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Decarbonization Framework of Estonian Coastal Ferries

Andres Laasma

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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.

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Eesti rannasõidu parvlaevade dekarboniseerimise raamistik

ANDRES LAASMA

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Contents

List of Publications

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

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

II **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. DOI: 10.4337/9781035321469.00014.

III **Laasma, A**, Aiken, D., Kasepõld, K., Hilmola, O.-P., Tapaninen, U. (2025). Data-Driven Propulsion Load Optimization: Reducing Fuel Consumption and Greenhouse Gas Emissions in Double-Ended Ferries. Journal of Marine Science and Engineering, 13 (4), #688. DOI: 10.3390/jmse13040688.

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:

IV Hunt, T., Tapaninen, U., Palu, R., **Laasma, A**. (2024). Small Island Public Transport Service Levels: Operational Model for Estonia. TransNav the International Journal on Marine Navigation and Safety of Sea Transportation, 18 (2), 315−322. DOI: 10.12716/1001.18.02.07.

V 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. DOI: 10.3390/jmse13020305.

Author’s Contribution to the Publications

The contribution to the papers in this thesis is:

I Main author. The author led the research design, performed the data collection and the comparative analysis on alternative fuels, and wrote the initial draft of the Introduction, Methods, and Results sections (with co-authors revising the Discussion and Conclusions).

II Main author. The author developed the decarbonization framework specific to the Estonian state ferry contexts, analysed vessel performance, and contributed to writing the sections on regulatory and policy implications.

III Main author. The author carried out the data-driven modelling for propulsion load optimization, interpreted the regression results, and wrote the primary discussion on emission-reduction outcomes.

IV The author participated in investigating small island service models and ferry transport planning, identifying how decarbonization could be integrated within diverse operational constraints.

V The author helped implement the methodological design for GHG emission comparisons in Estonian pilot fleet operations, bridging findings to broader ferry decarbonization strategies.

Introduction

International maritime transport is right now in the middle of a significant transition. This is driven by a mix of climate policy pressure, new technology options, and also changing expectations from society at large. Shipping has traditionally been described as the most energy-efficient way of moving cargo over long distances when measured per tonne-kilometre. However, its overall contribution to global greenhouse gas (GHG) emissions is still significant, about 2.9% of anthropogenic emissions according to the IMO (2020). Some forecasts, for example Psaraftis (2019) and Bouman et al. (2017), warn that the sector's share could grow further if trade volumes keep increasing and low-carbon propulsion options are adopted only slowly (see also Balcombe et al., 2019).

On the policy side, international regulation has started to draw more precise boundaries. The IMO's Revised GHG Strategy from 2023 set the ambition of reaching net-zero emissions "by or around 2050", with interim targets of 20–30% reduction by 2030 and 70–80% by 2040 compared with 2008. The European Union has gone further by adopting its Fit for 55 package, FuelEU Maritime regulation, and extending the Emissions Trading System (ETS) to shipping. These measures already affect decisions on vessel design, fuel selection, and operational planning (European Commission, 2021; EMSA, 2023). Although formally they apply only to ships above 5000 GT (See also the "Note on regulatory tonnage thresholds" in Chapter 1.4.), experience suggests that the indirect impacts of regulations will spread to smaller fleets too, for example, through fuel price changes, public procurement rules, or access to grants (Brynolf et al., 2014; Acciaro & Ghiara, 2017).

There is also a broader academic consensus that points in the same direction: decarbonization of shipping cannot rely on one single measure. Instead, it combines technical efficiency requirements (such as EEDI and EEXI), the introduction of alternative fuels, and better operational practices (Kontovas & Psaraftis, 2020; Rehmatulla et al., 2017). Recent reviews underline that ship energy efficiency research continues to expand, with emphasis on operational optimization, advanced monitoring, and energy indices as central tools for reducing emissions (Barreiro et al., 2022). Several life-cycle assessment (LCA) studies have shown that well-to-wake perspectives are essential because upstream methane slip or land-use change can offset the benefits seen at the exhaust (Balcombe et al., 2019; Gilbert et al., 2018). Alongside this, operational measures like slow steaming, route optimization, or even propulsion load balancing have been shown in earlier research (Johnson et al., 2013; Acciaro & Ghiara, 2017) to provide immediate reductions, even if they are not long-term solutions.

Placed against this international backdrop, Estonia makes an interesting case. Its state-owned coastal ferry fleet is small in global terms, but in the national context, it has a significant role in transport emissions. These ferries operate short, high-frequency routes to the islands, often in ice conditions during the winter. On routes like Virtsu-Kuivastu or Rohuküla-Heltermaa, annual emissions per vessel can reach 3000–4000 tonnes of CO_2-equivalent. Taken together, the system is a notable part of the country's transport-sector emissions. While such ferries fall below the ETS and IMO reporting thresholds, they are still affected indirectly by higher fuel costs, changes in procurement rules, and funding priorities. Estonia's forthcoming Climate Resilient Economy Act is expected to set national reduction targets, further aligning domestic regulation with EU climate neutrality goals. In addition, the National Energy and Climate Plan (ENMAK 2035) defines sectoral decarbonization pathways. It highlights emission reduction in domestic transport, including ferries, as part of Estonia's contribution to the EU's long-term climate objectives.

The operational requirements of these routes – short distances, harsh winter conditions, and strict timetables – both limit and enable decarbonization options. Battery-electric or hybrid propulsion faces challenges in sub-zero temperatures. At the same time, alternatives like LNG, methanol, hydrogen, ammonia, HVO, and biomethane each have their own advantages and clear trade-offs in terms of lifecycle emissions, retrofit options, and infrastructure needs. Decarbonizing such a fleet, therefore, requires an integrated framework that considers not only international and EU regulations, but also the local technical and institutional realities of a small state-owned fleet operating in cold climates.

This thesis asks a central question: how can Estonia phase in the decarbonization of its coastal ferry fleet in a cost-effective and technically credible way, while working within current infrastructure limits and regulatory uncertainty? The analysis builds on existing academic literature, especially on alternative fuels, efficiency indices, and operational optimization, and applies those insights to the Estonian case. The dissertation itself is based on a set of peer-reviewed articles, which are brought together and synthesized in Chapter 3.

Abbreviations

Abbreviation	Definition
ADA	Alternative Design Approval (per IMO frameworks)
AFT	Aft Engine (rear propulsion unit)
AI	Artificial intelligence
AIS	Automatic Identification System
ALBATTS	Alliance for Batteries Training and Skills (EU project)
AS	Aktsiaselts – Estonian public limited company (company type)
BC	British Columbia (as in BC Ferries)
BCG	Boston Consulting Group
BSFC	Brake Specific Fuel Consumption
CAPEX	Capital Expenditure
CBG	Compressed Biomethane Gas
CCS	Carbon Capture and Storage
CEF	Connecting Europe Facility
CEN-CENELEC	European Committee for Standardization / European Committee for Electrotechnical Standardization
CII	Carbon Intensity Indicator
CO2	Carbon dioxide
DCS	Data Collection System (IMO)
DMA/DMB	ISO 8217 distillate marine fuel grades: DMA (marine gas oil) and DMB (marine diesel oil)
DNV	Det Norske Veritas
DOI	Digital object identifier
DWT	Deadweight Tonnage
EBA	European Biogas Association
EC	European Commission
ECA	Emission Control Area
ECOETA	Maersk ECOETA – proprietary eco-efficiency vessel design concept (cargo sector, project-specific)
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EL	European Union (Estonian: Euroopa Liit)
EMS	Energy Monitoring System
EMSA	European Maritime Safety Agency
ENMAK	Estonia's National Energy and Climate Plan (NECP)
EPRI	Electric Power Research Institute
ERR	Estonian Public Broadcasting (Eesti Rahvusringhääling)
ESF	Estonian State Fleet (Riigilaevastik)
ETS	Emissions Trading System
EU	European Union
EU-ETS	EU Emissions Trading System
EV	Electric vehicle
FC	Fuel Consumption
FORE	Fore Engine (forward propulsion unit)

GDPR	General Data Protection Regulation (EU)
GHG	Greenhouse Gas
GO	Guarantee of Origin (energy attribute certificate)
GREET	Greenhouse gases, Regulated Emissions, and Energy Use in Technologies
GT	Gross Tonnage
GWP	Global warming potential
HVO	Hydrotreated Vegetable Oil
HVO100	100% hydrotreated vegetable oil (renewable diesel)
IC	Instruction Circular (administrative circular)
ICCT	International Council on Clean Transportation
ICE	Internal Combustion Engine
IEA	International Energy Agency
IGF	International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code)
IGF Code	International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels
II/III	Renewable Energy Directive II / III (EU)
ILUC	Indirect Land Use Change
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ISI	Institute for Scientific Information
ISO	International Organization for Standardization
KIK	Environmental Investment Centre (Estonia; Keskkonnainvesteeringute Keskus)
KPI	Key performance indicator
kW	Kilowatt
kWh	Kilowatt Hour
LBG	Liquefied biomethane (liquefied biogas)
LCA	Life Cycle Assessment
LCOE	Levelized cost of energy
LED	Light-emitting diode
LNG	Liquefied Natural Gas
LOA	Length Overall
MARPOL	International Convention for the Prevention of Pollution from Ships (MARPOL)
MATLAB	MATLAB – numerical computing environment
MCDA	Multi-Criteria Decision Analysis
MDO	Marine Diesel Oil
MEPC	Marine Environment Protection Committee (IMO)
MF	Motor ferry (vessel prefix)
MLP	Multi-Level Perspective

MLR	Multiple linear regression
MRV	Monitoring, Reporting and Verification (EU MRV)
MSC	Maritime Safety Committee (IMO)
MV	Motor vessel (vessel prefix)
MW	Megawatt
MWh	Megawatt-hour
NASA	National Aeronautics and Space Administration (USA)
nm	Nautical Mile
NMA	Norwegian Maritime Authority
NOx	Nitrogen oxides
OpEx	Operational Expenditure
PEMFC	Proton Exchange Membrane Fuel Cell
RED	Renewable Energy Directive (EU)
RPM	Revolutions Per Minute
RQ	Research question
RQ1	Research question 1
RQ2	Research question 2
RQ4	Research question 4
SCADA	Supervisory Control and Data Acquisition
SCR	Selective catalytic reduction
SDIR	Norwegian Maritime Authority (Sjøfartsdirektoratet)
SEA-LNG	SEA-LNG Industry Coalition
SOFC	Solid Oxide Fuel Cell
SOLAS	International Convention for the Safety of Life at Sea (SOLAS)
SPC-GEM	Pacific Community – Geoscience, Energy and Maritime Division
TCO	Total cost of ownership
TRAL	Transport and Mobility Development Plan 2021–2035 (Estonia)
TRL	Technology Readiness Level
TS	TS Laevad – subsidiary of Port of Tallinn (Tallinna Sadam)
TtW	Tank-to-Wake (emissions scope)
UCO	Used cooking oil
UNCTAD	United Nations Conference on Trade and Development
USA	United States of America
VTT	Technical Research Centre of Finland
WIC	Wind Influence Coefficient
WS	Wind speed
WtT	Well-to-Tank (upstream fuel scope)
WtW	Well-to-Wake (full fuel cycle)

1 Background and Context of Coastal Ferry Decarbonization

1.1 Maritime Decarbonization and Coastal Shipping

The urgency of climate action has transformed the transportation sector from a peripheral environmental concern into a central focus of international policy. Within this shift, maritime transport has assumed a paradoxical role. On one hand, shipping is known to be the most energy-efficient mode of large-scale cargo transport when measured per tonne-kilometre. On the other hand, its aggregate contribution to global greenhouse gas (GHG) emissions – roughly 2.9% according to the Fourth IMO GHG Study (2020) – positions it as a critical target for decarbonization strategies (UNCTAD, 2022). This proportion may appear modest, but due to the sector's projected growth and limited early action, it is among the most challenging sectors to decarbonize quickly. Maritime emissions are not only persistent but also widely distributed and closely tied to global trade, which complicates regulatory enforcement and uniform technological adoption (Transport & Environment [T&E], 2023).

In response, the International Maritime Organization (IMO) has progressively tightened its climate objectives. The IMO's Revised Greenhouse Gas Strategy, adopted in 2023, commits the sector to achieving net-zero emissions "by or around 2050," a notable escalation from previous, less binding targets (International Maritime Organization [IMO], 2023). This strategy also establishes intermediate checkpoints: a 20–30% reduction in total emissions by 2030 and a 70–80% reduction by 2040, relative to 2008 baselines. Crucially, the IMO's updated approach expands its scope beyond CO_2, encompassing methane and nitrous oxide, and introduces a well-to-wake lifecycle perspective for fuel evaluation, thereby foregrounding fuel choice as a cornerstone of compliance. However, enforcement remains decentralized and subject to flag-state implementation, resulting in uneven adoption across different geographies and vessel types.

Parallel to IMO efforts, the European Union has instituted a suite of climate policies that directly affect the maritime sector. Among the most impactful is the inclusion of shipping in the EU Emissions Trading System (ETS) from 2024 onward (European Commission, 2021). This marks a departure from prior carbon policies by internalizing the cost of GHG emissions into market behavior. Vessels with a gross tonnage (GT) that call at EU ports must purchase allowances for CO_2 emissions, starting at 40% coverage in 2024 and increasing to full coverage by 2026. Additionally, the FuelEU Maritime Regulation, part of the Fit for 55 legislative package, mandates a progressive reduction in the GHG intensity of the energy used on board, pushing shipping operators toward alternative fuels and energy sources. Notably, FuelEU Maritime includes a reward mechanism for ships using renewable fuels of non-biological origin, which could support early adoption of green hydrogen or ammonia, albeit with market and infrastructure challenges.

While these frameworks apply formally to larger vessels, their indirect effects are increasingly shaping the decisions of smaller vessel operators and national governments. Member states, including Estonia, are adapting their legal systems to reflect and anticipate these regulatory changes. Estonia's forthcoming Climate Resilient Economy Act is expected to mandate sectoral decarbonization targets in line with the EU's climate neutrality goal for 2050. Even though coastal ferries below the 5000 GT threshold are currently exempt from direct ETS compliance, they are not isolated from its economic consequences. Fuel prices, funding eligibility, procurement criteria, and national environmental taxes are all likely to evolve in ETS-aligned directions. Therefore, the decarbonization of smaller vessels cannot be delayed without risking economic disadvantage, policy non-compliance, or technological lock-in.

1.1.1 Estonia's Coastal Ferry System as a Strategic Case Study

Within this multilevel governance context, coastal shipping presents both a challenge and an opportunity. Ferries that operate on short, fixed routes – such as those in Estonia's coastal fleet – are not the main contributors to global maritime emissions in absolute terms. However, they play a disproportionately significant role in national inventories and public-sector carbon footprints. For instance, on high-frequency routes like Virtsu-Kuivastu or Rohuküla-Heltermaa, annual emissions per vessel can reach 3000–4000 tonnes of CO_2 equivalent, even with moderate speeds and limited tonnage. Across the entire state fleet, this aggregates to a significant portion of Estonia's domestic transport emissions.

At the same time, the characteristics of coastal ferries make them viable candidates for early decarbonization. Their fixed schedules, limited operational range, centralized ownership, and port-based routines simplify logistical coordination for refueling or recharging. Moreover, because they serve essential transport functions for insular communities, their decarbonization has high visibility and symbolic resonance, particularly in policy demonstrations. However, these advantages are counterbalanced by significant constraints. Estonia's coastal ferries must operate year-round, including in icy conditions where engine power demands rise and battery performance degrades. Shore power infrastructure is currently uneven, and many smaller ports lack the grid capacity to support overnight charging of high-capacity batteries (European Maritime Safety Agency [EMSA], 2023e). Safety regulations also complicate the adoption of novel fuels, particularly in areas close to passengers or sensitive ecosystems.

Consequently, the decarbonization of coastal shipping in Estonia – and in analogous northern maritime systems – requires more than retrofitting or incremental operational tweaks. It necessitates systemic transformation across fuel supply chains, propulsion architectures, regulatory definitions, and infrastructure planning.

To structure the complex field of maritime emissions mitigation, strategies can be grouped into four main domains, each offering distinct advantages, limitations, and maturity levels. This multifaceted framework helps clarify how individual technologies and practices interact within the broader context of decarbonization goals. The CO_2 reduction potential ranges presented in Table 1-1. These estimates are derived from synthesized data found in recent literature and technical reports by DNV (2023a), EMSA (2023d), and T&E (2023). These values represent indicative ranges based on vessel-class-independent studies and industry-wide operational averages. For instance, operational optimization (e.g., slow steaming, load balancing) can deliver reductions of 10–40% in fuel use and emissions, whereas switching to alternative fuels, such as green hydrogen or ammonia, may achieve reductions of 60–100% when considering a well-to-wake lifecycle assessment. These potentials were not derived from primary measurements in this thesis, but they serve to frame the strategic landscape for intervention planning.

Table 1-1 Maritime Decarbonization Pathways: A Multifaceted Landscape.

Strategy Type	**Description (incl. examples)**	**CO_2 reduction potential**
Alternative fuels	Transition to ammonia, methanol, hydrogen, HVO, LNG, biomethane; assessed on a well-to-wake basis.	60–100% (long-term)
Operational optimization	Slow steaming, timetable micro-adjustments, route/weather optimization, propulsion load balancing, real-time power-setpoint control.	10–40%
Energy / hull & design efficiency	Explicitly includes EEDI/EEXI (design indices for newbuilds and existing ships), hull-form improvements, advanced coatings, air-lubrication, propeller and wake-equalizing devices; where feasible, modest scale effects (capacity/right-sizing) while respecting draught/berth limits.	5–20%
Electrification & hybridization	Battery-electric vessels, shore power (cold-ironing), diesel-electric or hybrid ICE-electric systems on suitable routes/ports.	~20–60% (system/route dependent)

Source: Table constructed by the author using information from Bouman et al. (2017); Balcombe et al. (2019); Brynolf et al. (2014); Bicer & Dincer (2018); Lindstad et al. (2011); Du et al. (2022); Krata & Szlapczyńska (2018); Spinelli et al. (2022); Nicorelli et al. (2023); Kim & Steen (2023); Wang et al. (2021); Jeong et al. (2020); Perčić et al. (2022).

This classification is not merely theoretical - it informs the technical and policy structure of this dissertation. While all four pathways can be pursued in parallel, the choice of fuel is ultimately the determining factor for long-term compliance with decarbonization. Operational and retrofit strategies provide short-term savings, but only alternative fuels offer the emission reductions necessary for complete alignment with the 2050 climate targets.

1.2 Technological and Operational Optimization Strategies

As global pressure to reduce greenhouse gas emissions from maritime transport intensifies, shipping operators face the challenge of implementing emission-reducing measures in the near term, even while large-scale transitions to alternative fuels remain economically and logistically unfeasible. In this context, technological and operational optimization strategies have gained renewed attention. These approaches offer comparatively low-cost and quickly implementable methods for reducing fuel consumption and carbon dioxide emissions from existing vessels, without requiring fundamental changes to fuel types or propulsion systems. Such strategies are particularly relevant for small and medium-sized ferry operators, including public fleets in countries like Estonia, where the combination of fixed routes, frequent service, and seasonal conditions imposes both constraints and opportunities.

Operational optimization refers to practices that reduce energy demand by altering how vessels are operated. Among the most effective is slow steaming, a technique in which a vessel intentionally operates at speeds below its design maximum. By reducing hydrodynamic resistance, slow steaming can lower fuel consumption by 10 to 30 percent, depending on vessel class, engine type, and route characteristics (UNCTAD, 2022;

Lindstad et al., 2011; Pelić et al., 2023). This method has been widely used in container shipping and is increasingly adopted in RoPax and ferry services. However, in scheduled passenger services, its application is limited by the need to maintain fixed departure and arrival times due to consumers' demand. For this reason, partial slow steaming (where speed is reduced during low-load periods) may be more practical for Estonian ferries.

The use of dynamic routing is becoming increasingly important as weather conditions can now be monitored in real time, allowing ships to circumvent adverse conditions or adjust their course and speed for greater efficiency (Du et al., 2022; Krata & Szlapczynska, 2018). This requires integrating reliable forecasts into operational decision-making and aligning adjustments with timetable constraints. During longer ferry routes that traverse open seas, like Rohuküla-Heltermaa and Kihnu-Munalaid, these methods can be used in conjunction with adaptive speed control to lower engine load by 15 percent. Furthermore, the required equipment for such routing optimization is now integrated within digital platforms onboard vessels, making it possible for ships below 5000 GT.

A more technical, yet promising, operational method is propulsion load balancing. This refers to the allocation of power to different propulsion units, such as aft thrusters and forward thrusters, which is adjusted in real-time and aims to enhance efficiency at a given speed and during maneuvering. (Torben, Brodtkorb, & Sørensen, 2020; Artyszuk & Zalewski, 2021; Vergara, Alexandersson, Lang, & Mao, 2023) The public ferries employed by the Estonian government, equipped with telemetry systems, have demonstrated the use of load balancing to reduce fuel consumption up to 15% compared to baseline configurations (Laasma et al., 2025). These improvements can be achieved using existing propulsion frameworks without requiring physical changes, enabling scalability and retrofit applicability.

The energy-saving retrofits alongside hull maintenance are technologically focused changes that provide concrete benefits.

The growth of algae, barnacles, and other organisms on the hull surface results in an increase in drag and fuel consumption. Performing regular hull cleaning mitigates the drag-fuel efficiency impact and offers an energy savings of 5 to 10 percent. Additionally, advanced antifouling coatings, such as silicone-based paints and foul-release paints, have the potential to reduce fouling rates, increase maintenance interval periods, and improve fuel efficiency. Although these coatings may appear more expensive initially, they provide significant savings, especially in reduced fuel and maintenance costs over several years (Schultz et al., 2011; Demirel et al., 2017, 2019).

Another alternative is the addition of retrofitting propeller nozzles, ducts, or wake-equalizing devices. While these changes are more expensive than simply improving operational efficiency, the use of these devices enhances water management around the propeller, improving propeller efficiency. Savings between 5 and 10 percent are frequently observed, especially for vessels with high-load operation profiles (DNV, 2023a; Stark et al., 2022).

To provide a structured overview of the primary optimization strategies available to coastal ferry operators, Table 1-2 summarizes key interventions, their estimated reduction potential, cost level, and implementation complexity. The table is based on a synthesis of international technical literature and contextual data from the Estonian ferry fleet.

Beyond operations, design-based efficiency standards such as the EEDI and EEXI also drive improvements at the design stage (IMO, 2023); see Table 1-1, design-based efficiency (EEDI/EEXI).

Table 1-2 Summary of Technological and Operational Optimization Strategies.

Strategy	Category	CO_2 Reduction (%)	Cost	Complexity
Slow steaming	Operational	10–30	Low	Low
Hull cleaning	Technical	5–10	Low	Low
Antifouling coatings	Technical	5–15	Medium	Low
Propeller upgrades	Technical	5–10	Medium	Medium
Dynamic routing	Operational	5–15[a]	Low	Medium
Load balancing (telemetry)	Operational/Tech	10–15[b]	Medium	Medium

Source: Ranges synthesized from Lindstad et al. (2011); Bouman et al. (2017); Schultz et al. (2011); Demirel et al. (2017; 2019); Spinelli et al. (2022); Nicorelli et al. (2023); Du et al. (2022); Krata & Szlapczyńska (2018); Torben et al. (2020); Artyszuk & Zalewski (2021); Vergara et al. (2023).

[a] Dynamic routing: Ferry services often show lower annual average effects (≈1–5%); values near the upper bound (5–15%) occur during favourable weather windows or specific profiles. (Du et al., 2022; Krata & Szlapczyńska, 2018.)

[b] Load balancing: 10–15% reflects targeted, telemetry-supported power/thrust allocation; manoeuvring phases can exceed this, while steady-state cruising averages are typically lower. (Torben et al., 2020; Artyszuk & Zalewski, 2021; Vergara et al., 2023.)

The strategies discussed, although varied in approach, all aim to make older ships more fuel-efficient without the costly switch to new fuel or significant yard work. Because of this, they fit neatly into today's rulebooks, which require owners to make gradual cuts in emissions long before the final push to full decarbonization.

At the same time, it is crucial to recognize where optimization reaches its limits. Each adjustment trims the litres burned per passage, yet none alters the chemical makeup of the fuel. As a result, even in the best-adjusted vessel, burning diesel will still release a carbon footprint that clashes with net-zero goals. Under ideal conditions, stacking several upgrades can reduce consumption by 30 to 40 percent, but this still falls short of the long-term limits set by the IMO and the European Union. For this reason, optimization should be viewed as a stopgap tool, easing operators forward while they prepare themselves for the larger leap to clean and renewable fuels.

In summary, refined technology and smarter operations are crucial for closing the gap between current regulations and future sustainability objectives. For coastal ferry grids like Estonia's, these measures yield noticeable reductions in emissions, enhance service reliability, and provide real-time data on how each vessel performs. Though they cannot, by themselves, complete the energy shift, the improvements they provide prepare the field for the more systemic changes – new fuels and propulsion technologies – that will ultimately define that transition.

1.3 Alternative Fuels for Coastal Ferries

This section summarises alternative marine-fuel pathways relevant to coastal ferries and the Estonian operating context. It follows common practice in the literature when outlining environmental and operational considerations for fuel choices; the specific evaluation criteria and their weighting are presented in Chapter 2.

Figure 1-1 maps the strengths and weaknesses of seven proposed marine fuels across six relevant assessment areas. Using a radar chart highlights the complex trade-offs ferry operators face when choosing an onboard energy source. Each spoke represents a separate criterion derived from the MCDA process outlined in this thesis: potential GHG reductions, readiness of existing technology, performance in cold climates, ease of retrofitting, pressure on refueling infrastructure, and overall safety or handling burden. These headings align with the sectors typically reviewed under the EU taxonomy, the RED II sustainability checks, and the IMO lifecycle outlook on vessel emissions (European Commission, 2018; IMO, 2023).

Data for this figure were drawn from peer-reviewed articles, recent technology-readiness reviews (DNV, 2023a), operational assessments (Armstrong, 2022), and the GREET life-cycle modelling. Hydrogen and ammonia earned the highest GHG-reduction score of 100 because burning either fuel produces no direct CO_2, and renewable electricity can be used to drive their manufacture. Still, the feasibility and safety of retrofitting drag their overall ratings down; cryogenic tanks and poisonous vapours present serious challenges for passenger fleets (Pfeifer et al., 2020; Sánchez et al., 2023). Methanol ranks more evenly across the criteria-it fails the zero-emission test at the pipe, yet slots easily into existing engines and is already powering Northern Europe's ferries.

The chart confirms that HVO and biomethane still have little impact on emissions on their own, but deliver extremely high retrofit marks, qualifying them as low-risk options for public fleets. Battery-electric drivetrains, meanwhile, excel in on-road emissions and grid control, but lose points for their limited range and performance in frigid weather. LNG, once hailed as a breakthrough bridge fuel, now lags behind the next generation of feedstocks, although its familiar supply chain and cost edge continue to attract buyers. For LNG, well-to-wake performance is highly sensitive to methane slip (engine-out CH_4) and upstream methane leakage; recent measurements on LNG engines show substantial slip variability, and under typical rates, the net GHG benefit versus marine gas oil can vanish or reverse. (Lehtoranta et al., 2025; Sagot et al., 2025).

By displaying all fuels on a unified radar grid, the chart enables policymakers and operators to quickly identify which fuels consistently perform across categories versus those with more polarized profiles. The visual is used as orientation only; the formal MCDA and route-specific scenarios are presented in Chapter 2.

It is important to note that this radar chart provides a visual comparison based on unweighted scores. A formal, weighted Multi-Criteria Decision Analysis (MCDA) that builds upon these scores to provide a more robust ranking under specific strategic priorities is detailed in Chapter 2.

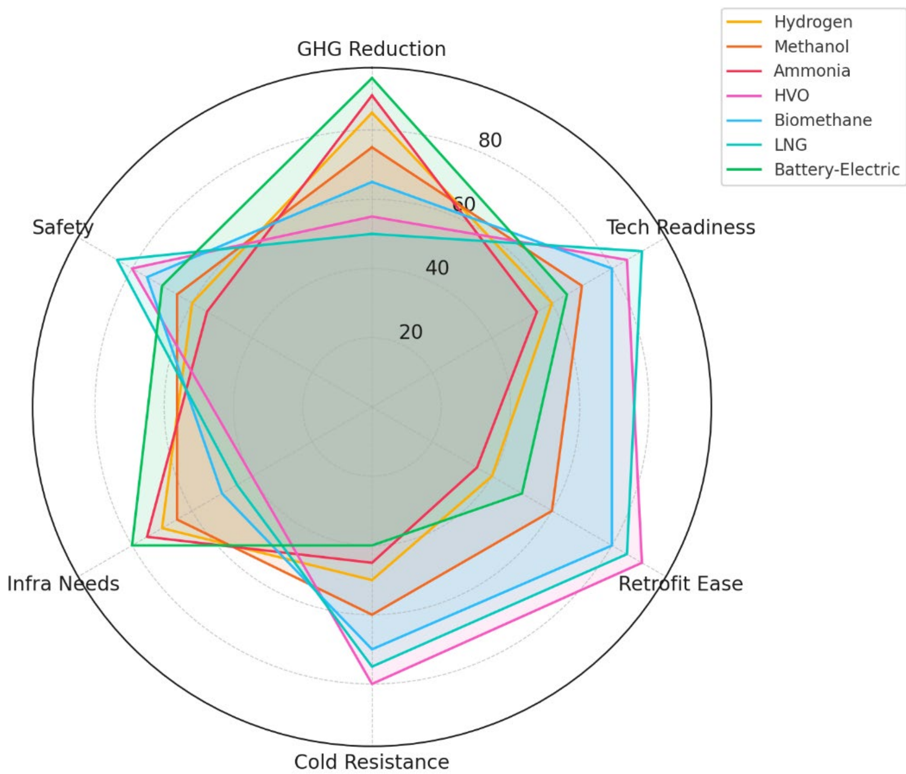

Figure 1-1 Alternative Fuels – Multi-Criteria Comparison.

