is strongly influenced by operational characteristics such as duty-cycle variability and utilisation patterns.

Article III, Decarbonization of Estonian Ferry Lines – Challenges and Opportunities, shifts the focus to a system-level assessment of regional ferry operations. Through scenario-based cost and emission analysis, the study examines how different technological options, infrastructure availability, and operational characteristics influence decarbonization potential at the fleet level. While regulatory and institutional conditions form part of the operating context, the analysis primarily addresses technical feasibility and economic implications, identifying practical barriers and opportunities for reducing emissions in inter-island ferry services.

Article IV, Business Opportunities for a Ground Effect Vehicle – Case of Canary Islands, explores an emerging transport concept as an alternative to conventional short-sea shipping. The study combines comparative cost and emission analysis with market feasibility assessment to evaluate the potential of ground-effect vehicles in inter-island transport. This case broadens the scope of the dissertation beyond conventional vessel technologies by examining how innovative concepts may contribute to emission reduction while enabling new business opportunities in specific regional settings.

Across all four studies, methodological consistency is achieved through the comparative evaluation of alternative propulsion and energy pathways based on empirical case data. Quantitative indicators, such as energy consumption, GHG emissions, and cost per unit of transport work, are complemented by qualitative assessment of operational feasibility and contextual constraints. these case studies provide a coherent empirical basis for analysing decarbonization options for small maritime vessels without claiming the development of a standalone analytical or policy framework.

Structure of the Research

This dissertation follows a publication-based structure. Four peer reviewed articles form the empirical core, each examining a specific vessel type or operational context while contributing to a structured evaluation of decarbonization pathways for small maritime vessels. The thesis includes an introduction, the four appended publications, a synthesis of findings, and concluding remarks outlining contributions and future research directions.

Chapter 1 introduces the background and motivation for small vessel decarbonization, identifies research gaps, formulates the research questions, and outlines the overall structure of the study.

Chapter 2 presents the literature review. It examines drivers and pathways of maritime decarbonization, including infrastructure and policy context, LCA methodology, technical measures (energy systems, hull design, propulsion and alternative fuels), operational measures, and emerging transport concepts. This chapter establishes the theoretical and technical foundation for addressing RQ1–RQ3.

Chapter 3 describes the methodological approach. It explains the multi-case study design and the integration of LCA, techno-economic modelling, scenario analysis, and operational data evaluation. The chapter clarifies, how the selected methods support the assessment of environmental performance (RQ1), economic feasibility (RQ2), and operational and infrastructural constraints (RQ3).

Chapter 4 synthesizes the findings of the four articles. It follows the research questions and compares environmental performance, economic viability, and feasibility across vessel types and regions.

Chapter 5 discusses the findings in relation to the broader maritime decarbonization literature. It interprets the technical and economic trade-offs identified in the case studies and evaluates how operational characteristics and infrastructure readiness shape viable decarbonization pathways.

Chapter 6 concludes the dissertation by summarizing the main findings, clarifying the scientific contributions, acknowledging limitations, and proposing directions for future research.

The chapters progress from contextual and theoretical grounding (Chapter 2), through methodological clarification (Chapter 3), to empirical synthesis (Chapter 4), interpretative discussion (Chapter 5), and final conclusions (Chapter 6). This structure ensures coherence between the research questions, the appended publications, and the overall contribution of the dissertation.

1 Drivers and Pathways of Decarbonization in Maritime Transport

1.1 Infrastructure and Policy Context of Maritime Decarbonization

Infrastructure and regulatory conditions shape the operating environment of maritime decarbonization. ports, shipowners, energy providers, and coastal administrations form an interdependent socio technical system in which vessel level technological improvements depend on suitable onshore facilities and energy supply systems (Acciaro & Sys, 2020; Psaraftis & Kontovas, 2021). Maritime decarbonization is therefore increasingly conceptualized as a system-level transition rather than a purely technological substitution process.

The transition toward low- and zero-carbon propulsion (including battery-electric systems, hydrogen, methanol, ammonia, and hybrid configurations) requires not only onboard technological adaptation, but also parallel development of port energy supply, bunkering infrastructure, grid integration capacity, and safety standards (Li et al., 2025; Zhou et al., 2024). Recent research on maritime energy transitions highlights that infrastructure readiness frequently determines whether technically viable propulsion solutions can be implemented at scale (Islam et al., 2025; Papalexopoulos et al., 2025). In this sense, technological feasibility and infrastructural feasibility are closely intertwined.

International regulatory developments have contributed to shaping the broader direction of maritime decarbonization. The International Maritime Organization (IMO), through MARPOL Annex VI and initiatives such as the EEDI, EEXI, and CII measures (IMO, 2011, 2023a, 2023b), has introduced performance-based requirements aimed primarily at improving energy efficiency and reducing GHG emissions in international shipping. At the European level, the inclusion of maritime transport in the EU Emissions Trading System (EU ETS) (European Commission, n.d.) and the adoption of the FuelEU Maritime Regulation (European Union, 2023a) further strengthen economic incentives for emission reductions within European waters.

However, much of this regulatory architecture has been designed with large ocean-going vessels and international trade routes in mind. Small and medium-sized vessels frequently fall outside direct compliance thresholds, yet they operate within ports and supply chains shaped by evolving regulatory expectations and energy-transition objectives. Literature increasingly acknowledges this asymmetry between regulatory scope and actual fleet composition, particularly in countries with extensive domestic and short-sea traffic (Armstrong, 2022; Vakili et al., 2025). Nevertheless, empirical studies examining how small-vessel fleets respond to indirect regulatory pressures and infrastructural dependencies remain comparatively limited.

National and regional initiatives (Government of Canada, 2026; IEA, 2025; Scottish Government, 2025; Simões & Erbach, 2024; Yougov, 2021) further influence the feasibility of decarbonization pathways, especially in maritime nations with dense ferry and coastal networks. Coastal states such as Norway, Finland, Sweden, Estonia, Scotland, and Canada have implemented electrification pilots, green public procurement schemes, port electrification programs, and targeted funding mechanisms for domestic fleets (Rødseth et al., 2023; Sæther & Moe, 2021). These initiatives show that infrastructure investment, contractual design, and public funding are key enablers of technology adoption.

Infrastructure constraints thus remain a major bottleneck in short sea shipping decarbonization, including limited electrical capacity in small ports, weak grid connections for high power charging, lack of alternative fuel bunkering, and absence of standardized charging interfaces (Islam et al., 2025; Papalexopoulos et al., 2025). Many regional ports were not originally designed to supply substantial electrical power during short vessel turnaround times, and upgrading transformers, cabling, and distribution systems can require substantial capital investment (deManuel-López et al., 2024; Pivetta et al., 2022; Yildiz et al., 2024). These infrastructural limitations are particularly pronounced in small maritime economies, where port infrastructure and grid capacity may be spatially constrained.

Infrastructure–policy interactions are well studied in large shipping segments and international trade corridors. In contrast, far less attention has been given to how these conditions affect decarbonization in small vessel fleets, which face limited onboard space, restricted capital access, and high operational variability (Gerlitz & Meyer, 2021). This literature gap reinforces the need for vessel-level empirical analysis that explicitly considers infrastructural readiness and operational context, dimensions that directly inform RQ3 of this dissertation.

1.2 Life-Cycle Assessment in Maritime Engineering

Life-cycle assessment (LCA) is a standardized methodological framework used to quantify the environmental impacts of products, processes, or systems across their entire life cycle, from raw material extraction through production, operation, and end-of-life treatment. Defined under ISO 14040 and ISO 14044 standards, LCA systematically evaluates inputs (energy and materials) and outputs (emissions and waste) in order to assess cumulative environmental burdens associated with a given functional unit. Within transport research more broadly, LCA has become a central analytical tool for evaluating decarbonization pathways, enabling comparison across technologies that differ not only in operational performance, but also in upstream energy requirements and material intensity.

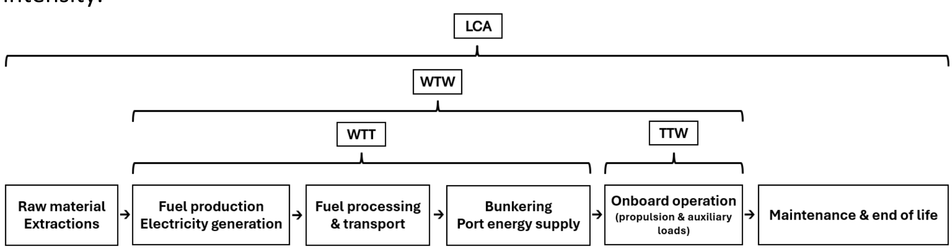

Figure 1. System Boundaries of Life-Cycle Assessment in Maritime Transport

Figure 1 illustrates the system boundaries commonly applied in maritime LCA. TTW (tank-to-wake) approaches include only onboard fuel combustion, WTW expands the boundary to upstream fuel production and supply. Full LCA further incorporates vessel construction, maintenance, and end-of-life processes.

In maritime engineering, LCA has increasingly been adopted to assess the climate performance of vessels and propulsion systems beyond direct fuel combustion. Historically, GHG accounting in shipping focused primarily on TTW emissions - that is, emissions generated during onboard fuel combustion. However, growing evidence demonstrates that upstream and downstream processes (including fuel extraction, refining, transport, electricity generation, vessel construction, battery manufacturing, and end-of-life treatment) can substantially influence total life-cycle climate impact (Aakko-Saksa et al., 2023; Roux et al., 2024). WTW approaches that include both fuel production and vessel operation have become central in maritime decarbonization research. LCA provides a more complete perspective than operational emissions accounting alone and reduces the risk of burden shifting across life cycle stages.

The relevance of LCA is particularly evident in the evaluation of electric propulsion systems. While battery-electric vessels produce zero exhaust emissions during operation, their overall environmental performance depends strongly on the carbon intensity of the electricity mix, battery production impacts, and replacement cycles. Broader LCA literature demonstrates that the environmental benefits of electrification are highly sensitive to upstream electricity sources and battery manufacturing assumptions (Lee et al., 2024; Wang et al., 2025). Studies consistently demonstrate that electrification delivers the highest GHG reductions in regions with low-carbon electricity grids, while benefits are more limited where electricity generation relies on fossil fuels (Roux et al., 2024). Consequently, evaluating only operational emissions may lead to incomplete or misleading conclusions regarding decarbonization effectiveness.

Similarly, alternative fuels (such as hydrogen, e-methanol, ammonia, and biofuels) exhibit substantial variability in life-cycle performance. Although fuels such as green hydrogen and e-fuels may achieve near-zero operational emissions, their upstream production pathways often involve high energy demand and associated emissions unless renewable electricity is used. Comprehensive reviews of maritime fuel LCAs demonstrate that WTW emissions can differ significantly depending on feedstock choice, production technology, and system boundary assumptions (Roux et al., 2024; Wang et al., 2025). Comparative analyses further indicate that e-fuels and biomass-based fuels may provide considerable GHG reductions relative to fossil marine fuels, but results remain highly dependent on methodological assumptions, allocation choices, and regional energy contexts (Kanchiralla et al., 2022; Lee et al., 2024).

LCAs of hydrogen and ammonia as marine fuels show strong decarbonization potential but highlight the importance of production pathways. When produced with renewable electricity, these fuels can greatly reduce global warming potential, whereas fossil-based hydrogen (e.g., steam methane reforming without carbon capture) or ammonia from carbon intensive energy systems greatly reduces climate benefits (Dong et al., 2024; Nguyen et al., 2025). In addition, biofuels may offer favourable WTW emission profiles yet raise broader sustainability concerns related to indirect land-use change, biomass availability, competition with food production, and certification frameworks. LCA provides the methodological structure necessary to evaluate such trade-offs transparently and consistently across competing fuel options.

Beyond fuel comparison, LCA is also used to examine vessel construction impacts, material selection, retrofitting strategies, and battery replacement cycles, thereby enabling a more holistic assessment of decarbonization pathways (Aakko-Saksa et al., 2023). In smaller vessels, where weight and space constraints are more pronounced, material intensity and storage requirements can have proportionally greater life-cycle implications. This reinforces the importance of consistent functional units and system boundary definitions when comparing technologies.

In small-scale maritime applications LCA is particularly valuable, because operational profiles are often irregular and characterized by varying load patterns, frequent manoeuvring, and standby phases. These operational characteristics complicate simple emission benchmarking based on distance travelled. This illustrates a central methodological insight: decarbonization outcomes are not solely technology-dependent but are also shaped by analytical scope, data quality, and boundary selection.

LCA has become essential in maritime engineering for comparing technologies, supporting regulatory development, and guiding vessel design and investment decisions. By integrating upstream and operational emissions within a single analytical framework, LCA enables robust evaluation of alternative propulsion and fuel systems under real-world conditions. In the context of this dissertation, LCA provides the methodological foundation for addressing RQ1 by systematically comparing the environmental performance of decarbonization pathways for vessels below 5,000 GT, while accounting for regional energy systems and infrastructural constraints.

The selection of LCA as a primary analytical method in this dissertation is motivated by its ability to capture the full environmental implications of alternative propulsion and fuel systems beyond operational emissions alone. In the context of maritime decarbonization, where upstream fuel production, electricity generation, and material inputs (such as batteries) can significantly influence overall climate impact, LCA provides a consistent and comparable framework for evaluating competing technologies. This is particularly relevant for small-vessel applications, where operational profiles vary and simplified emission metrics may not adequately reflect total environmental performance.

1.3 Technical Measures

In maritime decarbonization research, technical measures refer to engineering-based modifications and design interventions that directly influence vessel energy demand, propulsion efficiency, and fuel compatibility (Caprace et al., 2025; Wang et al., 2025; C. Zhang et al., 2024). Unlike operational measures (such as speed optimization) or regulatory instruments, technical measures involve physical changes to ship systems, components, or configurations (DNV, 2025b; Pariotis et al., 2016). They may be implemented either as retrofits on existing vessels or integrated into newbuild designs. Within the broader energy-transition literature, such measures are often described as supply-side or technology-driven interventions that alter the energy intensity and emissions profile of transport systems at the asset level.

Contemporary literature typically categorizes technical measures into five interacting domains: onboard energy consumers, hull design, propulsion and machinery systems, alternative fuels, and energy collection technologies (Barreiro et al., 2022; Battaglia et al., 2024). These domains collectively define the technological baseline of a vessel and determine its energy performance under given operational conditions. Improvements in any of these domains reduce overall fuel consumption, improve propulsion efficiency, or enable the integration of low- and zero-emission propulsion technologies. Importantly, these domains are interdependent: changes in hull resistance affect propulsion demand; propulsion configuration influences auxiliary loads; and fuel choice determines storage requirements and safety systems. Therefore, technical measures must be evaluated as part of an integrated onboard energy system rather than as isolated components.

For existing fleets, retrofitting represents a central decarbonization strategy (Buonomano et al., 2025; Ling-Chin & Roskilly, 2016; Verhelst et al., 2025). Retrofitting refers to the modification or upgrading of an already operational vessel in order to improve energy efficiency or adapting it to alternative fuels without full replacement of the ship. This approach is particularly relevant in short-sea shipping, where vessels often have long service lives and capital replacement cycles are constrained by financial and operational considerations. The global maritime fleet is relatively old in many segments, making incremental improvements through retrofitting an essential transitional pathway in the short and medium term.

Literature indicates that measures such as advanced hull coatings, propeller upgrades, air-lubrication systems, optimized propeller-hull interaction, and waste-heat recovery can together yield energy-efficiency improvements in the range of approximately 5-20%, depending on vessel type, operational profile, and retrofit scope (Kim & Steen, 2023; Sardar et al., 2025; Themelis, 2025; Vakili et al., 2025). While individual measures often provide modest reductions, cumulative implementation may generate meaningful decreases in fuel consumption and GHG emissions. Studies further emphasize that the actual realized savings depend heavily on operational patterns, maintenance quality, and baseline vessel condition - reinforcing the context-dependent nature of technical efficiency gains.

In short-sea shipping, hybridization and electrification are frequently identified as promising technical pathways, particularly for vessels operating on fixed and predictable routes with short sailing distances (Aksöz et al., 2025; Barnard, 2023; Katumwesigye et al., 2025; Papalexopoulos et al., 2025; Perčić et al., 2021; Wallenstein et al., 2025). Electrification is characterized by high drivetrain efficiency and elimination of onboard combustion emissions, while hybrid systems allow load balancing and optimized engine operation. However, the suitability of battery-electric propulsion is closely linked to operational regularity, turnaround time, port charging capability, and available grid capacity. These infrastructural dependencies distinguish small-vessel electrification from long-distance deep-sea applications.

Newbuild vessels allow for more comprehensive integration of low-emission technologies. Design-stage flexibility enables optimized weight distribution, structural accommodation of energy storage systems, and integration of advanced propulsion architectures. This includes full battery-electric systems, hydrogen fuel cells, dual-fuel engines, methanol combustion engines, and ammonia-capable internal combustion engines. Advances in battery energy density, power electronics, and thermal management have extended the feasible operational range of fully electric vessels to approximately 20-40 nautical miles under favourable conditions (Aksöz et al., 2025; Barnard, 2023; Katumwesigye et al., 2025; Lindstad et al., 2022).

At the same time, alternative fuel integration in newbuild designs introduces trade-offs related to storage volume, safety systems, and payload capacity - considerations that are particularly critical for vessels below 5,000 GT, where spatial margins are limited. Consequently, technical feasibility cannot be evaluated independently of vessel geometry, route characteristics, and port infrastructure readiness.

these technical domains determine the practical feasibility of emission reduction strategies in small and medium-sized vessels. Their effectiveness depends not only on technological performance but also on vessel-specific operational characteristics and infrastructure compatibility. In this dissertation, technical measures therefore form the engineering foundation for addressing RQ1 (environmental performance), while their interaction with route characteristics and infrastructure constraints directly informs RQ3 (contextual suitability).

1.3.1 Onboard Energy Consumers and System Efficiency

Energy consumption onboard ships is distributed across multiple subsystems, of which propulsion is typically the dominant but not exclusive component. Depending on vessel type, size, and operational profile, propulsion systems account for approximately 60-90% of total onboard energy demand, while the remaining share is consumed by auxiliary and service systems (Aurdal, 2023; Baldi et al., 2014; DNV, 2024). These include electrical power generation, HVAC (heating, ventilation, and air conditioning), navigation and communication equipment, lighting, cargo-handling machinery, and other hotel loads. In small and medium-sized vessels operating in short-sea and coastal environments, the relative importance of auxiliary loads is often higher than in deep-sea shipping due to frequent port calls, manoeuvring phases, and standby operations (Baldi et al., 2014; Bordin & Mo, 2019; Katumwesigye et al., 2025).

Passenger ferries, for example, require substantial energy for climate control, lighting, and onboard services, particularly in cold-climate regions where heating demand can be significant. Pilot boats and port-service vessels exhibit highly variable load profiles, as frequent acceleration, deceleration, and idling create fluctuating power demand patterns. Empirical and modelling studies indicate that auxiliary systems may account for a considerable share of total energy consumption during low-speed or harbour operations, where propulsion demand decreases but service loads remain constant (Baldi et al., 2014; Katumwesigye et al., 2025).

These characteristics highlight the importance of detailed energy auditing and load profiling as a foundation for decarbonization strategies. Energy audits involve systematic measurement and analysis of subsystem-level consumption to identify inefficiencies and prioritize interventions. Literature on maritime energy management emphasizes that digital monitoring systems, real-time performance tracking, and demand-based control strategies can significantly improve overall vessel efficiency. Such digital energy management approaches are particularly valuable for battery-electric and hybrid vessels, where balancing propulsion and auxiliary demand is essential for maximizing battery utilization and minimizing unnecessary generator operation (Barreiro et al., 2022; Viktorelius & Lundh, 2019).

A range of technical interventions can further reduce auxiliary energy demand. HVAC systems can be optimized through heat recovery systems, enhanced insulation, and automated climate-control algorithms. Similarly, LED lighting, high-efficiency pumps and compressors, and variable-frequency drives have been shown to reduce auxiliary power consumption by approximately 5-15%, depending on vessel type and baseline efficiency (Hüffmeier & Johanson, 2021; Su et al., 2012; Sylvester et al., 2019). Although individual measures may yield moderate savings, their cumulative implementation contributes directly to lower fuel consumption and reduced GHG emissions.

The importance of addressing onboard energy consumers beyond propulsion is reflected in Articles I-III of this research. In vessels operating on predictable short routes or with repetitive duty cycles, system-level optimization of both propulsion and auxiliary loads significantly influences environmental performance (RQ1) and economic feasibility (RQ2). Furthermore, high auxiliary shares in small vessels amplify the impact of infrastructural constraints, such as limited charging windows and grid capacity, reinforcing the relevance of operational and infrastructural context (RQ3).

1.3.2 Hull Design and Hydrodynamic Optimization

Hull geometry and propulsion interact closely, making hydrodynamic design a key determinant of vessel energy efficiency. For small and medium-sized ships operating under constrained power availability and limited onboard space, reductions in hydrodynamic resistance directly translate into lower energy demand and improved feasibility of low- and zero-emission propulsion systems. Unlike fuel-specific interventions, hull optimization reduces baseline energy requirements regardless of propulsion type.

Hydrodynamic resistance consists primarily of frictional resistance and wave-making resistance, both of which can be influenced through geometric optimization. Advances in computational fluid dynamics have enabled more precise tailoring of hull forms to defined operational speed ranges, which is particularly relevant for short-sea vessels and ferries operating at relatively stable service speeds (Onwuegbuchunam et al., 2019; Walker, 2025; Yang & Huang, 2016). Computational fluid dynamics-based optimization allows designers to minimize calm-water resistance while considering real operational profiles rather than theoretical design speeds.

Traditional hull features, such as bulbous bows, are designed to reduce wave-making resistance at specific speeds. However, when vessels operate under slow steaming conditions or altered service patterns, originally optimized bulb geometries may become suboptimal. Empirical and retrofit studies suggest that redesigning or modifying bulbous bows for reduced operating speeds can yield fuel savings of approximately 5% and improve hydrodynamic performance whenClick or tap here to enter text. hull geometry is aligned with actual operating profiles rather than static design assumptions (Grundsøe, 2013; Ship and Bunker News, 2013).

Wave-piercing hull designs represent a complementary innovation particularly relevant for small workboats, pilot vessels, and ferries operating in coastal or semi-exposed waters. Characterized by slender forebodies with reduced buoyancy, wave-piercing designs aim to minimize vertical accelerations and wave-making resistance, thereby improving seakeeping performance and operational stability. Improved motion behaviour can reduce power fluctuations and enhance overall energy efficiency in moderate sea states. Practical applications from shipbuilding demonstrate that such designs can contribute to smoother operation, improved comfort, and fuel savings in appropriate service conditions (Baltic Workboats, 2019).

Beyond geometric optimization, hull surface condition plays a significant role in frictional resistance. Biofouling increases surface roughness and can substantially raise fuel consumption over time. Advanced hull coatings, including self-polishing antifouling systems and silicone-based foul-release coatings, have been shown to reduce frictional drag and achieve fuel savings in the range of 5-10%, depending on maintenance practices and operational profile (Lagerström et al., 2022; Lloyds Register, 2025). These measures are particularly attractive for small vessels, as they require limited structural modification and can be implemented during scheduled dry-docking.

More advanced technologies, such as air lubrication systems (ALS), reduce skin-friction resistance by introducing air layers along the hull surface. Studies report efficiency gains of approximately 5-15% under favourable operating conditions, although performance depends strongly on vessel size, speed range, and sea state (Lagerström et al., 2022). While installation costs and technical complexity currently limit widespread adoption in small vessels, ALS illustrates the potential of resistance-reduction technologies to complement propulsion improvements.

Thus, hull design and hydrodynamic optimization constitute propulsion-independent efficiency measures that directly reduce energy demand regardless of the propulsion technology employed. By lowering baseline energy consumption, these measures enhance environmental performance (RQ1), improve economic feasibility through fuel savings (RQ2), and increase the practical viability of electrification and alternative fuels under operational and infrastructural constraints (RQ3). For small vessels with limited energy margins, hull-related efficiency improvements form a critical component of decarbonization strategy.

1.3.3 Propulsion and Machinery Systems

Advances in propulsion and machinery technologies directly influence vessel energy efficiency, emission performance, and operational flexibility. In small and medium-sized vessels, propulsion systems typically account for the dominant share of onboard energy consumption, making improvements in propulsive efficiency central to decarbonization strategies (Baldi et al., 2014; Yao et al., 2019). Unlike hull optimization, which reduces hydrodynamic resistance, propulsion-system improvements target the conversion efficiency between fuel energy and useful thrust.

1.3.3.1 Propeller and Hydrodynamic Interaction

Improvements in propeller design can significantly enhance overall propulsion efficiency. Developments such as high-efficiency fixed-pitch propellers, controllable pitch propellers, and contra-rotating propeller systems reduce rotational energy losses and improve wake interaction, resulting in measurable efficiency gains under steady and low-speed operating conditions typical of short-sea vessels (Gaggero et al., 2016; SINTEF, 2025). These gains are particularly relevant for ferries and service vessels operating within relatively narrow and predictable speed ranges.

Additional hydrodynamic improvements may be achieved through the use of ducts and nozzles, which enhance thrust performance for heavily loaded propellers at low speeds. Podded propulsion systems further improve manoeuvrability and can increase propulsive efficiency in confined or port-centric waters, where frequent course adjustments and low-speed operations dominate. For pilot vessels and harbour service craft, manoeuvrability improvements are often as important as pure fuel-efficiency gains.

1.3.3.2 Hybrid and Diesel-Electric Configurations

For vessels characterized by fluctuating power demand, hybrid propulsion architectures combining internal combustion engines, electric motors, and onboard energy storage provide significant operational advantages (Perčić et al., 2021; Wallenstein et al., 2025). By allowing combustion engines to operate closer to optimal load points while electric components handle peak or low-load conditions, hybrid systems reduce fuel consumption, improve part-load efficiency, lower emissions and reduce engine wear.

Diesel-electric hybrid configurations represent an important transitional pathway toward full electrification by decoupling power generation from propulsion demand. Instead of mechanically coupling engines directly to propellers, electricity is generated and distributed through a power management system. This configuration enables optimized generator dispatch and facilitates the integration of batteries or alternative fuels (Geertsma et al., 2017; Roslan et al., 2022).

In short-sea shipping, where duty cycles include frequent acceleration, deceleration, and standby phases, such flexibility is particularly beneficial. As demonstrated in Articles

I-III, predictable and repetitive duty cycles enhance the effectiveness of hybrid integration, especially when combined with digital energy management systems.

1.3.3.3 Machinery Efficiency and Engine Optimization

Machinery systems, including engines, generators, power electronics, and thermal management systems, also influence overall vessel performance (Yao et al., 2019; H. Zhang et al., 2025). Modern medium-speed marine diesel engines achieve thermal efficiencies of approximately 45-50% through advances in common-rail fuel injection, turbocharging optimization, electronic combustion control and waste-heat recovery systems.

However, incremental improvements in diesel efficiency alone cannot achieve long term decarbonization targets. Consequently, machinery development increasingly focuses on fuel flexibility, allowing engines to operate on low-carbon fuels such as methanol, biofuels, or ammonia-compatible blends (Radica et al., 2025; Reddy et al., 2023; Xiong et al., 2024).

Waste-heat recovery technologies, although more common in large ocean-going vessels, are also being adapted for smaller-scale applications (Miller et al., 2024; Singh & Pedersen, 2016). By converting exhaust heat into useful electrical or mechanical energy, waste heat recovery systems can further improve overall system efficiency. For small vessels, however, feasibility depends strongly on space availability and economic justification.

1.3.3.4 System Integration and Digital Energy Management

The integration of propulsion systems with digital energy management platforms represents a growing area of innovation. Real-time monitoring, predictive maintenance systems, and demand-based load control improve generator dispatch strategies and reduce unnecessary fuel consumption (Viktorelius & Lundh, 2019). For hybrid and battery assisted vessels, energy management systems optimize charge discharge cycles and reduce inefficient generator operation.

Vessels operating on predictable duty cycles benefit particularly from digital optimization, as energy consumption patterns can be modelled and controlled with higher accuracy. In small-vessel contexts, where energy margins and storage capacity are limited, such system-level optimization significantly influences both environmental performance (RQ1) and economic feasibility (RQ2).

1.3.4 Alternative Fuels

Transitioning from conventional marine diesel requires compatibility with alternative fuels that differ in chemical composition, energy density, storage requirements, and combustion characteristics. alternative fuels are therefore evaluated across three dimensions: life cycle GHG performance, onboard technical feasibility, and infrastructure compatibility (Roux et al., 2024; Wang et al., 2025; Zhou et al., 2024). For vessels below 5,000 GT operating in short-sea contexts, these dimensions are particularly sensitive to space constraints, route length, and port readiness.

Battery-electric propulsion has emerged as one of the most mature low-emission solutions for short-distance ferry and port-service operations (Aksöz et al., 2025; Laasma et al., 2022). Its primary advantages include high drivetrain efficiency and zero exhaust emissions during operation. However, it is widely noted in LCA literature (Lee et al., 2024; Wang et al., 2025) that the overall environmental performance depends strongly on electricity generation mix and battery production impacts. From a technical perspective, battery systems impose weight and volume penalties due to limited energy density, making them most suitable for fixed, predictable routes with reliable shore-side charging infrastructure. Thus, electrification performance (RQ1) is closely linked to infrastructure conditions and route characteristics (RQ3).

Hydrogen is frequently identified as a long-term zero-emission fuel, particularly when produced via renewable electricity (green hydrogen) (Dong et al., 2024; Nguyen et al., 2025). It offers high gravimetric energy density but low volumetric density, requiring large storage tanks and advanced safety systems. Fuel-cell propulsion systems provide high conversion efficiency and low noise, yet economic feasibility remains constrained by fuel production costs and limited bunkering infrastructure. For small vessels with restricted onboard space, storage volume and weight become critical design constraints, directly influencing both environmental performance and operational practicality.

Methanol has gained increasing attention as a transitional marine fuel, because it can be used in modified internal combustion engines and requires less extreme storage conditions than hydrogen or LNG (Karvounis et al., 2023; Nunes, 2025). When produced from biomass or renewable electricity (bio-methanol or e-methanol), significant WTW GHG reductions are achievable, although upstream emissions remain highly pathway-dependent (Roux et al., 2024). For small fleets, methanol's compatibility with adapted engine systems may reduce retrofit complexity compared to more disruptive fuel transitions. However, supply limitations and cost competitiveness remain key economic considerations (RQ2).

Ammonia is often discussed as a carbon-free fuel option with more favourable storage properties than hydrogen. Nevertheless, its toxicity, combustion characteristics, and immature engine technology present substantial technical challenges, particularly for small vessels (Dong et al., 2024; X. Zhou et al., 2024). Current research suggests that ammonia may be more suitable for larger vessels with greater storage flexibility and established safety systems, whereas its applicability to small-vessel fleets remains constrained by space, safety, and handling considerations.

Biofuels (including biodiesel, hydrotreated vegetable oil (HVO), and bio-LNG) are frequently described as "drop-in" or near drop-in solutions compatible with existing engine systems (Bedekar et al., 2024; DNV, 2025; Wang & Wright, 2021). Their principal advantage lies in reduced retrofit requirements and immediate integration into existing fleets. Life-cycle GHG reductions depend strongly on feedstock type, land-use impacts, and production pathways (Roux et al., 2024). For small vessels operating under capital constraints, biofuels may offer a pragmatic short- to medium-term pathway, balancing environmental performance (RQ1) with economic feasibility (RQ2). However, long-term scalability and sustainability certification remain ongoing concerns.

Hybrid configurations, combining batteries with diesel or alternative fuels, represent a transitional architecture that allows load levelling and improved engine efficiency (Kolodziejski & Michalska-Pozoga, 2023; Maydison et al., 2025). Hybridization is particularly advantageous in vessels with variable duty cycles (such as pilot boats and short-route ferries) where peak power demand and manoeuvring phases can be supported by battery systems, while combustion engines operate closer to optimal efficiency. Hybrid systems often enhance both emission reduction potential and operational flexibility, thereby linking environmental performance with infrastructural and operational constraints (RQ3).

Alternative fuel selection in small vessels is multidimensional. Environmental performance depends on life cycle production pathways, economic feasibility on fuel price and retrofit requirements, and technical suitability on storage space, route length, and infrastructure availability. Fuel transitions must therefore be assessed in relation to vessel specific operational and infrastructural conditions, not emissions alone

1.3.5 Energy Collection Systems

Energy collection systems complement onboard propulsion by harvesting renewable energy directly from the vessel's operating environment. Unlike alternative fuels, which substitute energy carriers, energy collection technologies reduce overall fuel demand by supplementing onboard power generation. In maritime decarbonization research, such systems are typically discussed as auxiliary efficiency-enhancement measures rather than primary propulsion solutions (Carjova et al., 2025; Guzelbulut et al., 2024).

Wind-assisted propulsion technologies (including Flettner rotor sails, rigid wing sails, and towing kites) have received increasing attention in recent years. Empirical and simulation-based studies report fuel savings ranging between approximately 5% and 20%, depending on vessel size, route characteristics, wind availability, and integration strategy (Carjova et al., 2025; Guzelbulut et al., 2024). While most applications have been concentrated in deep-sea bulk carriers and tankers, research suggests that selected short-sea routes with favourable wind conditions may also benefit from hybrid wind-assist configurations. However, spatial constraints, stability considerations, and manoeuvrability requirements may limit their applicability in smaller vessels operating in confined waters.

Solar photovoltaic systems represent another complementary energy collection measure. Although solar panels typically cannot supply propulsion power for maritime vessels due to limited deck area and relatively low energy density, they can meaningfully contribute to auxiliary loads such as lighting, navigation equipment, and onboard electronics (Pivetta et al., 2022). Integration of solar photovoltaic systems with battery storage enables peak shaving during port stays and reduces generator use during low-load conditions.

From a life-cycle perspective (RQ1), energy collection systems reduce operational fuel consumption and associated emissions without requiring fundamental changes to propulsion architecture. Economically (RQ2), their feasibility depends on capital costs, expected fuel savings, maintenance requirements, and vessel lifetime. For small vessels with limited deck space and strict stability margins, cost-effectiveness is highly context-dependent. Operationally (RQ3), the performance of wind- and solar-assisted systems is influenced by route regularity, geographic location, and seasonal variability.