Radar chart comparing seven alternative fuels (hydrogen, methanol, ammonia, HVO, biomethane, LNG, battery-electric) across six assessment criteria: GHG reduction potential, technology readiness, retrofit feasibility, cold-weather resilience, infrastructure needs, and safety.

Source: Author's analysis using Python 3.13 (matplotlib, pandas), based on Brynolf et al. (2014); Balcombe et al. (2019); ICCT (2023); DNV (2023); EMSA (2023d).

Figure 1-2 presents the same underlying data as Figure 1-1 but in a heatmap that highlights criterion-by-criterion differences. Scores are normalized per criterion to a 0–100 range using min-max scaling across the seven fuels; higher values indicate more favourable performance (100 = best-performing option among the assessed fuels on that criterion; 0 = least-performing). The heatmap is intended for visual orientation; the weighted, route-specific MCDA is described in Chapter 2 and reported in Section 3.3.

Cold-weather suitability is a key metric in evaluating any fuel or propulsion system, measuring whether the system can start, run, and remain safe, efficient, and reliable at sub-zero temperatures. The metric assesses how well the energy source retains its chemical and physical properties in cold conditions, whether the machinery will operate after a prolonged freeze, the amount of additional heat required by the equipment, and whether the arrangement complies with class rules for ice-going vessels. For instance, battery-electric systems typically lose range below 0 °C because lithium-ion cells pack less energy and their reaction slows. Additionally, hydrogen or ammonia are only available at cryogenic temperatures, requiring insulated tanks that ambient swings still stress (Mayanti et al., 2024; Sánchez et al., 2023). Likewise, lighter fuels such as methanol or gaseous hydrogen tend to burn cooler and produce less waste heat, so ships typically add auxiliary heaters to maintain crew warmth and engine temperatures above the frost line during the harsh Baltic winters (Mayanti et al., 2024; Sánchez et al., 2023).

Methanol generally earns a score between 75 and 90 across nearly every evaluated category, indicating solid overall balance. Hydrogen and ammonia record a perfect 100 for greenhouse-gas reduction, yet both plunge below 50 for safety and ease of retrofitting. Hydro-processed vegetable oil, or HVO, stands out as a near-term favorite, scoring 95 for retrofitting and 90 for cold-weather performance; however, its long-term climate benefit remains dependent on the feedstock origin (EMSA, 2023d). Battery-electric systems show sharp score disparities; they receive high marks for operational GHG but low grades for range and winter reliability, a result of limited energy density and performance drop at subzero temperatures (Mayanti et al., 2024).

The 0–100 scoring scale integrates directly with the weighting and aggregation used in the thesis MCDA. The whole procedure is presented in Chapter 2.

The scoring matrix shown here is especially useful for public buyers and policy-makers who need an open, defensible way to pick a clean marine fuel. By laying trade-offs on the table, the chart allows Estonia to tailor each route and roll out upgrades step by step, keeping budget and port capacity in mind.

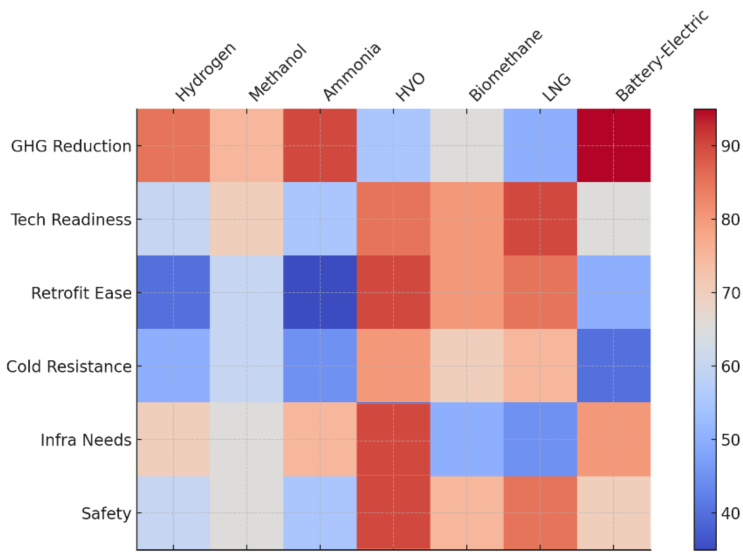

Figure 1-2 Heatmap of alternative fuels assessment scores.

This heatmap visualizes the normalized 0–100 scores across the same six criteria used in Figure 1, highlighting the absolute performance levels of each fuel. A score around 90 indicates top-of-group performance on that criterion; a score around 40 indicates a clearly below-average result within this set of seven fuels. Colours run from lighter (lower) to darker (higher). Unlike the radar chart, which emphasizes profile shape, the heatmap supports detailed quantitative interpretation and helps identify top and bottom performers per criterion. The scoring approach aligns with the MCDA framework described in Chapter 2 and draws on peer-reviewed data, technology reviews, and life-cycle models.

Source: Author's analysis using Python 3.13 (matplotlib, pandas), based on Brynolf et al. (2014); Balcombe et al. (2019); ICCT (2023); DNV (2023); EMSA (2023d).

1.3.1 Liquefied Natural Gas – A Transitional Option

Liquefied Natural Gas (LNG) has emerged in the past decade as a prominent transitional marine fuel, recognized for its ability to reduce air pollutants and offer moderate reductions in greenhouse gas (GHG) emissions compared to conventional marine fuels. From an operational perspective, LNG combustion significantly lowers emissions of sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter, making it initially one of the most viable decarbonization options (DNV, 2025; SEA-LNG, 2024a). Life-cycle assessments indicate that LNG GHG emissions vary widely on a well-to-wake basis relative to marine gas oil. However, the well-to-wake climate outcome is highly sensitive to upstream methane leakage and engine methane slip; recent measurement campaigns show substantial slip variability, and at typical rates, the net GHG benefit versus marine gas oil can vanish or reverse (ICCT, 2023; Lehtoranta et al., 2025; Sagot et al., 2025).

Environmental and Air Quality Benefits

Liquefied natural gas all but removes sulphur dioxide and sharply cuts soot, helping to clear the air around terminals and along coastal roads. Depending on the burner that shipbuilders choose, nitrogen-oxide emissions can fall by as much as 95 percent when LNG replaces heavy fuel oil (SEA-LNG, 2024a). That huge drop is why port passenger ferries, frequently docking in dense urban zones, are among the first vessels switching to cleaner gas.

Methane Slip: A Critical Climate Concern

Despite these advantages, methane slip (the release of unburned methane during LNG combustion) remains a significant climate concern. Over a 100-year timeframe, methane has a global warming potential (GWP) of 28–36 times that of CO_2, while over a 20-year horizon, it is significantly higher (IPCC, 2021). Engine improvements have largely eliminated slip in high-pressure two-stroke engines (used in ~75% of LNG ships) and reduced it by over 85% in new four-stroke models (SEA-LNG, 2024b). Nevertheless, methane slip and fugitive emissions during bunkering and handling remain relevant challenges, and can be elevated at low loads and in specific engine types; together with supply-chain methane leakage, slip is the key driver of LNG's well-to-wake performance (ICCT, 2023; Lehtoranta et al., 2025).

Infrastructure and Retrofit Considerations

Globally, the network of LNG bunkering facilities continues to expand. By early 2025, a fleet of 642 LNG-fueled vessels (excluding dedicated carriers) was recorded, alongside 264 units currently under construction (DNV, 2025). Nevertheless, Estonia's regional and island ports remain largely unserved, a gap that hampers any LNG transition among local ferries. Retrofitting existing diesel craft demands extensive, expensive work (cryogenic tanks, upgraded pipe runs, gas sensors, and navigation), safety codes, so projects gain traction only for vessels with years of profitable service ahead (DNV, 2025).

Regulatory and Economic Frameworks

The IMO's 2023 GHG strategy introduces mandatory measurement and lifecycle analysis of methane emissions from 2028 (IMO, 2023). Concurrently, the EU's FuelEU Maritime explicitly includes methane in the lifecycle GHG-intensity calculation and applies default slip factors; unless measured and controlled, these factors erode LNG's compliance advantage (ICCT, 2023; FuelEU Maritime, 2023).

Market Outlook
Even with regulatory hurdles and supply chain pressures, LNG continues to capture the bulk of new alternative-fuel vessel orders. By mid-2024, the global order book comprises more than 109 dual-fuel units, with three-quarters of them utilizing high-pressure, low-slip engines (SEA-LNG, 2024c). That concentration speaks to shipowners' comfort with LNG's proven performance and its seamless plug-in to ports' existing bunkering networks.

Relevance to Estonian Coastal Ferries
Schedule-sensitive, ice-prone Baltic routes argue against costly, untried infrastructure. Although LNG could reduce local NOx and particulate counts, persistent methane slip worries, fragmented bunkering, and steep retrofit bills keep the option on hold until Nordic regulators align investment plans and leak-mitigation technology. Without such coordination, LNG looks unsustainable for Estonian ferries.

1.3.2 Hydrogen
Hydrogen is widely recognized as one of the most promising long-term energy carriers for maritime decarbonization. Its key advantage lies in the absence of carbon atoms in its molecular structure, enabling zero CO_2 emissions at the point of use. The fuel's role is prominently featured in the European Green Deal and the EU Hydrogen Strategy, both of which position hydrogen as a central pillar in achieving net-zero targets across transport sectors, including shipping (European Commission, 2020; FuelEU Maritime, 2023).

Despite this strategic attention, the implementation of hydrogen as a primary marine fuel for coastal ferry systems (especially in colder northern climates) faces several technological, infrastructural, and regulatory barriers as follows:

- Hydrogen production at scale is still energy-intensive, and cold regions require cryogenic storage that adds weight and space penalties to small ferry hulls.
- Sea trials reveal performance trade-offs in power density, cycle efficiency, and safety monitoring that European test beds continue to examine.
- Bunkering and port codes lag behind pilot projects, leaving operators without firm timelines or certification pathways.
- Supply-chain consistency relies on renewable electrolysis, yet seasonal wind shortfalls in northern grids can disrupt firm fuel contracts.
- Shipping's global carbon pricing regime will eventually favor hydrogen as capex declines, but today's cost differential favors dense cargofuel.
- Research consortia, however, are already modelling small-network hydrogen hubs and benefit from echelon-scale electrolysis, so pilot-release timelines are tightening.

The following subsections assess these criteria in Estonia, using the same benchmarks applied to LNG in Section 1.3.1.

For short, high-frequency ferry routes, hydrogen's low volumetric energy density and boil-off/vent management make infrastructure and safety case decisive; lifecycle results vary widely with the electricity source used for electrolysis (Wang et al., 2023; IMO MEPC.376(80), 2023).

Environmental and Air Quality Benefits

When generated using renewable electricity and water by electrolysis (green hydrogen), burning the fuel inside an engine, turbine, or fuel cell emits no carbon dioxide, sulfur oxides, nitrogen oxides, or fine particulates. That clean combustion makes hydrogen cleaner on paper than any competing marine fuel. Because hydrogen leaves no ash or heavy soot, major ports and coastal towns could see clearer skies and healthier air. Fuel-cell systems also reduce the engine growl and shake typically felt on board, providing passengers and crew calmer voyages (IEA, 2023; Wang et al., 2023).

Lifecycle Emissions and Climate Considerations

When produced entirely with renewable power and burned in fuel cells, green hydrogen can reduce well-to-wake greenhouse gas emissions by more than 95 percent (IEA, 2023). That said, its round-trip energy efficiency trails that of straight electric propulsion: electrolysis typically runs at 60 to 70 percent, and compressing, liquefying, or storing the gas requires even more power (Hydrogen Council, 2023; Hydrogen Council, 2024). On Estonia's chilly decks, vehicles may require extra heating and careful humidity control to prevent cell freezing, which adds both weight and watt-hours. Also, whether stuffing a vessel with strong gas cylinders or building cryogenic chambers, larger tanks often swallow cargo space and limit voyage distance (Wang et al., 2023; Lloyd's Register, 2023).

Infrastructure and Retrofit Requirements

Currently, none of Estonia's maritime terminals feature hydrogen bunkering stations, sparking the first scramble that every new fuel faces: building, testing, and certifying the hoses, pumps, blowers, and safety warnings before fueling any ship.

Building the infrastructure to support hydrogen fuel at sea will demand sizable funding for high-pressure or cryogenic tanks, designated safety zones, and complementary pipelines (Lloyd's Register, 2023). Storing hydrogen is inherently challenging because boil-off can occur rapidly, and the gas is highly flammable (Lloyd's Register, 2023). Retrofitting current ferries typically proves impractical, meaning any hydrogen vessel will need to come off the ways, a factor that adds expense and limits yard capacity. Meanwhile, the IGF Code is still being revised; until the new hydrogen provisions are finalized, vessel classification will remain ambiguous (Lloyds Register, 2023; IMO, 2023).

Regulatory and Economic Context

Hydrogen's economics are location- and utilization-dependent: the levelized cost pivots on electricity price and electrolyser capacity factor. Under realistic 2024–2025 assumptions, renewable hydrogen remains more expensive than marine gas oil for coastal ferries unless supported by sustained subsidies or high carbon prices (Hydrogen Council, 2023). The IMO 2023 GHG Strategy highlights hydrogen-derived fuels for long-haul use but pairs this with requirements for safety rules and port infrastructure. EU policy recognises hydrogen, yet current instruments stop short of providing clear, investable revenue certainty for bunkering networks (European Commission, 2023).

Regional Initiatives

Collaborations, such as the BalticSeaH2 project, which establishes a cross-border hydrogen valley linking southern Finland and Estonia, demonstrate efforts to build comparative corridors for hydrogen supply and maritime use (BalticSeaH2, 2024; BalticSeaH2, 2025).

Relevance to Estonia's Ferry Fleet

Short, ice-class routes and tight budgets make hydrogen adoption unlikely in the short term, due to high costs and infrastructure deficiencies. Nonetheless, the growth of wind power and EU funding creates future opportunities. Hybrid configurations that leverage fuel cells for auxiliary loads, combined with battery systems, may be viable after 2035.

1.3.3 Methanol

Methanol is increasingly viewed as one of the most promising mid-term fuels for reducing ships' fugitive climate harm, offering a pragmatic mix of availability and environmental benefits. Because it stays liquid at normal temperatures, it slots toward existing bunkering pipes, and lifecycle greenhouse gas cuts can be significant, especially when the fuel comes from renewable feeds (GREET Collaboration, 2023; Brynolf et al., 2014; Maimaiti et al., 2023; Roux et al., 2024; ICCT, 2023).

Environmental and Air Quality Benefits

Turning methanol in a modern engine releases no sulfur oxides and slashes nitrogen oxides by up to 60 percent in dual-fuel setups (Ulstein & IMO, 2022). Soot levels also drop, protecting air quality around busy ports. When methanol is made from renewable sources (biomass or electrolysis powered by green electricity), life-cycle carbon cuts can hit 70 to 90 percent compared to marine gas oil (GREET Collaboration, 2023; Methanol Institute, 2024).

Lifecycle Emissions and Climate Considerations

Well-to-wake numbers support the 70-to-90 percent claim for green, while blue methanol, which utilizes carbon capture to convert methane waste, achieves closer to 50-to-60 percent savings (GREET Collaboration, 2023). Its energy weight is about 50 percent lighter than diesel, so the vessel's range could shrink unless bigger or densified tanks are fitted. Still, methanol cuts carbon now without the leakage risks linked to liquefied natural gas, methane slip, or indirect NOx emissions formed by ammonia. Tank-to-wake CO_2 cuts are modest for fossil methanol, so lifecycle gains depend on e-/bio-methanol pathways and assumptions regarding electricity/CO_2 sourcing (Maimaiti et al., 2023; ICCT, 2023).

Infrastructure and Retrofit Requirements

Existing diesel bunkering pipelines and pumps can accommodate methanol with only modest upgrades, including sealed pumps and corrosion-resistant stainless-steel fittings. Commercial methanol engines, whether dual-fuel or dedicated, are already on the market, and converting a vessel takes roughly the same time and budget as switching to LNG (Brynolf et al., 2014; Maimaiti et al., 2023; Roux et al., 2024; ICCT, 2023; Methanol Institute, 2024). Planned e-methanol manufacturing facilities in Scandinavia and the Netherlands are slated to come online between 2026 and 2027, further expanding production infrastructure (Methanol Institute, 2024).

Regulatory and Economic Context

Methanol is classified as a low-flashpoint fuel under the IGF Code, and its handling is therefore governed by the safety standards established by the IMO (IMO, 2023). The FuelEU Maritime Regulation classifies methanol much like hydrogen, allowing carriers to earn greenhouse-gas credits when the fuel is produced from renewable sources (European Commission, 2023). Analysts predict that the cost of green methanol will trend toward parity with marine diesel by the end of the decade, boosting its competitiveness (Hydrogen Council, 2023).

Relevance to Estonia’s Ferry Fleet
Methanol stands out as a practical near-term option for Estonia’s coastal ferry system. It can substantially reduce greenhouse gases while utilizing much of the port’s existing bunkering equipment and retrofitting current engines. Tanks fit within existing vehicle bays, and because methanol remains liquid even at sub-zero temperatures, ferries can refuel quickly in the coldest months. Trial vessels already sailing across Nordic routes have confirmed that the fuel performs reliably under typical marine loads (Brynolf et al., 2014; Maimaiti et al., 2023; Roux et al., 2024; ICCT, 2023). If funds and orders arrive on schedule, Estonia's first methanol-powered shuttle could enter service within five years.

1.3.4 Ammonia

Ammonia (NH_3) has begun to capture interest in maritime decarbonization because burning it produces no carbon and because existing ammonia supply chains are well-developed. The fuel aligns neatly with hydrogen-based roadmaps and is endorsed by the IMO’s 2023 emissions strategy as a medium-term zero-carbon option (IMO, 2023). Likewise, the European Commission includes ammonia in its Hydrogen Strategy blueprint for Europe’s clean energy transition (European Commission, 2020).

Still, ammonia has barely been tested on passenger ships. Its toxicity, potential for slip emissions, and corrosive nature create significant safety issues for ferries making frequent port calls and carrying the general public. Until these problems are resolved at scale, ammonia will remain a promising but cautious forward-looking choice for Estonian or any coastal fleet.

Environmental and Air Quality Benefits
Combustion of ammonia produces no carbon dioxide (CO_2) and contains no sulfur, making it an attractive candidate for cleaner-burning fuels. Nevertheless, the process still forms nitrogen oxides (NO_x), so resolving that issue with selective catalytic reduction (SCR) is necessary to pass the IMO Tier III test (IEA, 2022). Because ammonia burns at a cooler flame temperature, soot and black-carbon output are very low and cause far less visual plume damage along coastlines. Overall environmental impact turns mainly on how the ammonia is made: when produced by renewable electrolysis and air separation, the fuel can come close to a zero well-to-wake footprint, whereas grey or blue fuel made through steam methane reforming (with or without carbon capture) releases far more emissions (IEA, 2022; Hydrogen Council, 2023).

Lifecycle Emissions and Climate Considerations
When produced with renewable electricity, the well-to-wake greenhouse gas emissions from green ammonia can be more than 90% lower than those of conventional marine fuels, particularly if leakage during manufacturing and bunkering is minimized (IEA, 2022). The overall energy efficiency for a vessel using ammonia, however, suffers because extra power is needed for synthesis, cryogenic storage, and cracking when internal combustion engines are employed. After factoring these losses, rough engine efficiencies of 45 to 50 percent are recorded, falling short of similar figures for diesel or LNG (Machaj et al., 2022; Okumuş & Kanun, 2024; Dong et al., 2024).

Infrastructure and Retrofit Requirements
Adopting ammonia as a shipboard fuel demands either cryogenic tanks or high-pressure cylinders built from corrosion-resistant compounds, plus reliable leak sensors and hardened bunkering systems; these features are especially crucial on passenger ferries,

which operate close to urban centers (Yadav et al., 2022; EMSA, 2023a). New designs must also provide separate fuel compartments and sophisticated ventilation to mitigate the toxicity and pungent odor of ammonia in the event of spillage.

Formal Safety Assessment studies highlight toxicity-driven design needs (double containment, ventilation, gas detection) alongside comparatively low flammability; near-term pilots remain tightly controlled (Yadav et al., 2022; Lankahaluge et al., 2025).

Regulatory and Economic Context

Ammonia remains classified as a hazardous cargo under current international rules, and significant revisions to the IGF Code that would permit its widespread use are not yet finalized, leaving many classification and safety details incomplete (IMO, 2023; EMSA, 2023a). From an economic standpoint, the fuel becomes attractive only if the cost of green ammonia declines sharply and if carbon charges on rivals rise. Some analysts argue that in regions housing large renewable portfolios, parity with marine gas oil could be reached in the early 2030s, although outcomes will vary by location and pricing scenario (Hydrogen Council, 2023).

Relevance to Estonia's Ferry Fleet

Due to ongoing regulatory gaps, high retrofit costs, and limited bunkering facilities, ammonia is realistically a post-2035 choice for Estonia's ferry fleet, rather than a near-term solution.

Recent developments in the cargo sector, such as Maersk's ECOETA design, shed light on emerging marine technologies (new ammonia carriers set for 2026 delivery may have on board general engineering meshes for passenger ferries).

1.3.5 Hydrotreated Vegetable Oil (HVO)

Hydrotreated Vegetable Oil, often branded as renewable diesel, is rapidly emerging as a practical drop-in fuel for marine applications, particularly along coastal routes. Unlike many other low-carbon options, including conventional biofuels and liquefied natural gas, HVO sidesteps numerous logistical and regulatory hurdles, thereby enabling fleet operators to pursue immediate reductions in emissions (Krantz et al., 2023; EMSA, 2024a).

Environmental and Air Quality Benefits

Because HVO contains no sulfur, its use virtually eliminates sulfur oxides and significantly reduces particulate and nitrogen oxide emissions, without requiring the retention of existing diesel hardware (EMSA, 2024a; Sagin et al., 2023). When produced from certified sustainable feedstocks, lifecycle greenhouse gas emissions decrease by 60 to 90 percent compared to standard marine diesel, a reduction achieved without compromising cold-flow properties or thermal stability (EU RED II, 2018; IEA, 2023).

Lifecycle Emissions and Climate Considerations

Total well-to-wake savings remain sensitive to feedstock origin and certification: HVO made from residues or mixed wastes usually yields the most significant cuts, while fuels from energy crops may prompt indirect land-use changes and associated emissions. Under EU RED II, only documented waste-derived batches qualify for double-counting against the bloc's climate targets (EU RED II, 2018). HVO production pathways also tend to generate fewer fugitive emissions than liquefied gas or some alternative biofuels (IEA, 2023). Lifecycle performance hinges on feedstock (e.g., UCO vs. food-grade oils) and regional policy accounting; UCO-based HVO shows the most robust GHG reductions in recent LCAs (Krantz et al., 2023; Ajeeb et al., 2025).

Infrastructure and Retrofit Requirements

Storage systems, distribution lines, and bunkering equipment designed for conventional diesel can accommodate HVO with no expenditure on pumps, seals, or ventilation (Sagin et al., 2023). Likewise, vessels need no engine retrofits; operators can begin blending HVO into existing fuel streams and run today's engines with tomorrow's climate-friendly feedstock.

The plug-and-play nature of HVO means vessels can switch batches almost overnight, sidestepping the drawn-out retrofit periods and complex approvals that often undermine greener fuel strategies (EMSA, 2024a).

Regulatory and Economic Context

Regulatory and Economic Context Globally and under EU law, HVO is considered a fossil-equivalent diesel, yet it is permitted when supported by credible sustainability certificates (FuelEU Maritime, 2023; T&E, 2024). Its price sits slightly above that of traditional diesel, but carbon credits, plus forward-looking public-buying schemes, can close most of that gap. Analysts believe higher HVO demand could push jobs or cost parity with regular diesel into the early 2020s (IEA, 2023).

Relevance to Estonia's Ferry Fleet

For Estonia's busy coastal ferry network, HVO stands out as a fast and impactful path to lower net emissions, while avoiding the need for new bunkering docks or hull modifications (T&E, 2023; IEA, 2022). Because the fuel plugs into existing procurement logic, it suits state-run ships bound to fixed corridors. HVO also performs reliably in ice and sub-zero weather, eliminating the numerous challenges that cryogenic fuels still cause for crews and ports.

1.3.6 Biomethane

Biomethane (renewable natural gas) represents purified biogas produced mainly by anaerobic digestion of farm leftovers, wastewater sludge, and municipal food waste. In shipping, it serves as a near-zero-carbon alternative to LNG, seamlessly integrating into existing gas engines and bunkering systems. Estonia finds the fuel especially promising because local output is increasing, policy support is stable, and short-haul coastal ferries can readily utilize it (European Biogas Association [EBA], 2025; Mallouppas et al., 2023).

Environmental and Air Quality Benefits

Burning biomethane mimics fossil LNG; it emits almost no sulfur oxides, keeps NOx low, and releases virtually no particulates (Mallouppas et al., 2023). Its climate edge comes from a closed loop: methane that would otherwise leak from waste is captured and converted into fuel. When feedstock is managed well, some chains show net-negative lifecycle GHGs, showing that disposal mistakes can reverse progress (Boston Consulting Group [BCG], 2024).

Lifecycle Emissions and Climate Considerations

When manufactured from diverse waste feedstocks and upgraded according to current best practices, biomethane can deliver a reduction of more than ninety percent in well-to-wake greenhouse gas emissions compared with marine diesel. Unlike fossil LNG, which frequently suffers from methane slip during production, distribution, and combustion, biomethane can offset that leakage by preventing emissions at the feedstock stage (Zero Carbon Shipping, 2025). Modern two-stroke marine gas engines equipped with methane slip controls can reduce onboard emissions to below 0.2 percent, making biomethane one of the most climate-positive fuels available for deep-sea shipping. GHG reduction potential is highly sensitive to methane slip and upstream leakage; therefore, verified supply-chain control is decisive for achieving net reductions (Mallouppas et al., 2023; Krantz et al., 2023; Roux et al., 2024).

Infrastructure and Retrofit Requirements

Biomethane's principal advantage is technical neutrality: it seamlessly integrates into any LNG-ready vessel with no hardware modification required. Shore-side, the same bunkering, compression, and liquefaction terminals built for LNG receive and distribute it without costly modifications. Estonia's network is growing rapidly; by late 2024, Viljandimaa, Saaremaa, Pärnumaa, and Läänemaa will each have a new plant, increasing national capacity to over 120 million Nm3 per year (Invest Estonia, 2024). Meanwhile, the Estonian Biogas Association runs a central registry that tracks each batch and issues sustainability certificates to buyers (EBA, 2025).

Regulatory and Economic Context

Within FuelEU Maritime and RED II/III, biomethane is recognized via mass-balance and Guarantees of Origin/proofs of sustainability. FuelEU counts methane in lifecycle GHG and applies default slip/leak factors unless measured, so verified CH_4 control is critical for compliance. Over the mid-2020s and beyond, revenue certainty stems from the certificate value (biomethane/GO), ETS pass-through, and national support schemes; these instruments are evolving, but the principle is stable: compliance credit and cost advantage depend on sustainability documentation and measured methane performance, rather than the "drop-in" property alone.

Relevance to Estonia's Ferry Fleet

Estonia's ferry network, which serves short island routes with fixed timetables and frequent port turns, is an ideal match for biomethane's supply profile. The fuel's modular storage needs reduce dependency on large LNG shipments, thereby enhancing national energy resilience. A compressed-biomethane workboat, set to launch in 2025, will showcase this advantage as the first Baltic ferry powered by locally sourced CBG (Advanced Biofuels USA, 2025).

In contrast to liquefied biomethane (LBG), which is stored at a cryogenic temperature of –162°C, compressed biomethane gas (CBG) is stored at pressures of 200 to 250 bar in sturdy, pressurized tanks. This approach reduces energy losses that would otherwise occur during boil-off, simplifies logistics handling, and generally improves safety over the long term. Although CBG has a lower volumetric energy density than its liquefied counterpart, its advantages in ease of use and reduced capital outlay make it attractive for ferry corridors of up to about thirty nautical miles.