Energy collection technologies are best understood as supplementary measures that improve system efficiency rather than replace primary propulsion fuels. In small vessels, their role is incremental but valuable, especially when integrated with electrified or hybrid propulsion. By reducing auxiliary load and supporting energy optimization, they contribute to emission reduction without major structural modifications.

1.4 Operational Measures

Operational measures refer to strategies that reduce fuel consumption and emissions through changes in how vessels are operated rather than through physical modification of ship systems. Unlike technical measures, which involve engineering interventions, operational measures focus on voyage planning, speed management, maintenance practices, and decision-making processes. In maritime decarbonization literature, operational strategies are frequently identified as cost-effective short- to medium-term options capable of delivering meaningful emission reductions without large capital investment (Degiuli et al., 2024; Yuan et al., 2023).

One of the most widely discussed operational strategies is speed reduction, commonly referred to as “slow steaming.” Because hydrodynamic resistance increases approximately with the cube of vessel speed, even moderate reductions in speed can lead to disproportionate reductions in fuel consumption and associated GHG emissions. Numerous empirical and modelling studies confirm that speed optimization remains among the most effective immediate measures for reducing emissions in both deep-sea and short-sea shipping contexts (Degiuli et al., 2024; Robalo-Cabrera et al., 2025; Yuan et al., 2023).

Beyond speed management, route optimization and weather routing contribute to improved fuel efficiency by minimizing resistance-inducing sea states and avoiding unnecessary detours (Du et al., 2022; Duan et al., 2021; Latinopoulos et al., 2025; Robalo-Cabrera et al., 2025). Trim optimization and hull-condition monitoring further enhance performance by ensuring that vessels operate under hydrodynamically efficient configurations. Just-in-time arrival strategies reduce unnecessary waiting times at ports, lowering auxiliary engine operation and fuel use during anchorage. Maintenance regimes, particularly hull cleaning and propeller polishing, help to prevent efficiency losses associated with biofouling and surface degradation.

Digitalization plays an increasingly important role in enabling these operational improvements (Zeng et al., 2025). Real-time monitoring systems, voyage decision-support platforms, and performance analytics allow captains and fleet managers to adjust operational parameters dynamically (Dewan & Godina, 2024; Viktorelius & Lundh, 2019). Such systems integrate weather data, speed profiles, fuel consumption measurements, and engine performance indicators to support evidence-based decision-making. For vessels operating on predictable duty cycles (such as ferries examined in Article III) operational optimization can be systematically embedded into scheduling and charging strategies, directly influencing both emissions (RQ1) and cost performance (RQ2).

Operational measures also extend to fleet-level planning and service design. Route restructuring, timetable coordination, demand forecasting, and modal integration can significantly reduce overall system-level energy consumption. Optimizing charging windows, aligning grid availability with service frequency, and reducing peak load demands can enhance both technical reliability and economic viability (RQ3).

Human and organizational factors further influence operational effectiveness. Crew training, adherence to energy-efficient navigation practices, and management commitment to sustainability are essential for realizing projected fuel savings (Poulsen et al., 2022; Viktorelius & Lundh, 2019). Without behavioural adaptation, even technologically optimized vessels may underperform relative to theoretical efficiency potential.

Although operational measures alone cannot achieve full decarbonization, they provide immediate and scalable emission reductions while longer-term technological transitions are implemented. In small-vessel contexts (where capital investment capacity may be limited) operational optimization often represents the most accessible first step toward lower emissions. When combined with technical measures and alternative fuels, operational strategies enhance overall system performance and support context-sensitive decarbonization pathways.

1.5 New Means of Transport

In addition to incremental improvements to conventional vessels, maritime decarbonization research increasingly explores alternative transport concepts that aim to reduce hydrodynamic resistance or reconfigure maritime mobility systems. These emerging technologies do not merely improve existing ship designs, but attempt to alter fundamental performance characteristics such as drag, speed, and energy intensity.

One prominent category includes aerodynamic or surface-skimming craft, such as hydrofoils and ground-effect vehicles (GEVs), also known as wing-in-ground (WIG) craft. These vessels operate partially above the water surface, reducing hydrodynamic drag and enabling higher speeds with potentially lower energy consumption per transport unit under suitable conditions (Kerem et al., 2025; Sakornsin et al., 2020; Yang & Czysz, 2011). By exploiting the aerodynamic ground effect, GEVs generate lift close to the water surface, which can increase energy efficiency compared to high-speed displacement vessels. While such technologies present environmental potential (RQ1), their practical implementation depends strongly on market structure and operational conditions (RQ2 and RQ3).

Recent industry developments further indicate growing commercial interest in ground-effect craft. For example, an engineering company has announced the development of a commercial wing-in-ground vessel platform targeting regional and island transport applications, highlighting increasing institutional and technological momentum in this segment (Spray, 2026). Although large-scale deployment remains limited, these developments suggest that alternative vessel concepts are transitioning from experimental prototypes toward pilot commercial applications.

Another innovation pathway involves autonomous and remotely operated vessels. Automation may enable optimized routing, reduced crew-related energy demand, and lighter vessel configurations, potentially improving overall energy efficiency (Batista Santos & Santos, 2024; Gabrielii et al., 2024). Several Nordic pilot projects demonstrate the feasibility of small autonomous electric vessels operating on fixed routes (Gabrielli et al., 2024; Joki-Korpela et al., 2025; Raviv, 2026). While autonomy itself does not directly eliminate emissions, it can enhance operational optimization and enable fully electric configurations in controlled service environments.

Broader system-level innovations, such as green shipping corridors and multimodal integration with renewable energy systems, represent another dimension of emerging transport concepts (Akhavan, 2025; Ismail et al., 2024; Shangguan et al., 2024; Wang, 2025). In such configurations, maritime transport is embedded within larger energy ecosystems involving shore-side renewables, storage solutions, and coordinated logistics networks. These systemic approaches emphasize that decarbonization may result not only from improved vessels but also from reconfigured transport systems.

While many of these technologies remain in early deployment stages, they illustrate that maritime decarbonization is not limited to fuel substitution or efficiency improvements within conventional vessel architectures. For small-vessel and short-sea contexts in particular (where route distances are moderate and geographic constraints are pronounced) novel transport concepts may provide niche but meaningful alternatives. However, their suitability depends on environmental performance, economic feasibility, and infrastructure compatibility, reinforcing the integrated evaluation framework applied throughout this dissertation.

1.6 Integrated Decarbonization Pathways for Small Maritime Vessels

The literature reviewed in Sub-Chapters 2.1-2.5 demonstrates that maritime decarbonization is a multi-dimensional process shaped by interacting technical, operational, and system-level factors. While individual studies often focus on specific technologies, fuels, or policy instruments, the implementation of low-emission solutions in small-vessel contexts depends on the alignment between vessel-level engineering measures, operational practices, and broader infrastructural and market conditions.

At the technical level, decarbonization pathways involve modifications to hull design, propulsion and machinery systems, alternative fuels, and onboard energy systems. These measures directly influence energy demand, fuel compatibility, and emissions performance. Improvements in hydrodynamic efficiency, propulsion optimization, electrification, hybridization, and fuel substitution reduce greenhouse gas emissions and determine the baseline environmental performance of a vessel (RQ1). However, technical potential alone does not guarantee feasibility.

At the operational level, measures such as speed management, routing, scheduling, maintenance practices, and digitalization influence real-world energy consumption. Operational optimization can significantly reduce emissions without major capital investments, particularly in short-sea and ferry operations characterized by predictable duty cycles. Digital energy management systems further enhance system integration by optimizing load distribution, battery charge-discharge cycles, and generator dispatch. These operational factors influence both environmental performance (RQ1) and cost efficiency (RQ2), while also determining the practical suitability of technical solutions under specific duty profiles (RQ3).

At the system level, infrastructure availability, policy and regulatory context, and market conditions shape the external environment within which technical and operational measures are implemented. Grid capacity, charging infrastructure, alternative fuel bunkering facilities, investment support mechanisms, and contractual arrangements influence whether technically viable solutions can be deployed in practice. In small-vessel fleets, limited port infrastructure and capital constraints often represent decisive barriers. These systemic factors therefore condition operational feasibility and economic viability (RQ2 and RQ3).

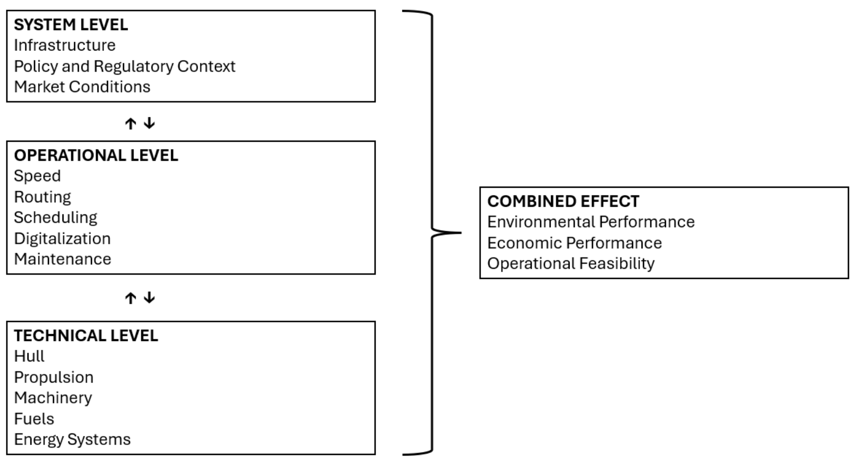

Figure 2. Integrated Decarbonization Pathways for Small Maritime Vessels. Compiled by author.

Figure 2 illustrates the interaction between these three levels. The technical and operational domains function within a broader system context, and their combined effect determines environmental performance (RQ1), economic feasibility (RQ2), and operational suitability under infrastructure constraints (RQ3).

The figure emphasizes that decarbonization outcomes are not determined by a single technological choice, but by the alignment between vessel technology, operational patterns, and system-level readiness.

Rather than representing a prescriptive framework, this synthesis conceptualizes decarbonization as a layered interaction process. For small vessels operating in short-sea and coastal contexts, the balance between these levels is particularly sensitive due to limited onboard space, high manoeuvring demand, short turnaround times, and infrastructure dependency. Consequently, effective decarbonization strategies must integrate engineering optimization, operational management, and infrastructure compatibility.

This synthesized perspective provides the theoretical grounding for the empirical analyses presented in Chapters 4 and 5. The case studies evaluate how environmental performance (RQ1), economic feasibility (RQ2), and operational-infrastructural constraints (RQ3) interact in real-world small-vessel applications, thereby linking the literature review to the dissertation’s empirical contribution. This integrated perspective also reflects broader socio-technical transition literature, which emphasizes multi-level interaction between technology, operations, and institutional systems.

2 Methodology and Research Design

2.1 Research Approach

The methodological contribution of this dissertation lies in addressing a topic often fragmented in the literature: the evaluation of environmental performance, economic feasibility, and operational constraints in the decarbonization of small maritime vessels. While existing studies frequently analyze these dimensions separately, this research integrates them within empirical case studies of short-sea and coastal operations.
A mixed-method, multi-case study design was adopted, enabling both quantitative assessment and contextual interpretation. Quantitative methods (including LCA, techno-economic modelling, and energy performance analysis) provide measurable insights into GHG emissions and financial viability. Complementary qualitative interpretation of operational conditions and infrastructural constraints situates these findings within real-world maritime contexts. By integrating these approaches, the dissertation captures how technological capability, investment requirements, and operational realities jointly influence decarbonization decisions in small-vessel fleets.

The case study approach draws on established methodological principles from social science and maritime research (Eisenhardt, 1989; Stake, 1995; Stopford, 2009; Yin, 2016). Case studies allow in-depth investigation of complex, context-dependent phenomena, which is particularly relevant for small-vessel fleets operating under variable technical, economic, and infrastructural conditions. They support the integration of multiple evidence sources (like operational data, technical performance metrics, cost data, and industry documentation) strengthening internal validity. By selecting cases that represent different vessel types, routes, and operational patterns, the study also supports external validity, offering insights transferable to comparable small maritime economies.

The analytical perspective further draws on maritime economics (Stopford, 2009) and techno-economic evaluation principles (Sullivan et al., 2012), which emphasize the interaction between capital investment, operating costs, technical performance, and market conditions. In this dissertation, these theoretical perspectives guide the evaluation of life-cycle emissions (RQ1), cost performance (RQ2), and operational feasibility under infrastructural constraints (RQ3).

Methodological quality in case study research is commonly evaluated through the criteria of internal validity, construct validity, and reliability (Yin, 2016). Internal validity refers to the degree to which relationships identified in the research accurately reflect causal or explanatory connections within the studied cases. Construct validity concerns whether the concepts and variables used in the analysis adequately represent the phenomena being investigated. Reliability refers to the consistency and transparency of the research procedures, ensuring that the analytical process can be understood and replicated by other researchers.

Internal validity was ensured through cross-verification of operational measurements, modelling outputs, and cost calculations. Reliability was strengthened by applying consistent analytical procedures across the four case studies. Construct validity was maintained through clearly defined functional units, system boundaries, and economic parameters, ensuring transparent representation of environmental and financial performance indicators.

2.2 Research Design and Logic

The research design follows a structured progression from vessel-level environmental assessment to economic feasibility evaluation and, finally, to operational and infrastructural considerations affecting implementation. This sequence reflects the three research questions and ensures a coherent analytical logic across the case studies.

At the first level (RQ1), the study evaluates the environmental performance of alternative propulsion systems and fuels using LCA and operational energy data. Articles I and II quantify greenhouse gas (GHG) emissions under WTW and TTW boundaries, allowing comparison between conventional diesel systems and low- or zero-emission alternatives. This provides empirical evidence on the magnitude of emission reductions achievable in small-vessel operations.

At the second level (RQ2), the research examines the economic feasibility of these technological alternatives. Techno-economic modelling, including life-cycle cost (LCC) analysis and payback calculations, is applied across Articles I-III to assess capital investment, operating costs, energy prices, and maintenance implications. This level of analysis determines whether technically viable solutions are also financially realistic for small fleets operating under constrained margins.

At the third level (RQ3), the study analyses operational and infrastructural constraints influencing implementation. Articles II and III assess storage limitations, duty-cycle variability, charging requirements, and port infrastructure readiness. Article IV extends this perspective by evaluating the feasibility of an emerging transport concept (ground-effect vehicle) under specific geographic and market conditions. Together, these cases demonstrate that decarbonization outcomes depend not only on emissions performance and cost but also on route characteristics, energy supply systems, and operational patterns.

Each case study builds upon the previous one. The analysis progresses from single-vessel comparison (Article I), to fuel substitution within a specialised fleet (Article II), to system-level evaluation of regional ferry operations (Article III), and finally to assessment of an emerging transport concept within a defined market context (Article IV). This layered structure enables both analytical depth and cross-case synthesis.

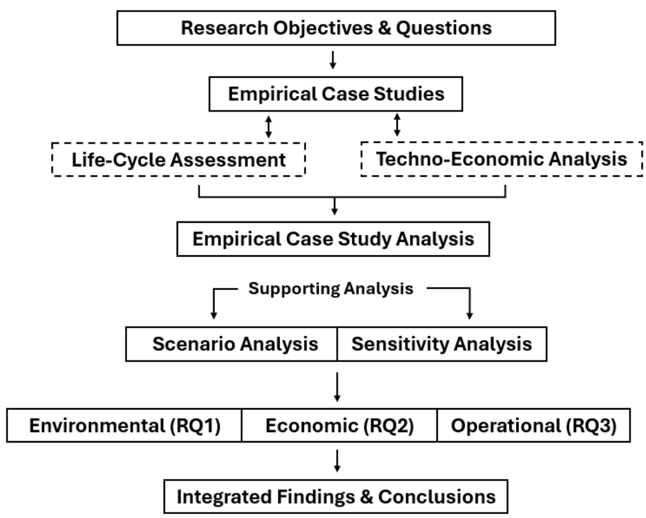

Figure 3. Research design and analytical procedure of the dissertation

Figure 3 presents the research design and analytical procedure applied in this dissertation. It illustrates how life-cycle assessment and techno-economic analysis are implemented within the case study structure, and how scenario and sensitivity analyses support the evaluation of environmental performance (RQ1), economic feasibility (RQ2), and operational constraints (RQ3).

2.3 Case Study Design

The four case studies collectively address the three research questions through complementary analytical lenses (Table 1). Articles I and II focus primarily on vessel-level environmental performance using WTW LCA, directly informing RQ1, while also highlighting operational characteristics and constraints relevant to RQ3. Article III extends the analysis to fleet-level techno-economic feasibility, addressing RQ2 and incorporating scenario-based evaluation of infrastructural and operational conditions relevant to RQ3. Article IV broadens the perspective to an emerging transport concept, integrating environmental and commercial assessment and thereby contributing to all three research questions. Together, the case studies provide a coherent empirical foundation for evaluating environmental performance, economic feasibility, and contextual implementation factors in small-vessel decarbonization.

Table 1. Case Study Design of the Thesis

Case Study	***Focus***	***Main Methods***	***Data Sources***	***Addressed RQs***
ARTICLE I Decarbonizing City Water Traffic: Case of Comparing Electric and Diesel-Powered Ferries	*Comparative environmental and economic performance of electric and diesel propulsion*	*WTW LCA, operational energy analysis; life-cycle cost modelling*	*Measured operational ferry data; electricity grid data; emission factor databases*	*RQ1, RQ2,*
ARTICLE II Comparative Analysis of the Alternative Energy: Case of Reducing GHG Emissions of Estonian Pilot Fleet	*Environmental performance and fuel substitution feasibility in pilot vessel operations*	*WTW LCA, fuel property modelling, sensitivity analysis*	*Fleet fuel consumption records; emission databases; national energy statistics; FuelEU Maritime*	*RQ1*
ARTICLE III Decarbonization of Estonian Ferry Lines – Challenges and Opportunities	*Technical and economic feasibility of decarbonization pathways at fleet level*	*Scenario modelling; cost and emission simulations*	*Operational fleet data; energy price scenarios; emission databases; national statistics; FuelEU Maritime*	*RQ2, RQ3*
ARTICLE IV *Business Opportunities for a Ground Effect vehicle - Case of Canary Islands*	*Environmental and commercial assessment of an emerging maritime transport concept*	*Comparative cost and emission modelling; market feasibility analysis*	*Manufacturer specifications; route demand data; transport statistics*	*RQ1, RQ2, RQ3*

2.4 Methods of Analysis

This dissertation applies a combination of quantitative and interpretative analytical methods to examine environmental performance, economic feasibility, and implementation conditions of decarbonization pathways in small maritime vessels. The selected methods correspond directly to the three research questions by evaluating (1) life-cycle environmental impacts, (2) techno-economic feasibility, and (3) operational and infrastructural constraints influencing implementation.

LCA was applied primarily in Articles I and II to quantify GHG emissions associated with different propulsion systems and fuel alternatives. Both TTW and WTW system boundaries were considered, covering emissions from fuel production, energy conversion, and onboard use. Functional units were defined based on operational output (e.g., fuel consumption per nautical mile or vessel operating hour), ensuring consistency with vessel-specific duty profiles.

LCA enables comparison across electric, hybrid, and fuel-based propulsion systems by incorporating upstream energy production processes in addition to operational emissions (ISO, 2006; Wang et al., 2025). Sensitivity analyses were conducted to account for variations in electricity mix, fuel carbon intensity, and energy supply assumptions. The reliability of LCA results depends on the quality of emission factors and fuel pathway data (Krantz et al., 2023), and therefore multiple sources were cross-checked to enhance robustness.

To evaluate financial feasibility (RQ2), techno-economic modelling was applied across all case studies. LCC analysis incorporated capital expenditure (CAPEX), operational expenditure (OPEX), fuel and electricity prices, maintenance costs, and discount rates (Kanchiralla et al., 2022). Payback period calculations were used where relevant to assess investment recovery time under different subsidy and energy price scenarios.

Scenario-based modelling and scenario analysis were used to explore how results change under different plausible future conditions rather than assuming one fixed set of inputs. In this research, a “scenario” refers to a consistent set of assumptions (for example, electricity mix, fuel prices, emission factors, technology costs, or infrastructure availability) applied to the same vessel or fleet context. Scenario analysis enables comparison of decarbonization pathways across alternative conditions, while sensitivity analysis tests how strongly individual parameters (such as energy price or carbon intensity) influence outcomes. these approaches support robust interpretation by identifying which findings are stable across uncertainty and which depend on specific assumptions.

Scenario testing allowed examination of cost sensitivity to changes in energy prices, carbon intensity, and infrastructure availability. While techno-economic models provide structured insight into investment viability, outcomes are inherently sensitive to assumptions regarding market conditions and financing parameters. Broader behavioural and financing constraints (such as risk perception and capital access (McKinsey, 2022)) were not explicitly modelled but are acknowledged as influencing real-world decision-making.

Article III employed scenario-based modelling to evaluate fleet-level decarbonization pathways under varying infrastructure, cost, and operational conditions. This approach enabled comparison of alternative technology combinations while accounting for infrastructure readiness, route characteristics, and operational patterns.

Scenario analysis supports RQ3 by identifying how contextual variables (such as charging capacity, fuel availability, and route length) shape the feasibility of decarbonization strategies (Psaraftis & Kontovas, 2021; Zis et al., 2020). Rather than predicting exact outcomes, the modelling framework provides structured comparison of alternative configurations under defined assumptions.

Across the research, the analytical methods are complementary. LCA provides environmental performance assessment (RQ1), techno-economic modelling evaluates financial viability (RQ2), and scenario analysis explores operational and infrastructural constraints influencing implementation (RQ3). By combining these approaches, the research captures the interaction between technical performance, economic feasibility, and contextual conditions in small-vessel maritime decarbonization.

The methodological integration is deliberately focused on environmental and economic evaluation rather than formal policy analysis. Regulatory frameworks are considered as boundary conditions influencing cost structures and investment incentives, but they are not independently analysed as policy instruments.

To ensure methodological transparency, key assumptions underlying the analyses are explicitly defined across the case studies. These include assumptions related to energy prices, electricity mix, fuel emission factors, technology performance parameters, and discount rates. While these assumptions are based on the best available data and literature sources, they introduce inherent uncertainty into the results. The implications of these assumptions are addressed through sensitivity and scenario analysis, which illustrate how variations in key parameters affect environmental and economic outcomes. Consequently, the results should be interpreted as scenario-dependent rather than universally fixed, reflecting the dynamic nature of maritime energy systems and technology development.

In addition, key assumptions applied in each case study (including energy prices, emission factors, technology performance parameters, and operational conditions) are explicitly defined within the respective articles and summarized in the synthesis. This ensures transparency and allows interpretation of results in relation to underlying modelling conditions.

3 Results

This chapter presents the empirical findings of the four publications and synthesizes them in relation to the three research questions.
The results are structured according to:

1. environmental performance
2. economic feasibility
3. operational and infrastructural constraints.

The chapter concentrates on measured and modelled performance outcomes, together with the factors affecting implementation in vessels below 5,000 GT, instead of focusing on regulatory instruments themselves.

The dissertation is based on four peer-reviewed articles, each addressing a specific aspect of small-vessel decarbonization. Article I focuses on vessel-level electrification, Article II examines alternative fuels in pilot vessels, Article III analyses fleet-level ferry decarbonization, and Article IV explores an emerging transport concept. Together, these studies provide a structured and complementary empirical basis for addressing the research questions.

3.1 Environmental Performance of Decarbonization Pathways

This section addresses RQ1: What is the environmental performance of alternative propulsion and fuel solutions for vessels below 5,000 GT?

Across the four publications, substantial GHG emission reductions are technically achievable for small vessels, although the magnitude of reductions varies significantly depending on propulsion type, fuel pathway, electricity mix, and system boundaries.

In Article I (Decarbonizing City Water Traffic: Case of Comparing Electric and Diesel-Powered Ferries), a WTW life-cycle assessment compared an electric ferry with its diesel-powered sister vessel operating on the same fixed urban route. The analysis showed that the battery-electric configuration generated approximately 75% lower GHG emissions than the diesel vessel under the prevailing electricity mix. Lower drivetrain losses and elimination of idling contributed to reduced operational energy demand. However, the results demonstrate that emission reductions are highly dependent on electricity carbon intensity, confirming that electrification performance is system-dependent rather than inherently zero-emission.

Article II (Comparative Analysis of the Alternative Energy: Case of Reducing GHG Emissions of Estonian Pilot Fleet) assessed alternative fuels for pilot vessels using WTW boundaries. Biomethane achieved the highest reduction potential (approximately 59% compared to marine diesel oil), followed by HVO and biodiesel with moderate reductions. However, upstream production pathways significantly influenced results. Hydrogen and synthetic fuels demonstrated theoretically deep decarbonization potential, yet their life-cycle performance varied depending on electricity source and production method. The findings confirm that fuel choice alone does not determine environmental outcome; upstream processes are decisive.

At fleet level, Article III (Decarbonization of Estonian Ferry Lines – Challenges and Opportunities) modelled emission scenarios for electrified and hybrid ferry operations. Electrification yielded significant emission reductions on short routes when combined with shore-side charging. Hybrid systems reduced fuel consumption by enabling engines to operate closer to optimal load profiles, while batteries absorbed peak demand. The modelling demonstrates that route length and operational regularity strongly influence achievable reductions.

Article IV (Business Opportunities for a Ground Effect Vehicle – Case of Canary Islands) extended environmental comparison to an emerging transport concept. The results indicate that GEVs can reduce emissions per transport work unit compared to short-distance aviation under high-load conditions. However, performance advantages are sensitive to utilization rates and route discipline.

Across all studies, three consistent environmental insights emerge: (i) electrification provides the highest emission reductions on short, predictable routes with low-carbon electricity, (ii) alternative fuels offer differentiated reduction potentials depending on life-cycle production pathways, and (iii) hybrid configurations improve efficiency in vessels with variable load profiles. Thus, meaningful decarbonization of small vessels is achievable, but emission performance depends on energy systems, operational stability, and system boundary assumptions.

3.2 Economic Feasibility and Investment Implications

This section addresses RQ2: What is the economic feasibility of these decarbonization pathways under real operational conditions?

While environmental performance is often technically promising, economic feasibility determines practical adoption. In Article I, life-cycle cost modelling showed that battery-electric propulsion involves higher upfront capital expenditure compared to diesel alternatives. However, lower operating costs and reduced maintenance contribute to long-term financial benefits. The calculated payback period was approximately 17 years without subsidies, reduced to about 10 years, when financial support mechanisms were included. The results demonstrate that electrification viability depends strongly on electricity prices, battery lifetime assumptions, and policy-based investment support.

In Article II, economic feasibility of fuel substitution varied substantially. Drop-in fuels such as HVO required minimal retrofit investment and therefore represented lower financial risk. In contrast, hydrogen or ammonia systems would require substantial infrastructure and onboard storage modifications, significantly increasing capital intensity. Storage penalties directly affect payload capacity and thus operational revenue potential.

At system level, Article III demonstrated that electrification becomes economically favourable only when route predictability and charging infrastructure reduce operational uncertainty. Infrastructure investments, particularly grid reinforcement and charging installations, may shift financial burdens between operators and public actors. This cost redistribution affects investment timing and financing structures.

Article IV approached economic feasibility from a business-model perspective. GEV deployment could become competitive on high-value, time-sensitive routes but remains sensitive to scale, demand stability, and cost assumptions. Unlike incremental retrofits, emerging concepts require coordinated market development rather than isolated vessel investment.

Across the cases, three recurring economic patterns are observed: (i) capital expenditure is immediate, whereas cost savings accrue over long horizons; (ii) infrastructure availability significantly alters financial outcomes; (iii) economic viability is highly route- and duty-cycle dependent. Thus, technical feasibility does not automatically translate into economic adoption. Small-vessel decarbonization is fundamentally an investment optimization problem constrained by capital intensity, infrastructure costs, and operational predictability.

3.3 Operational and Infrastructural Constraints

This section addresses RQ3: How do operational characteristics and infrastructure constraints influence the suitability of different decarbonization options for small vessels?

Across all case studies, operational patterns and infrastructural readiness emerge as decisive feasibility factors. In Article I, electrification success depended on fixed route length, predictable turnaround times, and reliable high-capacity shore charging. Battery capacity had to align with daily duty cycles. Without synchronized charging infrastructure, technical feasibility would not translate into reliable service.

Article II highlighted the influence of highly variable duty cycles in pilot vessels. Frequent manoeuvring, standby periods, and fluctuating loads reduce the practicality of certain propulsion options. Storage volume and weight constraints severely limit hydrogen or ammonia feasibility in small craft, demonstrating how physical vessel characteristics shape technology suitability.

In Article III, ferry-line modelling showed that infrastructure readiness (grid strength, charging capacity and port configuration) and service stability determine investment viability. Electrification becomes realistic only when operational planning and infrastructure deployment are coordinated.

In Article IV, route characteristics (distance, demand frequency and cargo type) determined whether the GEV concept was operationally viable. Emerging technologies are highly sensitive to utilization rates and route discipline.

Across vessel types, three structural constraints consistently appear: (i) limited onboard space for fuel storage or batteries, (ii) dependence on port-based infrastructure, (iii) sensitivity to duty-cycle variability. These findings confirm that decarbonization suitability is not solely driven by technology. Instead, adoption feasibility arises when propulsion systems align simultaneously with operational profiles, spatial limitations, and energy-system conditions.

3.4 Emerging Transport Concepts within Small-Vessel Decarbonization

While Articles I-III focus on improving existing vessel categories, Article IV broadens the analytical scope by examining an alternative transport concept. The GEV case illustrates that decarbonization strategies may extend beyond fuel substitution toward alternative vehicle configurations. Under certain geographic conditions (archipelagic networks with moderate distances and stable demand), GEVs may reduce emissions relative to short-haul aviation while offering competitive travel times.

However, economic viability remains niche-dependent and sensitive to scale. Certification requirements, infrastructure adaptation, and utilization rates introduce additional uncertainty.

The broader implication is that innovation-driven decarbonization may complement incremental technical improvements. For small maritime systems, emerging concepts may expand the solution space, provided operational and economic conditions support deployment.

3.5 Research Contribution

3.5.1 Addressing Identified Research Gaps

This dissertation addresses specific gaps in maritime decarbonization research concerning vessels below 5,000 GT operating in short-sea and regional contexts. First, while extensive literature exists on decarbonization of large ocean-going vessels and global shipping corridors, comparatively limited empirical attention has been devoted to small and medium-sized vessels such as ferries, pilot boats, and regional service vessels. These vessels operate under fundamentally different boundary conditions, including limited onboard space, frequent manoeuvring, short duty cycles, and high dependence on local infrastructure. The present research responds to this gap by providing vessel-level empirical analysis across multiple small-vessel categories.

Second, many existing studies evaluate environmental performance and economic feasibility separately. This dissertation systematically combines WTW life-cycle assessment with life-cycle cost modelling across real operational cases. By integrating environmental and economic evaluation within the same empirical framework, the research reveals trade-offs between emission reduction potential, capital intensity, and operational constraints.

Third, limited research has examined, how operational characteristics and infrastructure readiness constrain or enable decarbonization pathways in small fleets. The case studies demonstrate that route length, duty-cycle variability, grid capacity, storage limitations, and infrastructure coordination are decisive determinants of feasibility.

The dissertation treats international and EU climate ambitions as drivers shaping investment conditions and energy-market development, rather than examining policy instruments directly. Against this backdrop, the research provides empirical and techno-economic evidence on how small-vessel operators can respond to decarbonization pressures through viable transition solutions.

3.5.2 Originality and Innovative Aspects

The originality of this dissertation lies in its integrated and vessel-specific evaluation of environmental performance, economic feasibility, and operational constraints in small maritime vessels. A first element of novelty is the use of high-resolution empirical datasets from ferries, pilot vessels, and an emerging transport concept. Articles I-III incorporate measured operational data, route characteristics, manoeuvring profiles, and infrastructure conditions, enabling realistic decarbonization assessment beyond generalized modelling.

A second element of novelty is the consistent integration of life-cycle emission modelling and life-cycle cost analysis. This dual-perspective approach reveals concrete engineering and investment trade-offs, such as battery capacity versus vessel weight, fuel storage volume versus payload constraints, retrofit feasibility versus long-term emission reduction, operational flexibility versus technological maturity.

A third novel contribution is the inclusion of an emerging ground-effect vehicle concept within the decarbonization discourse. By evaluating both environmental performance and commercial feasibility, the dissertation expands the analytical scope beyond conventional propulsion retrofits and fuel substitution.

The novelty therefore lies not in geographic specificity but in the systematic, comparative, and integrated evaluation of decarbonization pathways for vessels below 5,000 GT under real operational dimensions.

3.5.3 Scientific Contribution

The scientific contribution of this dissertation can be summarized in three dimensions:

1. Empirical Contribution:

   The research provides detailed, vessel-level empirical evidence for small maritime vessels, a segment underrepresented in academic literature dominated by large-vessel studies.

2. Methodological Contribution:

   By combining WTW life-cycle assessment with life-cycle cost modelling and contextual operational analysis, the dissertation advances integrated evaluation frameworks in maritime sustainability research.

3. System-Level Insight:

   The findings demonstrate that decarbonization feasibility in small vessels is determined by the interaction between propulsion technology, duty-cycle characteristics, storage limitations, infrastructure readiness, and capital structure. This systemic perspective contributes to more realistic modelling of maritime energy transitions in regional and short-sea contexts.

These contributions extend maritime decarbonization research beyond technology-centric evaluation toward integrated techno-economic assessment in constrained operational environments.

3.5.4 Limitations of the Study

Several limitations must be acknowledged. First, the case studies reflect specific regional and operational contexts (Belgium, Estonia and Canary Islands). While the analytical framework is transferable, quantitative outcomes may vary under different electricity mixes, fuel markets, or infrastructure conditions.

Second, certain operational inputs relied on averaged or modelled duty cycles. Real-world variability may affect energy consumption and cost outcomes beyond modelled scenarios.

Third, techno-economic results reflect technology maturity and market conditions at the time of analysis. Battery performance, fuel availability, and infrastructure costs are evolving.

Finally, behavioral and financing dimensions were outside the analytical scope. Access to capital, risk perception, and institutional constraints may influence adoption decisions beyond purely techno-economic considerations.

These limitations clarify the conditions under which the findings should be interpreted.

3.6 Publications

The four publications provide complementary empirical foundations for addressing the three research questions.

Articles I and II primarily inform RQ1 (environmental performance) and contribute to RQ3 (operational constraints).

Article III primarily informs RQ2 (economic feasibility) and contributes to RQ3.
Article IV contributes to all three research questions by combining environmental, economic, and contextual assessment of an emerging concept.

3.6.1 Article I: Decarbonizing City Water Traffic: Case of Comparing Electric and Diesel-Powered Ferries

Purpose

This study examines the technical and economic feasibility of electrifying urban ferry operations as a strategy to reduce GHG emissions in short-distance water transport. The analysis focuses on two sister vessels operating on the same inland route, one powered by conventional diesel propulsion and the other by battery-electric propulsion. The objective is to compare energy consumption, life-cycle emissions, and operational costs under real operating conditions. The study also considers how broader regulatory ambitions for maritime decarbonization form the contextual backdrop for investment decisions in small-scale ferry operations.

Results

The results show that the electric ferry generated approximately 25% of the GHG emissions of its diesel-powered counterpart when assessed on a WTW basis, demonstrating substantial emission reduction potential under a relatively low-carbon electricity mix. In terms of operating costs, electric propulsion proved 21-31% cheaper per energy unit compared to diesel fuel in the analysed case.

However, the economic analysis indicates that capital investment remains a significant barrier. The calculated payback period for replacing a diesel vessel with an electric alternative was approximately 17 years and 6 months without financial support, decreasing to around 10 years and 1 month when government subsidies were included. This highlights the sensitivity of electrification viability to policy support mechanisms and investment conditions.

The study further demonstrates that onboard solar panels can cover a portion of auxiliary loads, including lighting and electronics, even during winter conditions, thereby improving overall energy efficiency. Nevertheless, operational constraints such as battery capacity, charging time, and range limitations must be carefully integrated into route scheduling to ensure service reliability.

Contributions

This article provides empirical evidence on the environmental and economic performance of battery-electric propulsion in small urban ferry operations. By combining measured operational data with WTW life-cycle emission assessment and life-cycle cost modelling, the study demonstrates under which conditions electrification can deliver substantial GHG emission reductions and long-term cost advantages.

The findings directly support RQ1 by quantifying the life-cycle environmental performance of electric propulsion relative to diesel systems. They address RQ2 by evaluating investment requirements, operating costs, and payback periods under realistic operational assumptions. Furthermore, the study contributes to RQ3 by illustrating how route predictability, charging infrastructure availability, and electricity mix characteristics influence the practical suitability of electrification in small-vessel contexts.

3.6.2 Article II: Comparative Analysis of the Alternative Energy Case of Reducing GHG Emissions of Estonian Pilot Fleet

Purpose

This study examines the decarbonization potential of alternative fuels in high-manoeuvrability pilot vessels operating under variable and demanding duty cycles. Unlike ferries with fixed routes and predictable schedules, pilot boats experience fluctuating load profiles, rapid acceleration, and frequent standby operation. The objective of the study is to evaluate the environmental and technical feasibility of replacing marine diesel oil (MDO) with lower-carbon fuel alternatives, including biomethane, biodiesel, hydrotreated vegetable oil (HVO), ammonia, and other emerging options. The analysis considers well-to-wake emissions, fuel properties, storage requirements, and operational constraints to assess suitability for small pilot fleets. Electrification was not analysed as a primary pathway in this case due to the operational characteristics of pilot vessels, which include highly variable duty cycles, frequent high-power demand, and limited opportunities for predictable charging. These conditions currently constrain the feasibility of fully battery-electric solutions, making fuel-based alternatives and hybrid configurations more relevant for evaluation in this context.

Results

The results indicate that significant GHG emission reductions are achievable through fuel substitution, although trade-offs vary considerably across options. Biomethane provides the highest emission reduction, approximately 59% compared to MDO, but requires up to 353% greater storage volume, posing serious spatial and structural challenges for small vessels. Biodiesel achieves a 41.2% emission reduction with a comparatively moderate increase in storage volume (up to 23%), while HVO reduces emissions by 43.6% and can be used in existing engine systems with minimal technical modification.

Ammonia presents long-term decarbonization potential due to its carbon-free composition, yet its low energy density, toxicity, and storage complexity currently limit practical applicability for small pilot boats. Across all options, the analysis demonstrates that storage weight, volume requirements, and vessel stability constraints are critical determinants of feasibility in small craft.

The study further indicates that the highly variable operating profile of pilot vessels significantly influences fuel consumption and emissions performance. Economic feasibility is therefore closely tied to vessel-specific duty cycles, annual operating hours, and fuel price assumptions.

Contributions

This article provides detailed empirical evidence on alternative fuel substitution in small, highly specialized pilot vessels operating under variable duty cycles. By combining WTW life-cycle emission assessment with fuel property analysis and techno-economic evaluation, the study demonstrates how storage requirements, vessel size limitations, and operational variability shape the environmental and economic viability of different fuel pathways.

The findings directly address RQ1 by quantifying the life-cycle environmental performance of multiple alternative fuels relative to marine diesel oil. They contribute to RQ2 by evaluating investment implications, retrofit requirements, and cost sensitivity across fuel options. Furthermore, the study informs RQ3 by showing how storage constraints, weight limitations, and irregular operating profiles influence the practical suitability of decarbonization strategies in small-vessel contexts.

3.6.3 Article III: Decarbonization of Estonian Ferry Lines – Challenges and Opportunities

Purpose

The third article examines decarbonization options for regional ferry lines operating in Estonia. The objective is to assess the technical and economic feasibility of alternative propulsion systems and fuels for island-mainland ferry connections, taking into account route characteristics, vessel specifications, and infrastructure requirements. The study evaluates retrofit possibilities for existing vessels as well as newbuild alternatives, including battery-electric, hybrid-electric, and selected alternative fuel solutions. Rather than analysing policy instruments themselves, the article considers regulatory and funding conditions as contextual factors influencing investment decisions.

Results

The analysis identifies multiple technically viable decarbonization pathways, including full electrification on shorter routes, hybrid configurations for medium-distance services, and the use of bio-based fuels as transitional solutions. However, feasibility varies considerably across routes depending on distance, turnaround time, grid capacity, and port infrastructure readiness.

High upfront capital expenditure for new vessels or major retrofits emerges as a primary barrier. Infrastructure constraints (particularly the availability of shore-side charging and reliable grid connections) significantly influence implementation timelines. The results also show that fuel price variability and uncertainty in long-term energy costs affect the economic attractiveness of alternative propulsion systems.

Scenario-based modelling was applied to compare costs and emission reductions under different technological and energy-price assumptions. This approach highlights trade-offs between emission reduction potential and investment requirements, demonstrating that technical feasibility alone does not determine optimal solutions. Instead, route-specific operational characteristics and infrastructure conditions are decisive.

Contributions

This article provides empirical evidence on fleet-level decarbonization pathways in short-sea ferry systems. By integrating energy performance modelling, life-cycle emission assessment, and life-cycle cost analysis within scenario-based comparisons, the study demonstrates how alternative propulsion technologies perform under different route and infrastructure conditions.

The findings directly address RQ1 by quantifying the emission-reduction potential of electrification, hybridization, and selected alternative fuels across ferry routes. They contribute to RQ2 by evaluating capital expenditure, operating costs, and long-term cost-emission trade-offs at fleet level. In addition, the study informs RQ3 by analysing how route length, charging windows, grid capacity, and infrastructure readiness influence the practical implementation and economic viability of decarbonization strategies. The results are transferable to other regional ferry systems with comparable operational structures and infrastructure conditions.

3.6.4 Article IV: Business Opportunities for a Ground Effect Vehicle – Case of Canary Islands

Purpose

This article evaluates the potential of a GEV as an alternative transport mode for regional cargo operations in the Canary Islands. The objective is to assess the environmental and economic performance of the GEV relative to existing inter-island transport modes, focusing on route suitability, operational costs, and emission implications. The study examines whether the specific geographic characteristics of the Canary archipelago (moderate inter-island distances and regular cargo flows) align with the technical and operational capabilities of ground effect technology.

Results

The results indicate that several inter-island routes are technically compatible with GEV operations, particularly those characterized by medium distances and predictable cargo demand. The analysis identifies high-value and time-sensitive cargo categories, such as fish and seafood, as the most suitable market segments due to their ability to tolerate higher transport costs in exchange for speed advantages.

Emission comparisons suggest that replacing short-distance air cargo operations with GEV services could reduce transport-related emissions per ton-kilometre under certain operational assumptions. However, the economic assessment reveals that current cost structures remain a limiting factor. Under the modelled demand and routing assumptions, transport costs per kilometre are higher than conventional maritime options, restricting competitiveness to niche cargo segments.

The study also notes that cost projections are sensitive to assumptions regarding scale effects, operational frequency, and potential future efficiency improvements. While environmental benefits are observable in comparative modelling, broader economic viability depends on market uptake, technological maturity, and potential external support mechanisms.

Contributions

This article broadens the analytical scope of the dissertation by examining an alternative transport concept beyond conventional vessel retrofits and fuel substitution. By combining emission benchmarking with route-level cost and market analysis, the study evaluates the technical performance and commercial feasibility of GEVs within a defined regional transport system.

The findings contribute to RQ1 by comparing the emission performance of GEV operations with existing maritime and air transport alternatives under specific operational conditions. They inform RQ2 through assessment of cost structures, utilization requirements, and route-level economic viability. Furthermore, the study addresses RQ3 by analysing how geographic characteristics, demand stability, certification requirements, and infrastructure compatibility influence the practical suitability of this emerging transport solution. By extending decarbonization analysis to innovative transport configurations, the article demonstrates how novel vessel concepts may complement traditional maritime services in short-distance logistics systems.

3.7 Synthesis of Findings and Overall Contribution

Across the four publications, a consistent conclusion emerges: decarbonization of small vessels is technically achievable, yet its implementation is structurally constrained by operational characteristics, economic conditions, and infrastructural readiness.

In relation to RQ1 (environmental performance), the case studies demonstrate that meaningful GHG emission reductions are attainable across multiple technological pathways. Electrification under low-carbon electricity conditions provides the highest emission reduction potential, while biofuel substitution and hybridization offer moderate, but practically implementable reductions depending on system boundaries and upstream fuel pathways. However, emission performance is not technology-intrinsic; it depends on energy supply characteristics, storage requirements, and operational profiles.

Regarding RQ2 (economic feasibility), the analyses show that life-cycle cost performance varies substantially across vessel types and routes. Although several low-emission technologies generate operational savings over time, their economic viability is strongly influenced by capital expenditure, fuel or electricity price structures, and infrastructure cost allocation. In small-vessel contexts, the temporal mismatch between upfront investment and long-term operational savings represents a central adoption barrier.

In response to RQ3 (operational and infrastructural constraints), the results demonstrate that propulsion performance and cost indicators alone do not determine feasibility. adoption depends on alignment between propulsion systems, vessel duty cycles and route structure, onboard storage and stability constraints, grid and port infrastructure readiness, and investment capacity.

Table 2 summarizes the key empirical characteristics and principal findings of each article, highlighting vessel type, major results, secondary insights, and their contribution to the overall thesis. Each article contributes a complementary perspective.

Table 2. Summary of Publications

Article	***Vessel Type***	***Major Findings***	***Secondary Findings***	***Main Contribution***
Article I	*Urban passenger ferry*	*Electric ferry emits ~75% less GHG than diesel on the same route; energy costs 21-31% lower*	*Payback period long without financial support (17.5 years) but reduced with subsidies; onboard solar supports auxiliary loads*	*Demonstrates that ferry electrification is technically feasible and environmentally effective, while economic viability depends on investment conditions*
Article II	*Pilot boats*	*Biomethane and HVO provide significant GHG reductions (up to 59%)*	*Storage volume and weight constraints are decisive; ammonia currently impractical for small vessels*	*Provides vessel-specific evaluation of alternative fuels, highlighting physical and operational constraints in small craft*
Article III	*Regional ferry fleet*	*Multiple technically feasible pathways (electric, hybrid, biofuels)*	*High capital costs and infrastructure readiness strongly influence adoption*	*Offers route-level comparison of decarbonization options combining energy performance and cost assessment*
Article IV	*Emerging regional transport concept*	*Potential emission reductions in inter-island cargo transport*	*Economic viability limited to specific routes and cargo types*	*Expands decarbonization analysis to innovative transport concepts through comparative cost and emission modelling*

Article I provides vessel-level evidence on electrification under real operational conditions. Article II identifies physical storage and operational constraints shaping alternative fuel feasibility in pilot vessels. Article III extends the analysis to system-level route optimization and infrastructure dependency in ferry networks. Article IV broadens the scope by assessing an emerging transport concept within defined geographic and market boundaries.

Figure 4 presents a conceptual synthesis of these empirical findings. The figure illustrates that the adoption of low-emission solutions in small-vessel contexts is determined by four interdependent domains: technical performance, operational context, economic conditions, and infrastructure readiness. Thus, small-vessel decarbonization cannot be understood through single-variable analysis. Viable pathways emerge only when environmental performance (RQ1), economic feasibility (RQ2), and operational-infrastructural compatibility (RQ3) align simultaneously. A technological solution that performs well environmentally may fail economically; an economically attractive option may be operationally infeasible; and technically viable systems may remain unrealized without supporting infrastructure.

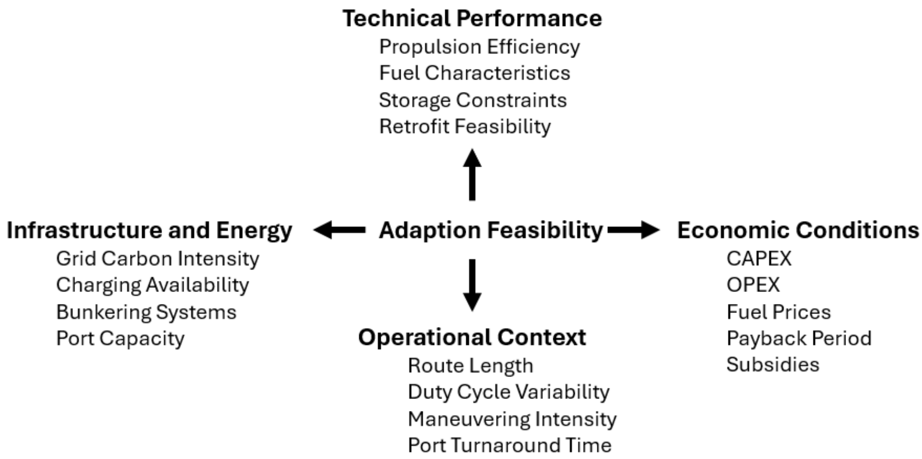

Figure 4. Systemic Interaction Model of Small-Vessel Decarbonization

The principal contribution of this dissertation therefore lies in providing integrated, vessel-level empirical evidence that clarifies how these interacting dimensions shape decarbonization outcomes in vessels below 5,000 GT. By systematically combining life-cycle emission assessment, techno-economic modelling, and operational context analysis across multiple vessel categories, the research advances understanding of small-vessel decarbonization beyond single-technology or sector-level modelling approaches.

Rather than proposing new regulatory instruments, the dissertation contributes a structured and evidence-based evaluation of how small maritime fleets can realistically implement emission-reduction pathways under real operational constraints.

While the findings of this dissertation are grounded in specific case studies, a distinction can be made between transferable insights and context-dependent results. Transferable findings include the general relationship between propulsion technology, duty-cycle characteristics, and energy efficiency; the importance of life-cycle assessment for evaluating environmental performance; and the role of infrastructure readiness in enabling decarbonization. These patterns are consistent across vessel types and regions. In contrast, quantitative results (such as emission reduction percentages, cost levels, and payback periods) are highly context-specific and depend on factors including electricity mix, fuel prices, route characteristics, and local infrastructure conditions. Therefore, while the analytical framework and qualitative insights are broadly transferable to smaller vessel decarbonization, numerical outcomes should be interpreted within their specific regional and operational context. This conclusion is further supported by recent large-scale assessments of marine propulsion systems, which similarly find that no single decarbonization pathway is universally optimal and that operational profile and utilisation significantly influence the relative performance of electrification, hydrogen, and renewable fuel solutions (Ricardo & ICOMIA, 2023).

4 Discussion

This chapter synthesizes the findings from the four research articles and interprets them within the broader context of maritime decarbonization for vessels below 5,000 GT. The discussion evaluates implications, identifies cross case patterns, and reflects on methodological robustness and constraints. It follows the three research questions and examines how environmental performance, economic feasibility, and operational and infrastructural conditions interact in small vessel decarbonization.

The interpretation of results is grounded in the combined analysis of empirical operational data, life-cycle modelling, and techno-economic evaluation, ensuring that conclusions reflect both measured performance and realistic operational constraints.

4.1 Environmental Performance in Context

the case studies show that vessels below 5,000 GT can achieve substantial GHG emission reductions through electrification, hybrid propulsion, and low carbon fuels. The comparison of electric and diesel ferry systems in Article I demonstrates that battery electric propulsion significantly reduces operational emissions when supplied with low carbon electricity. This aligns with previous research identifying short, predictable routes with frequent port calls as particularly suitable for electrification (Aksöz et al., 2025; Bouman et al., 2017; Lindstad et al., 2023; Perčić et al., 2021).

Consistent with earlier LCA studies, the environmental performance of electric vessels depends strongly on the carbon intensity of electricity and battery production (Roux et al., 2024; Wang et al., 2025). The results confirm that life cycle GHG reductions vary across scenarios and are greatest in regions with low carbon electricity systems.

The analysis of alternative fuels in Article II indicates that biofuels, hydrogen based fuels, and synthetic fuels provide varying GHG reduction potentials depending on upstream production pathways. This supports WTW assessments demonstrating that climate performance is highly sensitive to feedstock origin, production technology, and energy sources (Dong et al., 2024; Roux et al., 2024; Zhou et al., 2024). For instance, hydrogen produced from renewable electricity can achieve near zero operational emissions, whereas fossil-based hydrogen offers limited benefits. Similarly, biomethane and HVO can reduce emissions, but outcomes depend on feedstock and production conditions.

This finding is particularly relevant in vessel segments characterized by variable operational profiles, such as pilot vessels. In such cases, propulsion system suitability is strongly influenced by duty-cycle variability and utilisation patterns. Recent large-scale assessments similarly indicate that fully electric and hydrogen-based propulsion systems may face significant limitations in applications with highly variable operation, due to constraints related to energy storage, range, and onboard space requirements (Ricardo & ICOMIA, 2023).

These findings extend existing literature by providing empirical evidence from small vessel operations below 5,000 GT, a segment underrepresented compared to large ocean-going vessels and long-distance shipping (Frković et al., 2024; Law et al., 2022; Zis et al., 2020). The case studies demonstrate how electrification and alternative fuels perform under short sea and coastal conditions, helping to close this empirical gap.

The results show that significant emission reductions are achievable but highly context dependent. Electrification offers the highest reduction potential when combined with low carbon electricity, appropriate infrastructure, and suitable duty cycles (Articles I and

III). More broadly, the findings reinforce that emission performance is not intrinsic to propulsion technologies but depends on energy system context, upstream processes, and operational configuration, consistent with the framework outlined in Chapter 2.

4.2 Economic Feasibility and Investment Logic

Beyond environmental performance, the research highlights that the economic feasibility of decarbonization technologies remains a critical determinant of their adoption in small maritime fleets. The techno-economic analyses conducted across the case studies indicate that electrification and hybrid propulsion can be financially viable under certain operational conditions, particularly when fuel cost savings and reduced maintenance requirements compensate for higher initial capital investments.

These findings are consistent with previous techno-economic studies on maritime energy transitions, which emphasize that the economic attractiveness of low-emission technologies depends strongly on investment costs, fuel price differentials, operational profiles, and policy incentives (Kanchiralla et al., 2022; Laasma et al., 2022; Perčić et al., 2021; Psaraftis & Kontovas, 2021). In particular, battery-electric ferries have been shown to achieve favourable life-cycle cost performance when operating on fixed routes with high service frequency, enabling efficient utilization of charging infrastructure and reduced fuel expenditure.

However, the analyses conducted in this research also demonstrate that investment decisions remain highly sensitive to external economic factors such as electricity prices, fuel costs, and infrastructure investment requirements. Similar conclusions have been drawn in broader maritime decarbonization literature, which identifies economic uncertainty and capital intensity as key barriers to the adoption of alternative propulsion systems (Law et al., 2022; Zis et al., 2020).

For small-vessel operators, these investment challenges may be particularly pronounced due to limited financial capacity and shorter planning horizons compared to large international shipping companies. Consequently, the results of this research support previous studies suggesting that targeted policy instruments, public funding mechanisms, and risk-sharing arrangements may be necessary to accelerate the adoption of low-emission technologies in small maritime fleets (Acciaro & Sys, 2020; Rødseth et al., 2023).

Overall, the findings indicate that economic feasibility cannot be evaluated solely through capital investment comparisons. Instead, long-term operational cost structures, infrastructure investments, and regulatory developments jointly influence the financial viability of decarbonization pathways in small-vessel contexts. From an investment perspective, return on investment remains highly sensitive to infrastructure availability and energy price assumptions.

4.3 Operational and Infrastructural Constraints

The case studies demonstrate that operational characteristics and infrastructure availability play a decisive role in determining the suitability of different decarbonization technologies. In particular, route length, duty cycle regularity, port turnaround time, and energy supply infrastructure strongly influence the practical implementation of electrification and alternative fuel systems.

These observations are consistent with existing research on maritime energy transitions, which emphasizes that infrastructure readiness and operational patterns are critical enabling conditions for low-emission propulsion technologies (Acciaro & Sys, 2020; Papalexopoulos et al., 2025; Sardar et al., 2025). For example, electrification requires sufficient grid capacity and high-power charging infrastructure to support short turnaround times in ferry operations. Without adequate port energy infrastructure, even technically feasible propulsion systems may be difficult to implement in practice.

The findings of Articles II and III further highlight the challenges associated with applying generic decarbonization solutions to heterogeneous small-vessel fleets. Pilot vessels, passenger ferries, and service crafts operate under different duty cycles and energy demand profiles, which affects the suitability of specific propulsion technologies. Previous research similarly notes that the transferability of decarbonization solutions across vessel segments is limited, particularly when operational patterns differ substantially (Farrukh et al., 2023; Shi et al., 2023).

Infrastructure constraints are particularly relevant in smaller ports and regional maritime economies, where grid capacity and alternative fuel bunkering facilities may be limited. Studies examining port energy transitions have identified similar challenges, including limited electrical capacity, high infrastructure investment costs, and coordination challenges between ports, ship operators, and energy providers (deManuel-López et al., 2024; Pivetta et al., 2022).

the results confirm that decarbonization pathways in small-vessel contexts are highly context dependent. Technical feasibility, economic viability, and operational suitability must therefore be evaluated jointly rather than independently.

4.4 Innovation and System-Level Implications

The results of this research also highlight the importance of innovation and system-level transformation in achieving maritime decarbonization. While incremental efficiency improvements and alternative fuels can significantly reduce emissions, achieving long-term climate targets may require broader changes in vessel design, energy systems, and transport concepts.

The evaluation of a GEV in Article IV illustrates how alternative transport concepts may provide additional opportunities for emission reduction in specific geographic contexts. Similar emerging transport technologies have been discussed in the literature as potential complements to conventional maritime transport, particularly in regional and island transport systems (Kerem et al., 2025; Sakornsin et al., 2020).

In addition, recent research increasingly conceptualizes maritime decarbonization as a socio-technical transition involving not only technological innovation but also changes in infrastructure systems, energy supply chains, and institutional frameworks (Acciaro & Sys, 2020; Psaraftis & Kontovas, 2020). Within this perspective, vessel-level technological improvements must be supported by coordinated development of port infrastructure, renewable energy systems, and regulatory frameworks.

The findings of this dissertation contribute to this broader discussion by demonstrating how decarbonization pathways emerge from the interaction between technological capabilities, operational conditions, and infrastructure readiness. In small maritime economies with extensive short-sea transport networks, coordinated development of vessel technology and port energy systems may therefore be particularly important for enabling low-emission maritime transport.

4.5 Validity, Reliability and Limitations

The validity of the findings presented in this research is supported by the use of empirical operational data from real maritime case studies, combined with established analytical methods such as life-cycle assessment and techno-economic modelling. Applying consistent methodological approaches across multiple case studies strengthens internal consistency and enables cross-case comparison.

Nevertheless, several limitations should be acknowledged. First, LCA results depend on the quality and availability of emission factor data and assumptions regarding fuel production pathways. This is particularly relevant in low-utilisation vessel segments, where production-phase impacts may dominate total life-cycle emissions. Recent studies indicate that battery-electric propulsion systems may not always yield lower overall emissions in such contexts due to the significant contribution of manufacturing and replacement impacts over the vessel lifetime (Ricardo & ICOMIA, 2023). Previous studies similarly highlight that methodological choices, system boundary definitions, and energy pathway assumptions can significantly influence life-cycle emission estimates (Roux et al., 2024; Y. Wang et al., 2025).

Second, techno-economic analyses are inherently sensitive to assumptions regarding energy prices, infrastructure investment costs, and discount rates. Future changes in fuel markets, electricity prices, or regulatory conditions may therefore alter the economic feasibility of the technologies examined.

Third, although the case studies provide valuable empirical insights, the findings reflect specific operational contexts and vessel types. While the results are transferable to comparable short-sea and coastal operations, further research involving additional vessel categories and geographic regions would help to strengthen the generalizability of the conclusions.

Despite these limitations, the multi-case study design provides a robust empirical basis for examining the environmental and economic implications of decarbonization pathways in small maritime vessels. These limitations do not undermine the core findings but rather clarify the boundaries within which conclusions should be interpreted, a consolidated discussion of limitations is provided in Sub-Chapter 6.2.

In addition to the limitations discussed above, uncertainty plays an important role in evaluating decarbonization pathways for smaller maritime vessels. Key sources of uncertainty relate to future energy prices, infrastructure development trajectories, and technological learning curves. Energy price assumptions (including electricity and alternative fuel costs) significantly influence techno-economic outcomes, particularly in long-term life-cycle cost modelling. Similarly, infrastructure availability (such as charging capacity and alternative fuel bunkering) is subject to spatial and temporal variability, which may alter the feasibility of specific propulsion options across regions. Technological learning effects, including improvements in battery energy density, cost reductions, and fuel production efficiency, are expected to influence both environmental performance and economic viability over time. While scenario and sensitivity analyses partially capture these dynamics, the results should be interpreted as conditional on current assumptions rather than predictive of fixed future outcomes.

This research evaluates decarbonization pathways based on current and short-term technological and market conditions. While future developments in energy systems, fuel production, and technology performance are acknowledged, the analysis does not attempt to predict long-term scenarios beyond the defined assumptions. Instead, the focus is on providing evidence-based assessment of currently feasible pathways under realistic operational conditions.

5 Conclusions and Future Work

The maritime sector faces increasing pressure to reduce GHG emissions. While much of the global decarbonization debate has focused on large ocean-going vessels, smaller ships and short-sea operations operate under distinct technical, spatial, and economic constraints (Armstrong, 2022; Bouman et al., 2017; Lindstad et al., 2023). Limited onboard space, weight sensitivity, short and frequent route structures, infrastructure dependency, and tighter financial margins complicate decarbonization decisions in this segment. Similar structural constraints of small-vessel decarbonization have been identified in earlier maritime research (J. D. Caprace et al., 2025; Farrukh et al., 2023; Zis et al., 2020). This research has addressed this comparatively underexplored field by conducting empirical environmental and techno-economic analyses of alternative propulsion and fuel pathways for vessels below 5,000 GT.

5.1 Main Conclusions

In response to RQ1 (environmental performance), the findings demonstrate that substantial life-cycle emission reductions are technically achievable in small-vessel operations. Electrification provides the highest WTW reduction potential on short, predictable routes, particularly where low-carbon electricity and adequate charging infrastructure are available. Similar conclusions regarding the environmental performance of battery-electric vessels have been reported in previous maritime LCA studies (Roux et al., 2024; Y. Wang et al., 2025). Bio-based liquid fuels and hybrid configurations offer moderate but practically implementable reductions, especially in vessels with variable duty cycles or infrastructure limitations. However, environmental performance is highly dependent on system boundaries, upstream energy pathways, and operational alignment, which is consistent with findings from broader WTW maritime fuel assessments (Dong et al., 2024; Nguyen et al., 2025).

Regarding RQ2 (economic feasibility), the research demonstrates that technical feasibility does not automatically translate into financial viability. Although low-emission technologies may generate long-term operational savings, high upfront capital costs remain a principal barrier. Payback periods, cost sensitivity to fuel and electricity prices, and infrastructure cost allocation significantly influence adoption decisions. Similar techno-economic barriers have been highlighted in earlier maritime decarbonization research, where capital intensity and uncertain fuel price trajectories are identified as key constraints for the adoption of alternative propulsion systems (Kanchiralla et al., 2022; Perčić et al., 2021; Psaraftis & Kontovas, 2021). In small fleets with constrained capital reserves, investment risk becomes a decisive limiting factor.

In response to RQ3 (operational and infrastructural constraints), the research demonstrates that propulsion technologies must align with vessel duty cycles, storage limitations, port infrastructure, and grid capacity. Small vessels are particularly sensitive to trade-offs between energy density, weight, range, and safety requirements. Infrastructure readiness (especially charging systems and fuel supply chains) strongly conditions practical implementation. This observation aligns with earlier research emphasizing that maritime decarbonization depends on the interaction between vessel technology, infrastructure systems, and operational patterns rather than propulsion performance alone (Acciaro & Sys, 2020; Islam et al., 2025). Similar constraints have been identified in recent marine sector studies, which highlight that alternative propulsion systems such as battery-electric and hydrogen solutions may require reductions in operational range and performance to remain technically feasible, particularly in applications with limited onboard space and variable utilisation patterns (Ricardo & ICOMIA, 2023). The analysis further illustrates that emerging transport concepts, such as GEVs, may expand the solution space beyond incremental retrofits. However, their viability depends on route discipline, utilization rates, and commercial alignment, highlighting that innovation-driven decarbonization requires coordinated system development.

The research provides integrated empirical evidence clarifying how environmental performance, economic feasibility, and operational dimensions interact in smaller vessel decarbonization. Rather than proposing a new theoretical framework, the work contributes structured vessel-level evaluation that supports more realistic and context-sensitive transition strategies. In this sense, the research contributes empirical insight to a segment of maritime transport that remains comparatively underrepresented in the existing decarbonization literature (Farrukh et al., 2023; Zis et al., 2020).

5.2 Limitations of the Research

Several limitations should be acknowledged.

First, the case studies are context-dependent. Although the analytical methods are transferable, specific results reflect regional electricity mixes, fuel availability, infrastructure readiness, and operational patterns in Belgium, Estonia, and the Canary Islands. Direct generalization to other regions therefore requires contextual adjustment, which is consistent with observations in previous maritime decarbonization case-study research (Farrukh et al., 2023; Zis et al., 2020).

Second, while empirical operational data were used wherever possible, certain duty-cycle parameters (particularly for pilot vessels) were modelled or averaged. Real-world variability in speed, manoeuvring intensity, seasonal demand, and load factors may influence emissions and cost outcomes beyond model assumptions.

Third, technology performance and cost parameters are dynamic. Battery energy density, renewable fuel production pathways, and infrastructure investment costs continue to evolve. While battery production impacts are considered within the LCA framework, broader issues related to critical raw materials, mineral sourcing, and supply chain sustainability are not analysed in detail in this dissertation. These aspects are recognized as important and rapidly evolving areas of research, particularly in relation to battery technologies (Istrate et al., 2024; Peters et al., 2017). However, a comprehensive assessment of mineral resource availability, geopolitical dependencies, and long-term material sustainability falls outside the scope of this study. The findings therefore represent conditions at the time of analysis rather than fixed long-term projections.

Finally, behavioural and financing dimensions (such as risk perception, capital access, procurement frameworks, and stakeholder acceptance) were not analysed in depth. Previous research suggests that these institutional and financial factors may significantly influence adoption rates in maritime decarbonization transitions (Acciaro & Sys, 2020). Recognizing these limitations strengthens interpretation of the findings and clarifies the scope within which conclusions should be applied.

5.3 Future Research Directions

Building on the results of this research, several directions for further research can be identified. First, expanded vessel-level data collection across additional ship types and geographic regions would improve model accuracy and enable longitudinal assessment of decarbonization progress. Continuous monitoring of operational energy use and battery performance would strengthen empirical validation.

Second, further research on port-energy system interaction is needed. As electrification expands, coordinated modelling of grid capacity, renewable energy integration, peak maritime demand, and storage systems will become increasingly important. Previous research has highlighted the importance of integrated port–energy infrastructure planning in maritime energy transitions (Islam et al., 2025; Yildiz et al., 2024).

Third, comparative studies across small maritime nations and island regions could strengthen benchmarking and enhance transferability of techno-economic findings.

Fourth, as hydrogen-, ammonia-, and methanol-based systems mature, more detailed investigation of storage integration, safety requirements, and cost development in this vessel segment is required (Nguyen et al., 2025; J. Zhou et al., 2024).

Fifth, future work could examine behavioral, institutional, and financing mechanisms influencing technology adoption in small fleets, including procurement models, risk-sharing schemes, and access to capital.

Finally, innovation-oriented research may explore how emerging transport concepts influence regional mobility systems, logistics chains, and maritime clusters, particularly in geographically constrained areas.

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Fair winds, cleaner seas, and may the rum never run dry!

Abstract

Environmental and Techno-Economic Assessment of Decarbonization Pathways for Ships Below 5,000 GT

This doctoral thesis evaluates the environmental performance, economic feasibility, and operational constraints associated with reducing greenhouse gas (GHG) emissions in short-sea shipping, with particular focus on vessels below 5,000 gross tonnage (GT). While European climate initiatives such as the *Fit for 55* package and *FuelEU Maritime* have accelerated maritime decarbonization efforts, empirical research has largely concentrated on large ocean-going vessels. Smaller ferries, pilot boats, and regional service vessels remain comparatively underexamined despite their operational importance and distinct technical and economic constraints.