Table 1-3 CBG vs LBG for Estonian Ferry Deployment.

Criteria	CBG (Compressed)	LBG (Liquefied)
Storage Temperature	Ambient, 200–250 bar	–162 °C cryogenic
Infrastructure Cost	Lower (simpler tanks)	Higher (insulated tanks, boil-off systems)
Energy Density (volumetric)	~25% of diesel	~60% of diesel
Operational Complexity	Lower	Higher
Suitability for Short Routes	Excellent	Moderate (overqualified)
Cold-Climate Performance	Good	Good (if boil-off managed)
Fuel Source in Estonia	Widely available	Limited liquefaction capacity

Source: Compiled by the author from Mallouppas et al. (2023), EBA (2025), and Zero Carbon Shipping (2025).

Because most Estonian ferry routes stretch for less than twenty-five nautical miles, CBG delivers enough energy while also keeping costs and technical requirements low. Its adoption could be rolled out rapidly through mobile bunkering units fed from existing land-based refuelling stations, or via direct pipelined injection into storage tanks located at the port berth. Either option fits neatly within the existing infrastructure at Estonian harbours.

1.3.7 Battery-Electric and Hybrid Systems

Battery-electric (BE) and hybrid propulsion systems are increasingly recognized as effective and mature solutions for decarbonizing short-sea shipping. These systems deliver zero local emissions, reduced operational noise, and significant efficiency improvements compared to fossil-fuel-powered vessels Wang et al., 2021; Geertsma et al., 2017; Jeong et al., 2020; EMSA, 2023e). Their adoption is growing across Europe, particularly in Norway and Finland, and Estonia has already piloted hybrid retrofits in its public ferry fleet.

Environmental and Air Quality Benefits

BE systems eliminate all onboard emissions of SO_x, NO_x, CO_2, and particulate matter – benefiting densely populated coastal zones and marine ecosystems. Electric propulsion also reduces noise and vibration, enhancing wildlife protection and passenger comfort (IEA, 2022). When ferries are charged with renewable electricity, well-to-wake emissions approach zero. Estonia's grid incorporation of wind and solar (surpassing 30% in 2024) reinforces the business case (Elering, 2024).

Lifecycle Emissions and Climate Considerations

Lifecycle GHG emissions for electric propulsion systems can be up to 90% lower than those of diesel, assuming clean electricity usage. Battery production emissions, primarily from lithium-ion cells, amortize over 10–12 years and are offset by operational gains (IEA, 2022). However, the energy density of Li-ion batteries (≈100–180 Wh/kg) limits purely electric ferry range to about 10–15 NM (Lloyd's Register, 2023). In Estonia's winter, thermal regulation is essential to counter reduced battery performance (Fraunhofer ISI, 2023).

Infrastructure and Retrofit Requirements

Battery-electric ferries require high-capacity shore-side charging and grid upgrades. Retrofitting older ferries is challenging due to structural constraints, but hybrid systems with supplemental batteries offer an intermediate solution (Laasma et al., 2025). Plug-in hybrids enable partial electric operation during docking or peak efficiency phases. For instance, MV Tõll was retrofitted in 2019 with Corvus lithium-ion batteries, reducing diesel use by ~20% and enhancing docking emissions and handling (Ship Technology, 2019; MarineLink, 2019).

Regulatory and Economic Context

BE and hybrid systems qualify under FuelEU Maritime and can access national/EU funding via the Connecting Europe Facility and Green Transport Support instruments. Despite 25–40% higher upfront costs, operational savings through efficiency and maintenance remain significant (IEA, 2022). Battery prices continue to fall, and carbon pricing is improving cost competitiveness.

Relevance to Estonia's Ferry Fleet

Estonia's ferry network – comprising numerous island and coastal connections with high service frequency, fixed schedules, and relatively short route distances – makes it uniquely well suited for battery-electric and hybrid propulsion systems. These technological solutions offer immediate improvements in air quality, noise reduction, and operational cost savings, all of which are particularly valuable in the context of state-subsidized, publicly procured ferry services.

The conversion of MV Tõll in 2019 demonstrated that retrofitting existing diesel vessels with battery-hybrid systems is both technically and economically feasible. The successful deployment of Corvus lithium-ion batteries enabled the ferry to reduce diesel consumption by approximately 20%, while also significantly reducing noise and docking emissions. This pilot serves not only as a case study, but also as a scalable model for modernizing the entire national ferry fleet.

Given the structure of Estonia's maritime geography (short crossings such as Virtsu-Kuivastu (~4 NM), Rohuküla-Heltermaa (~12 NM), and Kihnu or Vormsi lines), most routes fall well within the effective range of current-generation hybrid or plug-in battery systems. Full electrification may not be immediately viable for every line due to energy storage limitations and cold-weather performance constraints, but hybridization offers a highly practical intermediate solution.

Moreover, many Estonian ferry ports are situated in municipalities with renewable energy ambitions and access to the grid, creating opportunities for establishing shore-side charging infrastructure. Grid integration would not only reduce fuel consumption but also enhance energy sovereignty by tying ferry operations into Estonia's growing wind and solar production capacity.

Looking forward, a nationwide hybridization strategy could be embedded in Estonia's national maritime and energy planning. This would include:

- Gradual retrofit programs prioritizing high-traffic routes.
- Installation of high-voltage shore power at key ports.
- Integration with smart grid and load balancing systems.
- Use of modular battery containers for operational flexibility.

Such a roadmap would align with EU Green Deal objectives, reduce GHG emissions in line with FuelEU Maritime targets, and enhance Estonia's leadership in clean Baltic Sea shipping. It would also provide predictability for domestic shipbuilders, operators, and technology providers, stimulating innovation and local economic growth.

In conclusion, hybrid-electric propulsion is not merely a pilot solution but a viable long-term strategy for decarbonizing Estonia's public ferry fleet. With proper investment in port electrification and vessel upgrade planning, Estonia could become a regional frontrunner in carbon-neutral short-sea shipping.

This thesis posits that hybrid propulsion systems (particularly diesel-electric configurations with battery integration) are central to Estonia's decarbonization architecture, rather than merely transitional. Their ability to balance operational redundancy, retrofit compatibility, emissions performance, and regulatory compliance under constrained infrastructure makes them uniquely suited for near- to mid-term deployment. This thesis, therefore, considers hybrid systems not only in their technological dimension but also as institutional and operational enablers of phased decarbonization. Their centrality is further examined in the techno-economic assessments presented in Section 3.3, and embedded into the strategic considerations and implementation scenarios detailed in Sections 5.1.2–5.1.3 and 5.3.

1.3.8 Comparative Summary of Fuels

Marine Diesel Oil (MDO) – a distillate marine fuel defined under ISO 8217:2024 (e.g., DMA/DMB grades) – serves as the baseline reference in this thesis for cost and emissions comparisons (ISO, 2024), however, its potential combination with carbon capture and storage (CCS) is not modelled due to significant scale, weight, and infrastructure constraints. While previous research, such as Lindstad et al. (cited in Article I), has suggested that the installation of carbon capture and storage (CCS) systems on fossil-fueled vessels could be an economically efficient method for reducing GHG emissions, potentially increasing costs by approximately 18% compared to conventional marine fuels, it is crucial to emphasize that this conclusion does not apply to the sub-5000 GT ferries that are the focus of this thesis. For small coastal ferries, integrating onboard CCS systems is technically unfeasible and economically unjustifiable under current conditions. The primary reasons for this exclusion are the significant volume and weight constraints of such systems, which would compromise vessel stability and passenger capacity, particularly in double-ended or island service vessels. Furthermore, Estonia currently lacks any infrastructure for offloading and transporting captured CO_2. Without such infrastructure, even CCS-equipped vessels would have no practical means of discharging captured emissions. Therefore, CCS systems are not included in the MCDA framework of this doctoral thesis, as the focus remains on feasible and genuinely low-emission solutions for the Estonian context.

Preliminary scoping for Estonia's sub-5,000 GT ferries indicates that integrating CCS is presently constrained by energy penalties, space/weight for capture and storage, and integration/safety complexity; detailed assessment is provided in Section 3.5 (Risso et al., 2023; Tavakoli et al., 2024; Ahmed et al., 2025).

The comparative evaluation of alternative fuels, synthesized in Table 1-4 and visualized in Figures 1 and 2, provides a semi-quantitative, context-specific overview of the technological and operational trade-offs involved in decarbonizing Estonia's coastal ferry fleet. This synthesis draws upon lifecycle assessment data, TRL mappings, regional infrastructure readiness, and operational feedback gathered from Estonian ferry operators and telemetric vessel logs (see Table 2-1; Laasma et al., 2025). The methodology, as laid out in Article III and structured in the thesis's integrated MCDA framework, assigns normalized 0–100 scores across six evaluation domains: GHG reduction potential, technology readiness level, cold-weather suitability, infrastructure compatibility, retrofit feasibility, and safety (Roux, 2024; Brynolf et al., 2014; Masum et al., 2023; Kanchiralla et al., 2022); EMSA, 2023c; see also Table 2-6).

Methanol and HVO emerge as strong near-term candidates, exhibiting consistently high scores across infrastructure, retrofit, and operational reliability, while still providing moderate to significant lifecycle GHG reduction. Biomethane, particularly in compressed form (CBG), scores highly in the Estonian context due to infrastructure compatibility, local production potential, and existing LNG vessel readiness (Table 2-1). Hydrogen and ammonia, despite their near-zero theoretical emissions and long-term potential, rank lower in current deployment feasibility due to unresolved safety, storage, and bunkering constraints. Battery-electric systems achieve excellent scores in the emissions and safety domains, but are constrained by range, charging infrastructure, and cold-weather energy degradation (see the technical evaluation matrix in Chapter 4).

To test the robustness of these rankings, a sensitivity analysis was conducted wherein the equal weighting of the six MCDA dimensions was rebalanced across three plausible procurement scenarios. In one scenario, emphasizing the ease and safety of retrofitting (priorities often seen in public sector acquisitions), HVO and methanol emerged as top choices due to their minimal integration barriers. A climate-maximization scenario, which favors lifecycle GHG reductions above all, shifted rankings in favor of hydrogen and ammonia, despite their current infrastructural deficits. Conversely, in a constrained-infrastructure scenario, biomethane ranked highest due to its use of existing LNG systems and growing local availability. These shifts underscore the flexible but sensitive nature of MCDA tools and demonstrate the necessity of tailoring weight matrices to project-specific constraints and objectives (Saaty, 2008; see Table 2-6).

This contextual adaptability becomes especially important when applying these insights to real procurement planning. For example, in a typical Estonian rural route replacement scenario (such as Munalaid-Kihnu or Laaksaare-Piirissaar, where route lengths are below 15 nm, ports lack cryogenic or high-voltage infrastructure, and year-round operability is mandatory), HVO emerges as the most viable solution due to its drop-in characteristics and cold-start reliability. Methanol may also be feasible given limited retrofit budgets and moderate infrastructure upgrades. On the other hand, for future-oriented green corridor routes, such as a possible EU-funded demonstrator between Rohuküla and Heltermaa, where shore-side electrification and zero-emission mandates are in place, battery-electric propulsion supported by renewable energy becomes the optimal solution. In such settings, hydrogen may also be considered, particularly in hybrid configurations or as part of broader state-subsidized innovation programs (European Commission, 2025; Table 2-1; Laasma et al., 2025).

These scenarios, informed by the comparative matrix and grounded in Estonia's actual route profiles and infrastructural constraints, illustrate how structured MCDA outcomes can guide complex maritime procurement decisions. They also bridge the gap between technical feasibility and strategic policy implementation, reinforcing the thesis's broader aim: to provide actionable, context-sensitive guidance for achieving cost-effective, scalable, and environmentally credible decarbonization of Estonia's public ferry fleet.

Table 1-4 Comparison of Alternative Fuels for Coastal Ferries.

Fuel Type	GHG Reduction (%)	Tech Readiness	Cold Suitability	Infrastructure Needs	Retrofit Potential
LNG	~20	High	High	Medium	Medium
Hydrogen	90–100	Medium	Low	Very High	Low
Ammonia	90–100	Medium	Medium	High	Low
Methanol	60–80	High	High	Medium	High
HVO	60–90	High	High	Low	Very High
Biomethane	70–90	Medium	Medium	Medium	High
Battery-Electric	100 (operational)	High	Low	Very High	Medium (newbuilds)

Source: Compiled by the author from peer-reviewed LCAs and official guidance, based on Laasma et al. (2024, 2025), Roux et al. (2024), Brynolf et al. (2014), Balcombe et al. (2019), ICCT (2023), EMSA (2023c), Sánchez et al. (2023), and Armstrong (2022).

Interpreting well-to-wake differences among candidate fuels in short-sea contexts benefits from measured operational datasets; a recent inland review highlights both the scarcity of real-world measurements and the value of standardized protocols, which this thesis reflects in its evidence standards. (Hörandner et al., 2024).

1.4 Regulatory Framework and Existing Practices

The regulatory environment governing maritime decarbonization has undergone a profound transformation over the past decade, evolving from aspirational goals into legally binding obligations across multiple governance levels. For coastal ferries (particularly those operated under public contracts or owned by national governments), this shift has direct implications not only for operational practices and fuel choices but also for long-term investment strategies, infrastructure development, and eligibility for funding mechanisms. While much of the regulatory focus has historically centered on ocean-going vessels exceeding 5,000 GT, smaller vessels are increasingly being drawn into the regulatory perimeter through indirect mechanisms, such as procurement criteria, emissions trading systems, and national climate legislation. Smaller fleets below common international thresholds are nonetheless affected indirectly via taxes, procurement rules, and funding eligibility embedded in national law and EU mechanisms.

At the international level, the regulatory cornerstone remains the International Maritime Organization (IMO), whose Revised GHG Strategy (2023) sets a target of net-zero greenhouse gas (GHG) emissions by around 2050, with intermediate goals of reducing total emissions by at least 20–30% by 2030 and 70–80% by 2040, compared to 2008 levels (IMO, 2023). The strategy also calls for zero- or near-zero-emission fuels to constitute at least 5–10% of international shipping's energy mix by 2030 (IMO, 2023 – 2023 IMO GHG Strategy).

In parallel, IMO is developing a mid-term "basket of measures" comprising a technical element (a goal-based marine-fuel WtW GHG-intensity standard) and an economic element (a pricing mechanism). Meanwhile, the MARPOL Annex VI, as adopted by MEPC.385(81); entry into force 1 Aug 2025 with early implementation from 1 Jan 2025, remains the principal legal instrument for pollution prevention from ships, and its recent amendments introduce tighter limits for nitrogen oxides, sulfur content, and GHG emissions (IMO, 2025).

To operationalize these goals, the IMO has adopted several regulatory tools:

- Energy Efficiency Design Index(EEDI) Design-stage efficiency index for new ships above 400 GT; phased in since 2013; indicates CO_2 per unit transport work at the design point.
- The Energy Efficiency Existing Ship Index (EEXI), mandatory from 2023 for ships above 400 GT, requires compliance with baseline energy performance standards.
- The Carbon Intensity Indicator (CII) rates ships on their operational efficiency (grams CO_2 per transport work) from A to E, with mandatory corrective actions for persistent underperformance.
- The Data Collection System (DCS) mandates annual fuel consumption reporting for ships above 5,000 GT, feeding into global benchmarking and regulatory refinement.

Source: IMO MARPOL Annex VI instruments – EEDI: MEPC.203(62) (2011); EEXI & CII: MEPC.328(76) (2021); DCS enhancements: MEPC.385(81) (2024); overview: 2023 IMO GHG Strategy.

However, these frameworks have limited direct applicability to most Estonian coastal ferries, which typically fall below 5,000 GT. Instead, regulatory influence is increasingly exercised at the European level. The EU Emissions Trading System (ETS), expanded to include maritime transport in 2024, applies directly to ships above 5,000 GT but indirectly affects smaller vessels through fuel price adjustments and national procurement criteria (European Commission, 2023a). Phase-in: 40% of 2024 verified emissions; 70% of 2025; 100% from 2026; CH_4 and N_2O included from 2026 (European Union, 2023). In parallel, the FuelEU Maritime Regulation, effective from 2025, mandates progressive reductions in the GHG intensity of energy used on board, with implementation pathways now being explored by member states for the inclusion of smaller public service fleets (European Commission, 2023b).

Further integration is achieved through the EU Monitoring, Reporting and Verification (MRV) Regulation, which harmonizes emissions accounting across EU voyages and is being aligned with IMO's DCS to facilitate compliance (European Commission, 2023c). The Renewable Energy Directive (RED III), also relevant, mandates that member states increase the share of renewable fuels in transport and includes marine fuels under advanced biofuel eligibility criteria (European Commission, 2023d).

Nationally, Estonia is advancing its Climate Resilient Economy Act, which introduces legally binding decarbonization pathways for all economic sectors, including maritime public transport. Early drafts indicate sectoral GHG reductions of 70% by 2040 and net-zero by 2050, with interim targets for state-owned transport services. Port regulations and safety frameworks are also evolving, although inconsistencies remain across bunkering, fuel handling, and emergency response procedures, particularly for novel fuels such as ammonia and hydrogen (Corvus Energy, 2024; EMSA, 2023d).

These multiple layers of regulation – some binding, others directional – can create uncertainty for ferry operators, especially when considering investments in alternative fuel systems. The absence of harmonized safety and classification standards for hydrogen and ammonia, for example, significantly complicates the design of vessels and the planning of port infrastructure. While the IGF Code (International Code of Safety for Ships using Gases or Other Low-Flashpoint Fuels) covers LNG and methanol, applications of ammonia and hydrogen remain in early-stage pilot regimes (DNV, 2023a; IMO, 2023).

One recent development with particular relevance for small nations is the emergence of Green Shipping Corridors, bi- or multilateral agreements between ports and governments aimed at accelerating the deployment of zero-emission routes. These corridors offer demonstrable value and often benefit from co-funding through EU innovation mechanisms, such as Horizon Europe or the Connecting Europe Facility (T&E, 2023).

The following table synthesizes the most relevant regulatory instruments for Estonian coastal ferries, summarizing their jurisdictional scope, target vessel types, implementation dates, strategic purpose, and practical implications for smaller maritime operators. This comparative overview helps clarify which frameworks have direct versus indirect effects and how they interact across governance levels.

Note on regulatory tonnage thresholds

Several instruments use different gross tonnage thresholds. IMO design/efficiency rules (EEDI/EEXI) apply from ≥400 GT; some IMO/EU reporting and carbon-pricing thresholds are set at ≥5000 GT (e.g., EU MRV/ETS and CII/MRV analogues), and certain national support schemes may start at ≥300 GT. This thesis focuses on Estonian coastal ferries mostly <5000 GT; therefore, global 5000 GT triggers affect them indirectly (prices, funding, technology choices), while 400 GT design/efficiency rules may apply directly to some vessels.

Table 1-5 Comparative Table of Regulatory Instruments.

Instrument	**Jurisdiction**	**Scope & Applicability**	**Start Year**	**Main Objective**	**Implications for Estonian Ferries**
IMO GHG Strategy (2023)	Global (IMO)	All ships (guiding); flag-state enforced	2023	Net-zero GHG by 2050	Sets global compliance tone; medium pressure
IMO Net-Zero Framework (2027, draft)	Global (IMO)	GHG fuel standard; pricing mechanism	2027 (est.)	Fuel GHG limit and global carbon pricing	Future-proofing is required for alternative fuels
MARPOL Annex VI	Global (IMO)	Mandatory GHG and air pollution limits	2005+	Prevent ship-based emissions	Basis for all emission regulations
EEDI	MO (MARPOL Annex VI, Ch. 4; MEPC.203(62))	Design-stage requirement for new ships ≥ 400 GT (ship-type baselines & reduction factors; ro-ro/ro-pax covered).	2013 (phased tightening thereafter)	Improve newbuild design efficiency – Attained EEDI (gCO_2 per capacity-distance) must meet Required EEDI	Newbuild or major conversion ≥ 400 GT; EEXI baselines limited immediate effect on current sub-5,000 GT vessels
EEXI	Global (IMO)	Ships ≥400 GT must meet efficiency thresholds	2023	Enforce energy performance in existing vessels	Some Estonian ferries affected; drives retrofitting
CII	Global (IMO)	Ships ≥5000 GT rated by CO_2 intensity (A-E)	2023	Benchmark and reduce operational GHG intensity	Indirect influence on small ferries
DCS	Global (IMO)	Fuel reporting for ships ≥5000 GT	2019	Data for global policy development	Sets reference points for future thresholds
IGF Code	Global (IMO/Class)	LNG/methanol covered; ammonia/hydrogen incomplete	ongoing	Safety protocols for low-flashpoint fuels	Safety framework incomplete for next-gen fuels
FuelEU Maritime	EU-wide	GHG intensity limits for energy on ships ≥5000 GT	2025	80% reduction in marine fuel GHG by 2050	Infrastructure and funding implications for smaller ferries

EU ETS (Maritime)	EU-wide	CO_2 quota obligations for ships ≥5000 GT; 100% intra-EU voyages / 50% extra-EU legs	CH_4 & N_2O from 2026; phase-in: 40% (2024) → 70% (2025) → 100% (2026)	Carbon pricing	Raises fuel costs; affects procurement logic
EU MRV	EU-wide	Reporting for EU-related voyages	2018+	Standardize GHG reporting	Operators must harmonize documentation
RED III Directive	EU-wide	Biofuel quotas for all transport, incl. marine	2024	Increase renewable energy in transport	Encourages HVO, biomethane in public ferries
Climate-Resilient Economy Act	National (Estonia)	Binding legal framework for climate neutrality	2025 (forthcoming)	Enforce ENMAK targets, define sectoral obligations	Will embed ferry decarbonization into national legal obligations
ENMAK 2035 (draft)	National (Estonia)	Climate and energy framework across all sectors	2024 (draft)	Establish national targets for renewables, storage, digitalization	Guides ferry decarbonization, supports integration with national energy strategy
TRAL 2021–2035	National (Estonia)	Strategic plan for all transport sectors, incl. maritime	2021	Sustainable, smart, and user-centric transport system	Provides strategic support for developing alternative fuel infrastructure in ports and reducing emissions in water transport
Port & Safety Regulation	Local/ National	Varies; governs fuel handling, storage	ongoing	Ensure safety of bunkering & emergency response	Fragmented implementation; cautious adoption of new fuels
Green Shipping Corridors	EU/Global	Voluntary agreements for zero-emission routes	2022+	Demonstrate feasibility of clean shipping	Estonia may pilot routes under EU funding initiatives

Source: Author's synthesis of IMO instruments (2023 GHG Strategy; MEPC.385(81); MSC.1/Circ.1621; MSC.1/Circ.1647; MSC.1/Circ.1687) and EU instruments (EU ETS extension; Regulation (EU) 2023/1805; Regulation (EU) 2015/757 as amended; Directive (EU) 2023/2413).

Since the early 2020s, the regulatory landscape for maritime decarbonization has undergone a significant shift, transitioning from non-binding EU and international targets to legally enforceable obligations at both the global and EU levels. Although Estonian coastal ferries under 5,000 gross tonnage are frequently exempt from headline instruments such as the EU Emissions Trading System and the IMO GHG Strategy, they still feel the ripple effects through rising fuel costs, changing procurement criteria, and the eligibility conditions attached to public innovation grants. By strategically aligning operations with evolving EU norms and participating in demonstration corridors such as the Green Shipping Corridor initiative, ferry operators can lower the perceived risk of future non-compliance, strengthen their license-to-operate with stakeholders, and gain access to comparatively cheaper project financing. To achieve widespread uptake of alternative fuels in small-vessel fleets, however, safety regulations, fuel quality standards, and technical certification procedures must be harmonized across jurisdictions.

1.4.1 Legal and Regulatory Gaps Concerning Non-Conventional Fuels

The decarbonization of short-sea shipping, therefore, hinges on the availability, technical viability, and regulatory acceptance of alternative fuels such as hydrogen, ammonia, and methanol. Although promising pilot projects are underway along the Baltic Sea and elsewhere, the regulatory framework remains uneven and fragmentary, especially for public-sector ferry operators that travel exclusively within national waters and under domestically issued permits.

International Fragmentation: Gaps in the IGF Code and IMO Guidance

The IMO has addressed the safe use of low-flashpoint fuels through the International Code of Safety for Ships using Gases or other Low-Flashpoint Fuels; however, critical provisions for non-conventional fuels still fall outside the IGF Code's scope because hydrogen, ammonia, and alcohols were not yet mature technologies at the time it was drafted.

The IGF Code originally factored LNG into its scope and later added methanol, yet its formal, mandatory rules still exclude hydrogen and ammonia as fuels (IMO, 2023). Ammonia's extreme toxicity and corrosiveness require ventilation, spill controls, and protective gear that exceed what most existing codes prescribe. Hydrogen, meanwhile, diffuses rapidly and ignites at very low energy, compelling ventilation, thermal insulation, and continuity in leak detection (IEA, 2023; EMSA, 2023).

In the absence of widely endorsed technical norms, most new vessels obtain permission only through one-off alternative design submissions. In Norway, for instance, the Maritime Authority's IC 1-2024 provides interim guidance; however, this pathway remains confined to national waters and is poorly aligned with other jurisdictions (Norwegian Maritime Authority, 2024). Consequently, builders face patchwork deadlines, owners shoulder higher liability, and the market at large is robbed of predictable, scalable solutions.

EU-Level Inertia and Sub-5000 GT Exclusion

The European Union has introduced a suite of climate policies aimed at shipping, including the FuelEU Maritime Regulation, a revised emissions trading scheme, and the Renewable Energy Directive III; however, most of these rules currently target ships larger than 5,000 gross tonnes. As a result, numerous short-sea and public-service ferries remain outside the formal scope, leaving their operators uncertain about the legal status of the new fuels they are considering and the safety codes that will eventually apply (European Commission, 2023a, 2023b, 2023d). That asymmetry encourages investments in alternative propulsion but does so in a regulatory patchwork marked by inconsistent safety standards.

Furthermore, while RED III encourages the use of blended renewable fuels, it does little to close the still-necessary gaps in bunkering safety procedures or in the classifications granted by different flag States. Because Member States each interpret and enforce the directives according to national law, a safety regime for ammonia or hydrogen can look very different at adjacent ports, causing delays and additional costs (EMSA, 2024a).

National Gaps in Estonia: Between Policy Intent and Operational Detail

Estonia's commitment to decarbonizing public transport is reflected in high-level strategies and public procurement criteria that reward low-carbon bids. Even so, the supporting rules, training programs, and testing facilities needed to manage hydrogen, ammonia, or advanced biofuels safely are still emerging, and pilot projects often move ahead with interim safety arrangements rather than fully binding codes.

As of early 2025, Estonia still lacks legally binding national standards for bunkering, vessel classification, or onboard safety tailored to hydrogen and ammonia, and emergency units in harbours work from incompatible guidance (CEN-CENELEC, 2025; EMSA, 2023a; EMSA, 2022). Although the country formally follows the EU maritime safety chain set out in Directive 2009/15/EC, practical alignment between Recognized Organizations (DNV, Lloyd's Register) and the Estonian Transport Administration is limited because both have scant hands-on experience with fuels other than LNG (Norwegian Maritime Authority, 2024). This regulatory backlog delays proactive rule-writing and leaves many smaller ports unprepared to service next-generation vessels using hydrogen or ammonia (IMO, 2025; EMSA, 2024).

Institutional Fragmentation and Operational Risks

Hydrogen deployment in Estonia is promoted under national energy programs and EU projects, such as BalticSeaH2. However, none of these high-level initiatives has yet produced enforceable safety criteria for ships, nor has it guided public buyers in drafting technical tenders. Consequently, the legal roadmap for alternative-fuel ferries remains patchy, providing designers and operators with no clear routes to approval, predictable access at ports, or dependable insurance coverage (Hydrogen Council, 2023). Absent harmonized rules backed by coordinated agencies, early adopters of non-conventional fuels (navigation companies, shipyards, and financial sponsors) are left carrying an uneven and excessive share of technical and financial risk.

The Estonian State Fleet (ESF; Riigilaevastik) is a state agency established in 2023 under the Ministry of Climate. ESF consolidates and manages the state's civilian vessels and owns/renews the state-owned small-island ferries, while contracted companies operate the ferry services themselves under public service contracts (e.g., TS Laevad; Kihnu Veeteed). Reliability and availability standards on the island routes are therefore specified in those contracts and enforced at the system level. Chapter 1.5 examines how lingering legal and governance ambiguities (especially around the ownership-operation split) affect the total cost of ownership (TCO) and the sequencing of future investments in ships and infrastructure.

1.4.2 Estonia's National Decarbonization Frameworks

At the time of writing, the ENMAK 2035 remains in draft form, under active public consultation and parliamentary review (Government of Estonia, 2024). Nevertheless, it offers the most transparent national roadmap to date for achieving climate neutrality by 2050, building on EU-level initiatives such as the Fit for 55 package (European Commission, 2021b). The strategy is structured around three pillars: energy security, affordability, and environmental sustainability. The forthcoming Climate-Resilient Economy Act is expected to formalize these targets and bind sectoral contributions, including from maritime operations (Government of Estonia, 2025). The decarbonization pathways proposed in this thesis (including hybrid systems, renewable fuel adoption, and shore-side electrification) align directly with ENMAK's cross-sectoral priorities.