The thesis integrates four peer-reviewed case studies that examine alternative propulsion systems and fuel pathways in small-vessel contexts. The analyses include a comparison between battery-electric and diesel ferries in urban transport, alternative fuel substitution in a national pilot fleet, fleet-level decarbonization scenarios for regional ferry lines, and an environmental and economic assessment of a ground-effect vehicle concept for inter-island transport. The studies apply well-to-wake life-cycle assessment, techno-economic modelling, and scenario analysis to evaluate emission reduction potential, investment implications, energy storage limitations, and infrastructure compatibility.

The findings demonstrate that substantial emission reductions are technically achievable in small-vessel operations. Electrification provides the highest well-to-wake emission reduction potential on short and predictable routes supported by low-carbon electricity and adequate charging infrastructure. For vessels with variable duty cycles or limited infrastructure availability, hybrid propulsion systems and bio-based fuels offer practicable transitional solutions. However, technology adoption is strongly shaped by trade-offs between energy density, storage capacity, operational range, capital expenditure, and infrastructure readiness. High upfront investment costs emerge as the principal barrier to rapid implementation in small fleets.

By integrating life-cycle environmental assessment with techno-economic evaluation across multiple vessel categories, the thesis clarifies how environmental performance, economic feasibility, and operational-infrastructural constraints interact in small-vessel decarbonization. The results provide empirically grounded insight into a segment that remains underrepresented in maritime decarbonization research, offering practical implications for vessel operators, infrastructure planners, and policymakers supporting the transition toward low-carbon short-sea shipping.

Lühikokkuvõte
Kuni 5000 kogumahutavusega laevade dekarboniseerimisvõimaluste keskkonna- ja tehnilis-majanduslik hindamine

Doktoritöö eesmärk on hinnata kasvuhoonegaaside (KHG) heitmete vähendamise keskkonnamõju, majanduslikku teostatavust ning operatiivseid piiranguid lähimeresõidus, keskendudes kuni 5000 kogumahutavusega laevadele. Kuigi Euroopa Liidu kliimapoliitika algatused, nagu *Fit for 55* pakett ja *FuelEU Maritime*, on viimastel aastatel kiirendanud meretranspordi dekarboniseerimist, on senised empiirilised uuringud keskendunud peamiselt suurtele ookeanilaevadele. Väiksemad parvlaevad, lootsilaevad ja regionaalsed teeninduslaevad on seevastu jäänud suhteliselt vähe uurituks, hoolimata nende olulisest rollist meretranspordis ning neile iseloomulikest tehnilistest ja majanduslikest piirangutest.

Doktoritöö põhineb neljal eelretsenseeritud teadusartiklil, milles analüüsitakse alternatiivsete kütuselahenduste kasutuselevõttu väiksemate laevade kontekstis. Uuringud hõlmavad aku-elektrilise ja diiselmootoriga parvlaeva võrdlust linnatranspordis, alternatiivkütuste kasutuselevõttu riiklikus lootsilaevastikus, regionaalsete parvlaevaliinide laevastiku tasandi dekarboniseerimisstsenaariume ning maapinnaefektil põhineva transpordivahendi kontseptsiooni keskkonna- ja majanduslikku hindamist saartevahelises transpordis. Analüüsides kasutatakse *well-to-wake* elutsükli hindamist, tehnilis-majanduslikku modelleerimist ning stsenaariumianalüüsi, et hinnata heitmete vähendamise potentsiaali, investeeringuvajadust, energiasalvestuse piiranguid ja infrastruktuuri sobivust.

Tulemused näitavad, et väikelaevade opereerimisel on võimalik saavutada märkimisväärne heitmete vähenemine. Elektrifitseerimine pakub suurimat *well-to-wake* heitmete vähendamise potentsiaali eelkõige lühikestel ja etteaimatavatel marsruutidel, kus on tagatud roheline elektrienergia ning piisav laadimistaristu. Muutliku tööprofiiliga laevade puhul või piiratud taristuga piirkondades võivad hübriidlahendused ja biopõhised kütused pakkuda praktilisi üleminekulahendusi. Samas mõjutavad tehnoloogia kasutuselevõttu kompromissid energiatiheduse, salvestusmahu, tegevusraadiuse, kapitalikulude ning infrastruktuuri valmisoleku vahel ning väikesemate aluste laevastikes kujunevad peamiseks takistuseks kõrged investeeringud.

Doktoritöö ühendab elutsükli keskkonnahindamise ja tehnilis-majandusliku analüüsi, et selgitada väiksemate laevade dekarboniseerimise keskkonna-, majandus- ja operatiivseid mõjureid. Töö tulemused täiendavad teadmisi väiksemate laevade dekarboniseerimise võimalustest ja piirangutest ning pakuvad sisendeid laevaoperaatoritele, taristu planeerijatele ja poliitikakujundajatele madala süsinikuheitega lahenduste rakendamiseks lähimeresõidus ja regionaalsetes meretranspordisüsteemides.

Appendix 1

Publication I

Otsason, R., Tapaninen, U. (2023). Decarbonizing City Water Traffic: Case of Comparing Electric and Diesel-Powered Ferries. Sustainability, 15(23), 16170. https://doi.org/10.3390/su152316170

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Article

Decarbonizing City Water Traffic: Case of Comparing Electric and Diesel-Powered Ferries

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Abstract: The maritime sector aims to achieve carbon neutrality by 2050. Consequently, shipping companies are investigating efficient and optimal ways to minimize greenhouse gas emissions. One of these measures includes vessels that operate on alternative non-carbon fuels. In this study, we compared a diesel-fuelled catamaran's greenhouse gas (GHG) emissions and its fully electric sister vessel, which operates on the same line. This study showed that the GHG emissions of the electric vessel were only 25% of those of its diesel-powered sister vessel. However, this figure highly depends on the source of electricity in the operating country. In this case, the energy cost of the fully electric vessel was 31% cheaper than the cost of diesel energy and the payback time without possible subsidy for replacing a diesel ferry with an electric one would be 17 years and 6 months. We also showed that the additional energy from solar panels sufficiently covers several application options for consumers even in winter, when there is low solar energy production. This study brings more insight into the academic literature on decreasing maritime CO_2 emissions from city water traffic. Regarding its managerial implications, our study findings can be used when shipping companies evaluate options for reducing their emissions. The results of this study show that using fully electric vessels has major benefits not only concerning carbon emissions but also financially.

Keywords: carbon neutrality; GHG emission reduction; full electric ferry; diesel ferry

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1. Introduction

The International Maritime Organization (IMO) has established a goal to reach carbon neutrality by 2050 [1]. In addition, the European Union (EU) in its Fit for 55 Package has set a target for 2050 to reach carbon neutrality across Europe [2]. Both regulation packages are directed towards vessels with a gross tonnage of more than 5000 GT, even though the emissions trading system also includes vessels above 400 GT.

However, the rules enacted by the IMO and EU do not apply to several different kinds of ships, including yachts, fishing vessels, tugs, offshore ships, and common city waterway ferries. Armstrong [3] claims that small ships are responsible for 15–20% of the total greenhouse gas emissions. In other words, there is a significant amount of unregulated GHG emissions.

On the other hand, there is a constant trend towards decarbonizing smaller ferries, in particular, in cities that have strong political green strategies. Both the market and trends are in the process of shifting to low-carbon shipping, and numerous viable fuel alternatives [4–11] are either in the process of being developed or are already in use. Hence, the coastal ferry industry has both the desire and the initiative necessary to make progress towards increasing the number of electric ferries [12].

Nevertheless, there is no fit-for-all solution for minimizing GHG emissions due to ship design, operational envelopes, weather conditions, routes, and port infrastructure. This study compares actual energy consumption and GHG emissions between fully electric and marine-diesel-fuelled catamaran ferries. The vessels are almost identical, and they operate on the same line. This study brings more insight into the academic literature on decreasing maritime GHG emissions where ferries are compared in their regular operation. Both ferries regularly operate in the same environment (same ferry line/route for both ferries), providing this study with a unique perspective as it illustrates their actual CO_2 emissions.

In this study, we reveal the actual GHG emissions of the ferries and calculate the payback time of the vessels. We also conducted an operational energy cost analysis. In addition, we calculated the amount of energy the solar panels on the vessels produce. Regarding its managerial implications, shipping companies can use our study findings to evaluate options for reducing emissions. More background information and studies about the actual difference in GHG emissions will help shipowners decide on the power system and type of energy used for urban waterway or road ferry traffic in both the new and retro building sectors. The results of this study show that using fully electric vessels has major benefits not only concerning carbon emissions but also financially.

2. Literature Review

Ships that operate worldwide commonly have conventional marine propulsion systems supplied with marine fuels. Most of them use heavy fuel oil (HFO), marine diesel oil (MDO), marine gas oil (MGO), or liquid natural gas (LNG). These heavy fuel oils have been used due to their high energy density and low price. However, the use of fossil fuels is being gradually banned by IMO and the EU. However, carbon-free shipping has a long road ahead.

Presently, there is no 'silver bullet' to achieve decarbonizing targets in shipping as multiple means are needed to reduce vessel emissions. Means of reducing exhaust emissions from ships can be roughly grouped into the following: (i) fuel solutions; (ii) ship design and technological development, (iii) choices of ship operations, such as speed optimization [13].

Numerous literature reviews describe various ways to reduce the carbon emissions of shipping, see, e.g., [14–17]. There are multiple methods for reducing carbon emissions, such as slow steaming, main engine de-rating, waste heat recovery, and alterations in operational patterns. In the shipping industry, these techniques are not new; in fact, they were initially developed to reap benefits such as minimizing operational expenses and reducing fuel consumption. Various guidelines and rules are focused on improving energy efficiency; however, they might not have effective long-term results [13].

As one alternative, several shippers are finding biodiesel to be the best-suited measure [18,19] to fulfil the rules and requirements set by the IMO. In urban waterway ferries, replacements for diesel engines with fully electric ones can be identified in various countries and locations [20–22]. There is also evidence of using hydrogen [23] and methanol [24,25] as fuel alternatives. Hydrogen is an energy-dense fuel in weight but low on energy-density in volume. Hydrogen has great potential in different regions [26,27], and hydrogen use has already been considered and implemented in some application areas, including transportation. Nevertheless, the greatest challenges to using hydrogen are connected to its transportation, storage, and production price. There are also safety concerns derived from its flammability. Similarly, methanol has already been used as a shipping fuel alternative, and the trend is growing rapidly [24,28]. Methanol's main drawbacks are connected to its low density and heating values; it also must be remembered that methanol is toxic and flammable [29]. In addition to the above-mentioned issues, it is widely dependent on price dynamics in different regions due to its production method. There have been different strategies [30] developed to assess the best-suited fuel alternatives; however, no uniform method can be used for all types of vessels and all navigational regions.

According to Hessevik [31], shipping companies join green shipping networks to learn about new technology. Knowledge of new technologies helps technical managers in decision-making; however, belonging to clusters is not the actual driver of fleet renewal. Retrofitting and new building are still a financial decision and having a green fleet of vessels <5000 GT has been an additional bonus in the sales or public relations aspect. After the European Parliament adopted the EU Climate Law in 2021 [32], member countries have more clear targets to achieve, and public authorities are encouraged to consider GHG emissions in their daily operations. Several cities and transportation authorities have already taken measures [33] to successfully implement the green shift in city transportation [34,35].

It should be stressed that to cover all the needs of future electricity resources (not only means of transportation), there must be strong collaboration between private enterprises, public initiatives, and governmental support [36]. Several low-emission fossil fuel alternatives depend on local resources. In some specific routes and countries, hydrogen is the most feasible alternative [37]. However, in many cases, hydrogen production still has several deficiencies [38]. Using fully electric power systems is suitable for inland waters, short distances, and a mild climate, offering great benefits under such conditions [39].

3. Methodology

In this study, we measured the emissions of two passenger catamaran ferries that navigate the same route in city traffic.

Both vessels operate on the river daily. The significance of this line is that the ferries sail on the same route (therefore, the change in weather conditions does not affect average consumption). The data collection time was 1 month in the winter period. Consumption data were collected directly from these vessels' integrated alarm monitoring and control systems.

During the data collection period, the regular daily working hours of the diesel ferry were approximately 11 h 20 min, and the working hours of the fully electric ferry were approximately 17 h 25 min. The difference in working hours was calculated from the ferry schedules while considering rush hours and the actual passenger load. The electric ferry operates for more hours because it is cheaper. According to the financial reports of the fleet, navigating a fully electrical catamaran is 21% cheaper in energy unit cost than diesel. The consumption cost comparison shows that Belgium has long been one of the most expensive countries in Europe for electricity [40]. However, even in Belgium, electricity in this inland waterway environment is financially more viable.

3.1. The Fleet

The vessels under study are owned by the Flemish government. The company has had a green fleet focus in action since 2009, the period before specific guidelines came into force. The diesel ferry analysed in the study was delivered in 2021 to substitute the old and less efficient river ferry. According to calculations conducted by the ship owner, the company has already saved 2.7 times in consumption costs with the new diesel catamaran compared to the previous old ferry and even more than the fully electric ferry.

In the future, this company is considering retrofitting diesel-fuelled propulsion systems using methanol. This method is supported by a recent study [41], which acknowledges methanol's suitability for small working ship retrofits of marine diesel oil. Depending on the vessel's specific purpose and the environment, there are other alternatives, e.g., ferries can be retrofitted to be fully electric.

3.2. Ship Particulars

The catamaran ferries under study have the same main dimensions (see Table 1).

Apart from the main dimensions, Vessel 1 also uses electricity to supply the vessel while not in operation at shore side. Vessel 2 uses minor amounts of marine diesel oil to supply the emergency generator. These consumptions were also considered in this study.

Both vessels have solar panels for supplying consumers. The systems consist of two sets with six 330 W panels each; therefore, in total, both vessels have 12 solar panels to produce additional energy from the sunlight. The study measurements were conducted in the winter period. Although the solar energy impact was minor, it reduced electrical energy consumption. Therefore, it was not included in the emissions calculation.

Table 1. Ship particulars.

	Vessel 1	Vessel 2
Type of vessel	Commuter ferry	Commuter ferry
Hull material	Aluminium	Aluminium
Superstructure material	Aluminium	Aluminium
Type of propulsion fuel	Diesel	Electricity
Maximum speed	18 km/h	18 km/h
Length overall	30.0 m	30.0 m
Breath moulded	9.5 m	9.5 m
Scantling draught	1.85 m	1.6 m
Gross tonnage	240 t	240 t
Crew	3	3
Passengers	200	150

The ferries' maximum passenger number difference is not due to technical limitations. According to the fleet owner, the passenger amounts never exceed 150 people. Therefore, lowering the passenger capacity saves from carrying unnecessary rescue equipment onboard and adds relevant storing space.

3.3. Operating Environment

The vessels operate on the same route daily (Figure 1). The operating distance for a one-way trip is very short, approximately 350 m. The harbour infrastructure has enough electrical reserves for battery charging, a significant benefit compared to other European city ports.

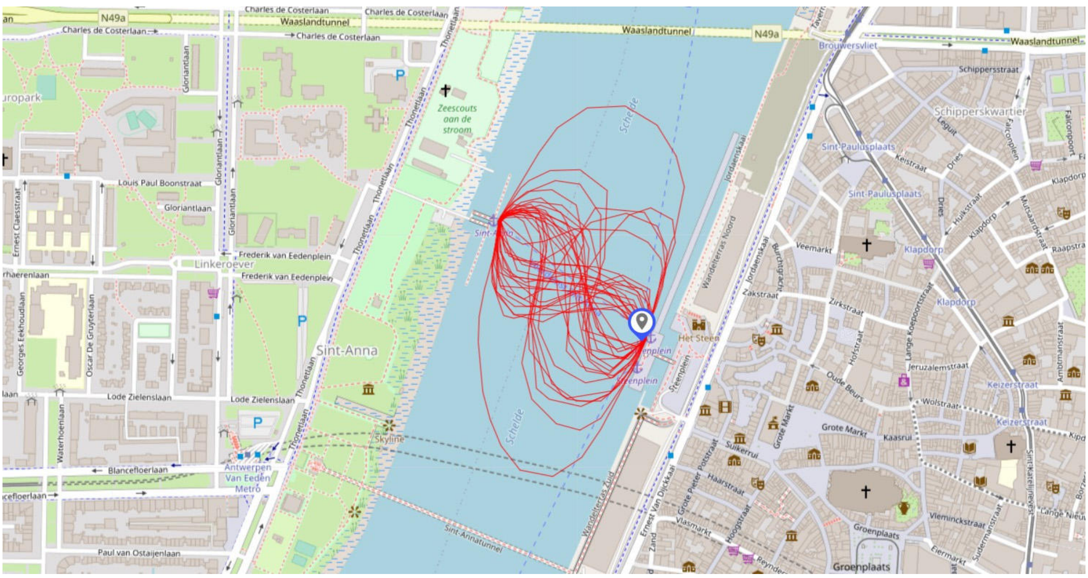

Figure 1. Ferry line route map. Red lines show the average route of Vessel 2 in one day.

It is also worth noting that the ferry is not the only alternative for crossing the river. There is also a tunnel for pedestrians and bicycles. Nevertheless, the ferry line is used monthly by 30,989 pedestrians and 19,311 bicycles on average.

3.4. Assessing GHG Emissions

We assessed energy consumption and GHG emissions according to EN 16258:2012 [42] requirements using the well-to-wheel (WTW) method. The well-to-wheel method is used to evaluate an energy source's efficiency and emissions considering its entire life cycle [43]. EN 16258 is the European standard for calculating and reporting GHG emissions from transportation. The standard contains general principles, definitions, system boundary descriptions, calculation methods, and data recommendations. The WTH method was used instead of TTW (tank-to-wheel) because according to the standard TTW emissions of electrical vehicles are equal to 0, actual operating emissions would always be in favour of fully electric vehicles.

3.4.1. Well-to-Wheels GHG Emissions for Marine Diesel Oil (G_{wD})

$$G_{wD}(VOS) = F(VOS) \times g_{wD} \tag{1}$$

where,
F(VOS) is the total fuel consumption used for the VOS (vehicle operation system);
g_{wD} is the well-to-wheels GHG emission factor for the fuel used in marine diesel oil;
g_{wD} = 3.53 $kgCO_2e/L$.

3.4.2. Well-to-Wheels GHG Emissions for Electricity (G_{wE})

The standard well-to-wheels energy factor is specified by the electricity supplier. GHG emissions energy factors and data from the European Commission Joint Research Centre (JRC) were used for assessment [44]. The GHG emissions were assessed accordingly:

$$G_{wE}(VOS) = F(VOS) \times g_{wE} \tag{2}$$

where,
F(VOS) is the total energy consumption used for the VOS;
g_{wE} is the well-to-wheels GHG emission factor for the average electricity emission factor used in EU countries;
g_{wE} = 0.254 tCO_2e/MWh.

Well-to-wheel GHG emissions for electricity vary due to electricity production methods. It is worth noting that GHG emissions from electricity might even be higher than fossil fuels due to different policies and governmental decisions [45].

Another significant factor is that due to the European Green Deal policy, the carbon intensity of electricity is changing, and the general trend is to be lowered even more in the coming years [46], making fully electric vehicles even more favourable.

4. Results

During the one-month data collection period, consumption varied depending on operating schedules and weather conditions. Figure 2 shows the average fuel rate of Vessel 1. The energy consumption of Vessel 2 is shown in Figure 3. There is a much greater difference in the fuel consumption of Vessel 1 than in the energy consumption of Vessel 2.

4.1. CO_2 Emissions

The results of calculations based on monthly resources are shown in Table 2. The electric ferry produced only 25% of the emissions of its diesel-powered sister vessel. The monthly total emissions were the same, as the electric Vessel 2 was operating 35% more hours per day.

Table 2. Total emissions from one month's operations and emissions per hour.

	Vessel 1	**Vessel 2**
GHG total emissions	15,923.8 $kgCO_2$	15,795.7 $kgCO_2$
GHG total emissions per working hour	43.5 $kgCO_2/h$	10.8 $kgCO_2/h$

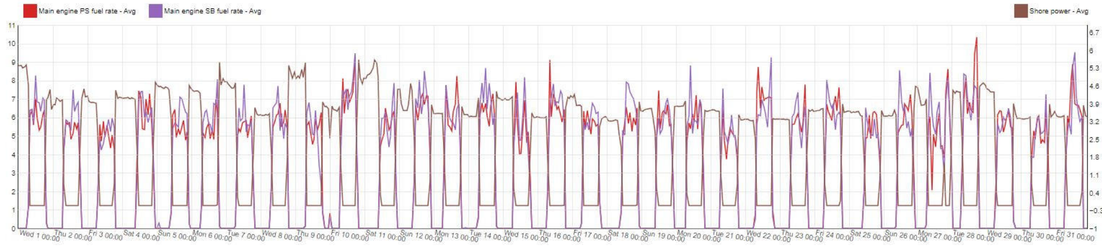

Figure 2. Vessel 1 average fuel rate for main engine and shore power charging.

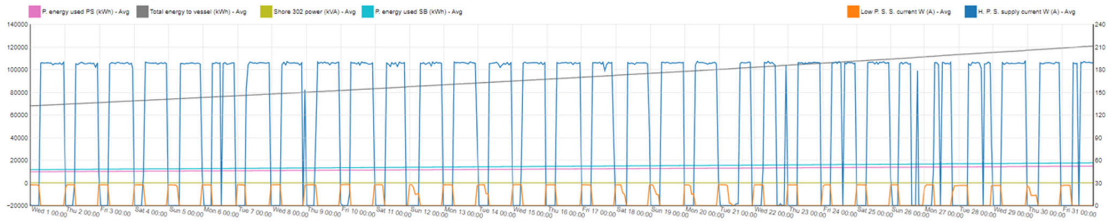

Figure 3. Vessel 2 energy consumption.

4.2. Emissions Comparison of Various Countries

We also calculated the potential difference in CO_2 emissions for these two ferries in different countries. The GHG emission calculation was based on 27 EU countries' average emission factors [47]. It must be emphasized that with the WTW method, emission factors in EU member countries vary due to electricity suppliers' different WTW energy factors. In other words, countries with higher amounts of renewable energy sources and lower energy consumption factors have lower GHG emissions.

Figure 4 shows that, if these vessels were operating in Estonia (which has a relatively high emission factor), the emission difference rate between the two vessels would be only 2.7 times. For vessels in Belgium (which has a relatively low emission factor), the difference would be 5.2 times, whereas for Sweden it would be 15.7 times. This comparison shows that using electricity for operating energy can have significantly less GHG emissions than a diesel-fuelled ferry in all European countries.

4.3. Solar Panel Production in Winter

In addition, we measured and analysed solar power during the period under study. This measurement was not included in the emission analysis of the previous chapter because of its minor impact on the total energy needed. According to the collected data, the total solar energy production for Vessel 1 and Vessel 2 in the measured month was 204.9 kWh and 160.4 kWh, respectively (see Table 3).

Table 3. Solar panel energy production during the data collection period.

	Vessel 1	**Vessel 2**
Solar energy production set 1	104.4 kWh	78.7 kWh
Solar energy production set 2	100.5 kWh	81.7 kWh
Total	204.9 kWh	160.4 kWh

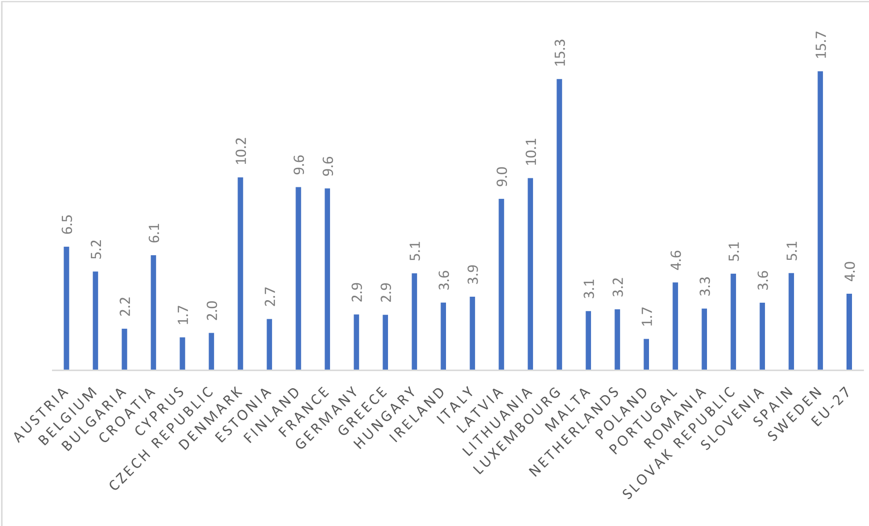

Figure 4. International comparison of the differences in emissions between the two ferries.

Figures 5 and 6 show the actual measured daily power produced by the solar panels. The figures show that on some winter days, energy production was minor for both vessels. These results are generally from cloudy periods.

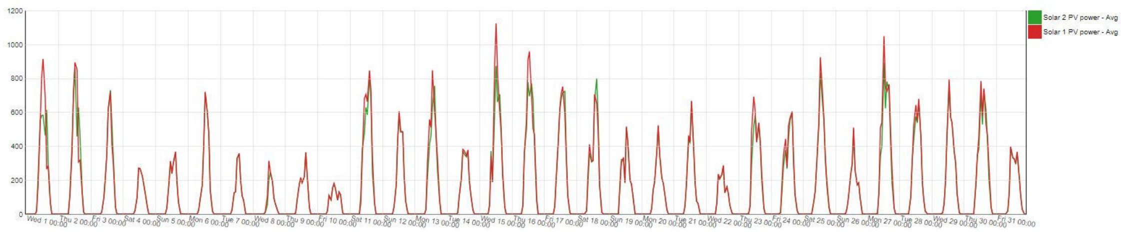

Figure 5. Vessel 1 solar energy power production.

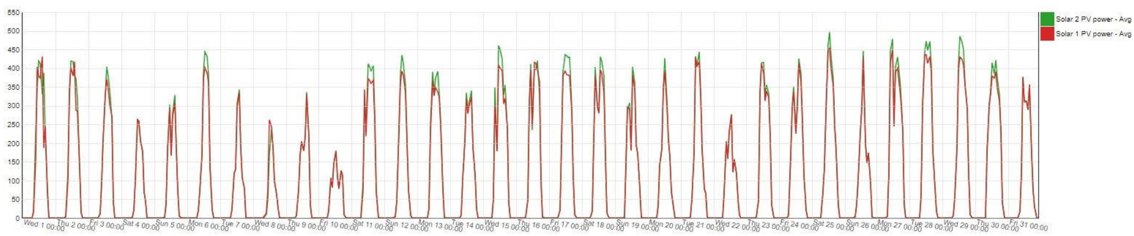

Figure 6. Vessel 2 solar energy power production.

Figures 5 and 6 show that even in winter, when there is low solar energy production, production can cover several application options and user areas during 11 h of navigation time (see Table 4); e.g., lighting the vessel during its operation could be alternatively covered by solar energy supply. The interior lighting analysis was conducted with all lighting switched on. In real life, the hull compartments' lighting is mostly switched off and used for only a few hours a month. Switching off the interior lighting in the passenger area in daylight saves even more electrical energy, allowing another consumer or consumer group to use the energy from solar panels.

Table 4. Possible applications for solar energy.

Consumer Group	Vessel 1	Vessel 2
Lighting	204.9 kWh	217.8 kWh
Signalling system	180.5 kWh	180.5 kWh
Fire system	19.8 kWh	24.8 kWh
Bilge water system	130.0 kWh	66 kWh
Entertainment system	84.5 kWh	34.9 kWh

4.4. Cost Comparison

The diesel and electric commuter ferries are newly built ships (delivered in autumn 2021 and 2022). The purchase price of the electric ferry was EUR 5,500,000 while the diesel ferry was EUR 4,300,000. The purchase price of the electric ferry was 27.9% higher than the construction costs of the diesel ferry [48,49]. It is worth noting that the electric ferry's higher price was caused not only by higher equipment costs, technical innovations, and inflation but also by the unstable market situation initiated by the COVID-19 pandemic during construction time.

We calculated the difference in cost between electric and diesel vessels. In other words, which alternative is more economical.

In the analysis, we assumed that both ferries operate equally 10 h a day. With this assumption, the annual fuel and electricity costs for Vessel 1 in Belgium would have been EUR 22,100. For vessel 2 this operational cost would be EUR 15,200.

The analysis was conducted with average electricity and marine fuel oil prices from Q4 2022 [50,51] in Belgium. The operational cost was calculated from average energy consumption (marine diesel oil and electricity only). This study did not include any technical crew costs, port fees, maintenance, consumer costs, or other relevant and significant expenses of normal operation.

The payback time of Vessel 2 in relation to Vessel 1 (more expensive by purchase cost) was calculated using the following formula:

$$t_p = \left(\frac{C_{pp}}{C_{cc}}\right) \quad (3)$$

where,
t_p is the payback time [years];
C_{pp} is the purchase price difference [€];
C_{cc} is the yearly consumption cost difference [€].

Due to the heavy purchase price difference, the payback time of replacing a diesel ferry with an electric one resulted in 17 years and 6 months.

Thereafter, we calculated the subsidy needed to reduce the payback time of this investment to <10 years. The target of <10 years considers the 20–30-year service life of both ferries. The calculation was determined using the following formula:

$$t_{ps} = \left(\frac{C_{pp} - S_{sub}}{C_{cc}}\right) \quad (4)$$

where,
t_{ps} is the payback time with subsidy [years];
C_{pp} is the purchase price difference [€];
S_{sub} is the subsidy amount [€];
C_{cc} is the yearly consumption cost difference [€].

The calculation showed that with a EUR 500,000 subsidy for purchasing the vessel, the payback time of investment in the vessel would be reduced to 10 years and 2 months.

Thereafter, we compared the operational energy cost differences in countries with different electricity prices. We found that operational costs would be 39.6% lower for Vessel 2 in Estonia. See differences by country in Figure 7 below.

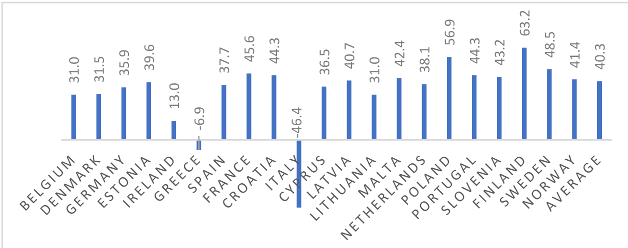

Figure 7. Difference in possible operational cost by country. Note that Ireland, Greece, and Italy are not included in the average calculation due to their disparity.

Finally, we analysed the approximate payback time in various European countries. The European average would be 12 years and 1 month but reduced to 7 years and 1 month with a subsidy of EUR 500,000. See Figures 8 and 9 below.

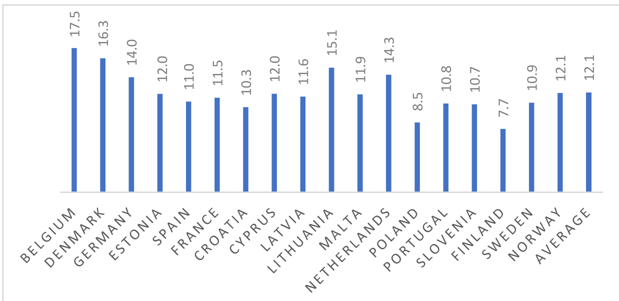

Figure 8. Payback time (years) by country. Note that Ireland, Greece, and Italy are not included in the average calculation due to their disparity.

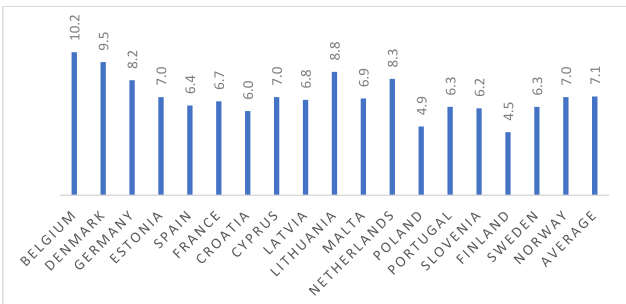

Figure 9. Payback time (years) by country with a EUR 500,000 subsidy. Note that Ireland, Greece, and Italy are not included in the average calculation due to their disparity.

5. Discussion

Many countries have begun using alternative green fuels in city traffic. Hydrogen is one of the most promising fuels. However, the vessel's lifetime plays a significant role in building hydrogen-fuelled ferries [52,53]. Currently, the infrastructure in most cities and ports lacks opportunities to supply hydrogen. In addition, hybrid solutions using other energy combinations have been used [24,27], but these are not as advantageous for urban waterways. Moreover, hybrid solutions are often heavier than one-type energy solutions and increase fuel consumption.

Transitioning the energy source to fully electric in all transportation modes also has natural resource challenges. According to a recent study [54], the demand for battery metals has grown, and annual volumes in 2050 are estimated to be 4–10 times higher than today. This demand implies a significant increase in mining metals such as lithium, nickel, cobalt, and manganese. The analysis also emphasizes that smaller batteries are key to reducing the demand for raw materials. This perspective benefits the shipping industry and ferry operation, especially coastal and inland ferries.

It is also essential to consider the operating area of the vessels. Important factors such as ice conditions and lack of infrastructure currently influence fully electric vessel applications; therefore, retrofitting the ferries to fully electric might not be sufficiently justified.

Despite focusing on the type of ship, other factors also benefit from fully electric ships [39]. Fully electric ferries have less noise and vibration than diesel ferries. This perspective is relevant not only to urban waterways but also to marine biologists and tourism. A study [55] involving whale watching by small ships was conducted in Iceland that, among other results, supports our findings on the importance of using fully electric ships from a financial perspective. Our research results are also supported by findings from other means of transport, where e-fuels and fully electric vehicles have been seen as potentially beneficial [56].

For this study, it is worth noting that there are also proposals to change the assessment of WTW emissions. Among these proposals is connecting carbon emissions to the country's electricity production, as the current methodology might not provide the necessary steps and actions [45]. Additionally, trade and political situations also heavily affect the electricity market [46].

According to the study, even though renewable energy resources such as solar panels may not be able to cover all energy resources for operating needs, there are several alternatives for specific application areas or consumers. For example, solar panel energy is an excellent choice for supplying ferries' interior lighting systems.

In our cost analysis, we found that in most countries, Vessel 2 had significantly lower costs of total energy used. It is worth noting that both the electrical energy and fuel oil markets are volatile and vulnerable to global trends and port infrastructure. According to these results, operation of Vessel 1 would have been economically similar or more viable in three countries (Ireland, Greece, and Italy) in Q4 2022. This finding shows no unique fuel alternative for all European countries. Although fully electric vessels might be low in GHG emissions, they have higher financial costs. These expenses must be obtained from external resources if the targets of the EU Fit for 55 package are to be reached.

The EU has set several supportive measures for helping member countries reach the goals targeted in the Fit for 55 package [57]. One of these measures is a fund to support the most affected citizens and businesses [58], which is an example of how affected companies and industries can find additional funds to support their efforts to become carbon neutral and obtain subsidies. As our study results show, using fully electric vessels has major benefits financially and for carbon emissions. Therefore, the EU, alongside states and local municipalities, should find supportive measures. Supportive measures cover subsidies and financial support for new building/retrofitting as well as finding partnerships, building a supportive infrastructure, and discovering means of supplying such vessels.

6. Conclusions

This study focused on the GHG emissions assessment of two commuter ferries operating in city traffic on the same line. A fully electric and a diesel-fuelled catamaran alternated the same route daily. Total energy and fuel consumption were measured for one month of regular operation for both ferries. Based on these measurements, the well-to-wheel impact of GHG emissions was calculated.

Our results showed that the electric ferry produced only 25% of CO_2 emissions compared to the diesel engine. Depending on the energy sources of various EU countries, GHG emissions for a working hour can be up to 15.7 times lower for fully electric ferries than for diesel engines.

The study also analysed solar panel energy production in winter periods and concluded that using renewable energy sources such as solar panels is justified for reaching carbon-free targets. Solar panel energy production can fully cover the energy needs of modern systems such as internal lighting or other important consumers.

With the assumed operation time, the payback time compared to the purchase price and operational energy costs in Belgium is 17 years and 6 months. However, with a subsidy of EUR 500,000, this length of time is reduced to 10 years and 1 month. Since electrical energy and diesel prices are volatile and vary between countries, these results depend on the country of operation. According to our study results, the EU corresponding average would be 12 years and 1 month, reduced to 7 years and 1 month with a subsidy of EUR 500,000.

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Appendix 2

Publication II

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Article

Comparative Analysis of the Alternative Energy: Case of Reducing GHG Emissions of Estonian Pilot Fleet

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Abstract: The FuelEU Maritime Regulation, part of the European Union's (EU's) Fit for 55 initiative, aims to achieve significant reductions in greenhouse gas (GHG) emissions within the maritime sector. This study assesses the feasibility of alternative fuels for the Estonian pilot fleet using a Well-to-Wake (WtW) life cycle assessment (LCA) methodology. Operational data from 18 vessels, sourced from the Estonian State Fleet's records, were analyzed, including technical specifications, fuel consumption patterns, and operational scenarios. The study focused on marine diesel oil (MDO), biomethane, hydrogen, biodiesel, ammonia, and hydrotreated vegetable oil (HVO), each presenting distinct trade-offs. Biomethane achieved a 59% GHG emissions reduction but required a volumetric storage capacity up to 353% higher compared to MDO. Biodiesel reduced GHG emissions by 41.2%, offering moderate compatibility with existing systems while requiring up to 23% larger storage volumes. HVO demonstrated a 43.6% emissions reduction with seamless integration into existing marine engines. Ammonia showed strong potential for long-term decarbonization, but its adoption is hindered by low energy density and complex storage requirements. This research underscores the importance of a holistic evaluation of alternative fuels, taking into account technical, economic, and environmental factors specific to regional and operational contexts. The findings offer a quantitative basis for policymakers and maritime stakeholders to develop effective decarbonization strategies for the Baltic Sea region.

Keywords: shipping; pilotage; GHG emissions; alternative fuels

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1. Introduction

The European Commission has adopted the Fit for 55 initiative to align the EU's climate, energy, transport, and taxation policies with its target of reducing net GHG emissions by at least 55% by 2030 [1]. By 2050, the European Green Deal aims for net-zero greenhouse gas emissions. Maritime transport, which accounts for 77% of European external trade and 35% of all trade, plays a critical role in the international supply chain and economy [2]. However, it contributes significantly to the EU's total GHG emissions, representing 13.5% of all emissions from the transport sector, following road transport (71%) and aviation (14.4%).

The current International Maritime Organization (IMO) and EU GHG emission measures focus on ships larger than 5000 gross tons (GT); some measures also apply to ships over 400 GT. However, these measures do not apply to a number of different kinds of ships, including fishing vessels, tugs, waterbuses, pilot boats, etc. Armstrong claims [3] that smaller ships are responsible for 15–20% of the total greenhouse gas emissions. In other words, there is currently still a significant amount of CO_2 that is unregulated.

Pilot boats are vital for maritime safety, ensuring safe navigation of vessels entering and departing ports or navigating hazardous areas. Recognized by the IMO in 1968 through Resolution A.159 (ES.IV), pilotage is compulsory in most port areas and territorial waters [4]. Despite their importance, pilot boats have not been widely studied scientifically, particularly regarding their environmental impact [5,6]. Typically small, fast vessels designed for year-round operation in varying weather and sea states, pilot boats are predominantly powered by marine diesel oil, resulting in high fuel consumption and GHG emissions [7]. In addition, there are also formalities of reporting for ships arriving in and departing from ports of the EU's member states [8].

In Estonia, pilotage services are provided by 20 pilot boats across six regions and 30 ports. The unique operational challenges arise due to ice cover for three months each year, necessitating ice-capable vessels during the winter season. These vessels incur significantly higher operating and capital costs but are inefficient during ice-free periods, remaining idle for most of the year. Additionally, Estonian ports are located within the Baltic Sea Emission Control Areas (ECAs) under MARPOL Annex VI, increasing the urgency of using environmentally friendly fuels [9].

As the EU aims for decarbonization by 2050, pilot boats, despite their small size, must adapt to low-emission technologies. State-owned pilot fleets, including those in Estonia, have declared their commitment to becoming carbon-free [10–15]. The limited data on pilot boats and their emissions highlights the need for research into effective GHG reduction strategies tailored to their unique operational characteristics. While numerous studies in the literature compare the technical, safety, operational, and feasibility aspects of alternative fuels for use in the maritime sector, no studies in the literature specifically focus on pilot boats. Given the unique design and operational demands of pilot boats, they warrant detailed investigation to identify optimal strategies for reducing their emissions effectively.

This study addresses the research gap by evaluating the feasibility of alternative fuels for pilot boats by using the Estonian pilot fleet as a case. Using a Well-to-Wake (WtW) life cycle assessment (LCA) methodology and operational data from 18 vessels, the study compares the GHG emissions, efficiency, costs, and storage requirements of alternative fuels, including biomethane, hydrogen, ammonia, biodiesel, and hydrotreated vegetable oil (HVO). The findings aim to provide actionable insights into decarbonizing pilot boats in the Baltic Sea region. Our main question is: Which alternative fuel could be the most prospective to be used in the Estonian pilot boat fleet?

The literature review in Section 2 primarily focuses on fuel alternatives that are suitable for implementation on smaller ships. The research environment in Section 3 describes the current Estonian pilotage fleet, its capabilities, and its operational restrictions. The methodology section in Section 4 illustrates how fuel consumptions were assessed for different fuel alternatives and how the GHG emissions were calculated. The results section is merged with discussions in Section 5, which is divided into several sub-chapters: first, we show the actual GHG emissions of the fleet in 2023, then we show the results of potential fuel alternatives with their fuel consumptions, and finally, GHG emissions of the fuel alternatives are calculated based on the pilotage areas. The section also illustrates possible scenarios for the pilot fleet's future while considering the research results. The conclusion summarizes the research with proposals for the fleet to reduce their GHG emissions.

2. Literature Review

The FuelEU Maritime Regulation was adopted in July 2023 as part of the EU's Fit for 55 package [16]. The regulation promotes the use of renewable, low-carbon fuels and clean energy technologies for ships, which is essential to decarbonizing the maritime sector.

Maritime transport accounts for 3–4% of the EU's total CO_2 emissions [17]. To achieve significant and cost-effective reductions, the EU Emissions Trading System (EU ETS) was implemented in January 2024 [18]. The EU ETS applies to ships with a GT of 5000 or more that enter EU ports, regardless of their flag. Under this system, shipping companies are required to purchase and use EU ETS allowances for each ton of CO_2 emissions reported within this scope. This measure is essential to promote energy efficiency, encourage the adoption of low-carbon solutions, and reduce the cost disparity between alternative fuels and traditional marine fuels. It also drives shipping companies, shipowners, and industry developers to accelerate decarbonization efforts.

The decarbonization of shipping currently involves all stakeholders in the maritime sector. However, no single solution can address all the sector's needs [19]. Pilotage, while a small component of the shipping industry, plays a significant role in port management and infrastructure. Although pilot boats are not directly covered by the IMO GHG strategy, their owner governments often have local and national goals to reduce greenhouse gas emissions. Pilotage companies are closely monitoring advancements in shipbuilding and retrofitting. In recent years, there has been increasing interest in alternative fuels to minimize the environmental impact of pilotage operations. This chapter provides an overview of various alternative fuels that could be adopted for pilot boats, examining their benefits and challenges.

Biodiesel offers several environmental and operational advantages, including being biodegradable, non-toxic, and low in sulfur, which significantly reduces SO_x emissions compared to traditional marine fuels [20,21]. Its oxygen-rich composition enhances combustion efficiency, leading to lower particulate and CO_2 emissions, and it can be blended with diesel with minimal engine modifications [22,23]. However, the lower energy density of biodiesel can create up to a 20% increase in fuel consumption, negatively impacting both range and efficiency [21,23,24]. Its high viscosity and poor cold-flow properties require heating systems in colder climates [21,25]. Safety concerns include potential corrosion in certain materials and challenges with storage and transport. While generally producing lower NO_x emissions [20,21,23], some engine configurations may experience increases. In addition, biodiesel remains costlier than conventional fuels [26–28], and global infrastructure for its use in shipping is limited [20,21].

Methanol is a promising alternative fuel for the maritime sector due to its environmental benefits, such as significantly reduced SO_x, NO_x, and particulate matter emissions compared to traditional marine fuels [29–33]. When produced from renewable sources like biomass or captured CO_2, methanol can drastically cut greenhouse gas emissions, though natural gas-derived methanol still has a lower environmental footprint than coal-based options [31,33,34]. However, methanol faces challenges, including its low energy density, requiring larger storage tanks, and its toxicity and corrosiveness, which demand specialized handling and safety measures [31,35,36]. Its low flashpoint requires additional safety precautions, while its lower cetane number and higher auto-ignition temperature necessitate engine modifications or the use of dual-fuel systems [29,31,37]. Despite these challenges, methanol is easy to store and transport in liquid form at ambient conditions, and its clean-burning properties and scalability make it a viable option for complying with future environmental regulations [36,38,39].

Sweden has pioneered the use of methanol fuel in pilot boats. The Swedish Maritime Administration introduced the world's first methanol-fueled pilot boat, Pilot Boat

120 SE [40,41]. This vessel was repowered with an adapted Scania V8 diesel engine, offering diesel-like performance with a much more favorable emissions profile. Methanol, especially green methanol, is a promising alternative due to its minimal emissions (no particulate matter, sulfur oxides, and very low nitrogen oxides) and potential for zero net CO_2 emissions. Methanol is increasingly being explored as a marine fuel, including for deep-sea shipping, due to its ease of use and compatibility with existing engine technologies. However, its installation costs are approximately 5% higher than those of standard diesel engines.

Hydrotreated Vegetable Oil (HVO) is gaining recognition as a drop-in biofuel due to its chemical similarity to diesel, enabling compatibility with existing marine engines and infrastructure without significant modifications [36,42,43]. This makes it an appealing option for retrofitting fleets to comply with stricter environmental regulations. HVO is sulfur-free, produces lower particulate emissions, and offers significant reductions in lifecycle greenhouse gas emissions, particularly when sourced from waste oils [36,43,44]. However, challenges include its limited availability, high cost compared to fossil diesel, and underdeveloped global supply chains [35,36,43]. Despite having a higher energy density than LNG [36,43], its expense may deter adoption without regulatory or financial incentives [35,36]. On the positive side, HVO's high flashpoint enhances safety in storage and handling, and its non-toxic nature reduces environmental risks from spills [36,37]. In addition, it can be integrated with exhaust gas treatment systems to meet NO_x standards, though extra equipment might be required [45,46].

The Dublin Port Company conducted successful trials using HVO in their pilot boats [47]. According to them, the use of HVO fuel in the pilot boats indicated a significant reduction in CO_2 emissions (between 80 and 90%) without requiring any modifications to existing diesel engines. This approach aligns with broader goals to reduce carbon emissions and improve sustainability in maritime operations.

Biomethane derived from biomass sources like landfill gas recovery and anaerobic digestion offers significant advantages as a marine fuel [36,44,45]. It can greatly reduce GHG emissions by recycling carbon that would otherwise be released from decomposing organic matter [26,34,48]. Combustion of biomethane generates very low levels of SO_x and NO_x, ensuring compliance with stringent environmental regulations [31,49]. Additionally, biomethane benefits from logistical compatibility with LNG, utilizing the same supply chains and storage systems, which facilitates a seamless transition for operators already using LNG [26,36,45]. However, biomethane's scalability is limited by the availability of organic waste sources, constraining its widespread adoption [30,34]. Despite this, it remains highly viable for inland waterway and short-sea operations, especially in regions with established biomethane infrastructure. Challenges include the energy-intensive processes involved in its production, such as collection, purification, and transportation, as well as higher costs compared to fossil fuels [26,50]. From a safety perspective, biomethane is relatively secure, with a high autoignition temperature and low toxicity, but it requires storage at very low temperatures or in liquefied form, presenting operational challenges [26,34,36]. Additionally, methane leakage must be carefully managed due to its potent greenhouse gas effect. Biomethane's clean emissions profile and suitability for dual-fuel gas engines [51] further position it as a promising sustainable fuel for short-distance maritime applications.

Hydrogen is a promising alternative fuel for marine applications, offering zero emissions when produced from renewable sources, as it emits only water vapor in fuel cells, eliminating CO_2, NO_x, SO_x, and particulate matter emissions [29,34,52]. Abundant and scalable through water electrolysis powered by renewable energy, hydrogen presents a viable pathway for maritime decarbonization [29,30,35]. However, its adoption faces challenges, including storage and handling complexities due to its low volumetric energy density, requiring compression or cryogenic liquefaction, which increases cost and operational difficulty [29,34,36]. Safety concerns arise from hydrogen's high flammability, while its production cost, particularly for green hydrogen, remains a significant economic barrier [30,34,36]. Although hydrogen can power both fuel cells and adapted combustion engines, its low energy density limits its feasibility for short-sea shipping, and the underdeveloped bunkering infrastructure further restricts its widespread maritime use [30,52]. The main drawbacks are high costs and low gravimetric density, due to the high weights of the metal hybrid tanks: for this reason, they are suitable mainly for stationary applications and for some transportation applications only, such as submarines and small boats [53,54].

Green hydrogen has demonstrated its utility, for instance, in a crew transfer vessel [55], indicating its potential applicability for pilot boats as well.

Ammonia has emerged as a promising marine fuel due to its carbon-free combustion, eliminating CO_2, CO, and unburned hydrocarbon emissions, which aligns with international maritime decarbonization goals [29,34,35]. Its scalability is supported by existing infrastructure from the fertilizer industry, facilitating its production and transportation [36,56]. However, ammonia faces significant challenges, including a high auto-ignition temperature and low flame speed, which complicate combustion in conventional engines [36,37,57]. Its toxicity and corrosive properties necessitate specialized handling, storage, and engine modifications, while its lower energy density requires more storage volume than diesel [34,36,58]. Additionally, ammonia combustion may increase NO_x and N_2O emissions, requiring systems like selective catalytic reduction (SCR), which reduce efficiency due to increased exhaust backpressure [36,59,60]. Although "green" ammonia production using renewable energy could make it a completely carbon-free fuel, this technology remains costly and under development [34,56].

3. Research Environment

Pilotage is a mandatory service regulated by Estonia's Maritime Safety Law. As of 1 August 2023, the State Fleet of Estonia oversees the management of state vessels (excluding those registered to the Defense Forces and Defense League), the maintenance of floating navigational aids, the execution of icebreaking operations, and the provision and development of pilotage services in Estonia.

The pilot fleet currently comprises 18 vessels specifically designed for pilotage. These boats range from 12 to over 20 m in length and are built to endure challenging seas, various weather conditions, and contact with different types of vessels. They are high-powered, making them both fast and durable, with some boats equipped with advanced ice-crushing capabilities. Below, Table 1 provides an overview of the main characteristics of these vessels, and Table 2 shows the propulsion and performance characteristics of the fleet. In recent years, the total number of pilotages in Estonian waters has remained relatively constant, indicating a stable market (Figure 1).

Table 1. Main ship data of Estonian State Fleet pilot boats.

Ship	Ice Purpose	Home Port	Year Built	LOA [m]	BOA [m]	Draught [m]	Displacement [t]
AHTO-01	icebreaker	Muuga	2009	16	5.3	2.47	63.68
AHTO-02	icebreaker	Pärnu	2011	16	5.3	2.47	63.68
AHTO-06	ice-capable—10 cm	Kunda	2002	13.5	4.56	1.6	14.6
AHTO-07	icebreaker	moving ports	2014	16	5.3	2.43	63.68
AHTO-09	icebreaker	Roomassaare	2014	16	5.3	2.43	63.68
AHTO-12	depreciated	Kunda	1966	12.5	3.95	1.5	22.6
AHTO-14	summer	Heltermaa	2015	14.22	4.5	0.83	21.4

Table 1. *Cont.*

Ship	Ice Purpose	Home Port	Year Built	LOA [m]	BOA [m]	Draught [m]	Displacement [t]
AHTO-15	summer	moving ports	2015	18.37	5.1	1.6	35.5
AHTO-17	ice-capable—10 cm	Roomassaare	2003	13.5	4.55	1.61	14.6
AHTO-19	ice-capable—10 cm	Virtsu	2003	14.1	4.56	1.61	15.7
AHTO-20	ice-capable—10 cm	Pärnu	2003	14.1	4.46	1.61	16
AHTO-21	ice-capable—10 cm	Heltermaa	2004	14.1	4.56	1.61	16
AHTO-23	ice-capable—10 cm	moving ports	2004	14.1	4.56	1.61	16
AHTO-25	ice-capable—15 cm	Muuga	2006	19.5	5.45	1.85	36.4
AHTO-26	ice-capable—15 cm	Meeruse	2007	19.5	5.45	1.85	35.8
AHTO-27	ice-capable—15 cm	Paldiski	2008	19.5	5.45	1.85	35.8
AHTO-28	ice-capable—15 cm	Rohuneeme	2008	19.5	5.45	1.85	35.8
AHTO-29	summer	moving ports	2010	17.6	5.4	1.4	25

Table 2. Propulsion and performance characteristics of the fleet.

Ship	Avg. Fuel Consumption [L/Mile]	Fuel Capacity [m^3]	Max Speed [kn]	Avg Speed [kn]	Engine Power [kW]	Engine Model
AHTO 01-02-07-09	11.61	6.3	10.4	7.8	852	DG SCANIA DI16
AHTO 06-17-19-20-21-23	4.88	1.1	22	19.8	525	MTU 8V2000M70
AHTO 12	2	2.76	8	4.6	162	IVECO
AHTO 14	5.97	1.6	27	25.6	736	Volvo-Penta D13
AHTO 15	6.18	3.0	27	22.8	958	Volvo-Penta D16
AHTO 25-26-27-28	7.79	5.5	22	19.4	900	MTU 10V2000M72
AHTO 29	7.02	4.0	35	30.6	1176	Volvo-Penta IPS 1050

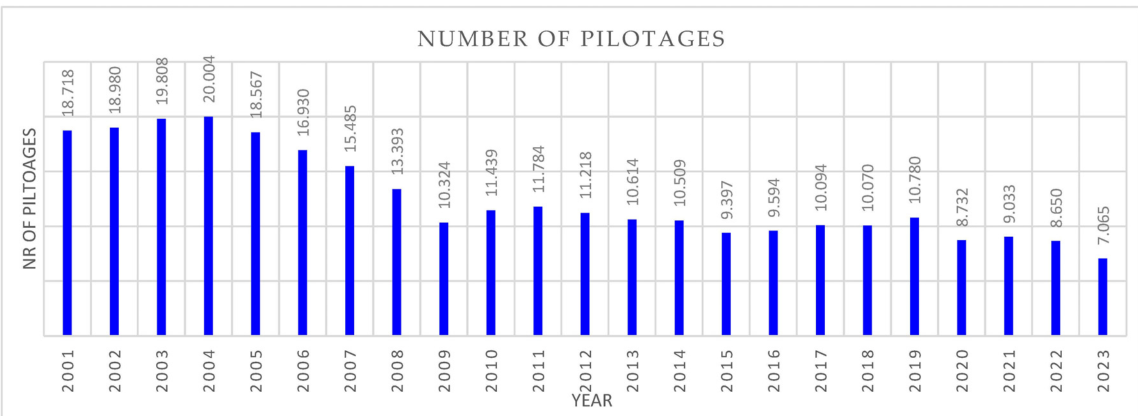

Figure 1. Yearly number of pilotages.

The coastline and pilotage conditions in Estonia, despite being a small country, are diverse. Variations occur in the number of pilotage operations per station and the average distances covered, influenced by trade flow and seasonal changes (Table 3). Based on the geographical distribution of Estonia's ports and primary trade routes, the country is divided into six distinct pilotage areas: Kunda-Loksa, Paldiski, Pärnu, Tallinn, Väinameri, and Sillamäe (Figure 2).

Table 3. Average pilotage data for 2023.

Area	Boat	Distance Max nm		Maximum Number Pilotages in 24 h	Total Distance of Pilotage in 24 h
	Location	Winter	Summer	Pcs	m
Kunda/Loksa	Kunda	7	13	8	60
Paldiski	Paldiski	8	8	11	90
Pärnu	Pärnu	3	7	9	65
Tallinn/Muuga	Meeruse	8	8	5	40
	Hundipea	20	20	15	150
	Muuga	20	20	14	160
Väinameri	Roomassaare	12	12	3	36
	Virtsu	30	30	3	50
	Heltermaa	30	30	3	50
	Veere	0	20	1	20

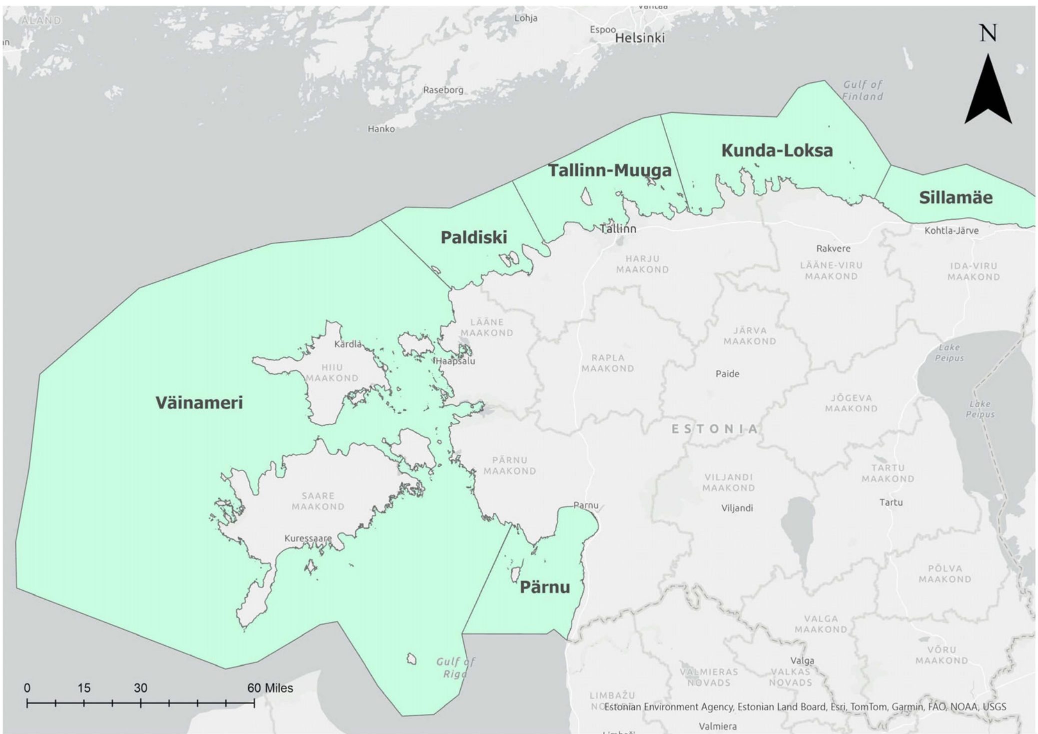

Figure 2. Estonian pilotage areas.

The current fleet of pilot boats in Estonia predominantly consists of vessels powered by diesel engines, reflecting the traditional approach to maritime operations. However, there is a growing interest in exploring more sustainable and diverse energy sources for future upgrades. While the current fleet has not yet adopted alternative propulsion systems, such as hybrid or electric engines, discussions are underway to consider these options as part of broader efforts to reduce emissions and enhance environmental sustainability in pilotage services.

4. Methodology

4.1. Data Collection and Calculation

This study aimed to evaluate the most promising alternative fuel options for the Estonian State Fleet pilot boats, considering technical feasibility, environmental impact, and economic considerations. The first step involved collecting data on current fuel consumption, average and the peak daily mileage, and other relevant specifications for each vessel in the fleet. Additional technical parameters, such as maximum speed, maximum power, and average operational speed, were also gathered. These details enabled precise calculations of engine performance and fuel requirements. Furthermore, the brake-specific fuel consumption (BSFC) for each engine model at both the maximum power and 50% partial power was obtained from technical specification catalogs [61–66].

Next, the peak daily mileage for each vessel was determined using daily mileage data to assess high-use operational demands. To estimate engine load at average speeds, the propeller law was applied, where engine load is calculated as a function of the cube of the speed ratio. Power at average speed was calculated by multiplying the maximum power by the cube of the ratio of average speed to maximum speed, providing a baseline for typical power consumption under standard operating conditions. The methodology of the propeller law is illustrated in Equations (1) and (2) [67]. As the Propeller Law is based on the relationship between shaft speed and engine load, and some experimental studies in the literature [68–70] confirm the existence of this relationship for small-sized engines, this method is also applicable to pilot boats under constant speed scenarios. Since average fuel consumption for each vessel was known but operational engine load was not, Equations (3) and (4) were used to estimate engine load. Given that BSFC varies with engine load, these equations facilitated the estimation of operational engine load through an iterative approach.

$$P_{max} = \frac{FC_{max}}{BSFC_{max}} \tag{1}$$

$$P_{avg} = P_{max}\left(\frac{v_{avg}}{v_{max}}\right)^{\frac{1}{3}} \tag{2}$$

$$BSFC_{avg,sp} = BSFC_{50\%} + (BSFC_{max} + BSFC_{50\%})\left(\frac{P_{avg}}{P_{max}} - 0.5\right) \tag{3}$$

$$FC_{avg,sp} = BSFC_{avg,sp} \ * \ P_{avg} \tag{4}$$

In Equation (1), P_{max} is the maximum power output (kW) calculated by dividing the maximum fuel consumption rate FC_{max} (kW) by the brake-specific fuel consumption at the maximum load $BSFC_{max}$ (kg/(kWh)). Equation (2) gives, P_{avg} the power needed at the average speed, calculated by scaling P_{max} by the cube of the ratio of the average to maximum speed ($\frac{v_{avg}}{v_{max}}$). Equation (3) estimates the average BSFC for a specific engine load ($BSFC_{avg,sp}$) and also the average engine load ($\frac{P_{avg}}{P_{max}}$) by interpolating between the BSFC values at 50% load and the maximum load ($BSFC_i$), adjusted by the load factor ($\frac{P_{avg}}{P_{max}} - 0.5$).

The peak energy need between bunkering operations and peak daily working hours of the vessels were other important parameters for determining the fuel tanks' capacities. The vessel capacities for each fuel type were key factors in comparing fuel alternatives, considering tank volume and fuel weight. For this purpose the maximum daily fuel consumption data were derived from the monthly fuel consumption data of each ship by the following formula where t_{bb} is the time (days) between bunkering and $FC_{daily,\ peak}$ is the daily average fuel consumption in the month in which the maximum fuel consumption for that ship was performed.

Fuel tank capacities for each type were determined by peak energy demand, full tank capacity, and daily operating hours $\left(h_{daily}\right)$. To estimate this, the maximum daily fuel consumption ($FC_{daily,\ peak}$) was calculated by averaging from monthly fuel consumption data for each ship that was used in the following formulas. In this formula, t_{bb} represents the time (in days) between bunkering (converted to hour for calculations), $FC_{daily,\ peak}$, is the daily average fuel consumption during the month when the vessel recorded its highest fuel consumption and FC_{avg} is the average fuel consumption of the vessel in average speed.

$$E_{tank,peak} = t_{bb} \frac{FC_{daily,peak}}{BSFC_{avg}} \tag{5}$$

$$h_{daily} = \frac{FC_{daily,peak}}{v_{avg} FC_{avg}} \tag{6}$$

The size of fuel tanks and the weight of the necessary fuel between bunkering operations serve as performance indicators for alternative fuels. Each fuel type varies in density and calorific value. Since pilot boats do not carry cargo, the weight and volume impact of alternative fuels is more pronounced compared to cargo ships. Since pilot boats are relatively small, the extra fuel weight or volume could lead to design challenges, potentially exceeding design weight and volume limits. These changes in weight and volume affect crucially the vessel's stability and metacentric height, especially during contact with other vessels. A critical change in metacentric height while the pilot boat is moving at high speed can lead to capsizing.

This study examines weight and volume costs through two scenarios. In the first scenario, the boats' original range with marine diesel oil (MDO) was maintained, so the alternative fuel capacity after retrofitting matched this range. In the second scenario, the range was adjusted based on the ships' past service times. These scenarios assess operational range preservation and adaptation to real-world usage, ensuring practical evaluation of alternative fuels. Both scenarios calculated weight costs, considering the relative power-to-weight ratio of the engines or motors and the weight of fuels. An assumption was made that after the retrofit, the ships would maintain the same propulsion power in both scenarios. For both scenarios, the relative weight and relative volume of each fuel were calculated first. These are the relative weights and volumes of alternative fuels to give the same energy amount theoretically.

$$m_{rel,i} = \frac{Q_{MDO}}{Q_i} \tag{7}$$

$$V_{rel,i} = \left(\frac{Q_{MDO}}{\rho_{MDO}}\right) / \left(\frac{Q_i}{\rho_i}\right) \tag{8}$$

Here, m_{rel} and V_{rel} are relative mass and volume of each fuel, Q_{MDO} and Q_i are calorific value of MDO and alternative fuels, and ρ_{MDO} and ρ_i are the density of MDO and alternative fuels.

In Scenario 1, the relative weight and volume costs of alternative fuels were calculated using specific equations. In these equations the relative weight and volume costs of alternative fuels were calculated for the same operation range, with the original fuel tank capacity in vessels.

$$m_{rel,cost,1} = \frac{P_b \times PWR_i + m_{rel,i} \times V_{fuel} \cdot \rho_{MDO} / \mu_i}{P_b \times PWR_{MDO} + V_{fuel} \times \rho_{MDO} / \mu_{MDO}} \tag{9}$$

$$V_{rel,cost,1,2} = V_{rel,i} \frac{\mu_{MDO}}{\mu_i} \tag{10}$$

where P_b is the brake power of the engine, PWR is the power to weight ratio for each propulsion system, V_{fuel} is the fuel tank capacity of the current ship design with MDO as fuel and μ_{MDO} and μ_i are brake thermal efficiency of MDO and alternative fuels.

In Scenario 2, the relative weight and volume costs of alternative fuels were determined based on optimized operation ranges derived from each vessel's service time. As the relative volume cost is unaffected by engine weight, the same method applies to both scenarios. While the volume costs of fuels may differ between scenarios, the relative rates remain consistent.

$$m_{rel,cost,2} = \frac{P_b \times PWR_i + m_{rel,i} \times \frac{E_{tank,peak}}{(Q_i \cdot \mu_i)}}{P_b \times PWR_{MDO} + \frac{E_{tank,peak}}{(Q_{MDO} \times \mu_{MDO})}} \tag{11}$$

Equations (9) and (11) were developed based on fundamental engineering principles to estimate the relative weight and volume costs of alternative fuels compared to MDO. Key parameters such as engine power, power to weight ratio, fuel tank capacity and brake thermal efficiency are considered in these equations. While Equation (9) assumes the same fuel tank capacity as currently used for MDO, Equation (11) incorporates energy requirements for peak operational scenarios. These equations have been specifically tailored to the operational characteristics of the fleet, providing a robust framework for evaluating fuel alternatives in this context.

The yearly fuel consumption for each vessel with each alternative fuel was calculated using Equation (12). This equation estimated the annual fuel consumption for each fuel type based on the vessels' previous service times.

$$FC_i = \frac{m_{rel,i} \times \mu_{MDO} \times FC_{MDO}}{\mu_i} \tag{12}$$

The OpEx (operational expenses) for each ship is a key performance indicator for evaluating alternative fuels. Although factors such as maintenance costs, amortization time, and service costs also impact operational costs, they require extensive data that is currently unavailable in the literature. Therefore, only the primary cost of operation—the fuel cost—is considered in calculating the operational costs. These costs are calculated using Equation (13).

$$OpEx_i = FC_i \times UC_i \tag{13}$$

Here, $OpEx_i$ indicates the yearly operational cost with each fuel and UC_i indicates the unit cost of each fuel in the Eastern European market.

Figure 3 provides a visual representation of the calculations. In the figure, the data sources are distinguished by color: yellow represents data collected from the Estonian State Fleet, blue denotes data obtained from engine producers' datasheets and instruction manuals, orange indicates data gathered from the literature, and purple signifies calculated or predicted values.