Another national strategic document of importance is the Transport and Mobility Development Plan for 2021–2035 (TRAL) (Ministry of Climate, 2023a). This plan sets a general objective to create a smart, sustainable, and user-centric transportation and mobility system. The TRAL has a strong focus on the need to reduce greenhouse gas emissions related to transport, encompassing all modes of transport, including waterways. Of particular relevance to the decarbonization of ferries is the plan's noted effort to develop port infrastructure for alternative fuels, which includes shore-side electricity and clean fuels to be used in the future.

Alongside the more overarching national documents, a more precise strategic framework exists for the maritime industry in the form of the "Estonian Maritime Policy 2021–2035," also known as the Maritime White Paper (Ministry of Climate, 2023b). This document aims to ensure the competitiveness and long-term development of Estonian maritime affairs, identifying innovation, digitalization, and environmental sustainability as key contributors to achieving this goal. The White Paper frames the green transition as a means to increase the sector's added value and modernize the fleet.

Thus, it provides political and strategic support for the decarbonization of coastal ferries, framing it not simply as a requirement but as a potential advantage for Estonia's maritime economy.

Strategic objectives outlined in the Maritime White Paper are implemented through specific action plans, such as the Maritime and Water Programme for 2025–2028 (Ministry of Climate, 2024a). This programme, overseen by the Ministry of Climate, utilizes both national and EU budgets to finance tangible projects that enhance safety and sustainability in the maritime sector. It encompasses a diverse range of issues from marine safety to water quality, and also includes provisions aimed at facilitating green shipping and eco-friendly port construction. Therefore, this programme serves as the main instrument through which public spending is directed toward efforts supporting the achievement of decarbonization priorities, bridging policy aspirations with real-world action.

1.4.3 National Regulatory Instruments and Scope Limitations

Examining the integrated climate policy framework at the national level reveals some core policies that, while important for the maritime industry as a whole, have a more sophisticated relevance for the public ferry fleet. One such example is the planned modification of fairway dues, which takes effect in 2026. This modification implements fees with a negative correlation to emissions. This is a direct fiscal policy tool designed to facilitate and drive decarbonization within the broader shipping industry by reducing the operational costs of lower-emission vessels (Ministry of Climate, 2024b).

Nonetheless, this notable measure does not apply to the coastal ferries, which are the focal point of this thesis. As dictated by Estonia's Ports Act, vessels operating on a licensed domestic route with a public service obligation are not subject to fairway dues (Ports Act, 2024). This statutory exemption means that while the reform is a key climate initiative for commercial shipping, it creates no direct financial pressure or incentive for the public ferry fleet. This underlines a pivotal policy issue: There is no mechanism for wide tax-based market instruments to decarbonize Estonia's state-contracted ferries, and it is, therefore, more reliant on other targeted policy options like direct government funding, designated aid frameworks, or stringent environmental stipulations in publicly funded contracts.

1.5 Economic Impact and Challenges

The shift to a low-carbon ferry fleet in Estonia carries a broad set of economic consequences that run well beyond the upfront capital outlay. Fuel-price swings, new shore-side facilities, vessel-life efficiency, ever-changing regulations, and the hazards that come with tendering and buying advanced technologies all factor in. As the following sections show, the relative price appeal of greener fuels depends not only on Estonia's specific situation but also on dependable, long-term policy backing.

1.5.1 Investment Costs and Technology Maturity

Alternative drive trains-hybrid-electric, pure electric, hydrogen, ammonia, and biomethane-present a wide spectrum of expected capital costs. Hydrogen and ammonia rank near the top of that range, chiefly because their storage, dispensing, and safety systems are complex, especially on smaller hulls where space is tight (EMSA, 2024; Sanchez et al., 2023). By contrast, HVO and biomethane can slot into many older engines with minimal hardware change, yet their appeal fluctuates with feedstock availability (Xing et al., 2021; Balcombe et al., 2019; Mawanti et al., 2024).

Fully electric and hybrid solutions sit in between: their up-front bill is hefty, but under steady duty cycles, the quicker fuel savings and lower maintenance offset the investment in a relatively short time.

The phased adoption of hybrid technology on MV Tõll, which recorded noticeable fuel savings, confirms that such upgrades are practical in Estonia's maritime sector (Offshore Energy, 2020; Ship-Technology, 2019). Similar trials in Norway show that vessels can pay back the capital cost within four to eight years, provided electricity prices stay steady and port charging upgrades receive public funding (E-ferry Consortium; Danfoss, 2020).

1.5.2 Lifecycle Economics and Operational Costs

Lifecycle cost models, typically referred to as LCOE or TCO, expose sharp differences between fuel pathways. Battery-electric ferries incur low day-to-day expenses and demand very little upkeep, yet they depend on uninterrupted access to power at every homeport (Otsason & Tapaninen, 2023; Gopujkar et al., 2024). Methanol retains compatibility with current maritime engines, but delivers only modest tank-to-wake cuts; deep WtW reductions require bio- or e-methanol (Masum et al., 2023). Hydrogen and ammonia promise deep decarbonization, in principle, but their costs for production, transport, and high-pressure storage remain significant (IEA, 2023; EMSA, 2023d). These economic divides are dynamic: they shift with the market price of carbon under the EU Emissions Trading System and the stricter mandates anticipated in RED III, both of which analysts expect will gradually favour truly zero-emission fuels (European Commission, EU-ETS FAQ; Directive (EU) 2023/2413-RED III).

1.5.3 Infrastructure and Retrofit Constraints

Infrastructure and Retrofit Constraints: Readiness of port infrastructure continues to impede large-scale, cost-effective fuel transitions. For battery-electric operations, harbours need fixed high-capacity chargers, upgraded grid capacity, and management software that synchronises charging with vessel schedules.

Larger facilities such as Kuivastu and Virtsu now have most of the infrastructure they need under planning. Yet, many small or remote terminals, Ruhnu included, remain off the grid and would require costly upgrades for full electrification (Clean Energy for EU Islands – Ruhnu, 2024; ERR News, 2025; Enefit Green, 2018).

Hydrogen and ammonia still need completely new bunkering systems and bespoke safety regimes, so initial capital and day-to-day operation will both be heavier than for almost any current fuel. Biomethane and HVO can slot into existing LNG and diesel pipes, yet limited supply contracts and on-site storage space still hamper ports' ability to deliver them at scale (EMSA, 2024 – ammonia safety; EMSA, 2023 – hydrogen report). Uncertainties in procurement timelines, availability, and price can easily turn these assets into stranded capital that never pays back.

A concise overview of strategic flexibility is presented in the Results (Section 3.2).

1.6 Research Questions and Delimitations

This chapter states the central research question and explains how it is operationalized through four sub-questions and the study's delimitations. This dissertation asks a central question: how can Estonia phase in the decarbonization of its coastal ferry fleet in a cost-effective and technically credible way, while working within current infrastructure limits and regulatory uncertainty? To operationalize this, RQ1–RQ4 address, respectively: (i) the regulatory drivers and their implications; (ii) the comparative techno-economic and operational feasibility of alternative fuels and retrofit pathways under Estonian conditions; (iii) the verifiable emission-reduction potential of operational/digital optimization using telemetry; and (iv) an integrated, phased decision framework for route- and fleet-level implementation (see Table 1-6 below). The remainder of this section also states the delimitations: the analysis focuses on scheduled coastal ferry services in a cold-climate context; safety and reliability requirements are treated as binding constraints; and results are interpreted with reference to current EU/IMO regulations and available infrastructure.

Table 1-6 Research Questions.

RQ (full sentence)	Addressed in the thesis	Linked articles (ID – role)
RQ1. What regulatory drivers from the IMO, EU, and the Estonian climate and energy initiatives shape the transition pathways for Estonia's public ferry fleet?	Ch. 1 (framework §§1.3-1.5); Ch. 4 (policy constraints)	II – Core
RQ2. What are the comparative techno-economic and operational trade-offs of key alternative fuel options (H_2, NH_3, methanol, biomethane, HVO, electrification) under Estonian conditions?	Ch. 1 (criteria §§1.3–1.5); Ch. 3.3 (MCDA base & sensitivity)	I – Core; V – Supporting
RQ3. How can real-time operational optimization (telemetry, load modelling, adaptive routing) improve energy efficiency and enable low-emission technologies?	Ch. 1 (§§1.5); Ch. 3.4 (operational scenarios)	III – Core; IV – Supporting
RQ4. What integrated strategic framework for phased decarbonization supports context-sensitive decision-making for public ferry operations?	Ch. 3.5 (synthesis across publications); Ch. 5 (policy & procurement, esp. §5.3 phases)	I–III – Core; IV–V –Supporting

Each research question is addressed through a dedicated combination of methods, including document analysis, TRL assessment, lifecycle cost modeling, telemetry-based simulation, and multi-criteria decision analysis (MCDA), as summarized in Table 2-6.

Delimitations

This study focuses on Estonia's publicly owned or publicly procured coastal ferry services and excludes foreign services and vessels operating abroad. The analysis prioritizes retrofit and operational efficiency for existing ferries rather than the full naval-architectural design of newbuilds. Infrastructure readiness and policy compatibility are reviewed for decision relevance; however, no full lifecycle assessments of port/energy infrastructure build-out or detailed supply-chain logistics are performed. Broader socioeconomic impacts (e.g., regional development, job creation) are outside the scope, even though they can affect real-world implementation.

The analysis concentrates on available, near-term options for which there is credible evidence of deployability in an Estonian coastal-ferry context. Options that are still highly speculative are set aside. For clarity, "highly speculative" here means lacking a credible deployment timeline for Estonian coastal ferries and/or a demonstrable prototype at ferry scale. Technologies such as hydrogen and ammonia are therefore reviewed technically and considered in longer-term scenarios (post-2035), conditional on progress in safety rules, production, bunkering, and storage.

A detailed description of the study's delimitations and limitations is provided in Sub-Chapter 2.7, offering a transparent view of the research boundaries and inherent constraints.

1.7 Structure of the Thesis

This doctoral thesis is primarily based on three core scientific articles that form the foundation of the research and directly address the first three research questions. These core findings are contextualized and expanded by two supporting articles, which provide additional validation and nuance. The synthesis of all five publications allows the thesis to answer the final, overarching research question by developing an integrated strategic framework.

The articles are arranged in the following sequence:

Table 1-7 Articles Included in the Thesis.

No.	Role	Full title	Authors	Venue / Details	Year
I	Core	*Evaluation of Alternative Fuels for Coastal Ferries*	Laasma; Otsason; Tapaninen; Hilmola	Sustainability 14(24), 16841	2022
II	Core	*Decarbonising coastal ferries: case of the Estonian state fleet ferry*	Laasma; Otsason; Tapaninen; Hilmola	in: Eftestøl, Bask, Huemer (Eds.), Edward Elgar	2024
III	Core	*Data-Driven Propulsion Load Optimization: Reducing Fuel Consumption and Greenhouse Gas Emissions in Double-Ended Ferries*	Laasma; Aiken; Kasepõld; Hilmola; Tapaninen	Journal of Marine Science and Engineering 13(4), 688	2025
IV	Supporting	*Small Island Public Transport Service Levels: Operational Model for Estonia*	Hunt; Tapaninen; Palu; Laasma	TransNav 18(2), 315–322	2024
V	Supporting	*Comparative analysis of the alternative energy: Case of reducing GHG emissions of Estonian pilot fleet*	Otsason; Laasma; Gülmez; Kotta; Tapaninen.	Journal of Marine Science and Engineering 13(2), 305	2025

When these central and supportive pieces are analyzed together, the dissertation aims to develop a comprehensive plan for decarbonization that goes beyond what any single article can achieve. By pairing technical feasibility with current regulations and detailed real-world data, this framework provides policymakers with a clear, comprehensive pathway for greening Estonia’s coastal ferries.

1.8 Research Gap and Scientific Contribution of this Thesis

Although the decarbonization of shipping has become a significant research theme, the majority of studies have focused on alternative fuels and technological innovation for large ocean-going vessels. For example, Brynolf, Fridell, and Andersson (2014) conducted one of the first comparative assessments of LNG, biogas, methanol, and biomethanol, emphasizing their potential to reduce emissions but without addressing the operational realities of smaller ferries. Similarly, Acciaro, Ghiara, and Cusano (2014) examined energy management and governance aspects in the maritime sector, but again with limited relevance to the specific needs of ferries under 5000 GT.

As a result, significant gaps remain in the academic coverage of short-sea shipping and small ferries. Most international regulation also continues to prioritize large ocean-going vessels, reflecting their dominant share of global emissions and their direct inclusion in IMO frameworks. In contrast, ferries under 5000 GT (despite their essential role in regional mobility and island connectivity) have been much less studied and are often only indirectly affected by global climate policy. This has been highlighted in recent reviews as a persistent imbalance in both regulatory and scholarly contexts (Psaraftis, 2019; Vakili, Ren, & Lähteenmäki-Uutela, 2025; Kasepõld, Aiken, & Tapaninen, 2025, manuscript submitted for publication).

Vakili et al. (2025) demonstrate that short-sea and domestic shipping are frequently overlooked in global decarbonization pathways, even though they can be significant regional sources of emissions. Likewise, Kasepõld et al. (2025, submitted) demonstrate that small ferries are underrepresented across technological, operational, and regulatory research strands, resulting in significant knowledge gaps in both life-cycle assessments and operational optimization studies. Complementing this, Barreiro, Zaragoza, and Díaz-Casas (2022) highlight the limited integration of monitoring and optimization tools in ship decarbonization research, despite the potential for such approaches to provide substantial benefits for smaller vessels.

Complementing this, a 2024 systematic review of inland navigation documents how few studies report onboard GHG measurements and cautions that uncalibrated activity-based models may bias estimates at lower loads – further underlining the empirical gap this thesis addresses for small coastal ferries. (Hörandner et al., 2024).

Taken together, these studies reveal a structural research gap: small ferries are rarely studied systematically, their operational realities are poorly represented in comparative assessments, and their regulatory treatment remains secondary to that of larger ships. This dissertation is positioned precisely within that gap, aiming to bridge the distance between international decarbonization debates and the specific requirements of the Estonian state-owned ferry fleet. To clarify how the literature has prioritized different themes and how this thesis responds to them, Table 1-8 maps the main academic focus areas in ferry decarbonization against the specific treatment of these themes in this dissertation.

Table 1-8 Academic focus in ferry decarbonization literature and its treatment in this thesis.

Thematic Area	Share of Studies (%)	Addressed in This Thesis
Alternative Fuels	21%	Yes
Economic Feasibility	19%	Yes
Regulatory Frameworks	18%	Yes
Electrification	14%	Yes
Environmental/Social Impacts	14%	Partially
Operational Measures	11%	Yes
Hybrid Propulsion Systems	3%	Yes

Source: based on Kasepõld et al. (2025, manuscript submitted), and the author's analysis.

While Table 1-8 situates this dissertation within the broader academic literature, it is equally important to contextualize these debates in the Estonian case. International research frequently draws upon large-scale pilots in Norway, Denmark, or other regions with abundant renewable electricity and favorable geographies for electrification. However, such experiences are not directly transferable to Estonia, where ferries serve short but high-frequency island routes under strict public service obligations. These routes operate throughout the year, including in harsh winter conditions with ice, which place very different technical and economic demands on vessels.

The Estonian context, therefore, provides a unique testing ground for assessing the practical applicability of alternative fuels and technologies under colder climatic and regulatory conditions. Battery-electric solutions that perform well in mild climates may struggle in sub-zero temperatures, where increased heating loads and ice resistance lead to higher energy demands. LNG and advanced biofuels may offer near-term reductions, but they require costly infrastructure and raise questions of long-term sustainability. Other options, such as hydrogen or ammonia, are frequently discussed in international research but are still absent in the small-ferry segment, partly due to safety, storage, and cost barriers.

To ground this discussion, Table 1-9 presents the main public ferry routes in Estonia together with the technical characteristics of the vessels serving them. These operational details are essential for understanding both the limitations and the opportunities for decarbonization. The table illustrates how high service frequency, shallow waters, and ice-class requirements together shape the feasibility of different fuel pathways.

Table 1-9 Selected Estonian public ferry routes and vessel characteristics.

Route	Distance (nm)	Typical vessel GT	Ice-Class	Notes
Virtsu-Kuivastu	4	~4999	Yes	Highest frequency and load volume
Rohuküla-Heltermaa	12	~4999	Yes	Longest route with heavy demand
Sõru-Triigi	9	~999	Yes	Inter-island route, ice-prone
Munalaid-Kihnu	10	~999	Yes	Moderate exposure
Pärnu-Ruhnu	55	~170	No	Long route, no ice-class
Leppneeme-Kelnase	10	~139	Yes	Frequent wind, daily schedule
Laaksaare-Piirissaar	4.5	~236	No	Seasonal, shallow conditions
Rohuküla-Sviby (Vormsi)	5.4	~999	Yes	Regular ice conditions

Source: Compiled by the author.

While Table 1-9 provides the operational baseline for the Estonian case, a further question concerns the transferability of solutions across different contexts. Research often presents electrification, LNG, hydrogen, or biofuels as if they could be universally applied, but real-world constraints suggest otherwise. For example, the Norwegian experience with battery-electric ferries has been enabled by fjord geographies, abundant hydropower, and relatively mild winters – conditions that do not apply to the Baltic. Similarly, LNG pilots in Southern Europe cannot be directly replicated in Estonia, where bunkering infrastructure is lacking and ice conditions complicate operations.

A critical contribution of this dissertation is therefore to examine the contextual applicability of decarbonization solutions for small ferries. Rather than treating technologies in isolation, it compares their strengths and limitations across technical, economic, environmental, and governance dimensions in relation to Estonian ferry operations. This approach highlights where international best practices can be adopted, and where adaptations or alternative strategies are needed.

To synthesize these insights, Table 1-10 compares the contextual applicability of major decarbonization options for small ferries. This table indicates which solutions are realistic under Estonian conditions, which require significant adaptation, and which are unlikely to be feasible in the near future.

Table 1-10 Comparison of contextual applicability for small ferry decarbonization.

Region / Country	Common Constraints	Similarity to Estonia	Example Application
Åland Islands (Finland)	Ice, short routes, low population	High	Hybrid-electric vessels
Coastal British Columbia	Long distances, infrastructure gaps	Medium	Diesel-LNG retrofits
Vanuatu / Fiji	No winter, limited port power	Low	Solar-assisted electric ferries
Sweden Archipelago	Seasonal ice, shore power in parts	High	Shore-based electrification
Japan (Inland Sea)	Ageing fleet, high frequency demand	Medium	Methanol and LNG pilots

Source: Author's synthesis drawing on the Åland M/S Skarven electrification feasibility (Elomatic, 2023), Finferries' Elektra/Altera technical data (Finferries, 2017, 2023), BC Ferries' Spirit-class LNG conversion releases (BC Ferries, 2018, 2019), and SPC-GEM notes on solar systems on vessels in Vanuatu/Samoa (SPC-GEM,2025a, 2025b).

As evidenced by Tables 1-9, 1-10, and 1-11, the dissertation builds a bridge between international scholarship and the operational realities of a small state-owned fleet. By integrating international research with the Estonian case, the dissertation makes both academic and practical contributions.

Scientific Contribution

This dissertation makes its contribution in three interrelated areas:

1. Directive compliance – analyzing how small ferries, though often excluded from IMO and EU mechanisms, are indirectly affected by regulation through fuel prices, procurement rules, and funding eligibility. In particular, Estonia's forthcoming Climate Resilient Economy Act and National Energy and Climate Plan (ENMAK 2035) are shown to have direct implications for public ferry operations.
2. Alternative fuels – providing a comparative, life-cycle-based analysis of LNG, methanol, hydrogen, ammonia, biomethane, HVO, and hybrid-electric solutions under Baltic conditions. Previous research (e.g., Brynolf et al., 2014; Gilbert et al., 2018) provides the methodological base, while this dissertation contributes by tailoring the analysis to Estonia's short, high-frequency routes and cold-climate operational constraints.
3. Operational optimization - using telemetry and propulsion performance data to demonstrate realistic efficiency gains. Johnson et al. (2013) and Barreiro et al. (2022) emphasize the need for stronger integration of monitoring tools. This dissertation contributes empirical evidence from Estonian ferries, demonstrating how such data can reduce fuel use and emissions.

Beyond these thematic areas, the dissertation's originality lies in integrating them into a phased decarbonization framework (2025–2050) for Estonia's coastal ferry fleet.

This contribution is grounded in a set of peer-reviewed articles authored by the candidate (Laasma et al., 2022, 2023, 2024, 2025). These articles progressively developed the methodological framework:

- starting from comparative fuel assessments,
- then incorporating MCDA with increasing criteria,
- applying vessel telemetry for operational optimization,
- and finally synthesizing these findings into an integrated national decarbonization pathway.

By systematically building on this body of work, the dissertation extends academic debates on ferry decarbonization while providing practical guidance for policymakers and fleet managers in comparable maritime nations.

2 Methodology and Research Strategy

2.1 Theoretical Framework

This thesis is situated within the theoretical domain of socio-technical transitions, employing the Multi-Level Perspective (MLP) as its guiding framework to analyze the complex process of maritime decarbonization. MLP theory explains how deep-rooted, transformative changes occur through the interplay of three analytical levels: the socio-technical landscape (macro-level), the socio-technical regime (meso-level), and technological niches (micro-level) (Geels, 2002).

Within this research, the current Estonian ferry network functions as a socio-technical regime, a long-lasting arrangement shaped by fixed assets (diesel engines, quays), routine public-tender cycles, and standard operating procedures (Unruh, 2000). Such a regime, once in place, often fights against swift transformation. Challenging this stability are technological niches, such as alternative fuels and propulsion systems (such as hydrogen, battery-electric systems, and HVO) that are emerging as potentially disruptive innovations.

The pressure for this regime to change comes from the socio-technical landscape, which includes macro-level developments like the IMO's 2050 net-zero target, the EU's 'Fit for 55' climate package, and Estonia's existing and forthcoming climate and energy initiatives. These landscape pressures create "windows of opportunity" for niche innovations to gain momentum and potentially reconfigure the dominant regime. The selection of methods in this thesis (including MCDA, TRL assessments, and lifecycle analysis) aligns with this transition logic, enabling a systemic evaluation of how these niche technologies can be strategically integrated into the Estonian ferry regime under intense landscape pressure.

Although the MLP model offers a solid framework, the thesis acknowledges that it occasionally downplays the role of individuals and firms in steering change. To counter this gap, the study design deliberately tracks agency inside the regime itself. Article III focuses on how daily choices by ferry companies affect energy use, while Article II examines how procurement rules and policymakers exercise institutional agency. By linking big-picture structure with on-the-ground decisions, the project presents a richer, more nuanced understanding of the MLP, tracing both the constraints and opportunities that actors encounter as they shape the socio-technical order.

2.2 Logic of the Research Design

This examination of Estonian coastal ferries employs a sequential explanatory mixed-methods strategy to map feasible decarbonization pathways. Maritime regulation, emerging technology, and day-to-day operating conditions interact in ways that a single method struggles to capture. Therefore, a deliberate blend of qualitative and quantitative tools is brought together. Work unfolds in three ordered steps: first, an interpretive review of changing rules and fuel options; second, simulation and performance modelling for numerical appraisal; and third, integration of findings into practical recommendations.

The initial step centres on a qualitative survey of policy and technology, cataloguing current and forthcoming instruments (FuelEU Maritime, the Fit-for-55 package, and the Estonian climate and energy initiatives) that shape small-ferry propulsion choices. Insights from this review guide the construction of a detailed decision framework. Building on that foundation, a techno-economic assessment follows, applying multicriteria decision analysis (MCDA) to weigh the trade-offs among fuels based on maturity, cost, emissions, and operability in cold conditions.

To translate these evaluations into real-world guidance, the study advances to quantitative modeling. It draws on telemetry data collected from a typical double-ended Estonian ferry between 2022 and 2024, using that record to run targeted simulations of propulsion-system emission-reduction strategies. By pairing theory with actual operational patterns in this way, the analysis gains a firmer empirical foundation.

2.3 Sequential Mixed-Methods Workflow

The workflow (Refer to Figure 2-1 Sequential mixed-methods research workflow) moves from system-level understanding to empirical modeling in a fine-grained manner. To gain a system-level understanding, a cutting-edge regulatory and technological landscape is developed, utilizing primary documents such as legal texts and climate strategies, alongside academic works. Knowledge gained from interviews with industry experts and a review of scholarship on low-emission maritime technologies forms the basis of a multi-criteria decision analysis model for this study. Within that model, hydrogen is graded cautiously, awarding modest scores based on its maturity level, the availability of bunkering stations, and performance in ice-class service to guard against unwarranted optimism. Notably, while green hydrogen exhibits a favorable emission lifecycle profile over time, recent studies (DNV 2023b; IEA, 2024; ALBATTS 2022) have identified persistent issues surrounding the complexity of fuel storage systems, commercial-scale availability transitions, and unresolved safety regulations and rules governing the safety of fuels required during transportation. As a result, hydrogen had short-term feasibility due to its strong long-term potential for compliance vis-vis zero-emission market expectations. Instead of applying estimations to the entire Estonian fleet or using external datasets, this study focuses on one operational ferry and utilizes its granular operational data. The Vessmon (v. 300-05.000.01) Energy Monitoring System collected data on fuel consumption, propeller rotation, and outside conditions. This system was developed and installed by the Estonian shipbuilder Baltic Workboats (Nasva Harbor, Saaremaa, Estonia). This system enabled precise energy load modeling, which determined how different throttle settings, routing, weather conditions, and energy utilization interplay.

Those separate analyses are then merged into a single, integrated framework that assesses the practical financial, technical, and seasonal viability of each possible decarbonization route for Estonia. The conclusion presents a stepwise plan that matches national and European targets, underpinned by empirical data, and sets clear milestones for reducing GHG emissions.

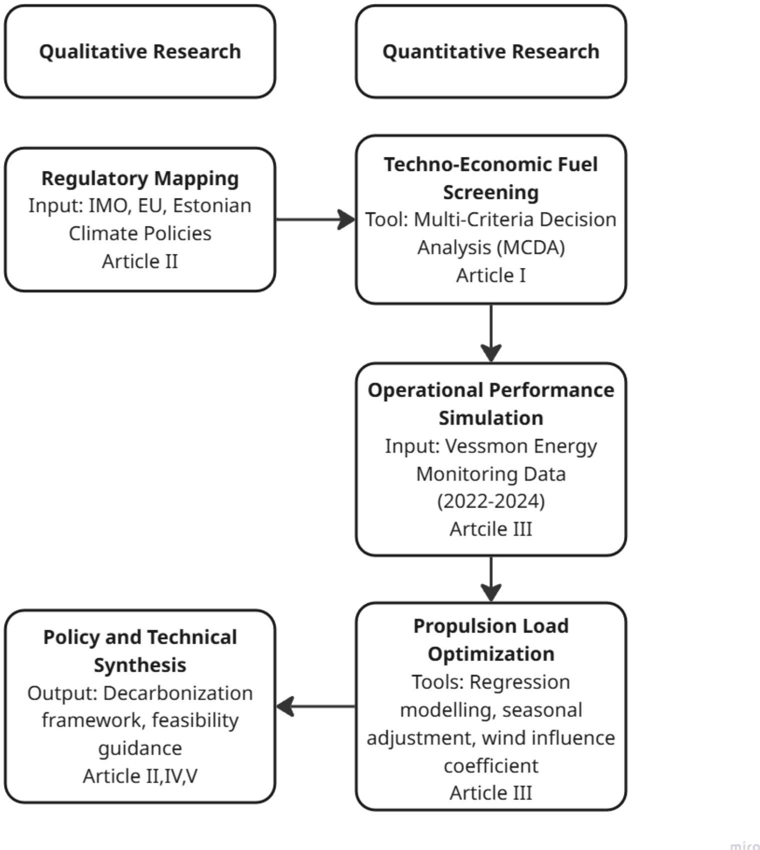

Figure 2-1 Sequential mixed-methods research workflow.
Source: Author's contribution.

2.4 Data Sources and Materials

To enhance rigor while capturing different contexts within a study's boundaries, diverse datasets are integrated, such as the telemetry dataset from an Estonian double-ended coastal ferry, as shown in the Table 2 summary of Data Sources Used in the Thesis. Such vessels are equipped with the Vessmon Energy Monitoring System, which captures propulsion metrics alongside fuel flow data, allowing for real-time monitoring of propulsion systems and consumption cycles. The multi-season dataset from 2022–2024 included winter ice performance periods, peak summer demand phases, and transitional shoulder seasons, providing comprehensive data variance. In addition to operational data, the research utilizes GREET 2021 as a data source to derive life-cycle emissions profiles for various fuels, thereby assessing their upstream environmental impacts. European Union and Estonian government policies provide the principal anchor for the regulatory framework. In contrast, peer-reviewed academic literature provides the empirical rationale and the methodological standards applied in this thesis. All telemetry and operational data were gathered specifically for this project, in partnership with the Estonian state ferry operator Kihnu Veeteed AS, during the 2022–2024 period. The resulting anonymized dataset has been validated internally and relies exclusively on original measurements, not secondary information.