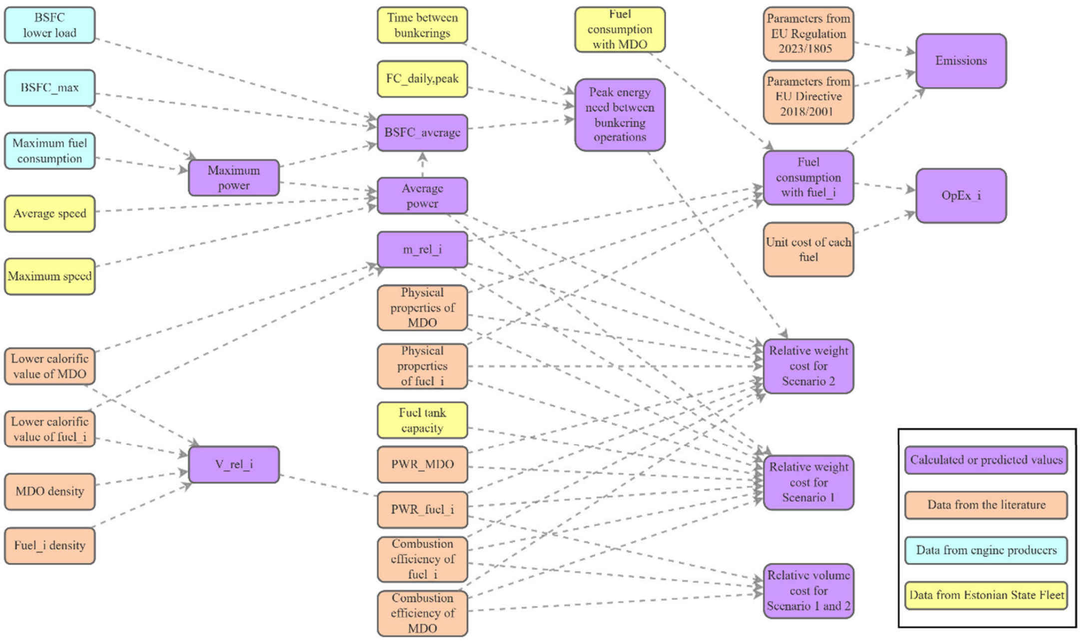

Figure 3. Flow diagram for calculations and predictions.

4.2. Fleet Performance and Alternative Fuels

Table 4 presents the brake-specific fuel consumption (BSFC) values for each vessel in the Estonian State Fleet. BSFC measures the fuel consumption per unit of power produced by an engine, typically expressed in grams of fuel per kilowatt-hour (g/kWh). These values were used to calculate the BSFC for each ship at specific engine loads. The data were sourced from the technical datasheets of each engine model, as provided by the manufacturers [61–66]. The BSFC at full load represents fuel consumption at maximum power output, reflecting the engine's efficiency at its highest load. However, ships typically operate at operating loads, defined as the percentage of maximum engine capacity utilized during regular operations. These operating loads were predicted using Equation (2) by applying the "Propeller Law" specifically to each ship in the fleet. While manufacturers provided BSFC data for reduced power outputs under varying engine speeds and lower load scenarios—representing load conditions chosen by the manufacturer—these lower loads do not align with the actual operating loads. Therefore, BSFC at operating loads was calculated using a linear regression-based method, as outlined in Equation (3). This method adjusts the formula to account for the power ratio between lower and full load, enabling an accurate prediction of BSFC under typical operating conditions.

Weight costs, volume costs, fuel consumption, and operational costs were calculated based on the operational ranges of each vessel. Key parameters include the energy needs of each vessel between bunkering intervals (which impacts the required fuel quantity on board) and peak working hours per day, as retrofitted ships must meet the operational demands of each vessel. Figure 4a,b illustrate each vessel's energy needs between bunkering operations, assumed to occur every 10 days, and the daily average working hours. It is important to note that energy needs and working hours vary across different months and operational conditions, and the values in the figures represent peak time conditions.

Table 4. BSFC values for the fleet at full load and lower loads.

	Full Load			Lower Load		
	BSFC	**Rpm**	**Rated Power**	**BSFC**	**Rpm**	**Rated Power**
	g/kWh		**kW**	**g/kWh**		**kW**
AHTO 01-02-07-09	213	1800	468	205	1500	445
AHTO 06-17-19-20-21-23	214	2250	720	205	1950	475
AHTO 12	220	2800	184	215	1400	92
AHTO 14	216	2400	735	206	1900	400
AHTO 15	210	1800	479	200	1200	400
AHTO 25-26-27-28	213	2250	900	211	1950	585
AHTO 29	212	2300	564	201	1400	185

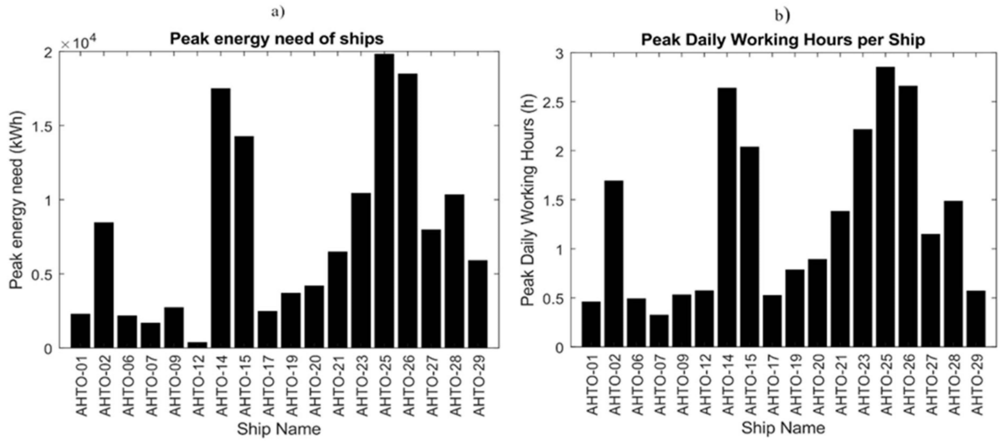

Figure 4. (**a**) Peak energy needs of the ships between bunkering operations; (**b**) peak daily working hours of the ships.

The peak energy requirements of the vessels vary significantly, ranging from 364 kWh to 19,800 kWh. These values represent the average energy demand of each vessel under peak operational conditions over a 10-day period. This indicates that if these energy needs can be met through alternative fuels and bunkering operations are conducted every 10 days, the vessels can operate without problems, even during peak scenarios. To analyze operability, the weight and volume costs for each alternative fuel, as well as for electric and hybrid propulsion options, were calculated under two scenarios. In the first scenario, the fuel quantity was determined to match the design range of each vessel. In the second scenario, the quantity was calculated to meet the energy needs for peak conditions, assuming a 10-day interval between bunkering operations. In addition, Figure 4b illustrates the peak daily working hours of the vessels, which vary from an average of 0.32 h to 2.85 h per day. This indicates that, even during peak operation, the vessels in the fleet are used for only a small portion of the day. This suggests that the current fuel tank sizes may be larger than necessary to meet the vessels' operational requirements.

Table 5 presents the physical and combustion properties of various fuels. Each fuel in the study was evaluated based on its energy density, volumetric density, required engine weight, combustion efficiency, and operational expenditures. These values in the table were used for the calculations for each fuel.

Table 5. The properties of various fuels *.

	Lower Heating Value (MJ/kg)	Density (t/m^3)	Relative Engine Gravimetric Energy Density	Fuel Cost (€/ton)	Relative Thermal Efficiency
MDO	42.7 [49,71,72]	0.84 [49]	1	672 [73]	1
Methanol	19.9 [49,71,72]	0.79 [49]	0.78 [74]	381 [75–78]	1.03 [72,79]
Biodiesel	37.5 [21,80,81]	0.88 [21,81,82]	1	1127 [73]	0.96 [21,80]
HVO100	44.1 [82–84]	0.78 [83–85]	1	1456 [73]	0.99 [82,86–89]
H_2 (SOFC)	120 [49,71,72]	0.023 * [49]	0.65 [90–95]	5000 [96,97]	1.3 [74,98]
H_2 (PEMFC)	120 [49,71,72]	0.021 * [49]	1.01 [90–95]	5000 [96,97]	1.21 [74,91,99]
Ammonia	18.6 [71,72,85,100,101]	0.68 [90,98]	0.78 [74,102]	590 [73]	1.03 [102–105]
Biomethane	36 [103,106]	0.25 * [92–94]	0.89 [107]	1150 [78,108]	1.04 [109,110]

* (at 300 bar, −15 °C).

For each fuel type, we estimated fuel consumption, operational costs, and exhaust emissions (Figure 5). The lower heating value and density of fuels, as well as their fundamental physical properties, were sourced from widely available references. Many alternative fuels, such as hydrogen, ammonia, HVO100, and methanol, are already commercially available for various applications, with some suitable for bunkering on marine vessels. Other fuels are also used across different industries. Fuel costs were obtained from global market data, focusing on prices in Estonia and neighboring European countries (Table 5). While there is considerable interest in these fuels within experimental and academic research, and some compatible engine models exist, there remains a lack of suitable engines that meet the power demands of the pilot boats analyzed in this study. Although smaller engines compatible with these fuels are expected to be developed soon, comprehensive data on their gravimetric energy density and combustion efficiency are currently unavailable. In this study, gravimetric energy density was estimated using instruction manuals for engines of various sizes. It was observed that as the lower heating value of a fuel decreases, the gravimetric energy density of the engine also declines. Fuels with lower heating values require larger engines due to the need for increased cylinder sizes. Relative efficiency values were derived from experimental studies comparing the combustion performance of alternative fuels in internal combustion engines, using diesel oil as the reference fuel.

4.3. Assessing Shipping Emissions

In July 2023, the FuelEU Maritime Regulation was adopted [111] with the aim to support decarbonization of the shipping sector by promoting the use of renewable, low-carbon fuels, and clean energy technologies for ships. In shipping, there are various methods to calculate emissions [112], and although several research studies [113–117] and proposals [118–123] have been conducted, there is still an open debate about the uniform methodology.

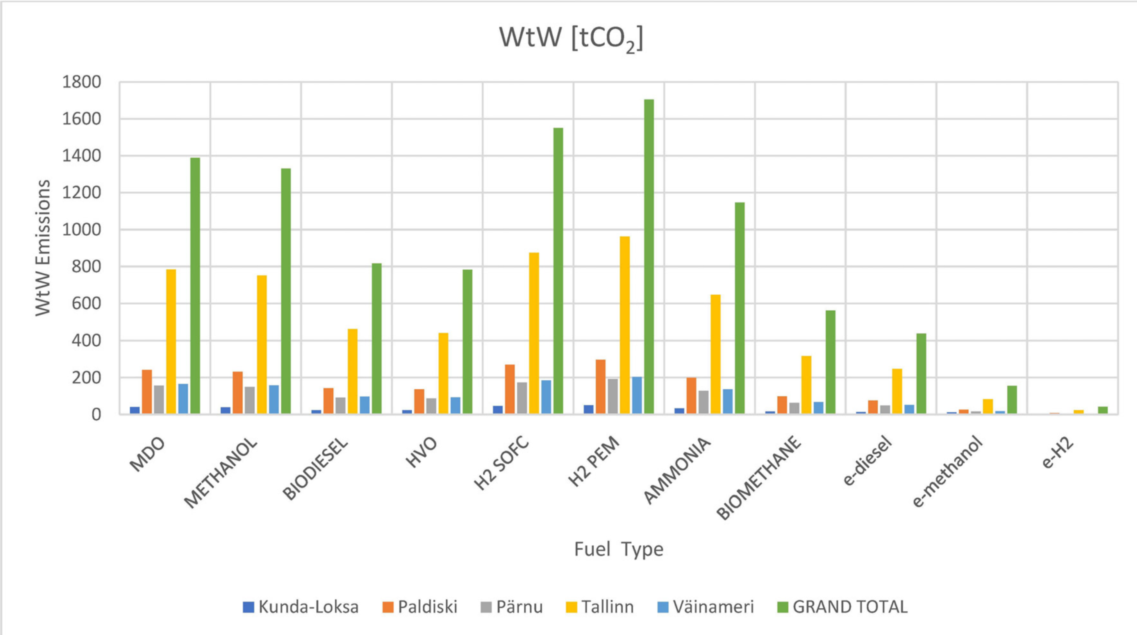

Figure 5. GHG emissions of the fuel alternatives by pilotage areas.

The life cycle assessment (LCA) is a comprehensive methodology used within the shipping industry to conduct a thorough evaluation of ecological impact while also considering the energy and emissions involved in constructing facilities, vehicles, or end-of-life aspects [124,125]. WtW GHG emissions are indicated as a subset of LCA, focusing specifically on fuel-related emissions.

The methodology for the current research [126] was derived from the geographical location and legislation. According to the suggestion of the IMO's Marine Environment Protection Committee (MEPC 77) life cycle guidelines, the GHG emissions should be estimated based on a Well-to-Wake method. The guidelines are proposed to be based on the sustainability and GHG emissions-saving criteria to incentivize the uptake of sustainable alternative fuels at the global level. The targets cover CO_2, methane, and nitrous oxide emissions over the full lifecycle of the fuels used onboard on a WtW basis. Therefore, this research focuses on the fleet's WtW GHG emissions.

Life cycle guidelines to estimate WtW GHG emissions are proposed by the EU [126] and IMO [127]. These suggested life cycle guidelines are based on sustainability and GHG emissions-saving criteria to incentivize the uptake of sustainable alternative fuels at the global level. The total GHG emissions include the Well-to-Tank (WtT) emissions of the energy carrier supply and the Tank-to-Wake (TtW) emissions of the total fuel use.

$$WtW_{GHG} = WtT(energy\ carrier\ supply) + TtW(fuel\ use) \tag{14}$$

The initial GHG assessment was calculated over a reference period of one year based on the collected data of actual fuel consumptions. The default emission factors that were used for the determination of the GHG intensity were established in accordance with the methodologies laid down in Directive (EU) 2018/2001 and Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport and amending Directive 2009/16/EC).

The total emissions depend on the fuel type and specifics. They are calculated by the following equation:

$$WtW_{GHG} = \sum_{i}^{n\ fuel} M_i \times CO_{2\ eq\ WtT,i} \times LCV_i + \sum_{i}^{n\ fuel} \sum_{j}^{m\ consumer} M_{ij} \times \left[\left(1 - C_{slip\ j}\right) \times \left(CO_{2\ eq,TtW}\right) + \left(C_{slip\ j} \times GWP_{CH4}\right) \right] \quad (15)$$

In this equation, i is the index corresponding to the fuels (for each specific fuel pathway) delivered to the ship over a reference period; j is the index corresponding to the different fuel consumers. The energy consumers considered are main engines, auxiliary engines, boilers, waste incineration plants, etc. k is the index corresponding to the connection points (c) where electricity was supplied per connection point. m is the index corresponding to the number of energy consumers. M_{ij} represents the mass of the specific fuel i oxidized in consumer j (in gFuel). $CO_{2eqWtT,i}$ are the WtT GHG emissions in gCO_2eq/MJ for each specific fuel, calculated according to an agreed methodology. $CO_{2eqTtW,I}$ are the TtW GHG emissions for in gCO_2eq/g Fuel for each specific fuel, when consumed on board by the fuel consumer j. $CO_2eqTtW, i = \left(C_{fCO2} \times GWP_{CO2} + C_{fCH4} \times GWP_{CH4} + C_{fN2O} \times GWP_{N2O}\right)_i$. C_{fCO2}, C_{fN2O}, C_{fCH4} are the emission factors in g of GHG/f of fuel. LCV_i represents the lower calorific value of the i fuel (considered in its own specific pathway) in MJ/g. $C_{slip\ j}$ represents fuel carbon slip in % of the mass of the fuel used by the energy converter j.

5. Results

5.1. Initial GHG Emissions

The initial GHG assessment, based on 2023 fuel consumption data from Estonian pilotage areas, calculated total emissions over a one-year reference period. The results for marine diesel oil are shown in Table 6.

Table 6. WtT, TtW, and WtW. emissions for Estonian pilotage areas in 2023, compiled by the authors based on actual fuel consumption data.

Pilotage Area	WtT Emissions	TtW Emissions	WtW Emissions	WtW Emissions
	[$kgCO_2eq$]	[$kgCO_2eq$]	[$kgCO_2eq$]	[tCO_2eq]
Kunda-Loksa	6592	34,895	41,486	41.5
Paldiski	26,860	142,195	169,055	169.1
Pärnu	25,563	135,325	160,888	160.9
Tallinn	109,656	580,503	690,159	690.2
Väinameri	47,086	249,266	296,352	296.4
TOTAL	215,756	1,142,185	1,357,940	1357.9

The calculation results show that the Tallinn pilotage area has the highest emissions, primarily due to its large ports and heavy sea traffic. The Väinameri area follows, which can be attributed to its complex operational patterns and extended pilotage distances.

5.2. Weight and Volume

Table 7 presents the comparative weight costs for each vessel in the fleet, with fuel quantities calculated to provide the same operational range as the original ship design. These values were calculated using Equation (9) and the parameters defined within it. The gravimetric density of alternative engines or fuel cells was also considered. This added weight is a significant factor for large ships, such as cargo or passenger carriers, as increased fuel weight reduces total cargo capacity. However, cargo vessels can offset this by adjusting cargo quantity to accommodate higher fuel weight. However, for pilot boats, additional fuel weight poses a more critical challenge due to their hull design and limited carrying capacity, which is optimized for lighter loads. This increased weight could exceed safety margins in hull design.

Table 7. Comparative weight * costs of the entire fleet using alternative fuels within the same design range.

	MDO	Methanol	Biodiesel	HVO100	H_2 Blue SOFC	H_2 Blue PEM	Ammonia	Biomethane
AHTO 01-02-07-09	1	1.74	1.11	0.98	0.77	0.57	1.83	1.13
AHTO 06-17-19-20-21-23	1	1.51	1.06	0.99	1.15	0.78	1.55	1.12
AHTO 12	1	1.88	1.15	0.98	0.55	0.45	1.99	1.13
AHTO 14	1	1.51	1.06	0.99	1.14	0.77	1.56	1.13
AHTO 15	1	1.58	1.07	0.99	1.04	0.71	1.63	1.13
AHTO 25-26-27-28	1	1.71	1.11	0.98	0.83	0.60	1.79	1.13
AHTO 29	1	1.59	1.08	0.99	1.01	0.70	1.65	1.13

* These options are calculated to meet a daily operation requirement of 4 h.

The findings show that methanol and ammonia lead to particularly high weight costs among alternative fuels. Despite strong industry interest in these fuels as alternatives to conventional options, their weight costs may render them less suitable for smaller vessels like pilot boats, especially when required to maintain the same range as the original design. However, operational adjustments—such as reducing tank size, thereby limiting range but allowing more frequent refueling— which can make these fuels viable alternatives.

The table also highlights that HVO100 and hydrogen reduce fuel weight costs relative to conventional diesel, while biomethane and biodiesel show a slight increase. It is essential to note that although the relative fuel weights remain constant across fuels, this study includes the weight costs of both the fuel and the engines required for each alternative fuel. Different fuels necessitate various engine types or fuel cells, each with unique gravimetric energy densities, and the fleet itself comprises vessels with diverse engine power capacities, contributing to weight cost variations even for the same fuel.

Like weight cost, volume cost is also a critical performance indicator for alternative fuels. While volume cost may be manageable for cargo vessels, it poses a greater challenge for smaller ships, such as pilot boats, due to their limited onboard space. Table 8 presents the volume requirements for various alternative fuels to achieve the same range as the original design. For MDO, this volume requirement matches the original tank capacity. These values were calculated using Equation (10) and the parameters defined within it.

Table 8. Tank volume needed [m^3] for the entire fleet using alternative fuels within the same range.

	MDO	Methanol	Biodiesel	HVO100	H_2 Blue (SOFC)	H_2 Blue (PEM)	Ammonia	Biomethane
AHTO 01-02-07-09	5.3	11.8	6.2	5.6	5.3	5.7	16.1	18.0
AHTO 06-17-19-20-21-23	0.9	2.1	1.1	0.9	9.3	10.0	2.8	3.1
AHTO 12	2.3	5.2	2.7	2.5	23.3	25.0	7.1	7.9
AHTO 14	1.3	3.0	1.6	1.4	13.5	14.5	4.1	4.6
AHTO 15	2.5	5.6	2.9	2.7	25.4	27.2	7.7	8.6
AHTO 25-26-27-28	4.6	10.3	5.4	4.9	46.5	49.8	14.1	15.7
AHTO 29	3.4	7.5	3.9	3.6	33.8	36.2	10.3	11.4

The findings suggest that biodiesel and HVO100 have acceptable volume costs; biodiesel requires a slight increase in tank capacity, while HVO100 actually reduces the necessary tank size. Additionally, liquid fuels like methanol, biodiesel, HVO100, and ammonia can utilize existing tanks with retrofitting, thereby lowering the retrofit capital cost. However, to match the original design range, methanol and ammonia require significantly larger tank volumes relative to MDO. Due to space limitations on pilot boats, these fuels may not be ideal alternatives when the goal is to maintain the same range. Biomethane and hydrogen, due to their gaseous form, also present high volume costs. It should also be noted that the storage conditions of the fuels calculated are −15 °C and 25 MPa. But liquified storage can also be an option which will decrease the volume cost considerably. Typically stored on deck, these tanks consume valuable deck space and, being located higher than bottom tanks, increase the vessel's GC (gravity center), potentially compromising safety margins.

Overall, as can be seen in Tables 7 and 8, both weight and volume cost analyses indicate that only biodiesel and HVO100 appear promising as alternative fuels to MDO if the same range is expected post-retrofit. However, reducing the operational range of vessels post-retrofit to lower onboard fuel weight and volume could be a viable option. Therefore, reviewing each vessel's operational history and performing alternative calculations to meet peak fuel requirements during high-demand periods could yield useful insights. If fuel capacity is optimized for peak requirements, a new perspective on alternative fuel feasibility could emerge. For this purpose, Tables 9 and 10 show the weight and volume costs of alternative fuels and propulsion units for an optimized range, calculated to cover peak energy demands for each vessel by using Equations (10) and (11), allowing for operations up to 10 days without refueling. Shortening bunkering intervals further would reduce both weight and volume costs.

Table 9. Relative weight costs * of the entire fleet using alternative fuels within an optimized range (Comparing to design MDO tank capacity).

	MDO	Methanol	Biodiesel	HVO100	H_2 Blue (SOFC)	H_2 Blue (PEM)	Ammonia	Biomethane
AHTO-01	0.46	0.62	0.47	0.45	0.62	0.41	0.63	0.51
AHTO-02	0.60	0.93	0.64	0.60	0.67	0.45	0.96	0.68
AHTO-06	0.85	1.20	0.88	0.85	1.11	0.73	1.22	0.96
AHTO-07	0.44	0.59	0.45	0.44	0.62	0.41	0.60	0.49
AHTO-09	0.47	0.65	0.48	0.46	0.63	0.41	0.65	0.52
AHTO-12	0.25	0.34	0.26	0.25	0.35	0.23	0.34	0.28
AHTO-14	1.54	2.63	1.70	1.51	1.29	0.93	2.75	1.74
AHTO-15	1.08	1.74	1.17	1.07	1.06	0.74	1.81	1.22
AHTO-17	0.87	1.24	0.90	0.87	1.12	0.74	1.27	0.98
AHTO-19	0.96	1.42	1.00	0.95	1.14	0.76	1.45	1.07
AHTO-20	0.99	1.49	1.05	0.98	1.15	0.77	1.53	1.11
AHTO-21	1.15	1.81	1.23	1.13	1.19	0.82	1.87	1.29
AHTO-23	1.42	2.37	1.55	1.40	1.26	0.90	2.47	1.60
AHTO-25	0.95	1.61	1.05	0.94	0.82	0.59	1.68	1.08
AHTO-26	0.92	1.54	1.01	0.90	0.81	0.58	1.61	1.04
AHTO-27	0.65	0.99	0.69	0.64	0.74	0.50	1.02	0.73
AHTO-28	0.71	1.11	0.76	0.70	0.75	0.52	1.15	0.80
AHTO-29	0.74	1.07	0.77	0.74	0.94	0.63	1.09	0.84

* These options are calculated to meet the one-day operation requirement at peak times.

Table 9 presents the weight costs of alternative fuels and propulsion units optimized to meet peak energy demands for 10 days without refueling. Interestingly, for vessels Ahto 14, Ahto 15, Ahto 21, and Ahto 23, the MDO requirements exceed the original design fuel capacity. This is due to the selected 10-day bunkering interval, implying that under peak demand conditions, these vessels cannot operate for 10 days without refueling using their original tank capacities. Peak demand scenarios, reflecting each pilot boat's unique operational patterns, show significant variation across vessels—while Ahto 12 experiences minimal peak-time usage, Ahto 14 has much higher operational frequency. The results demonstrate that all fuels, both liquid and gas, can meet peak energy demands at an acceptable weight cost, although methanol and ammonia remain somewhat high for certain vessels like Ahto 14, Ahto 15, Ahto 21, and Ahto 23. However, since shorter refueling intervals are feasible during peak periods, these fuels could still serve as viable MDO alternatives from a weight cost perspective.

Table 10. Tank volume [m^3] needs of the entire fleet using alternative fuels within an optimized range.

	Original Tank Volume	MDO	Methanol	Biodiesel	HVO100	H_2 Blue (SOFC)	H_2 Blue (PEM)	Ammonia	Biomethane
AHTO-01	5.3	0.5	1.1	0.6	0.5	4.9	5.3	1.5	1.7
AHTO-02	5.3	1.8	4.0	2.1	1.9	18.1	19.4	5.5	6.1
AHTO-06	0.9	0.5	1.0	0.5	0.5	4.6	5.0	1.4	1.6
AHTO-07	5.3	0.4	0.8	0.4	0.4	3.6	3.8	1.1	1.2
AHTO-09	5.3	0.6	1.3	0.7	0.6	5.8	6.3	1.8	2.0
AHTO-12	2.3	0.08	0.2	0.09	0.08	0.8	0.8	0.2	0.3
AHTO-14	1.3	3.7	8.3	4.3	4.0	37.5	40.2	11.4	12.7
AHTO-15	2.5	3.0	6.8	3.5	3.2	30.6	32.8	9.3	10.4
AHTO-17	0.9	0.5	1.2	0.6	0.6	5.3	5.7	1.6	1.8
AHTO-19	0.9	0.8	1.8	0.9	0.8	7.9	8.5	2.4	2.7
AHTO-20	0.9	0.9	2.0	1.0	1.0	9.0	9.6	2.7	3.0
AHTO-21	0.9	1.4	3.1	1.6	1.5	13.9	14.9	4.2	4.7
AHTO-23	0.9	2.2	5.0	2.6	2.4	22.3	23.9	6.8	7.6
AHTO-25	4.6	4.2	9.5	4.9	4.5	42.5	45.5	12.9	14.4
AHTO-26	4.6	3.9	8.8	4.6	4.2	39.6	42.5	12.0	13.4
AHTO-27	4.6	1.7	3.8	2.0	1.8	17.1	18.3	5.2	5.8
AHTO-28	4.6	2.2	4.9	2.6	2.3	22.1	23.7	6.7	7.5
AHTO-29	3.4	1.3	2.8	1.5	1.3	12.6	13.6	3.8	4.3

Table 10 outlines the tank volume requirements for the fleet when utilizing alternative fuels within an optimized range to cover peak energy demands over a 10-day period without refueling. Similarly to MDO, some ships face volume requirements that exceed their original tank capacity, particularly for methanol, ammonia, and gaseous fuels like biomethane and hydrogen. This challenge is more pronounced for vessels with higher peak operational demands, such as Ahto 14, Ahto 15, Ahto 21, and Ahto 23. For smaller vessels like pilot boats, the increased tank volume required by these fuels may surpass onboard storage limits and impact stability. In contrast, biodiesel and HVO100 exhibit more manageable volume requirements; biodiesel requires only a slight increase in tank size, while HVO100 can reduce the necessary tank capacity, aligning well with existing vessel designs. Additionally, liquid fuels like methanol, biodiesel, HVO100, and ammonia can be stored in retrofitted original tanks, potentially lowering retrofit costs. However, gaseous fuels such as biomethane and hydrogen, stored under conditions of −15 °C and 25 MPa, incur high volume requirements. Although liquefied storage could reduce tank size, gaseous tanks are often placed on deck, which can raise the vessel's center of gravity and impact stability.

Overall, liquid fuels emerge as the most feasible for maintaining original tank designs for peak-time scenarios in many vessels. Reducing operational range post-retrofitting could further optimize tank size and weight, enhancing safety margins and space utilization. For vessels with high operational demands, alternative fuel feasibility might be improved by adjusting tank sizes to meet peak-time energy needs, with the option for shorter refueling intervals to minimize volume requirements.

5.3. Operational Cost

The fleet's annual fuel consumption using various alternative fuels relative to conventional MDO is compared in detail, highlighting each fuel's distinct characteristics (Table 11). Hydrogen stands out with significantly lower consumption compared to MDO, owing to the high efficiency of fuel cells, which convert hydrogen into energy more effectively than combustion engines. This efficiency makes hydrogen a promising option for high-demand vessels, provided its storage and safety challenges can be addressed. Similarly, biomethane benefits from efficient combustion in engines designed for gaseous fuels, resulting in reduced fuel consumption compared to MDO. However, gaseous fuels like hydrogen and biomethane require deck-mounted storage tanks, which impact space and vessel stability. Methanol and ammonia, in contrast, require a near doubling of the fuel volume of MDO to meet the same energy demands due to their lower energy density. This is especially notable for high-demand vessels like Ahto 02 and Ahto 15. While ammonia has a slightly higher energy density than methanol, both fuels demand larger tank capacities or more frequent refueling, limiting their practicality in space-constrained vessels. Among biofuels, biodiesel and HVO100 perform closest to MDO. Biodiesel shows only a slight increase in annual fuel consumption, thanks to its relatively high energy density, making it an easy substitute with minimal operational impact. HVO100 is particularly favorable, often requiring less fuel than MDO, making it well-suited for vessels with high energy demands or limited storage capacity. Both biodiesel and HVO100 provide efficient, high-density energy sources compatible with existing storage infrastructure, offering practical, low-impact alternatives to MDO.

Table 11. Yearly fuel consumption of the entire fleet with alternative fuels.

Ship	MDO	Methanol		Biodiesel		HVO	H_2 Blue	H_2 Blue	Ammonia		Biomethane	
		Main Fuel	Pilot Fuel	Main Fuel	Pilot Fuel		SOFC	PEM	Main Fuel	Pilot Fuel	Main Fuel	Pilot Fuel
AHTO-01	614	1140	60.0	688	36	595	168	173	872	218	675	21
AHTO-02	25,356	47,049	2476	28,405	1495	24,551	6917	7156	35,990	8998	27,843	861
AHTO-06	10,080	18,703	984	11,292	594	9760	2750	2845	14,307	3577	11,069	342
AHTO-07	829	1538	81	929	49	803	226	234	1177	294	910	28
AHTO-09	2897	5374	283	3245	171	2805	790	818	4111	1028	3181	98.4
AHTO-12	512	951	50	574	30	496	140	147	727	182	563	17
AHTO-14	27,531	51,084	2689	30,842	1623	26,657	7511	7770	39,077	9769	30,232	935
AHTO-15	102,786	190,720	10,038	115,144	6060	99,523	28,041	29,007	145,891	36,473	112,868	3491
AHTO-17	70,010	13,006	685	7852	413	6787	1912	1978	9949	2487	7697	238
AHTO-19	11,239	20,853	1098	12,590	663	10,882	3066	3172	15,952	3988	12,341	382
AHTO-20	14,119	26,198	1379	15,817	835	13,671	3852	3985	20,040	5010	15,504	480
AHTO-21	13,351	24,773	1304	14,956	787	12,927	3642	3768	18,950	4738	14,661	453
AHTO-23	26,322	48,841	2571	29,487	1552	25,487	7181	7428	373,614	9340	28,904	894
AHTO-25	90,590	168,090	8847	101,482	5341	87,714	24,713	25,566	128,581	32,145	99,475	3077
AHTO-26	66,038	122,534	6449	73,978	3894	63,942	18,016	18,637	937,323	23,433	72,515	2243
AHTO-27	47,408	87,967	4630	53,109	2795	45,903	12,933	13,379	67,290	16,823	52,059	1610
AHTO-28	8193	15,201	800	9178	483	79,323	2235	2312	11,628	2907	8996	278
AHTO-29	10,950	20,319	1069	12,267	646	10,603	2987	3090	15,543	3886	12,024	372

Table 12 illustrates the yearly operational costs (EUR) for the fleet across various alternative fuels and propulsion configurations, providing insight into the economic impact of each option relative to conventional MDO. Methanol shows a moderate cost increase compared to MDO across most vessels, reflecting its current higher price due to lower energy density and infrastructure requirements, though this cost may decrease as methanol production scales. Biodiesel and HVO100 show higher operational costs, with biodiesel consistently more expensive than MDO due to its production process, while HVO100, though more efficient, remains costly as a relatively new fuel. However, as demand for biodiesel and HVO100 grows, advancements in production and distribution are likely to drive costs down.

Table 12. Yearly operational cost (EUR) of the entire fleet with alternative fuels.