Consultations were conducted with engineers from Baltic Workboats and personnel from Kihnu Veeteed AS who serve as subject matter experts. Their firsthand experience illuminated practical issues such as the limits of retrofitting, the performance of ice-class vessels, and other engineering constraints, all of which were integrated into the multi-criteria decision-analysis (MCDA) framework.

Alongside new survey data and analytical models, the study draws on numerous tables and figures (e.g., Article I, Tables 1 through 5, and Article II, Table 7.1) that are the author's own compilation or the authors' composition. These labels indicate that the material was synthesized and compiled from open-access databases, including Equasis and DNV Alternative Fuels Insight, as well as an extensive literature review and discussions with industry specialists, such as staff from the Estonian Maritime Academy and the Estonian State Fleet.

Such compilation involves qualitative assessment and structuring of data according to the criteria of this study, rather than the generation of new primary data.

Table 2-1 Summary of Data Sources Used in the Thesis.

Data Type	**Source**	**Purpose**
Vessel Operational Telemetry	Vessmon EMS (2022–2024), 1 Estonian ferry	Load optimization and propulsion modeling
Fuel Lifecycle Data	GREET 2021 model (Argonne National Laboratory)	Environmental performance of fuel alternatives
Regulatory Frameworks	FuelEU Maritime, Fit for 55, ENMAK 2035 (draft), Climate-Resilient Economy Act (forthcoming)	Policy scenario mapping, alignment with national climate strategy
Expert Feedback	Operators, shipyards, and naval architects	Validation of MCDA weights and criteria
Scientific Publications	Peer-reviewed academic literature (2013–2025)	Baseline information and results triangulation

Source: Author's elaboration based on telemetry and literature.

Among the policy sources consulted, the draft ENMAK 2035 provided essential national context, ensuring that the multi-criteria decision analysis (MCDA) and decarbonization scenarios were aligned with Estonia's evolving strategic energy priorities (Government of Estonia, 2024). The approach remained flexible, recognizing that both ENMAK and the Climate-Resilient Economy Act may undergo amendments before final adoption (Government of Estonia, 2025).

2.5 Analytical Tools

The research integrates both qualitative and quantitative methods to gain a comprehensive understanding of the decarbonization challenge. A multi-criteria decision analysis (MCDA) model was developed using a structured Excel-based framework. The model went through multiple iterations and internal calibration steps based on operational constraints, policy targets, and empirical data drawn from earlier fuel lifecycle and telemetry analyses (Laasma et al., 2022; Otsason et al., 2025).

In assessing alternative fuel and propulsion systems, the MCDA yields weighted scores for each option across six criteria: greenhouse-gas emissions, technology readiness, retrofit feasibility, cold-climate performance, infrastructure needs, and safety. By doing so, the framework provides a transparent view of the trade-offs between short-term implementation hurdles and longer-term climate gains.

These assessments were made under the "Technology Readiness" and "Cold-Weather Resilience" criteria in the MCDA model, which significantly impacted the weighted scoring of each fuel alternative. The readiness scale used follows standard TRL classification and draws from classification society reports (DNV, EMSA), supplier technical sheets, and known pilot projects.

To assess the relative importance of the six criteria within the MCDA framework – GHG reduction potential, technology readiness, retrofit feasibility, cold-weather resilience, infrastructure demand, and safety – a problem-centered weighting method was employed. This strategy aligns with established problem-structuring approaches in decision analysis, which are common when expert input is difficult to gather or varies widely (Belton & Stewart, 2002; Cinelli et al., 2021). Weights were established using a problem-structuring approach consistent with decision-analysis practice, combining literature-informed criteria, scenario runs, and alignment with binding policy constraints.

This follows established MCDA guidance on transparency, sensitivity testing, and context-specific weighting, and an analysis of binding legal and operational limits. The final weight set was designed to mirror the anticipated effect of each criterion on the successful roll-out of decarbonization for Estonia's coastal fleet.

The resulting weights (Table 2-2) reflect these foundational parameters. For instance, GHG Reduction Potential (30%) was assigned the highest weight as it directly corresponds to the central objective of this decarbonization framework and aligns with binding national and EU climate targets. In contrast, the lower relative weight for Safety (10%) does not imply it is of lesser importance. Rather, in this framework, safety is treated as a fundamental threshold criterion, or a non-negotiable "go/no-go" filter. Any technology not meeting a baseline level of established safety protocols was screened out prior to the comparative analysis. The significant weight for Cold-Weather Resilience (15%) directly addresses the unique and demanding operational context of the Baltic region, a key differentiator of this study. This strategic assignment of project-specific weights is consistent with standard MCDA practice, which allows for this approach when expert scores are difficult to obtain or show large variations (Belton & Stewart, 2002; Cinelli et al., 2014).

Table 2-2 MCDA Evaluation Criteria and Assigned Weights.

MCDA Evaluation Criterion	Assigned Weight (%)
GHG Reduction Potential	30
Technology Readiness	20
Retrofit Feasibility	15
Cold-Weather Resilience	15
Infrastructure Demand	10
Safety	10

Source: Author's elaboration based on Laasma et al. (2022), Otsason et al. (2025), Belton & Stewart (2002), and Cinelli et al. (2014).

While this structured process provides a defensible justification, an element of subjectivity is unavoidable in any weighting scheme. To explore this subjectivity and test the robustness of the findings, a comprehensive sensitivity analysis was conducted. This analysis moves beyond a simple two-scenario comparison to evaluate the performance of each technology under three distinct, plausible strategic viewpoints:

- The Policy-Driven Path: This scenario reflects the priorities of national and international regulators, assigning the highest weight to long-term GHG Reduction Potential to ensure alignment with binding climate targets.
- The Operator's Reality: This scenario models the perspective of a public ferry operator, prioritizing day-to-day operational reliability and risk mitigation. It assigns the highest weights to Retrofit Feasibility, Cold-Weather Resilience, and Safety.
- The Economic Case: This scenario represents the viewpoint of a public funder, aiming for the most cost-effective solutions. It prioritizes criteria that minimize public expenditure, such as Low Infrastructure Demand.

The specific weighting distributions for these three scenarios are detailed in Table 2-3. The resulting weighted scores for each technology under these scenarios are then presented in Table 2-4. This expanded analysis, based on the results in Table 2-4, allows for a more nuanced interpretation, highlighting not only which technologies are optimal under specific priorities but also which options prove to be robust contenders across multiple, competing strategic frameworks.

Each propulsion alternative (LNG, plug-in hybrid, battery-electric, HVO, green methanol, hydrogen, and biomethane) was assigned normalized scores on a 0–100 scale for six criteria, drawing on performance data from literature, prior lifecycle studies, and publicly available trials (Laasma et al., 2022; DNV, 2023a; SEA-LNG, 2024a).

Ranking outcomes proved sensitive to chosen weights, especially among midfield candidates. Under the baseline plug-in hybrids led, yet under the revised scheme, hydrogenated vegetable oil outpaced them. Hydrogen still showed strong long-run promise, yet its low readiness and heavy infrastructure cost kept scores modest in both tests. By contrast, biomethane remained a top contender across scenarios, thanks to its favourable retrofittability and solid lifecycle emissions record.

These findings highlight how essential transparent weighting is in multi-criteria assessments, especially in public-led procurements and fleet plans where stakeholder views differ widely.

Table 2-3 Weighting Schemes for Sensitivity Analysis Scenarios.

MCDA Criterion	Scenario 1: The Policy-Driven Path	Scenario 2: The Operator's Reality	Scenario 3: The Economic Case
GHG Reduction Potential	30	10	10
Technology Readiness	20	15	10
Retrofit Feasibility	15	30	20
Cold-Weather Resilience	15	25	10
Infrastructure Demand	10	10	40
Safety	10	10	10
TOTAL	100	100	100

Source: Author's elaboration, reflecting distinct stakeholder priorities for the sensitivity analysis.

Table 2-4 Resulting Weighted Scores from Sensitivity Analysis.

Technology / Fuel Option	Score (Policy-Driven)	Score (Operator's Reality)	Score (The Economic Case)
HVO	83.8	89.5	85.5
Biomethane	78.5	80.5	76.0
LNG	68.8	75.5	74.0
Methanol	65.8	68.8	56.5
Battery-Electric	70.0	62.5	52.0
Hydrogen	58.0	45.0	32.0

Source: Author's calculations based on the MCDA framework and weighting schemes in Table 2-3.

This dissertation proposes an integration of Technology Readiness Levels (TRLs) into the MCDA framework for assessing the technological readiness of systems based on alternative fuels and propulsion technologies. As defined by NASA and adopted by the European Commission in 2014 (European Commission, 2014; NASA, 2012), TRLs provide a universal metric ranging from TRL 1 (basic principles observed) to TRL 9 (actual system proven in operational environment).

The TRL values presented in Tables 4.1 to 4.7 are based on scientific literature rather than primary data collection. More recent technical evaluations conducted by classification societies such as DNV (2023a), EMSA (2024c), and IEA (2023) also served as footholds for more rigorous research. This method strengthens the accuracy of the provided TRL ratings with respect to maritime engineering pathways by reflecting consolidated specialist judgments regarding each energy pathway's technological progress.

As an illustration, HVO100 is labeled as TRL 9 because it is commercially used in maritime diesel engines, while ammonia and hydrogen propulsion technologies are given TRL values from 5 to 7, depending on their validation and limited use. These assessments were made under the "Technical Readiness" criterion in the MCDA model, which significantly impacted the weighted scoring of each fuel alternative.

With the inclusion of TRLs, the analysis remains aligned with Horizon 2020's method for evaluating emerging technologies and provides clarity and a solid foundation for Estonian coastal ferries' decarbonization pathway.

This thesis also applies life-cycle emissions assessment to alternative fuels in conjunction with technology maturity assessments for the evaluation of their environmental performance. Estimation of greenhouse gas emissions follows the Well-to-Wake (WtW) methodology, which includes upstream fuel production (Well-to-Tank) as well as the combustion onboard (Tank-to-Wake) processes. The calculation draws from emission factors and energy use data from GREET 2021: Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation, a model developed by Argonne National Laboratory (Argonne National Laboratory, 2021). The calculation draws from emission factors and energy use data from GREET 2021, as applied in the author's earlier publication (Laasma et al., 2022). No additional GREET modeling was conducted during the preparation of this dissertation. This model provides a consistent approach towards different fuel pathways because it quantifies CO_2-equivalent emissions. For some parameters, Estonia's electricity grid intensity, for example, regional data were used when possible to improve accuracy and relevance. The data derived was then integrated into the MCDA framework under the environmental impact parameter, enabling a comprehensive assessment of all fuel alternatives based on full life-cycle emissions analysis.

Signal processing, statistical analysis, and visualization of propulsion performance were conducted in conjunction with Python using its MATLAB-compatible libraries NumPy, SciPy, and matplotlib. For measuring the impact of AFT and FORE propulsion unit RPMs on fuel consumption, MLR models were developed. Seasonal effects were modeled with binary variables, while additional modifications incorporated a wind influence coefficient (WIC = $\cos(\theta)\cdot WS$) to account for headwind correction as discussed by Laasma et al. (2025).

The lowest decile of fuel consumption was used to isolate optimal propulsion configurations with percentile-based fuel use filtering techniques. From telemetry data, propulsion efficiency curves were derived, and fuel consumption under optimal conditions was simulated. This step required denoising, compensating for sensor drift, and external factors like ambient temperature and wave conditions.

Lifecycle emissions estimation is carried out using input parameters from GREET 2021. Where applicable, Estonia-specific emission factors (for example, electricity grid intensity) were employed to provide context. Actual bunkering and voyage logs served as the basis for model calibration, enabling a route-level impact assessment of alternative fuels or different propulsion strategies through identified potential savings.

Table 2-6 synthesizes the critical analytical elements of the thesis by integrating all foundational components into a holistic framework. It outlines the alignment of research questions, methodological steps undertaken, specific data sources utilized, and corresponding literature relevant to the study.

The MCDA weighting system was based on a literature-informed approach, drawing from international maritime decarbonization studies, complemented by sensitivity analyses where the relative importance of criteria (e.g., retrofit feasibility, climate benefit, safety) was varied across scenarios. While no formal stakeholder co-design was conducted, the sensitivity tests approximated public-sector and private-sector priority perspectives.

The assignment of weights within the MCDA framework followed a structured process combining quantitative data, literature review, and alignment with relevant policy frameworks. Specifically, the criteria and their weights were cross-checked against both international regulations (e.g., FuelEU Maritime, Fit for 55) and national strategies (e.g., ENMAK 2035 draft, Climate-Resilient Economy Act forthcoming) to ensure consistency with Estonia’s evolving energy and climate priorities (Government of Estonia, 2024; Government of Estonia, 2025). Quantitative targets, such as renewable energy shares or emissions reduction goals, were incorporated where available, while qualitative factors, such as digitalization priorities or policy emphasis on system flexibility, were addressed through expert judgement and sensitivity analyses. This approach ensured that the MCDA outputs reflect both technical feasibility and real-world policy constraints.

The approach reflects both technical feasibility and real-world policy constraints, cross-checking criteria and weights against FuelEU Maritime, Fit for 55, ENMAK 2035 (draft), and the forthcoming Climate-Resilient Economy Act.

2.6 Validity and Reliability

A dedicated focus on validity and reliability ensures the academic rigor and trustworthiness of the findings in this doctoral thesis. In this thesis, validity refers to the extent to which the methods and indicators accurately measure what they are intended to measure in the context of small-ferry decarbonization, and reliability refers to the consistency of results obtained by repeating the same procedures on comparable data. This study rigorously applies the principle of triangulation, which involves combining multiple independent methods, data sources, or theoretical perspectives to examine the same phenomenon. The primary aim of triangulation is to enhance the validity, reliability, and robustness of research outcomes, thereby reducing potential biases and strengthening the conclusions. As explicitly stated in the thesis, the entire approach is systematically supported by triangulation, using multiple data sources and analytical methods to ensure the validity and reliability of the findings.

Triangulation has been systematically implemented across several dimensions throughout this dissertation to ensure the robustness of the results:

- Methodological Triangulation: The study employs a sequential mixed-methods framework, integrating qualitative policy review with quantitative empirical modeling. This approach directly facilitates methodological triangulation, where diverse analytical techniques are used to confirm and validate findings. For instance, the Multi-Criteria Decision Analysis (MCDA) ranking of alternative fuels for coastal ferries (detailed in Article I) is based on life-cycle emission calculations (derived from the GREET 2021 model). These calculations are subsequently validated by expert feedback from operators, shipyards, and naval architects. Furthermore, the robustness of these findings is assessed through sensitivity analyses, varying key assumptions such as electricity prices, fuel availability scenarios, and emission factors. This multi-faceted assessment ensures that the alternative fuel evaluation does not rely on a single perspective but is cross-validated through various analytical standpoints.
- Data Source Triangulation: The dissertation leverages diverse data sources to corroborate results and provide a deeper understanding of the decarbonization challenge. For example:
  - Policy interpretations of international (IMO), European Union (EU), and national (Estonian Climate Resilient Economy Act, ENMAK) regulatory frameworks are derived from primary legal texts and climate strategies. These interpretations are then validated against multiple EU communications and national strategic documents to ensure consistency and plausibility.
  - Empirical operational telemetry data collected from Estonian double-ended ferries via the Vessmon Energy Monitoring System (presented in Article III) has undergone validation through static checks against onboard engine log records and manual review. This ensures the accuracy and real-world applicability of propulsion load optimization results.
  - Fuel life-cycle data from the GREET 2021 model (Article I) are integrated with Technology Readiness Level (TRL) mappings and operational feedback from the Estonian ferry. This provides a comprehensive environmental impact assessment that accounts for both theoretical potential and practical feasibility.

- Expert Triangulation (Indirectly, Investigator Triangulation): While direct investigator triangulation (involving multiple independent researchers analyzing the same dataset) is not separately detailed, the iterative process of technical consultations with maritime practitioners, including engineers, naval architects, and ferry operators, served as a crucial form of expert triangulation. This collaborative and iterative feedback process helped to corroborate underlying data, eliminate unrealistic parameters, and refine model parameter settings throughout the research.

This integrated approach significantly enhances the validity and robustness of the complex decision models presented in this dissertation. By triangulating qualitative assessments with quantitative modeling, particularly in domains where evidence may be incomplete or future conditions volatile, the study strengthens the trustworthiness and practical applicability of its decarbonization framework for Estonian coastal ferries. As reiterated in the conclusions, this "robust methodological approach, based on triangulation through multiple data sources and analytical methods, ensures the validity and reliability of the proposed framework," leading to context-sensitive and data-driven policy recommendations. Policy triangulation, expert consultation, and empirical telemetry analysis are all methods employed to validate the findings.

The data-driven modeling was based on vessel telemetry from the double-ended ferry Soela, covering multiple operational periods. While the models were internally validated using cross-period comparisons, external validation with additional vessels or routes was not conducted within this thesis and is identified as a future research need.

All figures and quantitative visualizations in this thesis were created using a combination of Microsoft Excel and Python 3.13 (matplotlib, pandas). Excel was used for data preparation and initial plotting, while Python scripts were applied to refine visual clarity, unify figure style, and generate more detailed graphics where needed. This dual-tool approach ensured that the visualizations aligned with the analytical framework of the research and met reproducibility and transparency standards outlined in the methodological design.

2.7 Limitations and Delimitations

This thesis acknowledges several important limitations and delimitations that define the boundaries of the research, inform the interpretation of results, and highlight areas for future work.

Time sensitivity and updateability

Maritime decarbonization is a fast-moving field: fuel prices, lifecycle datasets (e.g., CH_4 slip factors), and EU instruments (e.g., delegated acts under FuelEU Maritime, ETS parameters) are updated regularly. The figures and policy references in this chapter should be read as of September 2025; some may become outdated soon after submission. To mitigate this, assumptions are time-stamped, ranges and sensitivity analyses are reported, and conclusions emphasize direction-of-change and decision criteria rather than single-point estimates. Practitioners should re-run the MCDA with updated inputs for time-critical decisions.

Limitations

Despite its comprehensive approach, the study is subject to several inherent limitations.

First, the data sources used are constrained by availability and scope. While the analysis draws on operational data from Estonian state-owned coastal ferries, the dataset does not cover multi-year time series or include telemetry from all vessels in the fleet. As a result, some conclusions are based on partial or representative samples, and generalizations should be made cautiously.

Second, the multi-criteria decision analysis (MCDA) framework developed here uses weightings determined by the researcher, informed by literature review and expert consultation. However, the absence of formal stakeholder engagement, such as a Delphi panel or participatory workshops, limits the representativeness of these weights. While sensitivity analyses were conducted to test the robustness of the findings, the weighting process inevitably carries subjective elements.

Third, the modeling approach emphasizes simulation and scenario analysis, rather than direct experimental validation. For example, the performance of battery-electric and hydrogen systems under cold-climate Baltic conditions was assessed using published technical benchmarks, not real-world trials. The absence of pilot-scale demonstrations means that the estimates of energy efficiency, reliability, and operational challenges remain provisional.

Fourth, the economic assessment presented here focuses on capital and operational expenditures (CAPEX and OPEX) but does not incorporate the full range of market factors that could influence technology adoption. Carbon pricing, EU Emissions Trading System (ETS) dynamics, government subsidies, fuel price volatility, and financing mechanisms were deliberately excluded to keep the analysis technology-focused. As such, the cost figures should be read as indicative rather than predictive.

Fifth, although the study describes the methodological approach and tools used (including Python-based modeling and GREET life-cycle calculations) the underlying code and raw data are not provided as open-access materials. Full reproducibility would require access to proprietary datasets and software environments that fall outside the scope of this thesis.

Finally, the contextual focus on Estonia’s geographic, climatic, and regulatory environment constrains the transferability of results. While many findings may have relevance for other Baltic or Northern European ferry systems, caution is advised when applying them to settings with different operational profiles, vessel types, or governance structures.

Delimitations

The scope of this thesis was deliberately defined to maintain focus and feasibility.

The research is limited to Estonia’s coastal passenger ferries under 5,000 gross tonnage (GT) operating on domestic routes. Cargo ships, offshore vessels, private operators, and international services are outside the scope.

Only alternative fuels and propulsion technologies with a technology readiness level (TRL) of 5 or higher were included in the assessment. Early-stage experimental technologies, as well as fuels or systems lacking real-world deployments, were excluded to ensure practical relevance.

Carbon capture and storage (CCS) technologies were not considered. Although CCS has shown promise in large-scale shipping applications, its weight, space, and infrastructure requirements make it unsuitable for the smaller vessels studied here.

Environmental assessments focused primarily on well-to-wake (WtW) greenhouse gas emissions. Other environmental impacts, such as black carbon, nitrogen oxides (NOx), or particulate matter, were discussed qualitatively but not quantitatively modeled.

The regulatory and policy analysis was restricted to the EU, IMO, and Estonia’s national frameworks. Broader international or non-EU policy environments were not covered.

Implications

These limitations and delimitations are not weaknesses but rather guideposts that clarify what this thesis set out to achieve – and where further research is needed. Future work could include pilot-scale demonstrations under Baltic winter conditions, participatory MCDA development with industry and government stakeholders, expanded techno-economic modeling incorporating market dynamics, and cross-country comparative studies. By transparently defining its boundaries, this thesis aims to provide both a robust foundation for maritime decarbonization efforts in Estonia and a useful reference point for similar contexts elsewhere.

To provide a clear overview of the study's scope and boundaries, Table 2-5 summarizes the main elements included and excluded in the analysis, as well as the key limitations identified at the data, modeling, and interpretation levels. This summary helps situate the research within its practical context and offers readers a concise point of reference for understanding what was addressed, what was deliberately left outside the scope, and where the main constraints lie.

Table 2-5 Summary of Research Scope and Limitations.

Category	Included	Excluded
Vessel types	Coastal passenger ferries <5000 GT	Cargo vessels, offshore vessels, international routes
Fuels & technologies	TRL ≥5 fuels and technologies (e.g., HVO, biomethane, methanol, hybrid-electric)	Early-stage experimental fuels, CCS technologies
Operational scope	Domestic Estonian routes, fixed schedules	International routes, offshore or non-scheduled operations
Data limitations	Partial fleet data, literature-based estimates, GREET modeling outputs	Full fleet telemetry, multi-year datasets
Modeling limitations	MCDA with researcher-assigned weights, scenario-based simulations	Stakeholder-calibrated MCDA, full economic modeling (ETS, subsidies)

Source: Author's synthesis of research scope, methodological design, and limitations discussed in this thesis.

External validity is limited by the single-vessel telemetry base and the absence of out-of-sample validation on additional routes or hull forms. Results should therefore be interpreted as indicative for comparable Baltic short-sea contexts rather than universally generalizable. MCDA outcomes remain sensitive to criteria weights; sensitivity analyses are provided to bound this uncertainty.

2.8 Ethical and Data Governance Considerations

All data used in this project came from day-to-day work with the ferry operator and was stripped of names or IDs before any analysis. Anonymization to that standard means no crew-related, personally identifiable details linger in the dataset. Throughout the study, the author followed the ethical rules set by Tallinn University of Technology and stayed well within GDPR lines across Europe.

Data stewardship operated in alignment with established best practices for research data management. Sensitive datasets were stored in encrypted files, while all analytical outputs linked to documented scripts and parameter logs were made openly accessible to facilitate reproducibility. Because the study lacked human subjects and did not handle personal or classified information, formal ethical clearance was not deemed necessary.

Such measures collectively strengthen the scientific rigor, trustworthiness, and stability of the findings by addressing ethical considerations within a broad governance framework.

Alongside the wider ethical and data-governance standards upheld across this project, it should be acknowledged that several figures were generated with Python code written in collaboration with an external technician. The author personally examined every graphic to confirm that it faithfully depicts the findings and integrates smoothly into the analytical narrative. This assistance focused exclusively on refining visual clarity; neither the raw data, analytical procedures, nor final interpretations were influenced in any way.

Table 2-6 Integrated Methodological Framework for Thesis Alignment.

Methodological Step	**Corresponding Research Question**	**Main Goal**	**Data Sources & Tools**	**Validity and Ethical Considerations**	**Reference to Core Articles**
Regulatory and policy analysis (IMO/EU/Estonian)	1	Regulatory Mapping	IMO/EU documents, Estonian legislation	Triangulation with expert interviews	Article II
Multi-Criteria Decision Analysis (MCDA) for fuels	2	Alternative Fuels Assessment	Literature reviews, expert interviews	Peer review, stakeholder validation	Article I
Empirical data collection from ferry operations	3	Operational Optimization	Real-time operational data from ferries	Data validation, ethical compliance	Article III
Dynamic propulsion modeling with collected data	3	Operational Optimization	High-resolution operational data, R, Python	Sensitivity checks, model validation	Article III
Techno-economic analysis and optimization	2 & 4	Alternative Fuels & Framework Development	Cost databases, fuel data, MCDA tools	Cross-validation with industry standards	Articles I & III
Development of phased decarbonization framework	4	Phased Framework Development	Integrated findings from all analyses	Stakeholder consultations, iterative reviews	All Core Articles

Source: Compiled by the author based on the methodological workflow.

3 Results

This chapter reports what the thesis found. It brings together three strands: (i) route-level choices implied by the decision framework; (ii) fuel-pathway scores and viability assessments from the multi-criteria analysis; and (iii) measured effects from telemetry-based operational optimization. Each subsection is tied back to the research questions and the core publications that underpin the evidence. Where appropriate, we revisit the state-of-the-art figures introduced in Chapter 1 and show how the results sharpen or revise those baselines.

To make the chain from research questions to answers explicit, Table 3-1 links each RQ to the contributing publications and the core empirical or analytical findings they supply. This table is intended as a reading guide to the rest of the Results section.

Table 3-1 Map from research questions to publications, evidence, key findings, and implications.

RQ	Publications (as listed in thesis)	Evidence / Method (as defined in thesis)	Key finding (from thesis text)	Decision-relevant implication (from thesis text)
RQ1. Regulatory drivers shaping transition pathways	II – Core; contributes to RQ4	Regulatory/policy analysis of IMO, EU, and Estonia; mapped in the methodological framework (Table 2-6).	Mapping shows where high-level ambition collides with procurement logic and infrastructure readiness; misalignments slow uptake.	Tie decarbonization steps to procurement and port upgrades; use EU instruments (e.g., CEF/RRF) to de-risk first movers; feed the strategic framework in Ch. 4.
RQ2. Techno-economic & operational trade-offs of fuels	I – Core; V – Supporting; contributes to RQ4	MCDA of fuel pathways; TRL/LCA inputs; criteria/weights and framework per Table 2-6.	Thesis synthesis: hybrid-/fully-electric are viable; LNG is a transitional option; H_2, NH_3, and biomethane are promising but face notable constraints in the case context.	Prioritise short-route electrification/hybrids where shore power allows; prepare selective pilots for prospective fuels aligned with safety/bunkering timelines in Ch. 4.
RQ3. Operational optimization via telemetry	III – Core; IV – Supporting	High-resolution ferry telemetry; modelling/simulation; results summarised in Table 3-2.	Data-driven load management and seasonal tuning yield measurable reductions (see Table 3-2 ranges) and can be rolled out quickly.	Implement EMS-based SOPs and dashboards fleet-wide as a low-CAPEX first step; treat optimization as a bridge to later fuel shifts.

RQ4. Integrated phased framework for decision-making	I–III – Core; IV–V – Supporting	Synthesis of MCDA + telemetry + regulatory mapping into a phased roadmap (Sec. 4.4–4.6); alignment shown in Table 2-6.	The thesis delivers a route-level, phased pathway (2025–2050) that sequences operational wins and hybrids ahead of prospective fuels, in line with policy and port capacity.	Use the roadmap as a procurement playbook: sequence shore power → hybrids/biofuels → methanol/H_2 where/when codes and bunkering mature; pair with institutional actions in Sec. 4.7.

Source: Author's synthesis from the Research Questions table, Integrated Methodological Framework, and Comprehensive Summary of Thesis Publications.

3.1 Key Results at a Glance

The study examined a range of questions governing the maritime sector#s green transition, with a specific lens on Estonian coastal routes. A consistent conclusion across multiple datasets is that diesel-electric hybrids and full battery-electric drive systems are not only feasible but also advantageous; these options can be rolled out swiftly, carry positive economic metrics, and deliver clear environmental gains. LNG, once hailed as a game-changing bridge technology, now appears mainly transitional, chiefly because methane slip erodes its climate credentials by releasing unburned gas during operation. In this thesis, LNG is rated Moderate for small, ice-class coastal ferries. While engines, storage, and bunkering are mature in large-ship segments, scaling these solutions to sub-5,000 GT ferries in Baltic winter conditions is constrained by methane-slip mitigation, retrofit space/weight penalties, and local bunkering availability. These factors justify a "moderate" rating in this use-case, despite higher maturity in other segments.