	MGO	Methanol	Biodiesel	HVO100	H_2 Blue (SOFC)	H_2 Blue (PEM)	Ammonia	Biomethane
AHTO-01	413	475	800	866	838	867	661	790
AHTO-02	17,039	19,590	33,017	35,747	34,587	35,779	27,280	32,599
AHTO-06	6774	7788	13,125	14,211	13,749	14,223	10,845	12,959
AHTO-07	557	640	1079	1169	1131	1170	892	1066
AHTO-09	1946	2238	3772	4083	3951	4087	3116	3724
AHTO-12	344	396	667	722	699	723	551	659
AHTO-14	18,501	21,270	35,849	38,813	37,553	38,848	29,621	35,395
AHTO-15	69,072	79,410	133,840	144,905	140,203	145,037	110,586	132,144
AHTO-17	4710	5415	9127	9882	9561	9891	7541	9012
AHTO-19	7552	8683	14,634	15,844	15,330	15,858	12,091	14,449
AHTO-20	9488	10,908	18,385	19,905	19,259	19,923	15,191	18,152
AHTO-21	8972	10,315	17,385	18,822	18,211	18,839	14,364	17,164
AHTO-23	17,689	20,336	34,275	37,108	35,904	37,142	28,320	33,840
AHTO-25	60,876	69,987	117,959	127,711	123,567	127,828	97,464	116,464
AHTO-26	44,378	51,019	85,990	93,099	90,078	93,184	71,049	84,900
AHTO-27	31,858	36,627	61,732	66,835	64,666	66,896	51,006	60,949
AHTO-28	5505	6329	10,668	11,550	11,175	11,560	8814	10,533
AHTO-29	7359	8460	14,259	15,438	14,937	15,452	11,781	14,078

Hydrogen, used with both SOFC and PEM fuel cells, demonstrates considerably higher costs compared to MDO. While hydrogen fuel cells are efficient, the high current costs stem from limited infrastructure, production complexities, and storage requirements. As hydrogen technology matures and renewable hydrogen production expands, costs are expected to decrease, potentially making it a more competitive option for sustainable maritime energy. Ammonia and biomethane similarly show increased operational costs compared to MDO, with ammonia's infrastructure needs contributing to its higher cost, although like other fuels, its price could drop with further investment and advancements in production and storage technology.

While most alternative fuels currently show higher operational costs than MDO, the price landscape for these fuels is likely to evolve as production technologies improve and adoption rates increase. As economies of scale and supply chains develop for sustainable fuels, operational costs for options like methanol, hydrogen, and biodiesel are expected to decrease, making these fuels more viable in the long term.

5.4. Alternative Fuels' GHG Emissions

This study explored potential fuel alternatives for the Estonian State Fleet's pilot boats. E-fuels, which are synthetic fuels produced from captured CO_2 and hydrogen, showed the best results in terms of total GHG emissions. Despite their promise for the future, their current availability and readiness for use remain limited [128]. GHG emissions for the selected fuel alternatives were calculated based on estimated fuel consumption (Figure 5). Among conventional fuels, biomethane stands out as the most promising alternative, achieving a 59.0% reduction in emissions compared to MDO. HVO follows with a 43.6% reduction, and biodiesel ranks third with a 41.2% reduction in emissions relative to MDO.

Focusing on fuels' life cycle emissions, the results of this study align with findings from other sources [129,130], showing that the WtW GHG emissions of ammonia and hydrogen can exceed those of marine diesel oil. This is primarily due to their high WtT emissions, as illustrated in Figure 6. However, it is important to note that hydrogen and ammonia could significantly reduce WtW GHG emissions if produced using green renewable electricity or through steam reforming of natural gas combined with carbon capture technology [131]. Similarly, carbon-neutral biofuels emerge as promising alternatives for reducing GHG emissions, as their lower WtT emissions contribute to reduced total WtW emissions.

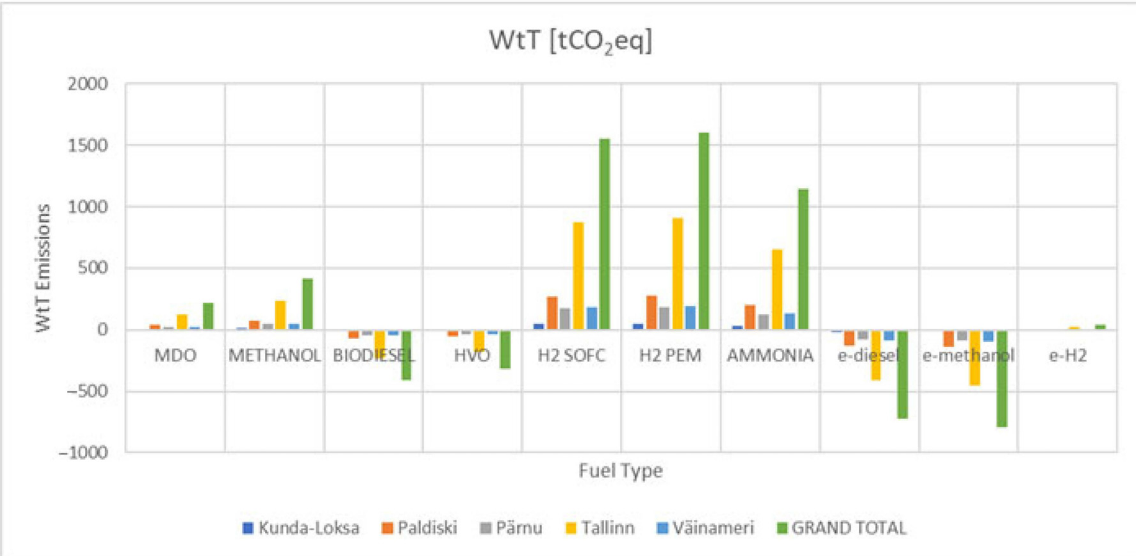

Figure 6. WtT emissions of alternative fuels.

E-fuels are widely regarded as promising energy carriers for the maritime industry and other transportation sectors, such as aviation [132,133]. Derived primarily from green hydrogen, their production requires vast amounts of renewable energy. A study by Transport and Environment highlights the significant focus on e-fuel projects but warns that production volumes will fall short of future demand, particularly as larger quantities of green fuels will be needed to meet FuelEU targets [134]. The study also identifies Denmark and Spain as leading producers and users of e-fuels, while Estonia is excluded due to limited availability, demand, and active projects. Additionally, the high cost of e-fuels [135] further complicates their adoption, making them an impractical option for the Baltic region at present. Given these challenges, carbon-neutral biofuels emerge as the most viable alternatives. The analysis focuses on these biofuels, as they offer a feasible solution within the region of operation, unlike e-fuels, which remain unfeasible for the time being.

The production of sustainable biofuels depends on a sustainable biomass feedstock. However, accurately estimating the availability of these feedstocks is challenging. While several sources offer estimates, there is a lack of comprehensive data on current production and land productivity [136]. As a result, forecasts are often unclear, and different approaches to estimating future biomass production and availability might lead to inconsistent and unreliable figures. Nevertheless, while the current use of biofuels in marine engine applications is very limited, there is significant potential for biofuels to capture a larger share of the total maritime fuel consumption and support the EU and IMO's GHG-reduction ambitions for the maritime industry. Recent regulatory developments in the EU covering GHG emissions and the lifecycle aspect of fuels provide several measures in line with the climate goals that could accelerate their adoption [137]. Carbon-neutral fuels, such as the biofuels identified in this study as the second most promising group, are characterized by combustion that contributes little to no net GHG emissions to the atmosphere. Assessing biofuels as renewable energy sources requires accounting for their overall environmental impact, production, distribution and supply chains, and storage in a lifecycle analysis methodology.

The shipping industry operates in a volatile market, carrying significant managerial risks. In the context of biofuels, rapid price fluctuations can make it challenging for companies to predict costs and plan effectively for the future. This uncertainty poses additional risks for stakeholders, particularly those heavily dependent on a consistent supply of specific fuels. From a managerial perspective, it is increasingly important not only to assess finances and market fluctuations but also to evaluate the feasibility and availability of new technologies and fuels. Pilot boats typically have a lifespan of 20–30 years. Given the moderate pace of regulatory changes aimed at achieving a carbon-free future, it may not be practical for smaller sectors of the shipping industry, such as pilotage, to pursue drastic shifts prematurely. Instead, the focus in selecting alternative fuels might need to prioritize local availability over GHG emissions, addressing the unique challenges posed by market volatility and operational constraints.

5.4.1. Biomethane

The study results indicate that biomethane is a highly promising fuel alternative for reducing the fleet's GHG emissions. Calculations show that switching to biomethane could reduce the pilot fleet's total WtW emissions by 59%. Beyond its emissions-reduction potential, biomethane is also an attractive option due to its strong availability in Estonia.

The evolution and feasibility of biogas across the world is currently uneven. The development depends on the availability of feedstocks, but also on the policies that encourage its production and use. Europe is the largest producer of biogas today [138]. According to the European Commission, Estonia can replace about 25% of the current natural gas consumption (imports) with biomethane [139]. Currently, 20% of its sustainable biomethane potential is deployed.

The production of biomethane in Estonia is rising [140]. The biomethane production in Estonia has grown from 0 GWh by the end of 2017 to 210 GWh by the end of 2023. There are around eight upcoming biogas plant projects under development, which can continue the growth to nearly 700 GWh [94]. At the moment, most of the produced biomethane is used in the transport sector, and there are several filling stations around the country [95]. In order to increase the consumption of biofuels in Estonia, the Estonian government plans to develop biomethane production based on local feedstock [141]. The target is to produce 100 million m^3 of biomethane by 2035, equivalent to 1 terawatt-hour per year.

Biomethane has been included in this study not only for its environmental benefits but also because it aligns with Estonia's strategic targets for promoting renewable energy sources. The Estonian government has identified the widespread use of biomethane as a key objective to support the country's transition to cleaner energy systems. However, its practical application areas, especially in the maritime industry, remain a topic of ongoing discussion. While the results of this study highlight the significant potential of biomethane to reduce GHG emissions, they also underscore its current limitations for use in pilot vessels. Biomethane's volume cost is substantially higher compared to other alternatives, which poses challenges for vessels with limited storage capacities. Additionally, the operational safety of biomethane, particularly concerning methane leakage and high-pressure storage requirements, is another critical issue that must be addressed before its adoption in maritime applications can become widespread. These limitations suggest that biomethane cannot yet be considered the best alternative for pilot vessels unless advancements are made in storage technologies and safety measures. However, given Estonia's strategic commitment to biomethane and the potential for future technological improvements, its inclusion in this study provides valuable insights for policymakers and industry stakeholders aiming to evaluate its feasibility under varying conditions.

5.4.2. HVO

According to the current study, using hydrotreated vegetable oil would reduce the pilot fleet's emissions by 43.6% in comparison with conventional marine diesel oil. HVO is gaining recognition as a leading fuel for meeting future energy needs. Made from sustainable sources like vegetable oils, vegetable, or residual raw materials, and even used cooking fats and oils, this innovative alternative is also considered as one of the key solutions for the future of the maritime industry.

One of the big benefits of using HVO is its bunkering. HVO can be bunkered similarly to MGO, but it is essential to take precautions to prevent contamination with other fuels. Also, some adjustments to the bunkering process may be required to accommodate HVO's unique characteristics, such as its lower density. It must be kept in mind that HVO is less corrosive and produces cleaner emissions than MGO, which could result in reduced maintenance requirements and extended periods between engine overhauls. While the long-term effects on engine wear are still under investigation, HVO is generally known to enhance fuel lubricity, which may benefit engine longevity [142].

The biggest challenges of using HVO are connected to the availability and price. HVO is not as widely accessible as conventional marine diesel, but its availability is expanding, particularly in areas prioritizing carbon emission reductions. It is more readily available in Europe and North America, where there is a stronger focus on sustainable fuel alternatives. HVO is also more costly due to the complexities of its production and the expense of its raw materials. However, its higher price may, in the future, be partially supported by governmental subsidies or incentives aimed at promoting the use of renewable fuels.

According to the Ministry of Climate of Estonia, increasing the adoption of HVO is one of the opportunities with the greatest potential for reducing greenhouse gas emissions [143]. In reality, the availability of HVO for shipping purposes is in the very early stages of development. Therefore, the transition to HVO in the pilot fleet would require additional input financially as well as solving challenges with the actual bunkering possibilities. Nevertheless, there are clear offers, for example, for trials using HVO and pilot boats [144]. Therefore, this alternative should be kept in focus for the future as the market expands and more solutions arise for smaller areas and more narrow markets.

5.4.3. Biodiesel

Biodiesel ranked as the third-lowest emitting fuel alternative on a WtW basis for the Estonian pilot fleet. Its greatest advantage lies in its compatibility with existing infrastructure, as no modifications to machinery systems or fuel tanks are required to transition to biodiesel.

According to the industry [145,146], there are several aspects of whether the supply can meet the demand for biodiesel. In addition, there are concerns over the quality of used cooking oil (which is the primary feedstock for biodiesel). Estimates of future biodiesel prices vary significantly, with projections for 2050 ranging from 25% to 300% higher than the cost of fossil fuels [147].

Apart from the above-mentioned, there are also practical challenges associated with using biodiesel in higher concentrations, which could lead to additional operational costs that are not reflected in current price estimates. Issues related to engine compatibility, fuel quality and stability, and potentially higher insurance would raise the total OPEX.

These uncertainties are further additional risks to meeting sustainability goals and GHG reduction targets, even though, at this point, biodiesel is a fruitful alternative today. Nevertheless, while focusing on hands-on actions that can be executed from this day and available infrastructure, biodiesel would potentially be the solution to reduce GHG emissions temporarily. In the long term, this transition might not be the most lucrative.

6. Conclusions

This study assessed the GHG emissions of the Estonian pilot fleet using various alternative fuels suitable for this sector. Fully electric and hybrid propulsion systems were excluded due to inconsistent electricity generation methods, variations in GHG guidelines, insufficient infrastructure, and limited applicability for pilotage operations. Using 2023 fuel consumption data, emissions were calculated and projected for alternative fuels based on a lifecycle well-to-wheel (WtW) approach. Several assumptions were necessary, which represent the study's primary limitations.

One limitation of this study is that the fuel cost data reflects current market prices at the time of analysis. Market conditions, geopolitical factors, technological advancements, and regulatory changes will significantly impact fuel prices over time. As such, the findings of this study are tied to present price levels and do not represent future economic scenarios, particularly for emerging alternative fuels where price volatility is expected to be higher.

Fuel costs were based on global market data, focusing on prices in Estonia and nearby countries. Availability was estimated using existing infrastructure and projected developments. Engine performance and efficiency were derived from technical specifications, including brake-specific fuel consumption (BSFC) values calculated using standardized methods. Partial load BSFC values were estimated using linear regression due to incomplete data for some engines.

The results identified biomethane as the most promising alternative, reducing WtW emissions by 59% compared to marine diesel oil (MDO). Biomethane also offers advantages such as local availability, economic feasibility, and competitive pricing. HVO100 and biodiesel showed reductions of 43.6% and 41.2%, respectively, and are compatible with existing infrastructure, minimizing transition costs. E-fuels, including e-diesel, e-methanol, and e-hydrogen, demonstrated strong GHG reduction potential when produced with renewable energy. However, high production costs, low availability, and storage challenges limit their current feasibility, especially in Estonia. Gaseous fuels like hydrogen pose additional safety and design challenges.

This study emphasizes the importance of lifecycle emissions analysis for alternative fuels, whose adoption relies on infrastructure, market conditions, and regulatory support, with further research needed on pilot station capabilities and economic viability. Future studies should focus on methodologies to evaluate GHG emissions for fully electric and hybrid ships, considering broader operational and environmental factors. Long-term assessments should address the economic and logistical implications of transitioning to alternative fuels, ensuring a comprehensive approach to decarbonizing the Estonian pilot fleet.

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Appendix 3

Publication III

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DECARBONIZATION OF ESTONIAN FERRY LINES – CHALLENGES AND OPPORTUNITIES

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Abstract

Decarbonization in the shipping industry plays a central role in global research and innovation activities. Ways to achieve zero-emission shipping include energy efficiency improvements, operational changes, the use of non-fossil fuels, retrofit and redesign of ships. Although the environmental regulations of the European Commission and the International Maritime Organization (IMO) apply only to ships above 5000 GT, the local industry representatives and authorities in many European counties also target greenhouse gas (GHG) emissions reduction from a wider shipping sector, including smaller ships and island ferries. To achieve the GHG emissions reductions, low-carbon fuels such as biodiesel, hydrogen, and its derivatives have been proposed for ferries along with direct electrification. From the design and operation viewpoint, these alternatives involve higher investment risk, including (a) capital-intensive infrastructure requirements, (b) powertrain implementation and onboard storage sizing, and (c) fuel availability and price volatility. This study focuses on an Estonian ferry line, which serves as the primary means of transportation for connecting the mainland. Consequently, it plays a critical role in facilitating the mobility of cargo and passengers to and from the islands. We analyse possible future energy system development paths to evaluate potential alternative fuels, based on existing ferries and local port infrastructure. Subsequently, we develop and apply an energy-transport optimization model to analyse alternative fuel investments from a techno-economic-environmental viewpoint. Finally, we present a preliminary comparative analysis of GHG emissions reductions and operating costs from the perspective of energy consumption, supporting the industry's decision makers in evaluating the future competitiveness of the shipping lines.

Keywords: decarbonization, shipping, alternative fuels, electrification

1. INTRODUCTION

The European Commission has adopted the Fit for 55 initiative to align the EU's policies on climate, energy, transport, and taxation with its target of reducing net-zero GHG emissions by at least 55% by 2030 [1]. This aligns with the European Green Deal, which aims to achieve net-zero emissions by 2050. Estonia's National

Energy and Climate Plan (NECP 2030) sets similar goals, targeting a 70% reduction in GHG emissions by 2030 and 80% by 2050, compared to 1990 levels [2].

Currently, IMO and EU GHG regulations focus on ships larger than 5,000 GT, with some rules applying to those over 400 GT. However, FuelEU Maritime [3], coming into effect on January 1, 2025, introduces exemptions for certain vessel categories, including passenger ships operating between islands with fewer than 200,000 inhabitants. Additionally, various vessel types- such as fishing boats, tugs, waterbuses, and pilot boats- are currently excluded from EU decarbonization regulations. Despite being smaller in size, these ships contribute to an estimated 15–20% of total maritime GHG emissions [4], highlighting a substantial regulatory gap.

Efforts are made to incentivize low-carbon fuels and power solutions with GHG intensity limits on energy used on board the ships. Nevertheless, the European Maritime Transport Environmental Report 2025 [5] reveals that the use of alternative fuels and sources of power has increased, despite being still marginal.

Estonia, located in northeastern Europe, has a population of approximately 1.3 million [6] and a coastline of about 3 800 km, nearly six times longer than its mainland border. It includes around 2 200 islands, many of which, especially in western Estonia, are historically and presently dependent on maritime transport.

Saare County, which includes Saaremaa (the largest island in the Baltic Sea) and Muhu (the third largest island in Estonia), has a low population density of 10.9 inhabitants per square kilometer [6]. These islands are primarily accessed by ferry services, with only limited support from aviation. Most passengers and cargo rely on a combination of sea and road transport.

This study focuses on an Estonian ferry line that operates between the mainland (port of Virtsu) and Muhu island (port of Kuivastu). Muhu island is connected to Saaremaa Island with a causeway, making the ferry connection the primary link to the mainland for the population of about 34 000 people [7]. Currently the ferry line has two double-ended ferries: one with conventional diesel engine and the other one with diesel-electric hybrid engine. In this study, we evaluate and assess the following research questions: (1) What is the energy demand for the ferry line under varying weather conditions? (2) Can this line be operated by fully electric plug-in hybrid ferries? (3) What are the GHG emission reductions and fuel operating cost savings if electric or other alternative fuel island ferries are deployed on this line?

The following study comprises of chapters: Methodology, Results and Discussion, Conclusion. Methodology section describes the currently operating ferries and analyses how the energy-transport optimization model was built. In the subsections also operating costs derived from the fuel consumption and GHG emissions are assessed. The results and discussion chapter brings out the findings of the analyse, including its GHG emission reduction and explains its main shortages. The conclusion chapter summarizes the study and points out the main aspects of continuation and future steps.

2. METHODOLOGY

2.1. System Description

The ferry route from the port of Virtsu on the mainland to the port of Kuivastu on the island of Muhu, shown in Figure 1 has the length of 3.7 nm, and depending on the season there are up to 30 daily ferry crossings. The time required for a one-way trip, considering the embarkation and disembarkation time of passengers and vehicles, and the time required for loading and unloading the ferry, is under normal weather conditions 35–45 minutes, with the crossing time not exceeding 28 minutes. The electricity grid in the region will be expanded in near future with a new 330 kV connection, enabling the construction of fast charging infrastructure.

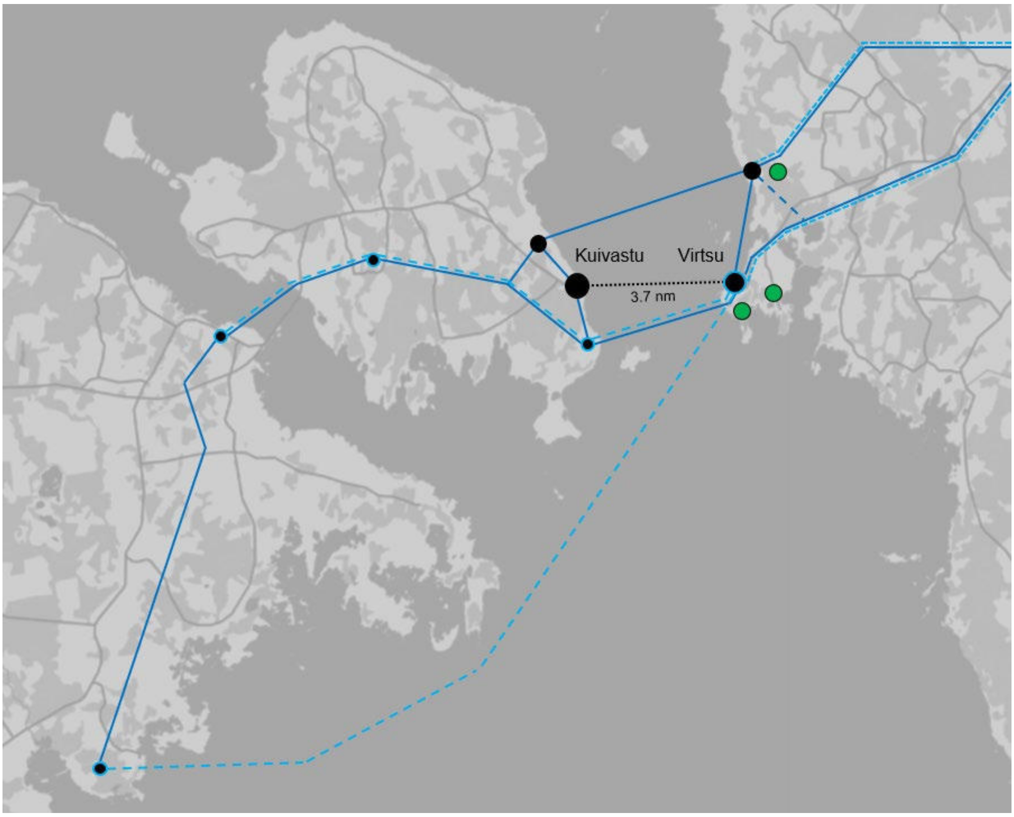

Figure 1 Illustration of the ferry route and the related infrastructure. Legend: port (large black circle), town or other node (small black circle), wind turbines (green circle), ferry route (dotted black line), electricity grid (330 kV: light blue line, 110 kV: blue line; existing: solid, planned: dashed), road (dark gray line). [8]

To evaluate the technical feasibility of the alternative fuel investments, the future energy system development paths must be considered. Currently, electricity charging infrastructure does not exist in the ports of Virtsu and Kuivastu. However, the electricity grid is sufficient for the charging infrastructure after the grid expansion. We assume that the electricity can be sourced at the hourly area price, with an additional transmission fee of 2 c/kWh and port operator margin of 2 c/kWh. The hourly area prices are retrieved from ENTSO-E [9]. For hydrogen, no large-scale green hydrogen production plants currently exist in Estonia. The fuel is estimated to be available in larger quantities and lower costs by 2030 through the Nordic Baltic Hydrogen Corridor [10], but would require an additional road transport step. By 2040, local production or potential expansion of the hydrogen transmission network would make the fuel more directly available for the ports located in the mainland [10]. As baseline value, we assume that hydrogen is available in compressed form at a constant price of 10 €/kg.

Biomethane (CBG) as sustainable marine fuel has several advantages with one of them being an alternative to reduce GHG emissions [11]. The evolution and feasibility of biogas across the world is currently uneven. The development depends on the availability of feedstocks but also on the policies that encourage its production and use. Europe is the largest producer of biogas today [12]. According to the European commission, Estonia can replace about 25% of the current natural gas consumption (imports) with biomethane. Currently, 20% of its sustainable biomethane potential is deployed. Beyond its emission reduction potential, biomethane is also an attractive option due to its availability in Estonia, which is also supported by the rise of production to the target of 100 million m^3 by 2035 [13]. Currently, most of the biomethane produced in Estonia is used in the transport sector and there are several filling stations around the country. For biomethane, we assume the baseline price to be 1.25 €/kg [14].

2.2. Ship Modelling

Currently, there are two sister ferries operating on the Virtsu-Kuivastu line. Depending on the season, the timetable for operating varies with less trips per day during winter period and more trips in the summer period. The double-ended sister vessels Piret and Tõll, the latter shown in Figure 2, were built in 2017. The newbuilt passenger ferries were using conventional marine diesel oil for operating, and in 2019, the ferry Tõll was retrofit to diesel-electric hybrid. The technical parameters for Tõll are shown in Table 1.

Figure 2 Passenger ferry Tõll.

Table 1 Technical parameters of the reference ferry Tõll.

Parameter	Value
LOA [m]	114
BOA [m]	19.7
Draft [m]	4.0
Gross tonnage [t]	4987
Speed [kn]	15
Main engine	2×1520 kW (MTU 16V400M03)
Auxiliary engine	2×1320 kW (MTU 12V4000M33F)
Battery capacity [kWh]	678
Passenger capacity	700
Vehicle capacity	150

To estimate the fuel consumption of the island ferries, data collection was conducted. The actual schedule data for 2024 was retrieved from the ferry operator. For each voyage, the speed profiles were determined based on minute-level AIS data [15]. Available charging time was estimated by subtracting one minute from the time at port due to charging connection and disconnection. The load profile was estimated based on a reported load example [16], which was time-normalised and divided into three sections following [17]: departure, cruising, and arrival. The instantaneous power consumption P_i was calculated using nominal power consumption P_o, operating speed v_i and its nominal value v_o, operating load x_i, scale factor n and overall efficiency η_{tot}, and auxiliary power consumption P_{aux} as follows:

$$P_{\mathrm{i}} = \frac{x_{\mathrm{i}}}{\eta_{\mathrm{tot}}} \cdot P_{\mathrm{o}} \cdot \left(\frac{v_{\mathrm{i}}}{v_{\mathrm{o}}}\right)^{n} + P_{\mathrm{aux}} \tag{1}$$

For overall efficiency, the conversion losses were estimated based on the power conversion system configuration. This resulted in the following efficiency estimations at nominal load: diesel (MDO) 41%, diesel-electric hybrid 38%, hydrogen (H2) 46%, biomethane (CBG) 46% and fully electric (EL) 88%. For simplicity, the auxiliary power consumption P_{aux} was estimated to be constant of 200 kW for all the alternative fuels. Finally, the simulated profiles were aggregated on a ten-minute level, maintaining the correct sequence of information whether the ferry is on route or in port.

In actual operations, power consumption varies due to external factors. One of the most significant in Estonian waters is the presence of ice conditions and low ambient temperatures. Ice conditions increase ship resistance depending on ice thickness, while navigation in ice requires slower speeds and more precise manoeuvring. Icebreaking effort, friction and vibration from ice contact, and heating auxiliary systems substantially increase the energy demand under winter conditions. The applied energy consumption calculation method does not adequately account for these factors, highlighting the need for physics-based simulations in further analyses. In this work, we approximate the influence of ice and weather conditions by scaling the calculated energy consumption with three factors: 1.0 for clear, 1.5 for average, and 2.0 for rough.

2.3. GHG Emissions Data

Life Cycle Assessment (LCA) is a comprehensive methodology which is used in various industry sectors to evaluate the environmental impacts associated with all scopes of a product's life cycle [18]. In maritime industry, this includes energy use and emissions linked to the construction, operating and decommissioning of ships. The EU and the IMO have introduced methodological frameworks [19,20] within the LCA context to support the consistent estimation of Well-to-wake (WtW) GHG emissions. These frameworks are built upon sustainability criterions and GHG emissions reduction targets, aiming to promote the adoption of low-carbon and sustainable alternative fuels on a global scale.

In this study, the theoretical GHG emissions for fuel alternatives are assessed according to the guidelines of FuelEU Maritime [3] by calculating WtW GHG emissions of the LCA. The total GHG emissions include the Well-to-Tank (WtT) emissions of the energy carrier supply and Tank-to-Wake (TtW) emissions of the total fuel use, and can be calculated as:

$$WtW_{GHG} = WtT_{energy\ carrier\ supply} + TtW_{fuel\ use} \tag{2}$$

Electricity generation methods across the countries in Europe vary significantly, for example in Latvia and Sweden electricity is produced from renewable sources of energy, whereas for example in Estonia and in Poland, fossil fuels are the main sources [21]. In the case of using fossil sources for electricity generation, electrification and hybridization may not always be carbon-free solution and might potentially produce significant amount of GHG emissions [22]. Due to the non-renewable sources in electricity production in Estonia, in this study the assessment for fully electric and diesel-electric hybrid ships is not assessed by FuelEU Maritime according to which coefficients in WtT and TtW are not applicable. For electricity, the WtW GHG emissions were assessed with equation:

$$WtW_{GHG} = E \cdot g_{\mathrm{el}} \tag{3}$$

where E is the total energy demand and g_{el} is the electricity emission factor. To represent the current grid electricity, the emission factor was estimated to be 417 g_{CO2eq}/kWh, based on the national electricity production mix in 2024 [23]. A similar method has been used in several earlier studies [24–26]. For an alternative scenario, where the electricity is either (a) primarily sourced from renewable production such as wind power or (b) the production mix in the market area develops and the emission intensity decreases, we considered emission factor equal to the neighbouring market area, i.e. Finland's 32 g_{CO2eq}/kWh [27].

2.4. Techno-economic Model

The economic feasibility of developed scenarios was studied with a linear cost-optimization program, implemented in Pyomo (version 6.8.2) [28] and solved with CBC (version 2.10.11) [29]. The model simulates the ferry operation at a ten-minute resolution and minimizes the objective function:

$$C_{\text{tot}} = \sum_{t=1}^{T} P_{\text{t,MDO}} \cdot c_{\text{MDO}} + n_{\text{charge}} P_{\text{t,el}} \left(c_{\text{t,el}} + c_{\text{grid}} \right) + P_{\text{t,H2}} \cdot c_{\text{H2}} + P_{\text{t,CBG}} \cdot c_{\text{CBG}} \quad (4)$$

which determines the total fuel operating cost C_{tot} from the calculated ten-minute power consumption P_t, fuel cost c, and for the electric configurations, charger efficiency η_{charge}, hourly electricity price $c_{t,el}$, and grid tariff c_{grid}. The alternative fuel configurations were individually simulated with single-parameter sensitivity analysis for on-board fuel storage and, for electric and hybrid-electric ferries, shore charger capacity. The analysis only considers fuel operating costs and excludes capital expenditures for initial investments and component replacements (e.g., battery, fuel cell).

Ferry energy demand was set as a hard constraint, creating an infeasible scenario if the demand was not met for example due to insufficient charging rate or on-board fuel storage capacity. Charging rate limits were imposed for the ferries depending on the alternative fuel: for electricity based on the charger capacity, for biomethane assuming a fast-filling station [30], and for hydrogen assuming shore-to-ship bunkering [31]. Additionally, the on-board fuel storage was initialized at 50% with a cyclic storage constraint, and state-of-charge constraint assumed depending on the alternative fuel: hydrogen 8–100% due to refueling margin [32] and electricity 10–90% to manage battery state-of-health.

3. RESULTS AND DISCUSSION

3.1. Comparison of fuel operating costs

We simulated two representative operational weeks with: a low-demand week with 115 trips and a peak-demand week with 177 trips. To capture operational variability, three energy consumption levels were considered across diesel, fully electric and diesel-electric hybrid scenarios, reflecting the effects of varied ice and weather conditions. For electric and diesel-electric hybrid scenarios, three charger capacities, i.e. 5.0 MW, 2.5 MW and 1.0 MW, were evaluated to account for infrastructure limitations.

Figure 3 presents the estimated reductions in fuel operating costs for the analyzed configurations. In all scenarios, diesel-electric hybrid operation offers cost improvements over diesel. Notably, higher charger capacities enable significantly greater savings, up to 46%, by allowing increased electric operation. However, this benefit diminishes in high-demand scenarios where the operation relies more on diesel. At the lowest charger capacity, hybrid systems even lead to higher costs, that is –5%, due to reduced overall efficiency. Similarly, the fully electric operation is highly dependent on charger capacity. Under the current operating schedules, full electrification is feasible only with the highest charger capacity and is not possible under the high-demand scenario. When feasible, however, fully electric systems provide the greatest cost reductions, i.e. 75–78%, compared to diesel. The small variation is due to higher consumption necessitating charging during more expensive hours. Among indirect electrification options, biomethane and hydrogen are technically feasible across all conditions. Biomethane slightly outperforms the diesel-electric hybrid option, savings being 58%, but in contrast, hydrogen results in a cost increase of 27% relative to diesel, primarily due to the expected high fuel price.

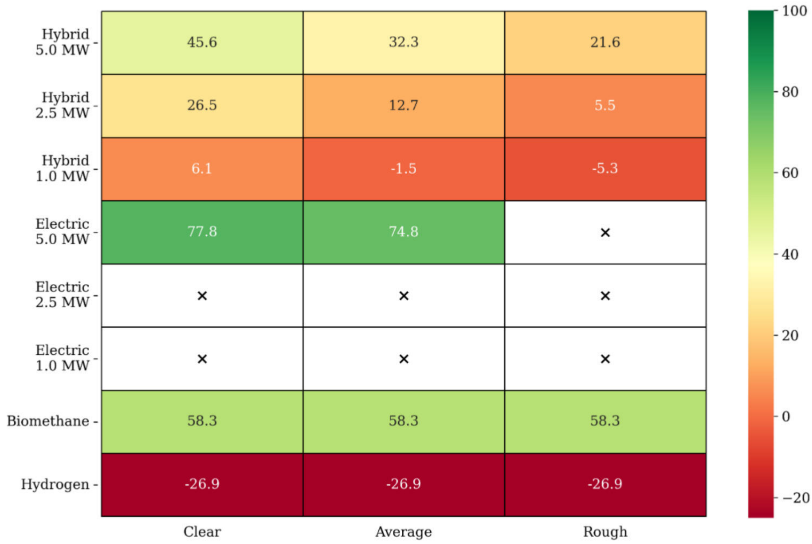

Figure 3 Relative fuel operating cost reduction (%) for different alternative fuel configurations in comparison to diesel-fueled operation for three levels of fuel consumption based on weather conditions clear, average, and rough. Infeasible scenarios are indicated with (x).