The investigation further considered hydrogen, ammonia, and biomethane as alternative marine fuels. Each option clearly offers pathways to cut emissions and could support medium-to-long-lived ferry fleets. Nevertheless, scholarly reviews increasingly argue that none will likely enter service in the next five years because of safety worries, patchy refuelling networks, and undeveloped technology maturity (DNV 2023a, IEA 2024, T&E 2023). Other assessments place current maritime hydrogen systems at TRL 5–7, pointing to isolated pilot projects and outstanding policy gaps that block regulatory approval and affordable vessel designs (FuelEU Maritime Assessment 2023; Lloyds Register, 2024). These observations make it plain that extensive permits, consistent safety codes, and large infrastructure capital must precede hydrogen becoming a realistic near-term choice for coastal ferry operations.

Advanced telemetry analysis enables real-time data acquisition, thereby enabling dynamic optimization of propulsion systems as well as ferry operations. Predictive modeling allows operations to fine-tune strategies in real-time, resulting in propulsion system optimization. Such novel operational techniques minimize fuel consumption as well as other emissions drastically while improving operational expenditure because they deliver immediate benefits without extensive infrastructural alterations.

Emissions, fuel availability, and suitability for ice navigation are some criteria captured in Table 3-2 which summarizes the alternative fuel comparison evaluation.

Table 3-2 Summary of Alternative Fuels Assessment.

Fuel Type	Technical Readiness	Emission Reduction	Economic Feasibility	Ice Navigation
Hybrid/Electric	High	Excellent	Moderate	High
LNG	Moderate	Moderate	Good	Good
Hydrogen	Moderate	High	Low	Moderate
Ammonia	Low	High	Low	Moderate
HVO	High	Moderate	Moderate	Good
Biomethane	Moderate	High	Moderate	Moderate

Source: Author's synthesis from articles I–III.

3.2 Strategic Flexibility and MCDA Findings

This section consolidates the thesis's own decision-support outputs and therefore sits within the Results. It translates route profiles and infrastructure realities into fuel-and-propulsion choices that work in practice, rather than in principle. The core message is that no single option dominates across Estonia's network; instead, battery-electric and hybrid systems excel on short, frequent legs with dependable shore power, while drop-in fuels can bridge gaps where port-side logistics exist. On longer or heavier routes, hydrogen and ammonia remain prospective options contingent on advances in safety, bunkering, and storage. These conclusions build directly on the MCDA framework developed for the thesis and are quantified further below.

The wide range of loading patterns and seasonal demand across Estonia's ferry network, from the rapid Virtsu-Kuivastu shuttle to the longer Sõru-Triigi and Ruhnu-Pärnu routes, prompts authorities to consider distinct fuel choices. The decision framework defined here (applied in Chapter 4) indicates that no single option dominates every route. Battery-electric or hybrid systems perform best on short, frequent legs with dependable grid access (Wang et al., 2021; Geertsma et al., 2017; EMSA, 2020). Green methanol and HVO are credible interim fuels where port-side logistics already exist (Ammar & Seddiek, 2019; Krantz et al., 2023; ICCT, 2023). Hydrogen or ammonia could be suitable for longer or heavier ferries later, provided cost and safety barriers are addressed (EMSA, 2023; EMSA, 2024; CEN-CENELEC, 2025; IMO MSC.1/Circ.1687, 2025). In parallel, digital load forecasting and telemetry-based scheduling can increase fuel productivity by up to 10–15% on average (case-dependent) (Du et al., 2022; Krata & Szlapczyńska, 2018; Artyszuk & Zalewski, 2021; Vergara et al., 2023). Such measures are growing ever more critical as the ferry sector faces tighter budgets and uncertainty in demand.

This synthesis aligns with the thematic findings summarized in Table 3-3, which captures how economic feasibility, regulatory frameworks, and operational integration remain underrepresented in the ferry decarbonization literature – areas this thesis directly addresses.

Table 3-3 Thematic Coverage of Ferry Decarbonization Literature in This Thesis.

Fuel Type	Advantages	Challenges	Citation
Hydrogen	Zero-carbon at point of use (fuel cells); high specific energy by mass	Low volumetric energy density, high production/storage cost, infrastructure gaps; most suitable for short-sea/short routes	(EMSA, 2023; Xing et al., 2021)
Methanol	Lower emissions vs. VLSFO; compatible with existing engines/retrofits	Fossil methanol still emits CO_2; deep WtW cuts require bio- or e-methanol	(Ammar & Seddiek, 2019; ICCT, 2023)
Ammonia	Carbon-free combustion potential; global industrial supply chains exist	Toxicity; combustion/NOx challenges; safety & bunkering infrastructure needs	(EMSA, 2024; Machaj et al., 2022)
HVO	Drop-in fuel; significant life-cycle reduction possible (esp. UCO-based)	Not zero-carbon; feedstock/ILUC constraints; availability limits	(Krantz et al., 2023; ICCT, 2023)
Biomethane	Renewable; compatible with existing LNG engines/infrastructure	Limited sustainable supply; methane slip and upstream leakage risks; costs	(Mallouppas & Yfantis, 2023; Roux et al., 2024)

Source: Comparative statements synthesised from peer-reviewed reviews and official guidance: EMSA (2021, 2023, 2024); Xing et al. (2021); Ammar & Seddiek (2019); ICCT (2023); Krantz et al. (2023); Mallouppas & Yfantis (2023); Roux et al. (2024).

3.2.1 Public Procurement and Investment Risk

This subsection reports thesis-derived findings on how procurement rules and capital-risk allocation shape feasible decarbonization choices on Estonia’s routes. The emphasis is on evidence from the thesis’s MCDA outputs and publication-based case material, rather than general legal background. Where relevant, we point back to Chapter 1 for regulatory context and forward to Chapter 5 for actionable recommendations.

Estonia has shown ambition in draft laws like the Climate Resilient Economy Act of 2025, but binding targets and shared funding rules that protect early investors are still absent. Until such frameworks appear, ferry firms carry the full weight of high up-front bills, uncertain eligibility for state grants, and the risk that newly purchased vessels arrive before the necessary shore power is ready (Laasma et al., 2024).

Tendering practices still fixate on the lowest initial bid and usually ignore total emissions over each asset’s life, meaning operators naturally choose proven hardware rather than the disruptive technologies that a green transition actually needs.

By contrast, Norway has built procurement rules that weigh entire lifecycle emissions and accept the higher up-front cost of zero-emission ferries (Bach et al., 2020). Without similar levers, Estonia may watch its own climate targets lag while rivals deploy greener tech faster.

In an effort to mitigate ecological hazards and motivate private capital toward greener shipping, the State has rolled out preliminary, tangible support initiatives. Central to this push is the Environmental Investment Centre (KIK) programme, initiated in 2024, which finances upgrades that reduce emissions from the commercial fleet (Environmental Investment Centre, 2024). Funds can be directed towards retrofits, such as hybrid propulsion packages, LED lighting, improved hull paints, and wastewater treatment units that cut fuel burn and formal effluent releases. Still, access is limited: only vessels with a gross tonnage of 300 tonnes and above are eligible, and applicants must be private legal entities. This means that TS Laevad OÜ, which operates ferries on the main island corridors, can submit a proposal. Yet, the Estonian State Fleet (Riigilaevastik), owner of several smaller public ships, is left outside the scheme (Environmental Investment Centre, 2024). Despite these exclusions, the KIK initiative unequivocally signals the government's readiness to use fiscal tools for decarbonization, and it sets a benchmark that could, over time, be extended to include additional state-owned craft.

3.3 Multi-Criteria Evaluation of Alternative Marine Fuels

This subsection reports the thesis's fuel-pathway scores and viability assessments as derived from the MCDA model and supporting literature, updated to 2024–2025 where applicable. The focus here is on the measured trade-offs among greenhouse-gas reductions, retrofit feasibility, cold-climate performance, infrastructure needs, safety, and technology readiness.

This subsection presents a structured evaluation of key alternative marine fuels and propulsion systems for coastal ferries, including hydrogen, methanol, ammonia, hydrotreated vegetable oil (HVO), biomethane, liquefied natural gas (LNG), and battery-electric/shore-side electricity systems. Each option is assessed based on a comprehensive set of criteria: greenhouse gas (GHG) reduction potential, technology readiness, cold-weather suitability, infrastructure demands, retrofit feasibility, and safety. A notable gap in this thesis is that while marine diesel oil (MDO) is thoroughly considered as the conventional benchmark fuel for multi-criteria comparison analysis, it is not critically analyzed as a fossil-derived fuel with its own lifecycle environmental and technological eco-footprint. It is taken for granted rather than analyzed, despite being commonly adopted within the Estonian coastal ferry and pilot boat fleets. It is important to note that in this doctoral thesis, marine diesel oil (MDO) has primarily been treated as a reference fuel, against which the GHG emission reduction potential of alternative fuels is assessed, rather than as an active decarbonization solution. Therefore, a detailed analysis of MDO's lifecycle impact is not the focus of this work, which is directed towards researching new, low-emission solutions.

In the wider decarbonization literature, MDO is progressively more recognized not as a sustainable long-term option, but as a borderline transitional fuel incompatible with both IMO and EU targets on greenhouse gas reduction. The comparison disproportionately favors non-fossil-based propulsion without a targeted evaluation of MDO's climate impact.

Additionally, although there is theoretical promise in the mitigation pathway of carbon capture and storage (CCS), the application of onboard CCS on small vessels such as coastal ferries faces numerous practical challenges. Laasma et al. (2024) note that the adaptation of CCS to MDO-fueled ships increases CAPEX and OPEX by over 18% relative to baseline efficiency. This increase stems from the expenditures associated with additional equipment and energy necessary for CO_2 separation, as well as separate storage facilities. Most importantly, these estimates are based on capturing 70 to 90% emissions – within ideal conditions – not zero emissions.

Jeongmin Lee et al. (2024) further elaborate that for vessels under approximately 1000 GT, the mass, volume, and energetic cost associated with adding CCS systems make them impractical. For these vessels, space restrictions coupled with short route durations do not allow for economies of scale sufficient to make CCS efficient or enable small port infrastructures to offload and transport the captured CO_2.

Lastly, focusing on the entire life cycle, as done by Xing et al. (2021), shows that exhaust emission captures do not solve the fossil fuel extraction, refining, and marine logistics carbon footprint; hence, MDO+CCS cannot be labeled “climate neutral.”

Considering the combination of all constraints (such as technological, economic, logistical, and lifecycle considerations), this thesis does not incorporate MDO+CCS scenarios into its MCDA framework. Instead, attention is given to more achievable and truly low-emission options. However, future studies could investigate pilot projects along with policy frameworks that would allow CCS modifications for small vessels in favorable regulatory conditions.

Cold-weather performance assessments were derived from peer-reviewed studies and technology reports (e.g., DNV, 2023a; Mayanti et al., 2024), focusing on system-level technical parameters under subzero conditions. No empirical winter field trials were conducted in Estonia; therefore, the cold-weather scores reflect modeled and literature-based performance estimates.

3.3.1 Hydrogen – Technical and Deployment Viability Assessment

Hydrogen holds a significant position within long-term strategies for decarbonization of maritime activities owing to its zero-carbon burning profile. Its inclusion in the strategic deployment phase (post-2035) reflects the policy ambition to achieve full decarbonization, acknowledging the need for significant advancements in R&D, safety standards, and infrastructure. However, the application potential in short-sea and ice-class ferries is limited due to underdeveloped technologies and storage issues. Despite these challenges, pilot projects demonstrating hydrogen’s potential are already underway, such as the MF Hydra in Norway, the world’s first hydrogen-operated ferry. The following table collates barriers and enabling conditions from recent evaluations.

Table 3-4 Hydrogen – Technical and Deployment Viability Assessment (2024–2025).

Dimension	Status (2024)	Implication	Source
Technical Maturity	TRL 5–7	Not fully ready for commercial deployment	DNV (2023b), Lloyd’s (2024)
Storage & Safety	High-pressure/cryogenic	Expensive & space-intensive	IEA (2024), FuelEU (2023)
Bunkering Infrastructure	Pilot projects only	Inadequate for consistent operations	T&E (2023), EMSA (2022)
Cost vs Diesel	3–6× higher	Economic barriers without subsidies	Hydrogen Council
Regulatory Certainty	Partial	Requires harmonized maritime standards	Lloyd’s Register (2024)

Source: Author’s calculations based on MCDA and scenario modeling.

3.3.2 Methanol – Technical and Deployment Viability Assessment

Methanol is an alternative that has been gaining traction because of its global supply chain, simpler storage, and the opportunity to reduce GHG emissions partially when sourced from renewables. Its use in Estonian ferries may be advantageous because of the ease of achieving compatibility and the minor adjustments needed for conventional engines.

Table 3-5 Methanol – Technical and Deployment Viability Assessment (2024–2025).

Dimension	Status (2024)	Implication	Source
Technical Maturity	TRL 8–9	Deployable with minor engine modifications	Park et al. (2024)
Supply Chain	Commercial availability	Infrastructure exists in several ports	EMSA (2023c)
Emission Profile	Moderate (non-zero CO_2)	Depends on renewable source input	IEA (2023)
Safety & Toxicity	Low-moderate	Safer than ammonia/hydrogen	ABS (2022)
Cost vs Diesel	1.5–2× higher	Competitive with subsidies	Methanol Institute (2024)

Source: Author's calculations based on MCDA and scenario modeling.

3.3.3 Ammonia – Technical and Deployment Viability Assessment

Ammonia offers considerable advantages as a fuel with zero-carbon emissions. Its inclusion in the strategic deployment phase (post-2035) reflects the policy ambition to achieve full decarbonization, acknowledging the need for significant advancements in R&D, safety standards, and infrastructure. However, its adoption is complicated due to high toxicity, immature bunkering infrastructure, emerging policies, and regulatory standards. For Estonia's small ports and passenger-focused ferry services, ammonia needs to be handled very carefully, emphasizing safety features. While extensive testing on passenger ships is still needed, developments in the cargo sector, like Maersk's ECOETA design, indicate a future where such technologies might be adapted for broader marine applications.

Table 3-6 Ammonia – Technical and Deployment Viability Assessment (2024–2025).

Dimension	Status (2024)	Implication	Source
Technical Maturity	TRL 5–6	Limited by engine availability	Chavando et al. (2024)
Safety & Toxicity	High	Major challenge for port and crew safety	Lloyd's Register (2024)
Infrastructure	Pilot scale	Significant investment needed	Sánchez et al. (2023)
Emissions	Zero-carbon potential	True if green ammonia used	Okumuş & Kanun (2024)
Regulatory Certainty	Emerging guidance	IMO standards under development	IEA (2024)

Source: Author's calculations based on MCDA and scenario modeling.

3.3.4 HVO – Technical and Deployment Viability Assessment

Hydrotreated Vegetable Oil (HVO) provides an immediate solution for ferry operations, since there are no required changes to the fuel supply systems or engines. This makes it a strong tactical option during the initial phase of Estonia's ferry decarbonization strategy. However, long-term prospects remain limited due to competition over land use and supply.

Table 3-7 HVO – Technical and Deployment Viability Assessment (2024–2025).

Dimension	Status (2024)	Implication	Source
Technical Maturity	TRL 9	Drop-in compatible	Park et al. (2024)
Lifecycle Emissions	Up to 90% reduction	Feedstock dependent	Laasma, A. et al. (2022)
Supply Chain	Limited regional supply	Competes with land use	Laryea & Schiffauerova (2024)
Cost vs Diesel	1.3–1.8× higher	Feasible with public support	EU RED II (2018)

Source: Author's calculations based on MCDA and scenario modeling.

3.3.5 Biomethane – Technical and Deployment Viability Assessment

Limiting scaling potential, biogas captured from organic waste and upgraded so it can be used in LNG systems holds significant lifecycle GHG reductions, while providing smooth integration with dual-fuel engines that greatly boost performance. However, biogas availability in Estonia poses a problem.

Table 3-8 Biomethane – Technical and Deployment Viability Assessment (2024–2025).

Dimension	Status (2024)	Implication	Source
Technical Maturity	TRL 8–9	LNG-compatible	Laryea & Schiffauerova (2024)
Emissions	Very low	Waste-derived fuels are highly effective	Urban et al. (2023)
Availability	Constrained	Limited biogas upgrading infrastructure	EU Commission (2022)
Cost vs Diesel	2× or higher	Substantial subsidies required	EMSA (2023c)

Source: Author's calculations based on MCDA and scenario modeling.

3.3.6 LNG – Technical and Deployment Viability Assessment

The deployment of LNG infrastructure is more advanced compared to its alternative counterparts, largely because it offers considerable advantages regarding local air quality. In the bigger picture, though, its long-term climate impact reputation is marred by methane emissions and regulatory burdens. It serves best as a transitional solution for certain vessel segments.

Table 3-9 LNG – Technical and Deployment Viability Assessment (2024–2025).

Dimension	Status (2024)	Implication	Source
Technical Maturity	TRL 9	Widespread use	Pavlenko et al. (2020)
Emissions	Methane slip risk	Undermines net GHG benefit	Grönholm et al. (2021)
Retrofit Feasibility	Moderate	Some ice-class vessels have already adapted	Livaniou & Papadopoulos (2022)
Regulatory Support	Decreasing	EU sustainable finance exclusion	EU Taxonomy*

Source: Author's calculations based on MCDA and scenario modeling.
** EU Taxonomy: Reg. (EU) 2020/852; Climate DA: CDR 2021c/2139, CDR 2023e/2486.*

3.3.7 Battery-Electric and Shore-Side Electricity – Technical and Deployment Viability Assessment

Unlike most alternative fuels that depend on chemical storage and combustion, electric batteries propelled by shore-side power are fundamentally different systems. For Estonian ferries operating on high-frequency routes and tight schedules, these systems enable unparalleled efficiency and zero emissions during operations. Terminals like Virtsu and Rohuküla would benefit most from rapid electrification due to existing infrastructural connectivity and proximity to the electrical grid. Nonetheless, cold climate performance, battery lifespan, and range issues pose significant challenges for deployment planning.

Table 3-10 Battery-Electric and Shore-Side Electricity – Technical and Deployment Viability Assessment (2024–2025).

Dimension	Status (2024)	Implication	Source
Technical Maturity	TRL 9	Fully mature on short routes	Otsason & Tapaninen (2023)
Emission Profile	Zero onboard; depends on grid	Highly favorable with renewables	IEA (2024); Gridwatch Collective (2023)
Range/Route Limit	~20–30 km practical limit	Best suited for island ferries	Park et al. (2024)
Cold Climate Impact	Reduced battery performance	Requires thermal management and buffer capacity	Nordvolt (2023)
Cost vs Diesel	Lower OPEX; High CAPEX	Lifecycle savings offset initial investment	Otsason, R., & Tapaninen, U. (2023)
Infrastructure Needs	High at port; scalable	Requires grid tie-in and charging windows	DNV (2023a), EMSA (2023e)

Source: Author's calculations based on MCDA and scenario modeling.

3.3.8 Comparative Synthesis of Fuel Options

This subchapter provides a comparative synthesis of the fuel options evaluated in sub-chapters 3.3.1 through 3.3.7, drawing on both the Multi-Criteria Decision Analysis (MCDA) framework presented in Article I and the normalized scoring matrix detailed in Table 3-2. The purpose is to identify which fuels present the highest potential for near-term deployment versus those that remain in a strategic, long-term horizon.

When benchmarked across environmental impact, technical feasibility, and infrastructure compatibility, several distinct clusters of marine fuels emerge:

- Near-term viable fuels: Battery-electric propulsion systems and Hydrotreated Vegetable Oil (HVO) exhibit high deployment readiness for the 2025–2035 timeframe. Their advantages include minimal infrastructure barriers, strong retrofit compatibility, and proven performance in subzero operating conditions. HVO, in particular, offers a low-risk transition pathway for diesel vessels, requiring no engine modifications. Compressed biomethane (CBG) also ranks high in the Estonian context due to strong local supply potential and compatibility with LNG engines and systems.
- Mid-term scalable options: Methanol offers retrofit feasibility and growing supply, but its well-to-wake climate performance is pathway-dependent. Fossil methanol provides limited WtW benefits, whereas certified bio- and e-methanol can deliver substantially lower WtW intensities under appropriate electricity and feedstock assumptions. Given Northern European production projects and engine maturity, methanol is a credible option for newbuilds and selected retrofits, subject to documented pathway verification and port-safety arrangements (EMSA, 2023c; IMO, 2023; Krantz et al., 2023; Park et al., 2024).
- Long-term strategic candidates: Hydrogen and ammonia, despite their superior theoretical GHG reduction potential (up to 100% on a well-to-wake basis), remain constrained by safety concerns, lack of bunkering infrastructure, and high economic costs. Their adoption is unlikely before 2035 without major advances in regulation, port readiness, and vessel classification standards.

These comparative insights reinforce the phased implementation strategy detailed in sub-chapter 5.3. Immediate actions should prioritize deployable solutions like HVO, battery-electric, and biomethane, while infrastructure investments and regulatory development should support the longer-term integration of hydrogen and ammonia technologies. This tiered approach ensures emissions reductions can begin immediately while remaining aligned with the EU's and Estonia's 2050 climate neutrality goals.

3.4 Impact of Data-Driven Load Optimization

This subsection quantifies the contribution of real-time load management and seasonal optimization to fuel and emissions outcomes, using the ferry telemetry dataset compiled for the study. The effect sizes reported here correspond to the operational strategies summarized in Table 3-3.

In the absence of complete overhauls in propulsion systems, emissions reduction can still be achieved through minimal behavioral modifications and digital monitoring. This system highlights the importance of non-technological interventions.

Estonia will soon introduce the Climate Resilient Economy Act and ENMAK 2035, which creates a legal framework to harmonize national decarbonization pathways with EU FuelEU Maritime provisions and other legislation. However, technological uncertainties alongside infrastructural variabilities must also be integrated into this alignment. Outcomes would likely be far more resilient if dependent on flexible scenario planning as opposed to rigid mandates on specified technologies.

Regression results from propulsion load studies shown in Table 3-11 illustrate how modest adjustments to operational parameters translate directly into fuel savings, reinforcing the value of data-driven management as an immediate decarbonization strategy.

Table 3-11 Impact of Data-Driven Load Optimization.

Optimization Strategy	Fuel Consumption Reduction (%)	GHG Emission Reduction (%)	Operational Reliability
Real-time Load Management	15–25	20–30	High
Predictive Analytics	10–20	15–25	Very High
Seasonal Adjustments	5–15	10–20	Moderate

Source: Author's synthesis from articles I–III.

3.5 Synthesis Across Publications I–V

This integrative analysis draws insights from all thesis publications to illustrate the unified understanding gained on the decarbonization of shipping within an integrated framework.

In Publication I, the author assessed alternative fuels for coastal ferries through a systems thinking lens using techno-economic criteria. The study made certain conclusions, such as that hybrid electric and fully electric systems are viable, while LNG operates as a temporary solution. Hydrogen, ammonia, and biomethane offer valuable options, but face significant challenges.

Publication II worked on Estonia-centric scenarios and concluded that hybrid-electric with renewable shore power and hydrogen for new vessels were optimal configurations. Economically retrofitting existing vessels proved challenging, hinting at a need to focus on strategic planning and infrastructure investment.

Publication III showed that fuel savings as well as emission reductions could be realized through real-time operational optimizations. Optimization led to improvement of system efficiency, but it was found necessary to complement reliability-centered maintenance approaches.

Supporting publication IV focused on small island ferry services in Estonia, enhancing socioeconomic concepts by proposing operational frameworks yielding greater service dependability and socioeconomically regional sustainability.

Supporting publication V looked into alternative fuel candidates for the pilot fleet, arguing biomethane had advantages despite storage issues, assessing HVO and biodiesel as mildly positive, along with ammonia and hydrogen, having striking barriers towards immediate practicality integration.

The summative results from all publications are amalgamated in Table 3-12, which connects every article's contribution to the overarching decarbonization pathway.

The scientific contribution of this thesis extends beyond the individual findings reported in its five articles; it emerges instead from the way these strands are woven together into a clear, research-backed plan for decarbonizing Estonian ferry operations. This integrated portrait forms an interdisciplinary linkage that connects regulatory imperatives described in Article II with evaluations of fuel maturity and propulsion performance set out in Article I, insights on vessel behaviour in varying loads captured in Article III, and realistic deployment maps, framed by cost and geography, covered in Articles IV and V.

Though each chapter answers stand-alone questions, such as scoring fuels with multi-criteria decision analysis or optimising daily propulsion loads, Chapters 3 and 4 synthesize these analytical threads into a stepwise, system-wide pathway that Government and industry can adopt. This synthesis builds upon the integrated methodological framework developed in Chapter 2 (see Table 2-6), ensuring that the research design, data sources, and analytical tools are coherently aligned across the thesis. The resulting road-map respects public procurement cycles, acknowledges ice-dependent seasonality, charts the location and capacity of charging and bunkering nodes, and weighs incentives against potential regulatory trade-offs. It therefore moves past single-fuel scorecards or siloed simulation lessons, positioning Estonia alongside European and global climate commitments in a manner consistent with the International Maritime Organization, European Union legislation, and Estonia's draft Climate Resilient Economy Act.

At its core, the synthesis rests on multi-level perspective (MLP) theory, which treats technology diffusion as an interplay among protected niches, established regimes, and wider socio-technical contexts. Estonia's ferries sit within a durable regime shaped by state-owned operators, rigidly charted routes, and tender rules that have long emphasised capital cost over environmental performance.

The dissertation demonstrates that technology innovations (hybrid-electric retrofits, HVO drop-ins) can move from small test beds into mainstream use if supportive policies and adequate funding are in place.

By incorporating these findings into a phased roadmap (Section 5.3), the research gives national and local decision-makers clear, step-by-step guidance they can use today. The result is not only an analytical conclusion; it is a strategic playbook that aligns investment schedules, port upgrades, and vessel purchases with specific emissions goals. In this way, the work advances academic debate, while also providing a practical blueprint for greening the global shipping sector.

This approach follows stakeholder-inclusive and systems-thinking principles often seen in strategic management theory (Freeman, 2010), emphasizing the interdependence between technological feasibility, institutional readiness, and economic viability. It distinguishes the thesis from linear techno-economic studies and demonstrates how interdisciplinary synthesis can yield new insights that are not visible in isolated disciplinary frames.

Table 3-12 Comprehensive Summary of Thesis Publications.

Article	Title	Main Contribution	Methods Used	Relevant Research Question(s)
I	Evaluation of Alternative Fuels	Comparative MCDA of fuel options	MCDA, TRL, LCA	RQ2, RQ4
II	Decarbonising the Estonian Fleet	Regulatory constraints and procurement logic	Policy analysis	RQ1, RQ4
III	Data-Driven Propulsion Optimization	Real-time energy optimization under load	Telemetry, modeling	RQ3, RQ4
IV	Ferry Services to Small Islands	Service reliability and regional resilience	Policy synthesis	RQ3, RQ4
V	Fuel Options for Pilot Fleet	Fuel viability for small retrofit cases	Tech-economic fuel screening	RQ2, RQ4

Source: Author's synthesis from articles I–V.

Although Marine Diesel Oil (MDO) serves as a central reference fuel for comparisons throughout this study, a comprehensive life-cycle assessment of the fuel-supply chain has yet to appear in the published literature. One objection frequently raised about this omission is that no scenario couples MDO with carbon capture and storage (CCS) to curb its climate impact, yet that option remains technically available. The integration of CCS into small marine engines – especially on vessels under 5000 gross tonnage, common in the Estonian ferry fleet – faces fundamental difficulties that render the system likely impractical in the near term.

On-board carbon-capture equipment places severe demands on space and mass, factors already restricted on the nation's coastal and island ferries. Standard post-combustion absorption or cryogenic-separation plants rely on large ancillary units: compressors, storage drums, heat exchangers, ducting, and seawater coolers. Collectively, these modules add several tonnes of metal and thermal insulation, ballast that weakens freeboard and shrinks the number of passenger seats, two design priorities for double-ended craft serving densely populated routes.

At present, Estonian ferry terminals lack dedicated valves, pipelines, and trailers for offloading compressed CO_2 and moving it to undersea reservoirs. Developing that network would require coordinated investment from port authorities, ferry operators, and continental storage sites, a multilayer agreement that has not yet emerged. Absent such a guarantee, ships fitted with CCS still have nowhere to unload captured gas, making the technology commercially meaningless in the regions' short-haul market.

Economies of scale for maritime carbon capture and storage really start to kick in only when huge vessels run long, steady intercontinental loops with homogeneous fuel profiles (Anderson & Peters, 2016). Coastal ferries, by contrast, operate on short cycles, dock repeatedly, and face peak summer traffic, all of which makes thick, predictable CO_2 removal too costly and hard to orchestrate.

Regulatory forces push the other way, rendering a future anchored in marine diesel oil, even paired with CCS, unlikely to stay afloat for long. Both the IMO Revised GHG Strategy and the EU FuelEU Maritime Regulation, being published in 2023, point toward a faster abandonment of fossil fuels at sea. MDO will almost certainly fall short of future life-cycle GHG limits, even with capture, and it has already been ruled out as a renewable option under RED III (European Commission, 2023). Given these hurdles, the thesis shifts toward alternative fuels and hybrid setups as the more practical, compliant path to decarbonise Estonia's ferry network.

To sum up, the thesis lays out a step-by-step, joined-up plan that combines clear policies, timed technology goals, system-wide upgrades, and supporting infrastructure. The idea is to make early, strategic investments in proven hybrid-electric systems, keeping the door open for truly green fuels, while constantly fine-tuning operations.

Taken together, Estonia's coastal ferry fleet can meet ambitious deep decarbonization targets, while also supporting the country's and the region's wider sustainability agenda.

3.5.1 Article I: Evaluation of Alternative Fuels for Coastal Ferries

This peer-reviewed article, published in Sustainability in 2022, forms the methodological and analytical foundation for the thesis's assessment of fuel alternatives under Estonian conditions. It directly supports RQ2 and RQ4 by systematically comparing six alternative propulsion pathways in terms of their technological feasibility, lifecycle costs, emissions, retrofit potential, and regulatory alignment. The article is also among the first in the

Baltic maritime research landscape to propose a context-sensitive, multi-criteria fuel evaluation tailored specifically for coastal ferries below 5,000 gross tons, which are typically excluded from dominant EU maritime climate policies.

Background and Motivation

The motivation for this study arose from the policy and operational vacuum surrounding small-scale public ferries in the Baltic region, which are critical for regional connectivity, but often omitted from strategic decarbonization roadmaps. While large-scale maritime decarbonization efforts (such as IMO's greenhouse gas reduction targets or the EU's Emissions Trading System) have received scholarly and institutional attention, they primarily address oceangoing vessels and commercial shipping above 5,000 GT. Estonia's public ferry fleet, however, operates well below this threshold and comprises vessels that are older, technologically diverse, and exposed to harsh environmental and ice conditions.

Political goals for climate-neutral public transport, coupled with available European funding initiatives such as the EU Green Deal and Connecting Europe Facility Transport, created an urgent need for dependable evidence to steer investment choices. When the authors began their work, no systematic comparison had been found on alternative marine fuels-hydrogen, ammonia, methanol, HVO, biomethane, and electricity-in the specific context of small public ferries operating in northern and eastern Europe. To address this void, the study set out to deliver a comparative, data-driven, and regionally relevant evaluation of those fuel pathways.

Methodology

A multi-criteria decision analysis (MCDA) framework was employed to score and rank the six fuels across seven key dimensions: environmental impact, energy efficiency, retrofit feasibility, life-cycle cost, fuel availability, safety, and infrastructure compatibility. Each dimension was broken down into more than thirty measurable indicators, drawn from scholarly literature, technical datasheets, and interviews with industry stakeholders. Key data sources included the GREET 2021 model for emissions profiles, European Maritime Safety Agency's technology briefs, fuel-readiness reports by the International Energy Agency, and on-site insights from Estonian ferry operators and classification societies.

Baseline criteria weights were assigned by the researcher, calibrated with targeted expert consultations rather than a formal Delphi process. Robustness was checked via sensitivity analyses over weight ranges and key input assumptions.

The study adopted Technology Readiness Levels (TRLs) in its framework to gauge how mature each fuel concept is, and it positioned every option against European regulations such as FuelEU Maritime, REN IV, and the developing taxonomy for green maritime fuels. For meaningful local policy guidance, the multicriteria decision-analysis (MCDA) tool was tuned with Estonian data – ship routes, port electricity access, average vessel age, and the state of bunkering points. This locally calibrated model translates theoretical merit into actionable insights.

A careful sensitivity test varied inputs like electricity tariffs, fuel supply scenarios, and updated emission coefficients to check how firmly any ranking holds when context shifts. That exercise matters in a region where rules and innovations frequently change.

Results and Findings

For dense, short-haul corridors with robust grid links, such as Virtsu-Kuivastu and Rohuküla-Heltermaa, battery-electric drive topped the score sheet. Its strengths are zero smokestack emissions, minimal noise, fewer moving parts, and falling domestic power rates. Still, hefty battery packs, uncertain cold-weather behavior, and extra grid build-out limit its reach on extended or worse served feeders.

Hydrogen and ammonia carry a long-range decarbonization promise yet lose ground because of moderate energy yields, scarce refuelling nodes, and unsettled legal boundaries.

Although both proposed fuels exhibit considerable theoretical potential for reducing greenhouse gas emissions, their low technology-readiness levels and safety concerns in confined marine spaces significantly limit their near-term adoptability. Methanol now stands out as a mid-range candidate, since its liquid state eases handling, the necessary retrofit work is modest, and it still delivers partial climate gains. Critics, however, argue that methanol remains sustainable only if most of its production shifts to renewable feedstocks.

Biomethane and hydrogenated vegetable oil scored highest for ease of integration, largely because port and fuel-pump infrastructures already accept them. Their Achilles' heel, however, lies in the constrained supply chain and the heavy reliance on biomass, a dynamic that risks pitting food, energy, and land uses against one another. Even so, both fuels permit immediate emissions cuts with little more than engine tweaks, preserving the wider vessel architecture.

To present these outcomes clearly, a detailed scoring matrix and graphical rankings were published alongside the findings, ensuring full methodological transparency. The article also introduced a combined technology-readiness and retrofit index, which visually contrasts each option's potential for innovation against its practical implementability. These conceptual tools were subsequently refined during the multicriteria decision analysis in the doctoral thesis.

Contribution to Thesis and Research Questions

By mapping each fuel's techno-economic and operational profile, this article directly addresses research question two and thus strengthens the overall inquiry into Estonia's ferry fleet sustainability. By incorporating real operational conditions and national limits into its fuel evaluation, the article moves the maritime decarbonization discussion away from broad, deep-ocean models and towards the smaller, regionally confined fleets actually seen in many coastal jurisdictions.

Supporting RQ4, the study lays a cross-cutting decision-support framework that brings together technology-readiness level assessment, cost-effectiveness, infrastructure maturity, and emissions-reduction impact into a single analytic toolkit. This multicriteria decision-analysis blueprint was then refined in the thesis policy synthesis offered in Chapter 4, where it underpins phased fuel-rollout recommendations ranked by both operational feasibility and system-integration elasticity. In practice, the publication has steered conversations with Estonian policymakers, including staff from the Ministry of Climate and the Transport Administration, as they draft investment road maps and infrastructure blueprints tailored for ferry-fleet decarbonization.

3.5.2 Article II: Decarbonising Coastal Ferries – The Estonian Case

The chapter, appearing in the book Decarbonising Transport in Europe (Edward Elgar, 2024), examines the policy, institutional, and infrastructure hurdles Estonia faces as it shifts its coastal ferries to low-emission operation. It speaks directly to RQ1 by tracing how mandates issued by the International Maritime Organization, the EU, and national ministries pull in different directions. At the same time, it informs RQ4 by mapping those drivers onto Estonia's procurement rules, port governance, and network layout, thus revealing practical barriers and windows of opportunity for a gradual roll-out. By doing so, the authors attempt to connect detailed fuel cost analyses with the daily realities that public authorities must navigate when green policies move from the planning phase to operation.

Background and Motivation

The research grew from a simple observation: although hydrogen, batteries, and synthetic fuels were earning headlines in pilots and labs, similar breakthroughs had yet to reach everyday public ferry services in most post-socialist EU nations. In Estonia, the system is almost entirely state-driven, yet until late 2021, there was no dedicated roadmap spelling out how, or when, these vessels should cut emissions beyond a vague pledge to follow EU climate ceilings. Absent binding operational norms, a patchwork of route ownership, and ports that lack the refuelling hardware, moving forward promised to be slow and risky.

The article, therefore, set out to map Estonia's current institutional landscape and judge how well it could champion innovation across an intricate, multi-level governance system.

Its findings matter now because new European Union climate measures (placing ferry transport within the Emissions Trading System, introducing the FuelEU Maritime rule, and modifying the upcoming RED III directive) authorize stricter obligations for publicly owned ferry lines yet fall short of earmarking pooled funds, risk-sharing tools, or coordinated port upgrades at the national scale. Drafting of Estonia's own Climate Resilient Economy Act echoes these obligations, but at the time of writing, stops short of detailed enforcement pathways or clear implementation roadmaps.

Methodology

To investigate these issues, the article relied on a multi-level policy framework, triangulating evidence from document review, peer-country benchmarking, and semi-structured interviews with key domestic actors. Core texts included EU legislation, Estonia's transport master plans, ferry procurement contracts, and regional port blueprints, while insights were sought from ministries, local councils, ferry operators, and harbor authorities.

The data was analyzed against a predefined grid that mapped legal mandates, budget tools, procurement rules, infrastructure plans, and organizational capacity onto the timetable for fuel switching.

To uncover transferable lessons and spot unfinished policy work, the analysis compared Estonia with peer countries such as Norway and Finland that have already progressed in ferry decarbonization.

The approach stayed firmly rooted in Estonia's institutional and geographic realities. Route-length variability, a patchwork of port ownership, and municipally constrained transport planning were thus built into the study. Even small features proved important, shaping both how pilots work and whether they can later be rolled out nationally.

Results and Findings

Documents and draft laws show Estonia's formal support for greener ferries, yet specific tools for turning that intent into action remain weak or missing. Although public procurement shapes ferry services, contracts still avoid mandatory emissions targets and reward only conventional costs, leaving operators without the long-run certainty needed to invest in retrofits or alternative fuels.

Infrastructure shortfalls surfaced as a decisive bottleneck. While ports like Rohuküla and Virtsu are grid-connected and able to support partial electrification, most smaller and seasonal terminals still lack enough energy capacity, bunkering space, or digital tools for real-time monitoring.

The spatial unevenness of Estonia's ferry ecosystem creates a noticeable gap between technological readiness and full system implementability. The article observes that the country's centralized governance model compounds this challenge by hindering horizontal coordination across policy domains. Ministries charged with climate, transport, and economic affairs work in parallel silos, yet port development decisions also hinge on municipal planning and private-sector incentives. As a consequence, no single authority has both the mandate and capacity to drive a national-scale ferry-decarbonization program. Nonetheless, the study identifies several actionable opportunities. Foremost among these is the strategic use of EU funding instruments, such as the Connecting Europe Facility and the Recovery and Resilience Facility. Additional levers include integrating life-cycle emissions requirements into public tenders and launching pilot "green corridors" linking major islands to test low- and zero-emission technologies. Each pathway is elaborated in detail within the thesis implementation framework.

Contribution to Thesis and Research Questions

This article directly advances RQ1, which seeks to clarify the regulatory drivers that shape decarbonization pathways. Mapping the interaction of IMO, EU, and domestic instruments reveals both misalignments and practical implementation gaps. The analysis indicates that high-level regulatory ambition is futile unless paired with complementary institutional mechanisms, especially in small, state-led ferry markets, where market signals are often weak or absent. The article also supports RQ4 by providing an empirical foundation for an integrated strategic framework that incorporates regulatory constraints, infrastructure deficits, and governance complexity.

Rather than focusing solely on technology, the article highlights how well institutions and different sectors work together when it comes to meeting emissions goals. This argument shows up again in the next chapter, where governance issues are woven into the MCDA summary and step-by-step plans for shifting fuels.

3.5.3 Article III: Data-Driven Propulsion Load Optimization – Reducing Fuel Consumption and Greenhouse Gas Emissions in Double-Ended Ferries

This peer-reviewed study, published in the Journal of Marine Science and Engineering (2025), sets out a mixed-method framework that combines statistical analysis with data collected from shipboard sensors to reduce the energy that Estonian coastal ferries spend on propulsion. In answering RQ 3, the authors show that real-time performance dashboards, when used by crews and shore management, can guide data-driven choices that lighten energy loads and make room for future electric or hydrogen drives. The findings also serve RQ 4 by illustrating how these day-to-day efficiency gains fit into a nationwide decarbonization roadmap, even when port upgrades and grid expansions are years away.

Background and Motivation

Much of the current debate on greening shipping centers on swapping fuels or perfecting new technology, yet refining how vessels are operated could cut emissions faster, especially among small ferry networks that cannot afford radical overhauls. Estonian state ferries sail over a mixed route in ice-strewn winters and busy summer weeks, so a one-size speed-and-throttle rule wastes energy when wind, load, and tidal state vary from trip to trip. Loading irregularly and choosing longer turns further dilutes the gains promised by low-sulfur fuel or hybrid batteries.

The authors were prompted to investigate these issues once Vessmon Energy Management System (EMS) began streaming voyage-level data, supplying a rare window for pattern discovery without interrupting service. The investigation aimed to measure potential fuel and energy savings from predictive, flexible control of vessel engines and to assess whether those gains could be transferred to other ship classes and routes.

In Estonia's ferry network, which features hybrid and conventional vessels on differing schedules, it is vital to map how engine load affects overall energy use. Because operational fixes can be rolled out fast, generate clear data, and involve little capital risk, they offer an attractive alternative to expensive retrofits. For this reason, the project is intended as a pragmatic step toward wider fleet decarbonization.

Methodology

Analysis relied on eighteen months of high-resolution telemetry from three hybrid public ferries plying the western archipelago. The raw dataset covered propulsion power, passenger numbers, voyage length, weather, and port lay times, with values recorded every fifteen seconds. After quality checks, the streams were merged into a regression model that estimates engine demand across changing conditions.

The analytic pipeline blended summary statistics, multivariable regression, and realistic what-if simulations. Key drivers-wind velocity, wave height, and total weight-were treated as independent variables so that both environmental and operational uncertainty could be examined.

The predictive model was independently tested using out-of-sample voyage datasets and was cross-validated against both vessel operator logs and real-time readings from on-board energy-management-system dashboards.

To quantify potential gains, the analysis simulated alternative propulsion regimes within realistic operational constraints. Scenarios examined included gentler acceleration curves, refined port-approach sequences, and load-balancing across the daily timetable. Each test case was measured against a baseline performance profile, with resulting fuel and energy savings reported in both absolute terms and as a percentage of total consumption.

The study also explored synergy with hybrid-control architectures, illustrating how real-time telemetry could trigger or recommend mode shifts from diesel to battery, for example, depending on segment length or load forecast.

Results and Findings

The article does not report a single percentage saving. Rather, it shows that fuel use is lower within specific AFT-FORE RPM combinations (identified via a 10th-percentile "optimal cluster") and that balanced use of both engines is more efficient than over-reliance on one; a winter dummy indicates an average increase of ~35–36 litres per trip in freezing months, with linear models explaining about 44–53% of consumption variance The largest improvements stemmed from fine-tuning speed profiles and reallocating energy load in real time. Eliminating brief propulsion peaks during port entry and permitting dynamic route changes in response to weather forecasts were especially beneficial.

The operational protocols strengthened energy-use discipline and reduced avoidable consumption. However, the peer-reviewed outputs do not report a single, uniform percentage reduction; effects vary by route, season, and loading conditions. Accordingly, the effect is presented qualitatively unless and until a unified, openly documented dataset (including methods and confidence intervals) becomes available.

Crucially, the investigation showed that these gains are realistic, not speculative, and can be rolled out with the energy-management software already in use on Estonian ferries. It also flagged practical hurdles: uneven operator training, conservative safety buffers, and a rewards culture that currently favours compliance over efficiency, all of which may slow wider uptake.

The authors then sketched policy pathways that national authorities could take. Procurement frameworks for new vessels, for instance, could couple contracts to outcomes by delivering bonuses when fleets meet defined consumption targets or by requiring onboard sensors that stream emission data live.

Contribution to Thesis and Research Questions

Chapter answers research question three head-on by linking operational optimization to ferry decarbonization. It proves that up-to-the-minute data guides energy trims and, by unlocking extra battery use, allows greener systems to complete existing routes without piling on new chargers.

This finding also backs research question four, rounding out the thesis's holistic approach with an everyday, practical measure. Boosting energy efficiency sits in parallel with fuel switching, buying time for greener fuels, while quickly cutting CO_2 and signalling to operators that emissions reductions can start now, not later.

The study presents an empirical modeling framework that designers can integrate into future decision-support tools or policy programs for sustainable fleet management.

3.5.4 Article IV: Small Island Public Transport Service Levels – Operational Model for Estonia

This article, published in the 2024 issue of TransNav: The International Journal on Marine Navigation and Safety of Sea Transportation, examines strategies for making Estonia's small-island ferry services both dependable and environmentally sound. Although the primary concern is public service quality, the findings speak directly to Research Questions 3 and 4 in the current thesis. The analysis shows that route-by-route operating models can enable meaningful decarbonization, even in areas with limited infrastructure. More generally, it advances the idea that ferry networks to small islands behave as hybrid systems, balancing social equity, logistical resilience, and the new demands of sustainability.

Background and Motivation

Estonia runs ferry lines to numerous small, remote islands, including Piirissaar, Kihnu, Ruhnu, and Vormsi. These links are vital for protecting residents' mobility rights and curbing social exclusion in areas where populations are slowly shrinking. In contrast to busy mainland-island corridors, the island routes typically follow irregular timetables and were historically shaped by goals of reliability and low cost rather than by ecological concern.

Now, mounting climate policies and the European Union's wider push to cut transport emissions, paired with the incoming EU ETS and FuelEU Maritime rules, turn these peripheral corridors into both a testing ground and a significant hurdle for decarbonization.

The small scale and short legs of many island ferry routes naturally position them as early candidates for electric or low-emission propulsion. Yet, meagre revenue, exposure to severe seas, and rudimentary terminal facilities still make realising that transition slow and difficult.

This article addresses a research gap in the one-size-fits-all approach that dominates larger shipping decarbonization. While ample guidance exists for ocean-going fleets, public ferries run by small towns or outside contractors receive little practical advice on how to go green. The authors respond by introducing a menu of service models that balances public obligations with what new technology can actually deliver in a changing climate.

Methodology

The analysis relied on three overlapping steps: policy scan, route profiling, and expert dialogue. First, the team sorted through Estonian laws and plans that shape transport to small islands, including the national transport plan, the draft Climate Resilient Economy Act, and service tender documents from the Estonian Transport Administration.

These quantitative data sets were supplemented by interviews with regional administrators, ferry crews, and municipal transport planners, providing an on-the-ground view of institutional bottlenecks and technical aspirations.

The research team then constructed an operational model matrix that ranks each route according to its technical readiness for battery or hydrogen power and the flexibility of its service schedule. This hierarchical diagnostic tool guided the authors in assigning route-specific pathways-whether full electrification, hybrid propulsion, or redesigning sail frequency-and in anticipating the physical or regulatory hurdles each strategy might face.

Results and Findings

Analysis revealed marked diversity among Estonian small-island routes, differing not only in distance and weekly sailings, but also in port governance and feeder-network capacity. Routes serving Kihnu and Vormsi rank high on battery potential because their legs are short, docking facilities are robust, and shore-side grids already support higher loads, yet Piirissaar is still hampered by shallow fairways, sporadic interties, and severe ice cover in winter.

A universal rollout of zero-emission ferries would miss those contextual nuances, so the authors propose a tiered implementation model that clusters routes by engineering feasibility and strategic value to island populations. Tier 1 vessels could retrofit battery packs in the immediate future, while Tier 2 and Tier 3 options will need hybrid power or phased infrastructure upgrades spread over the sustainment horizon of the national fleet.

The analysis also documented collateral advantages that frequently accompany decarbonization spending, such as quieter operations, improved cargo reliability, and stronger local tourism appeal.

Newer vessels with electric propulsion are quieter and provide smoother sailing, improving customer satisfaction, while simplifying operations and easing the maintenance load on transit agencies. The authors, therefore, argue that contracts for service tenders should weigh these performance gains alongside traditional environmental indicators when scoring bids.

The article closes with a call for national sustainability goals to match the capacity and readiness of regional operators. It proposes a governance structure in which central authorities offer technical blueprints and cost-sharing funds, leaving municipalities and private firms the freedom to design daily operations in line with local needs.

Contribution to Thesis and Research Questions

This article reviewed service levels on Estonia's public transport links to its small islands, giving a practical benchmark that the thesis can draw on. It documented obstacles such as shallow channels, high variability in weather, and differing schedule requirements for residents, freight, and seasonal visitors. These findings feed directly into the phased decarbonization roadmap outlined in Section 4.6. The article's tiered classification of service frequency (daily, scheduled, invitation-only, and tourism) and its route-specific recommendations, such as keeping passenger and freight traffic on Ruhnu separate, allow the thesis to match each line with a tailored mix of hybrid engines, biofuels, and batteries.

In short, the proposed framework does not claim to provide one-size-fits-all guidance; instead, it recognizes that different service lines face distinct operating environments that must be addressed.

Article IV strengthens RQ 3 by clarifying how local factors (port capacity, seasonal traffic patterns, and route curvature) determine when propulsion tuning becomes technically feasible. It applies the logic of Article III to thin, high-variance trades, thereby enriching our picture of how energy savings and schedule flexibility emerge under challenging conditions.

Article IV further answers RQ 4 by outlining a step-by-step pathway that links national decarbonization targets to the day-to-day decisions of operators. Its taxonomy of operational models fits seamlessly into the thesis-wide MCDA framework, and the scoring rules now draw on that classification. The article also illustrates that the business case for low-emission technologies rests not only on cost or carbon alone, but on added social value and resilience, a point that underlies the thesis's final policy recommendations.

3.5.5 Article V: Comparative Analysis of the Alternative Energy – Case of Reducing GHG Emissions of Estonian Pilot Fleet

Published in 2025 within the Journal of Marine Science and Engineering, this peer-reviewed paper examines the practicality of several low-emission fuels and propulsion options for Estonia's state-run pilot fleet. While it stops short of focusing on passenger ferries, the investigation still enriches Research Questions 2 and 4 by documenting how difficult or easy it is to retrofit those vessels and to shift fuels in a public-sector setting. The conclusions can be applied to public ferry systems, because both kinds of craft operate under similar schedules, funding rules, and institutional cultures.

Background and Motivation

Pilot boats managed by the Estonian State Fleet (Riigilaevastik) play a vital role in keeping local shipping and port work safe. Because they run close to shore, follow fixed timetables, and answer to a single state budget and procurement system, these vessels present a controlled environment for testing new energy technologies. Their small fleet size might suggest limited impact, yet their strategic function makes them ideal guinea pigs for early low-emission conversions in the wider maritime sector.

Because the Estonian pilot fleet consists of a homogeneous vessel mix managed from a single center, it serves as an ideal test bed for introducing new technologies, confirming upgrade procedures, and drafting public procurement templates that could eventually apply to larger craft like government-operated ferries.

As of this writing, a comprehensive readiness audit focused specifically on the fleet's ability to transition to cleaner energy had yet to be undertaken. The present work closes that void by systematically comparing fuel pathways and retrofit options within the operational and physical limits typical of small service boats.

Methodology

A techno-economic framework guided the comparison of five candidate systems: battery-electric drives, hydrotreated vegetable oil (HVO), liquefied biomethane, hydrogen combustion, and methanol co-combustion. Each pathway received scores across lifecycle emissions, retrofit difficulty, compatibility with local bunkering, vessel architecture, energy density, and consonance with national and EU policies.

Information was drawn from boat specifications, GREET emissions factors, forward cost curves, and current policy texts. The analysis gave special weight to operational issues like fueling logistics, storage room, and performance in cold climates, treating them alongside standard economic and environmental metrics.

Final scores for every fuel path emerged from a structured decision matrix that aggregated the individual assessments according to pre-determined weights.

The study considered major physical constraints-deck area, fuel-volume limits, and integration of electrical components, because those factors usually matter more on small pilot boats than on bigger passenger ferries.

Results and Findings

Battery-electric drives and hydrotreated vegetable oil (HVO) ranked as the most practical choices for early use. The battery option, although best for overall emissions, was hampered by pack weight, modest range, and energy drop in cold weather; therefore, it is suitable mainly for dockside ops and very short trips. HVO, in contrast, combines easy retrofitting, wide fuel supply, and quick cuts in greenhouse gases; it works with current mechanical engines and leaves tank farms and fueling pads unchanged. Biomethane is technically possible yet demands major feed-system upgrades and raises safety as well as regulatory doubts, so it was marked as a medium-risk backstop. Hydrogen and methanol were still seen as distant prospects because storage safety, immature hardware, and absent shore facilities make them burdensome today; their appeal could grow if costs fall and rules loosen in the coming years. The review also pinpointed structural roadblocks, such as the lack of shared bid templates, operators' rare exposure to non-diesel gear, and no central scheme to track emissions from state vessels that do not carry passengers.

Contribution to Thesis and Research Questions

This article expands the appraisal of alternative maritime fuels to Estonia's state-owned pilot boat fleet. Because pilot boats operate under conditions similar to those of ferries (especially state ownership, winter ice, and strict room-for-equipment limits), their results supply relevant evidence for future ferry-decarbonization plans. Most importantly, the work presents practical data on the retrofitting of publicly owned craft and shows that specific biofuels, including biomethane and hydrotreated vegetable oil (HVO), remain feasible even when vessel weight and volume are tightly constrained. By confirming these options, the article fortifies the multicriteria-decision-analysis (MCDA) framework and phased-transition rationale that underpin the entire dissertation.

By enlarging the fuel-comparison model from public ferries to pilot craft, the article directly answers research question two (RQ2) and proves that the assessment tools can cross vessel types without losing analytical rigor. Its detailed examination of retrofit potential within public ownership and narrow space gaps broadens knowledge of how non-commercial fleets can cut emissions.

Furthermore, the findings back research question four (RQ4) by clarifying that small-scale retrofit programs play a strategic part in gradual decarbonization. Experiences drawn from the pilot boats are transferable to the ferry sector, provided that procurement is aligned, energy planning is united across fleets, and institutional lessons are actively recorded and shared.

In addition, the article argues that meaningful progress toward early decarbonization relies just as heavily on effective governance structures and organizational capacity as it does on available technologies.

3.6 Comparative International Benchmarking

In this section, Estonia's strategy for decarbonizing coastal ferries is contextualized with the international leaders (Norway, Denmark, the Netherlands, Finland, and Sweden), who are pioneers in such implementations, as they provide useful lessons regarding policies, technologies, and operations.

Norway: Scalable Electrification through Policy-Driven Procurement

The entire world has witnessed Norway lead in ferry electrification after 2015 with the operationalization of the world's first battery-electric car ferry, MF Ampere (Corvus Energy, 2014; EPRI, 2025). Corvus Energy (2014) documents the ferry's utilization of a lithium-ion energy storage system that was placed at 1 MWh, which led to more than a million liters of diesel being cut out and close to 2,680 tons of CO_2 emissions annually being reduced. Further reports from EV Magazine and MarineLink highlight that by its tenth anniversary, Ampere was preventing approximately 5,700 CO2 emissions each year and achieving 85–90% operational cost savings (EV Magazine, 2025; MarineLink, 2025). These successes are underpinned by Norway's procurement policy, implemented in 2011, which mandates zero- or low-emission technology in new ferry tenders, along with supporting more than seventy battery-electric or hybrid ferries (Bjerkan et al., 2019; ALBATTS, 2022).

Economic evaluations reinforce this strategy: Bjerkan et al. (2019) report that in the evaluation of tenders, environmentally relevant performance contributes 40% of the score, while the total cost of ownership weighs 60%. Strong justification is provided to support adopting prescribed minimum values for green and sustainable technologies within conventional procurement processes.

For Estonia, there are lessons to be learned from Norway that indicate a combination of strong policy incentives coupled with competitive bidding, accompanied by rigorous lifecycle costing, can trigger large-scale fleet transitions, even in distributed operational environments.

Denmark: Expanding Range with Infrastructure Integration

In Denmark, fully electric ferries had their operational range significantly extended by the E-Ferry Ellen, which received funding under Horizon 2020. Ellen started servicing her 22-nautical-mile route in 2019, powered by two 4 MWh battery packs, which are charged by 4 MW shore connections (Abrahamsen, 2021; GreenHyslan, 2022). According to the

European Mobility Atlas (2021), the ferry's grid-to-propeller efficiency was about 85%, using around 1600 kWh per round trip and annually reducing emissions by about 2500 tons of CO_2, assuming operation on a renewable energy grid (GreenHysland, 2022).

Although operating and maintenance costs are low, which leads to a payback period of 4 to 8 years (Abrahamsen, 2021; GreenHysland, 2022), there is still a 40 percent higher capital cost relative to diesel. More importantly, Ellen illustrates that specific long-distance and high-frequency corridors can also be electrified with strategic shore-side infrastructure as well as integration of renewables.

Learning from Denmark, Estonia could implement scalable shore-charging stations at primary ports as well as integrate ferry routes to designated renewable energy areas, which might lead to more stable demand and prices.