3.2. Estimated emissions of alternatives

Figure 4 presents WtW GHG emissions for the simulated period consisting of two representative operational weeks. With diesel, baseline emissions of 139 tCO_2eq are reached. For diesel-electric hybrid configurations, emissions follow the trend of fuel operating costs, depending on charger capacity, which governs the required diesel consumption. With current grid electricity, emissions range from 92 to 141 tCO_2eq; with low-emission electricity, from 37 to 124 tCO_2eq. Similarly, emissions for the fully electric configuration depend on electricity sourcing. With current grid electricity, emissions are 74 tCO_2eq, not significantly lower than for hybrid. However, with low-emission electricity, emissions decrease to 5 tCO_2eq. This represents an optimistic scenario, as Estonia is currently a high-emission electricity market area, and such values are unlikely to be achieved solely through grid electricity in the near term. Hydrogen yields the lowest emissions at 4 tCO_2eq but, as discussed earlier, faces challenges related to fuel availability. The same considerations as for electricity apply, though low emissions are likely due to the required compliance with green hydrogen regulations such as RFNBO [33]. Biomethane also provides a significant reduction, with emissions of 23 tCO_2eq.

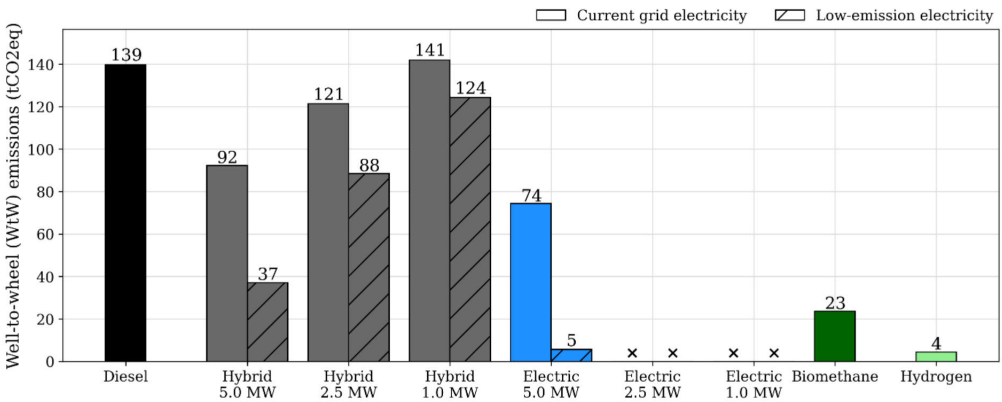

Figure 4 WtW GHG emissions for different alternative fuel configurations in average weather conditions with two alternative options for electricity sourcing. Infeasible scenarios are indicated with (x).

4. CONCLUSION

Battery-electric propulsion systems are gaining increasing attention in various maritime applications due to benefits including low airborne and underwater noise, reduced vibration and low-emission operation. From the perspective of fuel operating costs and GHG emissions, fully electric island ferries appear to be promising option for the studied Estonian route and warrant further investigation. Among the alternative fuels, biomethane offers a more practical option than hydrogen for hybrid configurations due to its availability through existing supply chains. Thus, this study highlights both practical and theoretical implications for the specific route and environment as it brings out challenges and opportunities for low carbon future in realistic aspects.

However, the analysis identified uncertainties that should be addressed in future research. Fully electric island ferries show promise for the studied Estonian route due to low operating costs and emissions. The economic analysis should be expanded to compare investment needs for port-side and onboard systems, and to include sensitivity analyses on key parameters such as electricity and fuel prices. Furthermore, the studied ferry operates in regions partially covered by ice, posing challenges for fully electric operation. Based on the infeasibility shown by the conducted simulations, it remains uncertain whether fully electric vessels can maintain the current schedules under continuous rough weather conditions, highlighting the importance of hybrid system availability. Improving energy consumption estimates under such conditions will require the integration of weather information, e.g., wind and wave conditions, and physics-based simulations.

From the GHG emissions perspective, the fully electric configuration resulted in a 47% reduction in WtW GHG emissions compared to diesel when using current grid electricity. A significantly greater reduction, up to 96%, is achievable under scenarios assuming low-emission electricity. These results underscore both the importance of electricity sourcing and the shortcomings in current GHG assessment guidelines, which vary by country and lack consistency. Electricity generation methods vary widely across EU countries, many of which do not yet rely on fully renewable sources. Consequently, fully electric or diesel-electric hybrid ships operating in different countries may exhibit high WtW GHG emissions despite using the same technologies. This highlights a critical shortcoming in the current guidelines and underscores the need for further development by regulatory bodies such as the IMO and FuelEU Maritime to standardize the evaluation of GHG emissions for fully electric ships.

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Conflict of interest: None

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Appendix 4

Publication IV

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BUSINESS OPPORTUNITIES FOR A GROUND EFFECT VEHICLE - CASE OF CANARY ISLANDS

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The need to decarbonise and reduce pollutant emissions from maritime transport is facilitating the studies of ground effect vehicles. Technical development in recent decade concerning unmanned flights in drones has supported this development. These vehicles could have much higher speed than sea vessels and they are estimated to be less costly compared to air transport. Unmanned operations without passengers enable wider range of transport connections (even in difficult conditions). In this research we analyse prototype vehicle called Airship and its possible use in different routes of intra Canary Islands' transport. We suggest the most lucrative routes and cargo groups. Initial cost and revenue considerations are made over the life-cycle of Airship. As a result, we can point that there are three main factors determine the success of the transport operations. They are: the number of journeys per day, business days operating per year and freight price.

Keywords: Ground effect vehicle, wing in ground (WIG), airship, Canary Islands, routes, cargo, costs, profitability

1. Introduction

The European Union has a strategic interest in ensuring the continuous performance of short sea shipping. According to the European Commission short sea shipping has a strong role in reaching EU transportation goal of reducing 60% of greenhouse gas (GHG) emissions generated by transport and by 2030 the shift of 30% of road freight over 300 km to other modes. On the other hand, the short-sea shipping impact on the local air pollution has led to the several stringent regulations for marine fuels not only in EU (Directives 1999/32/EU, 2005/33/EU, 2012/33/EU, and 2016/802/EU) but also under MARPOL Annex VI (Tichavska *et al.*, 2019).

There are various studies conducted about short sea shipping and their influencing factors and significance (Kelmalis *et al.*, 2023; van den Bos *et al.*, 2018). Nevertheless, shipping is the cheapest mean of transport and therefore all possible alternatives and optimal low emission or carbon free vehicles on sea should be given higher importance.

Unmanned Aerial Vehicles (UAVs; e.g., drones or aircrafts) have increased in popularity, and they could be used simultaneously for planned tasks through one control room or location (Laghari *et al.*, 2023). Development and use of these vehicles started in the early 2000s within defence purposes of USA (Adamski, 2017; Laghari *et al.*, 2023) – currently they are applied in civilian, military and business purposes. It is still an open question, in which routes, weather conditions and in which seasons UAVs can operate reliably for home deliveries of freight (Yowtak *et al.*, 2020) – no person on board increases tolerance for severe weather. Key benefit comes from the lack of pilot or personnel on board – this enables much freedom e.g., in the design of "fixed wing" aircrafts and enables better performance for small vehicle.

One sub-class of unmanned vehicles is the wing in the ground crafts (WIG) or ground effect vehicles (Amir *et al.*, 2016). These are classified under jurisdiction of International Maritime Organization (IMO) as long as they have flight altitude capability only up to 150 meters (Amir *et al.*, 2016). Ground pressure in these vehicles creates opportunities for lower emissions (affecting local NOx, SOx, PM, CO and global CO_2 environments), lower maintenance costs, simplified vehicle structures as compared to airplanes and these vehicles do not need airports and/or other larger landing areas (Amir *et al.*, 2016; however, these vehicles need sea area instead of airports). Smallest ground effect vehicles reach some hundred km of operating distance, and typically are estimated to have top speeds of 100-150 km/h (Amir *et al.*, 2016; Papadopoulos *et al.*, 2022). In a case of unmanned vehicles (Papadopoulos *et al.*, 2022), range is leaned to shorter distances (like 300 km; Papadopoulos *et al.*, 2022) as they are typically fuelled by electrical system, while often older technology (combustion engine) reaches distances of 1000 km and longer (Amir *et al.*, 2016).

In the research of Papadopoulos *et al.* (2022) the WIG vehicle was able to carry payload of 300 kg and operate 300 km within range. In the study of Nebylov and Nebylov (2021) the vehicles were traditional airplanes manned with pilots and could have take-off mass of 800 tons.

In this research we are interested in novel unmanned electrical propulsion system vehicles, which can serve 500 nm distance, and are capable of carrying cargo of 1000-4000 kg. In the pilot operating environment of Canary Islands, potential routes are mostly concerned populous islands and their food transportation needs.

To study these aspects an international collaboration project called Airship is executed. Airship aims to lay the foundations of a new class of fully electrical unmanned aircraft system, the UWV (Unmanned WIG Vehicle) that brings together speed, flexibility and energy efficiency. The aim of the research vehicle is to study and develop new technologies in zero-emission energy, on-board AI and in automatic flight control that overcome the challenging technological problems that flying in ground effect poses, allowing such vehicles to become autonomous. The main goal of this study is to focus on actual potential and specific application for this vehicle (Figure 1).

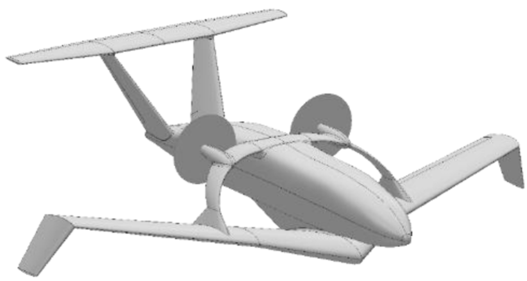

Figure 1. Isometric view for the model of Airship (source: Airship project)

The main research questions of the study are: (i) Which ports in the Canary Islands could potentially be used for inter-island cargo transport by UWV craft Airship? (ii) Which routes would be the most optimal in respect of potential consumers and shortest distances? And (iii) What would be the minimum feasible annual freight revenue?

This research is structured as follows: In section 2 we introduce the cargo transport environment of Canary Islands for ground effect vehicle. Section 3 presents the methodology and data for assessing the most lucrative routes and ports. As an addition we consider revenue opportunities and evaluate it against number of different cost factors (arising from investments such as depreciation and interest rates, and then different operating expenses). Section 4 presents the main findings. Research is concluded in Section 5.

2. Research Environment of Canary Islands

2.1. Inter-Island Traffic in Canary Islands

The Canary Islands are organised administratively into two provinces with the capital in the central islands of the archipelago. Maritime import/export transport in the archipelago is based on two main ports, located in Tenerife (Santa Cruz) and Gran Canaria (Las Palmas also called as La Luz). Las Palmas is the most important port in the archipelago. It is an international hub, the largest in the Mid-Atlantic Ocean in terms of container handling (Tovar *et al.*, 2015) and the fourth largest port within the Spanish system

(Puertos y Terminales, 2023). However, in terms of inter-island freight traffic, the ports of Las Palmas and Tenerife are of similar importance in the Canary Islands maritime network, which is completed by nine ports administratively grouped in two port authorities, one for each province. There are also 16 autonomous (small) ports managed by the autonomous government.

According to an analysis completed by a logistics company (Rhenus Group, 2022), air transport accounts for barely 0.12 % total trade flow. Sea traffic to Santa Cruz (Tenerife) and Las Palmas (Gran Canaria) ports account for 91 % of the imports from the Spanish mainland. The inter-island freight traffic is characterised by the polarisation that exists around the two ports of the capital islands, which play a distributive role to and from the other ports. Therefore, the smaller islands move rather more modest volumes of goods, in no case exceeding 1.5 million tonnes.

The Canary Islands have highly developed ferry traffic with several route options from one island to another. The routes are operated by different operators and various types of ships.

The sea ports of Canary Islands handle practically all the products imported from the Spanish mainland of which Andalusia region dominates.

An alternative for sea transport in the region is air transport, which accounts for a minor part of the trade flow. This minor part is mainly handled in airports of Gran Canaria and Tenerife Norte. The lively air traffic in Canary Islands is covering inter-island flights and other domestic and international flights. The focus on air transportation is on passengers.

The Canary Islands have traditionally benefited from transport subsidies in order to compensate for the disadvantages of their insularity and distance from mainland Spain. The residents of Canary Islands are supported by the government with 75 % subsidy for domestic and inter-island travel (for buying tickets of both by air and sea transport). There are also subsidies for sea and air transport of industrial or agricultural goods to or from the Canary Islands, including grants to compensate for the additional costs incurred by operators of certain fishery and aquaculture products in the Canary Islands, as provided for in the European Maritime, Fisheries and Aquaculture Fund (European Parliament (2021), for the programming period 2021-2027 (Government of Canary Islands, 2024).

Castanho *et al.* (2020) have carried out a study to assess the transportation sustainability of Canary Islands archipelago. The study was conducted through exploratory tools by using the accessibility and connectivity indicators over the socio-economic impacts. According to the findings of the study, the accessibility is categorized in five main groups (having very high, high, medium, low or very low accessibility). The findings regarding accessibility factors of the islands were included to the study and based on the highest distribution analyse another assessment for suitable ports with significant factor of having also good accessibility were conducted.

2.2. Environmental Issues

The International Maritime Organization (IMO) has set a goal to reach carbon neutrality by 2050 (IMO, 2023). Similarly, the European Union (EU) has set a target in its Fit to 55 package to reduce the net greenhouse gas (GHG) emissions by at least 55% by 2030 and achieve carbon neutrality by 2050 (European Parliament, 2022). On the other hand, IMO and EU maritime regulatory regime also aims to substantially reduce air pollution for coastal areas and port cities (Tichavska and Tovar, 2019).

With these tightening regulations also transportation sector must take effort to reduce their emissions. For shipping the possible ways to minimize exhaust emissions are grouped into three main categories: fuel and energy solutions, ship design and technical development and choices of ship operations (Barreiro *et al.*, 2022).

Transportation sector is responsible for 28.9% of the EU's total greenhouse gas emissions (European Parliament, 2024). Although aviation and shipping each account for only about 4% of the EU's total greenhouse gas emissions, it is essential to focus on reducing them significantly, since these means of transport currently also grow the fastest. Sea and air transport are essential for life in the Canary Islands. Having low emissions solutions for these transportation modes are therefore the key factors of meeting the targets of Green Deal (European Commission, 2024).

In December 2020 the European Commission published a strategy to ensure and support the transportation system achieving green transformation (European Environment Agency, 2023). One of the obtainable ways to reach the carbon neutral targets in transportation is using carbon free alternative fuels. Fully electric ships are considered well suited to short-sea shipping (Laasma *et al.*, 2022). On the other hand, ships operate at relatively low speeds, which might be crucial for cargo with short shelf life.

Transportation is affecting environment and nature in several ways. Apart from the direct impact of emitting GHG emissions, there are also other important issues that affect the environment. The Canary

Islands ports are subject to EU air quality legislation, as maritime transport is a major source of air pollution. Tichavska and Tovar (2015a, b) calculated the external costs derived from ship emissions in the port of Las Palmas, showing the type of information needed to inform policy measures that contribute to the internalisation of estimated external costs. In fact, a potential benefit from the implementation of UWV is the external cost derived from cargo vessels that could be avoided.

Canary archipelago is a unique area for its biodiversity of various wildlife species (Escánez *et al.*, 2021). There is evidence of significant disruptions to sea and underwater species caused by the ferry traffic (Ritter, 2010). Due to flying mainly above sea, the alternative environmentally friendly vehicle Airship is having several benefits also to wildlife and sea spices. The fully electrical alternative vehicle has low noise and vibration levels. This aspect is relevant to wildlife, but also to the habited areas, urban planning and tourism, which has the largest share of the economy of Canary Islands.

However, the most significant environmental impact of the Airship is not only low greenhouse gas emissions (GHG), but also the reduction in local air pollutants. The Airship is designed to be fully electric vehicle. While using only green energy for operating the new type of vehicle will be carbon neutral in the whole tank-to-wheel (TTW) section meaning the operating and transporting cargo would be with zero emissions. The significant aspect of this to the Canary Islands is to support filling the European Green Deal and Fit-for-55 goals.

3. Methodology and Data

3.1. Methodology

According to Tapaninen (2020, p 102) the factors affecting profitability of a shipping route are: variable costs (crew, maintenance), fuel and port dues, capital costs and administration. The income depends on the frequency and speed of the vessel, and size of the cargo hold as well as utilisation and fill rate (Tapaninen, p. 79) in addition to freight from transported cargo ton. In this study we focus on capital costs, fuel (electricity) and port dues, and length of the journey as well as frequency per day in addition to freight.

The gravity model has become a standard transportation planning procedure for estimating interzonal trip interchanges. Gravity model of international trade traditionally states that bilateral exports are proportional to economic size and inversely proportional to geographic distance. There are several interpretations to the traditional gravity model (see for example Ravishankar *et al.*, 2014; Kabir *et al.*, 2017.). Gravity models have also been used for dynamic interrelations studies (Seppälä, 1997), but in this case we take only a static approach.

In the case of economics, the trade flow between the countries is generalized according to equation derived from the Newton's law (Pal and Kar, 2021):

$$F_{i,j} = M_i^{\alpha} M_j^{\beta} D_{i,j}^{\gamma},$$

where

m_i - Economic mass for country *i*,
m_j - Economic mass for country *j*,
$D_{i,j}$ - Geographical distance between country *I* and country *j*,
$F_{i,j}$ - Force of trade flow between country *I* and country *j*
α, β, γ - parameters of the model.

Shipping distances between the ports can be assessed according to the following formula:

$$D_{i,j} = \min_{i,j}\{distance(P_i, P_j)\},$$

where

$D_{i,j}$ - distance between the ports,
P_i - a port of the country i,
P_j - a port of the country j.

In this aggregated model, the economic mass of an island was studied in four different ways: 1) populations, 2) tourism, 3) population and tourism together, and 4) island accessibility.

The shipping cost of goods between country *i* and country *j* directly was calculated on the distance $D_{i,j}$ between them. Therefore, the force of trade flow between country *i* and country *j* decreases as the shipping cost increases.

3.2. Ports and distances

First, in this study the analyse for finding best ports to be used by the alternative vehicle was carried out by gravity model simulations with considering the economic mass of the islands and distances between the local ports. The economic mass of an island is represented by the population, tourism or sum of population and tourists.

Distanes from the seaports of Canary Islands are calculated in Table 1 below. Las Palmas (Gran Canaria) and Santa Cruz (Tenerife) are the locations for cargo hubs for the whole archipelago as they are supplied with suitable storing and cooling facilities.

Table 1. Seaport distances (nm) in Canary Islands
GC-Gran Canaria; T-Tenerife; LP-La Palma; L-Lanzarote; F-Fuerteventura; LG-La Gomera; E-El Hierro; SM-Spanish mainland

Distance matrix (nm)	Las Palmas (GC)	Agaete (GC)	Santa Cruz (T)	Los Cristianos (T)	Santa Cruz (LP)	Arrecife (L)	Playa Blanca (L)	Corralejo (F)	Puerto Del Rosario (F)	Morro del Jable (F)	San Sebastian (LG)	Valle Gran Rey (LG)	La Estaca (E)	Cadiz (SM)	Huelva (SM)
Las Palmas (GC)	0	29	54	83	144	113	96	93	104	57	103	123	145	689	698
Agaete (GC)	29	0	39	60	127	131	114	111	129	81	79	91	121	701	710
Santa Cruz (T)	54	39	0	47	108	148	132	129	152	104	67	80	109	704	711
Los Cristianos (T)	83	60	47	0	69	184	167	164	183	139	22	38	69	747	766
Santa Cruz (LP)	144	127	108	69	0	229	212	210	228	193	53	44	57	753	757
Arrecife (L)	113	131	148	184	229	0	20	23	34	81	204	216	246	587	600
Playa Blanca (L)	96	114	132	167	212	20	0	9	26	75	187	200	229	611	624
Corralejo (F)	93	111	129	164	210	23	9	0	18	74	186	196	227	612	625
Puerto Del Rosario (F)	104	129	152	183	228	34	26	18	0	48	201	213	244	620	633
Morro del Jable (F)	57	81	104	139	193	81	75	74	48	0	156	168	199	666	678
San Sebastian (LG)	103	79	67	22	53	204	187	186	201	156	0	16	48	753	758
Valle Gran Rey (LG)	123	91	80	38	44	216	200	196	213	168	16	0	14	767	768
La Estaca (E)	145	121	109	69	57	246	229	227	244	199	48	14	0	794	799
Cadiz (SM)	689	701	704	747	753	587	611	612	620	666	753	767	794	0	50
Huelva (SM)	698	710	711	766	757	600	624	625	633	678	758	768	799	50	0

3.3. Cargo

According to OECD in November 2023, Canary Islands exported cargo for 224 million € and imported for 408 million €. The highest impact to the economics of Canary Islands has by far tourism. Besides tourism, fishing is one of the most important sectors.

Fishing has traditionally been a significant primary activity, while having several roles in reducing poverty, job creation, strengthening and assuring food sufficiency and sovereignty, but also increasing the value of various products. The fishing fleet of the area is almost exclusively artisanal, giving to fishing industry also a social aspect (González *et al.*, 2020). In addition to the fishing in open seas, also fish farming shows growing trends in the industry (Cantillo *et al.*, 2023).

Based on the statistical data collected from the Canary Islands Statistics Institute (ISTAC) the five recent years average of cold fish export from the Canary Islands varies from 2600 to 4600 tons (Table 2). The frozen fish export varies from 245 000 tons to 331 000 tons (Table 3).

Table 2. Export of cold fish from major fishing ports (tons)

	Yearly export in tons				
Port	**2023**	**2022**	**2021**	**2020**	**2019**
Arrecife (L)	443	1097	683	1146	1291
Puerto Del Rosario (F)	3	13	10	14	16
Las Palmas (GC)	86	101	95	120	78
Arinaga (GC)	10	5	9	0	3
Santa Cruz (T)	2115	1702	2112	2825	3230
TOTAL	2657	2918	2909	4105	4618

Table 3. Export of frozen fish from major fishing ports (tons)

	Yearly export in tons				
Port	**2023**	**2022**	**2021**	**2020**	**2019**
Arrecife (L)	8552	10788	9631	10588	12431
Puerto Del Rosario (F)	3179	3153	3409	2033	403
Las Palmas (GC)	231631	270365	228269	204177	195773
Santa Cruz (T)	40328	46665	29385	28061	44267
TOTAL	283690	330971	270694	244859	252874

Fish is a complex type of cargo with short shelf life. This sets the limits and often also additional requirements to its transport as travel time to the customer is crucial. For Airship this, on the other hand, is additional advantage – the costs of transport are significantly lower than with traditional air transport, but also significantly faster than with traditional sea transport. While the average transport of the container ship from the Canary Islands to the Spanish mainland is 7-14 days or 36 hours with the passenger vessels, Airship could cover this within 3-4 hours. However, as the unmanned electrical vehicles, which already operate are mostly in 270 nm range, the focus to this study is kept to inter-island transport of fish and other seafood.

Planning and managing cargo transportation of inter-island traffic it is also relevant phase of the route and vehicle type optimization. This is also the reason, why the study focuses on fish. The most efficient and feasible use of Airship is transporting all other types of cargo with short shelf life by departing from the cargo hubs in Tenerife and Gran Canaria and brining fish and seafood at returning to the from other islands.

3.4. Revenues and Costs

There are numerous different routes in Canary Islands available to be used for Airship/Ground Effect Vehicles, but in our analysis most lucrative is the route between Gran Canaria and Tenerife due to the existence of cargo hubs near their ports. This could be served with two seaports from both islands (Agaete and Las Palmas from Gran Canaria, and Santa Cruz and Los Cristianos from Tenerife). Distances between these seaports differ, but in general they are around 100 nm (shortest is Agaete-Santa Cruz, approx. 39 nm, and longest Arrecife-Los Cristianos, approx. 184 nm). Whichever is the used route from these, it means that this route could be served up to six journeys per day (in one direction). Vehicle needs flight time of 1.5 hours, and then unloading and loading of cargo at seaport takes approx. one hour. If operations start in early morning hours (like 7 am), it is possible to make six journeys until very late evening hours (e.g., 22 pm).

Simulation model of revenue and costs was conducted (see interactive model: InsightMaker, 2024). Revenues are arising from freight operations, and we assume that Airship can carry cargo having weight between 1000 to 4000 kg. In simulation model it is assumed that freight amount on each occasion is random uniform function having minimum of 1000 kg and maximum of 4000 kg (and having then average of 2500 kg of cargo on board). Freight revenues (annual) depend then on journeys made in a day, business days operated in a year, and freight price (together with freight weight). Journeys per day and business days operated are having connection also to costs – port payments and electricity costs (these are dependent on operations volume).

In cost side, we have incorporated Airship fleet price (assumed to be 2 mill. EUR; this is estimate for two vehicles that we are able to achieve needed service level in one route), which is assumed to serve 20 years. In simulation model we assume linear, or fixed, annual depreciation in this period. Charging infrastructure (100 000 EUR) is included in the price of GEV fleet, and it will increase annual depreciation and interests paid (assumed 20 years of usage period). Interest costs of fleet is assumed to follow depreciation programme (loans are paid with depreciation amounts), and these are of course highest in the early years (as depreciation is done only in minor scale). Interest rates (annual) follow random uniform function, where minimum is 3 % and maximum 10 %. Electricity costs are dependent on assumed consumption per one journey (540 kWh), price of electricity (0.3 EUR per kWh) and within annual total amount of journeys (journeys per day times business days operating). Annual maintenance costs are 6 % from original fleet price. Port payments are based on the annual number of journeys and port payment of 200 EUR per visit. In addition to these, there is annual fixed costs of overhead and management (operations and sales) of 200 000 EUR.

4. Results

4.1. Ports and Routes

The results of the study show that there are several possible routes for piloting cargo transport by the Airship. As mentioned in the methodology, we calculated the economic mass in four different ways: 1) residents of the island, 2) nights of the tourists, 3) residents and tourist together and 4) island accessibility.

First: potential ports for cargo transport by Airship were analysed first by potential customers focusing on residents as priority. As a result, the most significant ports for the service are: Arrecife (Lanzarote), Puerto Del Rosario (Fuerteventura) and La Estaca (El Hierro).

Second: Similar analysis was conducted by considering the number of nights at tourist accommodation establishments of the islands. The results are common to previous findings with ports of the highest distribution as follows: La Estaca (El Hierro), Santa Cruz (La Palma) and Valle Gran Rey (La Gomera).

Third: While analysing tourism, population and distances together the calculation resulted to Las Palmas (Gran Canaria), La Estaca (El Hierro) and Santa Cruz (La Palma).

By analysing possible cargo for the fast mean of transport groups with short self-life are prioritized. Las Palmas (Gran Canaria) and Santa Cruz (Tenerife) are the locations for hubs as they are supplied with suitable storing and cooling facilities.

The Canary Islands is a small territory with short distances between various destinations, when the focus is on bird-eye view. On the other hand, while focusing land transportation factors, which are essential for final delivery to the customers and the whole logistics chain, it is important to consider the sustainability of the island land transportation.

For the fourth: focus factors of accessibility from the research of Castanho (2020) were used and included to support the verification. Based on the highest distribution analyse it was found that suitable ports with significant factor of having also good accessibility are: Arrecife (Lanzarote), Puerto Del Rosario (Fuerteventura), Santa Cruz (La Palma) and La Estaca (El Hierro).

Based on the analysis of different aspects from possible consumers and logistics chain potentially suitable ports were found. By having main home ports in Las Palmas port in Gran Canaria and Santa Cruz in Tenerife route alternatives are created by going from the hubs to the western and eastern islands in range and an additional line to connect the hubs is created (Table 4). The route alternatives are calculated by minimizing the distances between the findings from the results of the suitable port analyse. Depending on the cargo capacity it is possible to optimize the routes with round-trip to one island only.

Table 4. Routes and ports of proposed lines

	Origin port	**Destination ports**	**Route total distance [nm]**
Eastern line 1	Las Palmas (GC)	Arrecife (L) - Puerto Del Rosario (F)	254
Eastern line 2	Santa Cruz (T)	Arrecife (L) - Puerto Del Rosario (F)	337
Western line 1	Las Palmas (GC)	La Estaca (E) - Santa Cruz (LP)	274
Western line 2	Santa Cruz (T)	La Estaca (E) - Santa Cruz (LP)	347
Connection line 1	Las Palmas (GC)	La Estaca (E) - Santa Cruz (LP) - Santa Cruz (T)	364
Connection line 2	Santa Cruz (T)	Arrecife (L) - Puerto Del Rosario (F) - Las Palmas (GC)	343

It should be borne in mind that when it comes to the main objective of the Trans-Insular Transport Axis, which is to allow goods to cross from one end of the archipelago to the other in the same day, as reported by (Delgado-Aguiar and Hernandez-Luis, 2019) *"there is currently an inconsistency in the schedule of shipments from Tenerife to Gran Canaria when the goods come from the western islands, and in Fuerteventura when the goods come from Lanzarote. This makes it necessary to spend the night on one of the islands, which significantly increases the cost of the shipments, if not paralysing them*". Therefore, the proposed routes (Table 5) have a good chance of solving this problem by contributing to the cohesion of the territory by improving accessibility, in line with the objective of the Trans-Insular Transport Axis policy.

4.2. Costs and Feasibility

As simulation model was run for several times and with different parameter values, it became evident that three main factors determine the success of operations (see InsightMaker, 2024). They are journeys per day planned, business days operating per year and freight price. It is so that Airship should serve at least four journeys per day, and operating days per year should be 250 days or more. Most sensitive changes are for the freight price. If this falls to 0.3 EUR per kg or below, then it is very difficult to have any profitability left in 20 years observation period. However, if freight rate increases to 0.5 EUR per kg, then running this freight service is clearly profitable. We also added as fourth slider for parameter value of charging infrastructure investments. Based on our simulation runs, it influences profitability, but only marginally and needs to have cost of several hundred thousand EUR to hold real importance.

The study shows that depending on the unit price of freight having profitable new mean of cargo transport is possible. Unit prices for cargo with short shelf life are always higher from the ones with long shelf life. This is mainly due to the speed of transport, but also due to the need of having other special resources (e.g., cooling facilities). The Airship would meet the requirements of fast delivery and it also has the possibility of adding other cargo specific resources as the above-mentioned cooling or freezing facilities.

5. Conclusions

We are witnessing change in transportation logistics from two fronts: one is regulatory as within EU we have numerous agreements and objectives set for future emission reduction, and another one is the opportunity to use new technologies and vehicles within transportation. In this work we have analysed one of the emerging new opportunities, which is ground effect vehicle called Airship. This vehicle is currently at prototype stage, so all the evaluations concerning its technical and economical capability are preliminary, and initial. Based on our analysis, it seems to be the case that used operating environment of Canary Islands fits Airship due to the general distances between islands, and main locations. We were able to identify potential main routes for implementation the pilot project as well. It also seems to be the case that some food items, like fish, could be most potential as main cargo group (due to its daily need, and high enough volume).

While substituting all inter-island cargo carried by air transport with the new green mean of transport would support achieving the environmental targets of becoming carbon neutral by 2050, but also gain a reduction in frequency needs for airplane flights and in addition minimizing and optimizing cargo carried by ferries. As a result, optimizing cargo transportation in inter-island traffic to ferries for goods with long shelf life and to the new vehicle for goods with short shelf life reduces significantly emissions emitted of the whole cargo transportation in Canary Islands. According to the findings of the research, the pioneering and primary ports for piloting the Airship service are Santa Cruz in La Palma island, Arrecife in Lanzarote island, Puerto Del Rosario in Fuerteventura island and La Estaca in El Hierro island. These results are also supported by a relevant finding of being the ports that export fish and seafood. This finding is important as fishing is playing significant role in the life and economy of local inhabitants of these islands. Another relevant finding, while analysing port verification results and local fish export, is that currently the port of La Estaca in El Hierro is a minor fish and seafood exporter. In case the island export focuses only on fish and seafood, La Estaca should be excluded from the results. On the other hand, there are other relevant export articles with short shelf life (e.g., tomatoes) that could possibly be transported and having La Estaca still as one destination ports would support cargo transportation of one additional island and possibly also the whole western lines.

Apart of just examining transportation costs per km for Airship (compare e.g., Papadopoulos *et al.*, 2022; Yowtak *et al.*, 2020), we did put this vehicle to serve some predetermined route (like ferries). We assumed in the simulation model that Airship shall serve two destinations daily (journeys per day between these destinations) and with some given amount of business days from year. Our approach mimicked that of sea ferries or sea vessels used in some route, and all costs were incorporated based on this logic. Results showed that despite very disciplined use of Airship in predetermined route, it is difficult to achieve low transportation costs for cargo. It cannot be said that ground effect vehicle would be impossible to be used in cargo operations, but its cargo groups being served are limited. Possibly the selected fish and seafood could be lucrative as they could tolerate higher transportation costs due to limited sales time.

It should be noted that our results are conservative as there are potential benefits from emission reduction/elimination (global and local) that could be monetised and are not included in our model. If they were included, they would increase the margin on the freight price or allow a more flexible range of freight prices consistent with the benefits. The same could be said of subsidies for sea transport to compensate for the additional costs incurred by operators transporting certain fishery and aquaculture products to or from the Canary Islands.

As for further research in the area, we would be interested to examine specific cargo alternatives and transportation costs in situation, where there is e.g., some investment support for examined vehicles, subsidies are given for its operations (like low cost or free of charge electricity) and/or it is receiving state or EU supported low interest rate loans. These together of using new vehicles in numerous routes instead of one, would be natural further study on cost efficiency of ground effect vehicles. In addition, technologies develop over time, and amount of cargo on board could increase over time too – bringing transportation costs down as well.

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For more information concerning Airship project, please visit: https://airshipproject.eu/

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