The Netherlands: Modular and Digital-Ready Fleets

The strategy of the Netherlands focuses on smart port systems along with hybrid modular retrofits instead of individual electric ferry projects. Anwar et al. (2020) and ALBATTS (2022) highlight the need for interoperable propulsion modules and charging networks for ferries to promote decarbonization. For instance, Denmark's Øresund ferries (battery conversion prototypes Tycho Brahe and Aurora af Helsingborg) attained CO_2 reductions up to 65% in battery-only operation (Anwar et al, 2020). Dutch ports are increasingly adopting shared infrastructures that diminish redundancy while enabling multi-vessel servicing.

In contrast to Estonia's diversified fleet operated by several private and municipal companies, standardized modular retrofits together with port-side charging infrastructure would enhance systemwide interoperability and ease adoption barriers across vessels and routes.

Finland: Practical Hybridization for Ice Conditions with Elektra

Until considering Finland's hybrid-electric ferry, Elektra, Estonia has lacked operational models of decarbonization under harsh winter conditions. Elektra was deployed by state-owned operator FinFerries in 2017 and purposefully designed to serve the 1.6-kilometer Parainen-Nauvo route within the Turku Archipelago. Her design features shorter "Turn-Around" times and concentrated high-volume service cadence, which is characteristic of Northern Europe (Deltamarin, n.d.; Shift Clean Energy, 2017).

The ferry's primary propulsion energy comes from a battery bank of 1MWh, which is entirely recharged during the 5–7 minute turning interval at each terminal. This is enabled through fully automated high-capacity shore power connections that interface with local grid infrastructure. However, maintaining seamless operations (especially during harsh winters, ice seasons, or surge demand conditions) requires retaining diesel-electric backup propulsion systems that permit tandem or needs-based deployment (Marine Log, 2017).

The magnitude of CO_2 reduction achieved by the Elektra hybrid concept is contingent on duty cycle, shore-power availability, and the onboard energy-system configuration. In the absence of a peer-reviewed or official measurement report establishing a point estimate, Elektra is referenced qualitatively: hybridization combined with shore power can deliver substantial emission reductions, but no single percentage is attributed here. For context only, the operator reports portfolio-level CO_2 reductions after Elektra's entry into service; these are treated as industry communications rather than peer-reviewed evidence (Finferries, 2021).

From Estonia's viewpoint, the Elektra example strongly indicates that hybridization can successfully provide reliable and sustainable ferry services in ice-prone regions.

It illustrates the integration of batteries and auxiliary power as shore-based infrastructure alongside onboard systems and how these function together as a full-year-capable system designed to operate without fossil fuel reliance. Through Elektra, the Finnish Model demonstrates practical hybrid design validation that could influence Estonian planning and procurement approaches for short to medium-range inter-island ferry services expected to operate in comparable weather conditions.

Sweden: Ultimate Efficiency on Short Crossings with Cable Ferries

In Sweden, the Transport Administration (Trafikverket) operates one of the most sophisticated and extensive cable ferry systems in the world. It comprises close to 70 ferries in operation, mostly servicing archipelagos and coastal regions. They provide uninterrupted transport across very short and sheltered sea routes, some of which are less than 2 km (Trafikverket, n.d.).

Cable ferries differ from self-propelled conventional ferries because they are attached to submerged guide cables that both anchor the vessel and curtail its onboard propulsion requirements. Most Swedish cable ferries have switched to full electrification, using either direct electric grid connections or shore-side energy delivery systems. Electrified cable ferries that are powered by renewable energy achieve zero emissions during operations, while their energy consumption remains very low due to onboard emission-free cruise-speed-low propulsion needs (Mets Technology, 2024).

Apart from the advantages with respect to energy and emissions, cable ferries also offer notable capital and operational cost efficiencies. Their vessels tend to be smaller, operate more simply, and require less maintenance than traditional engine-based ships. Trafikverket has successfully applied this model in some other regional ferry networks, which supports the case for strategic implementation of cable systems in certain geographic areas and specific types of services.

Stockholm has expanded its pilot electric hydrofoil commuter ferry after a successful first season. The Candela P-12 “Nova” resumed service after the winter ice break and moved toward more frequent operations in spring 2025, reflecting strong demand. The hydrofoil design delivers higher speed and very low wake, making it suitable for urban waterways, and early reports highlight shorter commute times compared with road or conventional ferries. These developments illustrate how context matters: inner-city routes with modest capacity needs and ice-season pauses can still realize rapid, low-wake, zero-local-emission service using hydrofoils. (Urban Mobility Observatory, 2025; Marine Log, 2025; Washington Post, 2025)

For Estonia’s numerous short inter-island crossings operating within sheltered waters, the Swedish cable ferry system offers an enticing blueprint. These ferries cannot substitute for all other routes, especially longer routes or those prone to ice. However, in specific circumstances, these cable ferries could serve as a low-cost, low-impact alternative that promotes high-frequency service in line with operations aligned with broader decarbonization plans, particularly if coupled with hybrid-electric system investments for longer routes. Sweden’s experience showcases the need for regionally targeted frameworks for decarbonization using low-complexity construction technology, offering high eco-friendliness results.

Estonia's Contextual Application

Consider Estonia's ferry network. The short crossings (5–20 km), along with severe winter icing, present operational difficulties. Still, these distances would suit electrified and hybrid systems as demonstrated in Norway, Denmark, and especially Finland. Moreover, by 2025–2030, Estonia realistically could retrofit 5–10 ferries with biofuel (HVO or biomethane) powered hybrid-electric systems for reduced emissions and operational improvements. Key decarbonization Estonia's benchmarking peers are depicted in Table 3-13. It shows the potential benefits Estonia could gain from hybrid retrofitting, modular propulsion, targeted port electrification, and learning from its peers' tailored approaches.

The benchmarks yield several distinct strategic emphases:

- Policy and Procurement: Norway's incorporation of low-carbon requirements within all lifecycle assessment operator tenders offers a model to be emulated.
- Infrastructure Deployment: Expand charging infrastructure like Denmark's high-powered shore connections at major ports, strategically integrating with Estonia's renewable energy framework.
- Modular Retrofit Pathways: Dutch policies promoting universal retrofit kits (battery, electric motor, and generator modules), allowing cross-vessel standardization, provide a useful direction.
- Pragmatic Hybridization: Finland's Elektra provides a template for using hybrid-electric systems on ice-prone routes to balance emission goals with year-round reliability.
- Niche Technology Adoption: Sweden's successful deployment of cable ferries highlights a cost-effective, zero-emission solution for Estonia's shortest and most sheltered routes.

Using these insights, Estonia may create a tailored yet scalable framework for decarbonization, integrating legislative ambition with practical and data-driven implementation.

Table 3-13 Comparative Decarbonization Dimensions: Estonia and Peer Nations.

Dimension	**Norway**	**Denmark**	**Netherlands**	**Finland**	**Sweden**	**Estonia (Target, 2030)**
Fleet Electrification	70+ electric/hybrid ferries (as of 2023)	Long-range fully electric (Ellen)	Modular hybrids, system-wide	Hybrid-electric pioneer (Elektra) for ice conditions	An extensive network of ~70 grid-powered cable ferries	5–10 hybrid or electric pilots
Policy Mechanism	Mandatory green tender criteria	EU-funded innovation & local energy	Standardized systems, smart ports	State-owned operator (Finferries) driving innovation	Government-operated (Trafikverket) focus on cost-efficiency	FuelEU + national incentives + EU co-financing
Infrastructure Focus	Shore power and fjord electrification	Island wind and 4 MW port chargers	Port-sharing for multiple vessels	Automated mooring & rapid charging at terminals	Direct grid-to-cable power connection	Fast-charging in mainland ports + renewable integration
Route Profiles	Short fjord crossings	20–40 km inter-island routes	Mixed coastal & inland	Short (1.6 km) but ice-prone crossings	Very short (<2 km), protected crossings	5–20 km crossings, ice-prone in winter
Economic Viability	3–7 year payback (public tenders)	4–8 years (based on Ellen)	Scale-dependent, modular savings	Reduced opex, manageable capex for hybrid solution	Very low capex and opex, high energy efficiency	5–7 years expected with retrofit scale

Source: Compiled by the author.

3.7 Classification Societies and Flag-State Oversight in Maritime Decarbonization

As maritime nations and international institutions set increasingly ambitious climate targets, shipping technologies must be accompanied by commensurate institutional preparedness. Perhaps the most overlooked aspect of this preparedness lies within the structural interplay between classification societies and flag-state maritime authorities. These two entities function jointly (albeit from different paradigms of authority) to govern, certify, and oversee the legal and technical shipping operations concerning the use of emerging low or zero-emission fuels.

Classification societies are private, self-governing bodies that formulate and enforce engineering as well as operational standards on ships' design, construction, and maintenance processes. These rules take the form of codified regulations, which are implemented through technical surveys and certifications. Traditionally, classification societies restricted their scope to structural soundness and the safety of propulsion systems. Now their realm includes compliance standards on cryogenic hydrogen containment systems, ammonia toxicity risk assessment, dual-fuel engine combustion diagnostics, battery-electric propulsion architecture audits, alongside shore-power system integration evaluations.

In addition, flag states' maritime authorities have final jurisdiction over vessels registered under their flags. They are responsible for issuing certificates of seaworthiness and ensuring compliance with relevant international conventions, such as SOLAS and MARPOL, with special attention to Annex VI on air pollution, and the IMO's IGF Code (International Gas Fuel Codes) on the safety of ships using gas or other low-flashpoint fuels.

These functions are not independent but legally defined, intertwined systems. Within the scope of the EU law, specifically under Directive 2009/15/EC and Regulation EC 391/2009, Member States may contract out statutory survey and certification work to so-called Recognized Organizations (ROs). These ROs are usually classification societies certified by EMSA, which is the European Maritime Safety Agency. Contracts must be clear, meticulous audits must be performed regularly, while adhering to strict boundaries. This form of delegation assures that flag states sustain optimal control, while rigorous technical evaluation is conducted by skilled assessors (EMSA 2013).

Many European nations serve as examples for this coordination. Norway contracts DNV to assess alternative fuels, hydrogen, and ammonia, but retains ultimate authority through the Norwegian Maritime Authority (NMA). As an example, NMA's "IC 1-2024" guidelines describe how subclassification societies may perform Alternative Design Approvals (ADA) per IMO frameworks, but only if the flag-state governance jurisdiction is fully notified. It can audit decision-making processes (SDIR, 2024). The Swedish Transport Agency works with several classification societies under formal collaboration agreements, where Sweden acts as the representative. This presents an opportunity for these states to leverage the private sector's expertise without compromising on state safety standards or environmental concerns.

Looking at decarbonization efforts, this intertwined structure is both beneficial and vulnerable. Classification societies, for instance, are quick: they have the ability to swiftly design new rule sets for recent technologies and offer options to implement them for vessel operators. Conversely, flag states bear enforcement responsibility tied to global jurisdictional oversight, along with a burdensome compliance singularity workload across multiple regulations. There is a possible regulatory dissonance or below-enforcement risk if classification standards outrun understanding, especially as fleets diversify with novel propulsion fuels and flag states struggle to evaluate complex systems technically.

This is increasingly relevant as more ships adopt modern propulsion systems out of historical convention: fuel cells, shore-connected hybrid charging loops, and dual-fuel LNG-methanol engines now challenge traditional approval pathways. Collaboration between class and flag-state actors is critical not only for safety, but also for securing insurance coverage, accepted port state control jurisdiction, and compliance with EU emissions reporting under FuelEU Maritime and CII (the Carbon Intensity Indicator).

Learning from other countries that have successfully managed this interface offers important insights for Estonia, a country aiming to change its ferry fleet within harsh climatic, operational, and regulatory limits.

3.8 Revisiting the State-of-the-Art Figures 1–2 in Light of the Results

This section re-examines the pre-thesis synthesis presented in Figures Figure 1-1 and Figure 1-2 in light of the empirical results of this thesis. The purpose is to determine which propositions from the initial state of the art remain valid once confronted with measured performance and cost-aware feasibility, and which require revision for the Estonian coastal-ferry context (routes under ~5,000 GT, winter operations, and shore-power constraints). The exercise is confined to alignment versus misalignment; final cross-sectional conclusions are provided later in the work.

Figures 1-2 outlined a near-term pathway in which battery-electric/hybrid architectures would be the most credible under current infrastructure, with auxiliary combustion retained for winter and peak-load resilience. They further implied a sequencing whereby methanol could scale earlier than hydrogen, where retrofit space and class approvals allow, while hydrogen remains promising but time-dependent on bunkering safety, supply reliability, and power-density requirements. LNG was viewed as, at best, transitional for small coastal routes due to methane slip and asset lock-in risks. The synthesis also stressed that route geometry, lay-time, weather, and ice conditions would shape real-world outcomes, and that governance (Alternative Design/IGF) together with procurement design would materially influence deployment.

The empirical results substantiate and refine this picture. The Battery-Electric and Shore-Side Electricity – Technical and Deployment Viability Assessment (2024–2025) confirms that shore-charged batteries can supply a substantial share of route energy where quay power and lay-time are adequate (Table 3-10). Analysis of propulsion-load management and related measures demonstrates measurable reductions even without fuel switching Table 3-11 (Impact of Data-Driven Load Optimization). Fuel-pathway assessments sharpen the sequencing: methanol remains technically and operationally credible where space and safety cases are managed and class/IGF engagement starts early (Table 3-5 – Methanol – Technical and Deployment Viability Assessment (2024–2025)); hydrogen enters later or via targeted pilots given current constraints on safe bunkering, supply and energy density (Table 3-4 – Hydrogen – Technical and Deployment Viability Assessment (2024–2025)); HVO ja biomethane provide auxiliary/winter-resilience roles in hybrid architectures, subject to availability and emissions accounting (Table 3-7 – HVO; Table 3-8 – Biomethane); and LNG is not prioritised for <5,000 GT coastal routes under the assessed conditions (Table 3-9 – LNG). These updates are consistent with the Summary of Alternative Fuels Assessment and the thematic coverage mapping (Table 3-2; Table 3-3). For traceability from research questions to evidence and implications, see Table 3-1 – Map from research questions to publications, evidence, key findings, and implications; a consolidated overview and international perspective are provided in Table 3-12 – Comprehensive Summary of Thesis Publications and Table 3-13 – Comparative Decarbonization Dimensions: Estonia and Peer Nations.

Taken together, the updated state of the art for Estonian coastal ferries is a hybrid-electric design space in which shore-charged batteries function as the primary energy source and biofuel-capable internal-combustion engines provide resilience for winter and peak-load conditions; methanol emerges as a pragmatic mid-term option where space/class constraints are resolved; hydrogen proceeds via targeted pilots or later phases subject to bunkering safety and supply maturation; and LNG is not a priority under current small-route conditions. Operational optimization should be treated as baseline practice, while governance formalizes class partnerships (Alternative Design/IGF) with owner-side control and procurement staged for charging upgrades, battery scaling, and fuel-ready provisions.

4 Discussion

This chapter interprets the results in light of the research questions and the wider literature. For each RQ, it explains what the evidence shows, why it matters, and where the limits lie. The discussion then considers how the findings shift established narratives about small-ferry decarbonization, including the role of route profiles, cold-climate constraints, and public procurement. The chapter closes by outlining the uncertainties that remain (technical, regulatory, and economic) and how they shape the recommended transition sequence set out in Chapter 5.

4.1 Discussion: Positioning Results vs Literature

The thesis locates its findings within socio-technical transition theory and the applied shipping literature by linking route-level evidence to the Multi-Level Perspective (MLP) on how innovations diffuse through niches into established regimes. In this framing, Estonia's state-operated ferry network represents a durable regime shaped by tender rules, service obligations, and winter reliability constraints. Against that backdrop, the results show why certain options act as low-friction niches while others require regime-level change. In particular, HVO behaves as a "drop-in" niche that integrates with existing bunkering and propulsion, whereas biomethane typically enters as liquefied biogas and demands new delivery architectures and higher safety scrutiny – hence a steeper path to scale. This explains the different roles these biofuels play in the phased roadmap.

Methodologically, the work extends standard multi-criteria assessments by coupling MCDA with high-resolution ferry telemetry. While MCDA is common in environmental and energy planning, few studies integrate it with operational records from small coastal ferries. Using empirical load patterns, seasonal effects, and route specifics improves the precision and credibility of the scores and clarifies when operational optimization can substitute for early CAPEX. In that sense, the results refine rather than replace prevailing models, showing how contextual performance data sharpen decision outputs for short-sea services.

Relative to established fuel-comparison literature, the thesis contribution lies in tailoring widely used frameworks to short, frequent routes and to cold-climate performance. Prior studies provide the methodological base; the present results add route-level boundaries (charging windows, ice periods, berth compatibility) and thereby re-rank options under Baltic conditions. This helps explain why battery-electric excels on very short, grid-served legs, why methanol emerges as a mid-term candidate under handling/retrofit constraints, and why hydrogen and ammonia remain prospective pending safety codes and bunkering.

External validation from Nordic cases supports these interpretations. Evidence from Finland and Sweden indicates that hybrid-electric propulsion can meet reliability needs in sub-zero conditions when paired with shore power and appropriate redundancy. These benchmarks reinforce the thesis's near-term emphasis on hybrids and port electrification for comparable Estonian routes and help align the results with broader Northern European practice.

Finally, by focusing on public-service vessels, the thesis broadens a literature often centred on commercial fleets. The findings show how procurement cycles, budget caps, and safety certification timelines shape technology choices just as surely as life-cycle metrics do. That institutional lens clarifies why a phased approach (operational optimization and hybrids first, prospective fuels as codes and infrastructure mature) fits small, state-owned fleets under winter constraints.

4.2 Implications for Maritime Decarbonization

The findings reported here point to urgent pathways the global shipping community must pursue to mitigate climate risks. Assets become financially stranded if future rules tie them to narrow tech baselines, so regulators should pair strict standards with flexible room for innovation, and port authorities must support extensive refueling networks, while operators rethink routines that exceed normal practice. A persistent lag sits between lawmakers' ambitions and the rapid pace of viable low-carbon tools, yet shipowners can bridge that gap today by adopting proven electric, hybrid, and hydrogen, ammonia, or biomethane-powered systems.

Limiting costs and ease of implementation justify 'operational optimizations' as low-hanging fruit to capitalize on within the existing framework implementation ecosystem. Data-driven management not only contributes to enhanced emission reduction quotas but also improves ferry reliability and efficiency within a sustainability context while long-term infrastructure development remains underway.

Despite perceptions associating battery-electric ferries with exorbitant capital expenses, they yield substantial long-term value from a lifecycle cost standpoint. Up to 75% GHG emissions reductions coupled with approximately 31% lower operational costs, fuelled by reduced diesel alternatives (Otsason & Tapaninen, 2023). Simplified maintenance directly translates into lowered servicing expenses, while regenerative braking systems contribute towards cost-saving strategies central to fostering sustainable operations landscapes – green recovery and bailout efforts.

Estonia encounters severe winter conditions, which may hinder operations dependent on pure electricity. However, they may be able to utilize seasonal hybrid power on some shorter inter-island routes like Virtsu-Kuivastu, Kihnu-Munalaid, Rohuküla-Sviby, and Sõru-Triigi. Advanced retrofit approaches that embrace partial electrification enable cost-efficient early decarbonization, while waiting for infrastructure reliant on green hydrogen or ammonia to develop.

The expanded sensitivity analysis provides further critical insights that extend beyond a simple ranking of fuels. The results, presented in Table 2-4, demonstrate that the optimal decarbonization choice is highly contingent on underlying strategic priorities. A key finding is the emergence of Hydrotreated Vegetable Oil (HVO) as a uniquely robust alternative. Scoring highest in both "The Operator's Reality" (82.75) and "The Economic Case" (83.00) scenarios, and a close second in the policy-driven scenario, its performance underscores its viability as a versatile, low-risk solution capable of satisfying diverse stakeholder interests.

A critical examination of specific fuel pathways reveals further nuances. A noteworthy outcome is the performance of biomethane. While it benefits from growing local production and high GHG reduction potential, its overall ranking is constrained by a significant practical barrier captured within the 'Retrofit Feasibility' criterion. As the existing ferry fleet cannot be easily or safely retrofitted for liquefied gas fuels, its widespread adoption is mainly dependent on a capital-intensive, newbuild-oriented strategy. This contrasts sharply with drop-in fuels like HVO, which require minimal upfront investment in the existing fleet.

Similarly, the analysis highlights the highly contingent nature of the battery-electric solution. While this technology is mature and offers significant potential for zero-emission operations, its viability is fundamentally tied to massive public investments in grid infrastructure. The MCDA framework captures this weakness through a low unweighted score in the 'Infrastructure Demand' criterion. The fact that the battery-electric option achieves a competitive score of 72.00 in the “Policy-Driven Path” scenario is a direct result of that scenario’s priorities, which heavily favor high GHG reduction potential and technology readiness, while assigning a low weight to infrastructure challenges. Its score drops significantly in “The Operator’s Reality” (62.00) and “The Economic Case” (54.00) scenarios, where practical constraints and costs are emphasized. The analysis thus makes a critical trade-off explicit: the battery-electric pathway is a strong contender only if a strategic decision is made to absorb the immense infrastructural costs.

From the perspective of socio-technical transitions, the complementary positions of HVO and biomethane can be elucidated through the dynamics enshrined in the Multi-Level Perspective. HVO, classified as a “drop-in” biofuel, operates as a niche innovation that merges with the prevailing socio-technical configuration with minimal friction. It capitalizes on the prevailing bunkering infrastructure and the propulsion technology in the current fleet, such that it surmounts regime opposition and simultaneously delivers measurable reductions in greenhouse gas emissions from the outset.

In contrast, biomethane occupies a similarly salient niche on account of its local production potential and its ability to deliver deeper greenhouse gas intensity abatement. Nonetheless, it faces a substantially steeper gradient of regime inertia. As noted, its deployment in the maritime sector customarily materializes as Liquefied Biogas (LBG), necessitating the acquisition and deployment of distinct fuel delivery and propulsion architecture. Retrofitting historic passenger vessels for LBG incurs significant technical and regulatory complexity, compounded by elevated safety scrutiny. The effective scaling of biomethane, therefore, pivots on a capital-heavy orientation towards designing and commissioning new vessels, a trajectory that tests the fiscal appetite of fleet operators. Consequently, despite both biofuels occupying strategically meaningful niches, their positions within the overarching transition pathway are distinct: HVO functions as a frictionless transitional biofuel, sustaining the current hardware configuration, whereas biomethane charts a successor course directed at the next hardware generation.

4.3 Theoretical Implications

This thesis contributes to socio-technical transition theory by demonstrating how route-level constraints and public service governance influence the niche-to-regime pathway in small ferry systems. Using the Multi-Level Perspective (MLP) as a lens, Estonia’s coastal ferry network can be read as a durable regime in which procurement rules, winter reliability, and safety certification reinforce incumbent combustion technologies; niches form where shore power is available and operational data allow tighter control of propulsion (battery-hybrid modes, load optimization) (Geels, 2002). The results demonstrate that hybrids and shore-charged batteries constitute low-friction niches that can scale without immediate regime overhaul. In contrast, hydrogen and ammonia remain niche-protected options whose diffusion is contingent on new bunkering and safety regimes. This aligns with transition accounts that emphasize the co-evolution of technology, infrastructure, and regulation rather than substitution by technical merit alone (Geels, 2002).

Second, the findings refine shipping-specific decarbonization narratives by qualifying when widely cited options actually rank highest once cold-climate and lay-time constraints are considered binding. Prior comparative assessments identify promising long-term potentials, but often at an ocean-going scale (e.g., LNG and methanol as candidates; hydrogen/ammonia as vectors for deep decarbonization) (Brynolf et al., 2014; Bouman et al., 2017; Balcombe et al., 2019). Here, the Estonian context re-orders those rankings: battery-electric/hybrid moves to the front on very short, grid-served legs; methanol emerges as a mid-term option where retrofit space and class approvals allow; LNG's role is tempered by methane slip and asset-lock-in risks on sub-5,000 GT routes in winter; and hydrogen/ammonia remain prospective pending safety codes and bunkering (EMSA, 2023; DNV, 2023; Balcombe et al., 2019). This extends prior literature by specifying route-bounded feasibility windows rather than aggregate potentials.

Third, on the methods side, the work demonstrates how decision frameworks evolve when MCDA is integrated with operational telemetry. While MCDA is common in energy planning, integrating it with ferry EMS data strengthens internal validity and reveals when operational optimization can substitute for early CAPEX, bridging a gap noted in efficiency-focused studies (Johnson et al., 2013) and policy syntheses that call for better monitoring (EMSA, 2023). This helps reconcile top-down rankings with bottom-up practice: empirical load patterns, ice-season penalties, and berth compatibility become first-class criteria rather than afterthoughts. In transition terms, this is an example of niche empowerment via data – reducing uncertainty and enabling stepwise regime alignment (Geels, 2002; Johnson et al., 2013).

Collectively, these implications position small-ferry decarbonization as a managed sequence of niche consolidations (operational optimization – hybrids/shore power – fuel-ready designs) that gradually reshapes the regime under public-procurement constraints, rather than a single disruptive substitution.

4.4 Policy Alignment and Future Directions

Meaningful progress towards maritime decarbonization will not occur unless emerging technologies are matched with sound, forward-thinking policies. Estonia's draft Climate Resilient Economy Act, therefore, arrives at an opportune moment, providing a legislative platform through which rigorous, sector-specific decarbonization targets can be integrated into the country's broader environmental framework. Drawing from this study, it is recommended that lawmakers prioritize immediate investments in hydrogen, ammonia, and biomethane refueling infrastructure, while simultaneously supporting the public-financed rollout of hybrid and fully electric vessels as short-to-medium-term bridging solutions.

For these objectives to be realized, regulations must be clear and unambiguous, incentives must be aligned, responsibilities among port authorities, ship operators, and fuel providers must be well-defined, and genuine cross-sector collaboration must be institutionalized. Additionally, policy architecture should be deliberately agile, enabling rapid adaptation whenever breakthroughs occur or market dynamics shift.

In parallel with advancing technical assistance, a clear and consistent regulatory environment is essential to lower the risks that shipowners and port authorities perceive. Wang et al. (2023) maintain that global maritime law must evolve to cover new accident types associated with ammonia and hydrogen propulsion systems. Such reform should outline legally binding spill-response steps, establish port-centered emergency drills as standard training, and clarify who is liable for ecological damage caused by autonomous operations outside port limits, when vessels are moored or briefly docked with their crews momentarily disconnected from command. By embedding these elements in statute, regulators can safely broaden the operational zones for net-zero fuels and keep climate targets on track, while drafting principal legislation, such as Estonia's climate and energy initiatives, proceeds.

The research findings demonstrate a clear alignment with the core priorities of the draft ENMAK 2035 and the forthcoming Climate-Resilient Economy Act (Government of Estonia, 2024; Government of Estonia, 2025). Specifically, the proposed roadmap enhances energy security by reducing fossil fuel dependency, supports affordability through cost-stable hybrid and biofuel systems, and advances sustainability through substantial GHG reductions. Furthermore, the integration of real-time operational data mirrors ENMAK's push towards a digitized, flexible, and smart energy system (Government of Estonia, 2024).

4.5 Operational and Technical Barriers

Maritime decarbonization faces an array of operational and technical hurdles, a finding consistently corroborated throughout this study. Upgrading existing ferry fleets demands considerable capital, careful project sequencing, and dedicated dry-dock time, making retrofits both costly and logistically complex. At the same time, the wholesale adoption of alternative fuels (hydrogen, ammonia, or biomethane) is hindered by patchy refueling networks and a shortage of cryogenic or high-pressure storage facilities.

Simply removing these bottlenecks requires coordinated public and private investment in bunkering sites, clear industrial benchmarks, and universal safety standards. While such large-scale infrastructure projects have begun, their pace depends on regulatory clarity; in the interim, low-cost gains are still possible. The integration of Advanced Analytics now enables fleet operators to fine-tune voyage plans and engine settings, achieving measurable efficiencies with minimal capital investment.

4.6 Managerial Implications

This chapter synthesizes insights primarily drawn from Articles I–V, with Article I informing the MCDA framework, Article III supporting propulsion optimization strategies, and Article II contextualizing regulatory constraints. The integration across these domains forms the basis for the strategic phasing outlined in Sections 4.6–4.7.

This doctoral thesis has explored the case for decarbonizing coastal ferry transportation in Estonia, analyzing the interplay between innovation, policy frameworks, and business practices. Estonian coastal ferries are often neglected in international discussions (with small, ice-class ferries operating in short-sea environments typically receiving limited attention) within the context of international climate responsibilities and regional policy shifts, including the IMO's Initial and Revised GHG Strategies and Europe's "Fit for 55" and FuelEU Maritime packages.

Navigating this challenge requires addressing the fundamental question of how to reduce emissions from state-operated ferry fleets given rigid infrastructure constraints, seasonal operational variability, economic limitations, and subsidized fares. This challenge is approached using a sequential mixed-methods framework consisting of regulatory mapping, techno-economic modeling, granular operational telemetry, and high-frequency data analysis.

This inquiry reveals that Estonia's geographically and climatically diverse ferry network lacks a single technological pathway towards achieving decarbonization targets. Instead, bottom-line results converge on immediate shifts toward biofuels and hybrid propulsion systems, with long-range plans leaning toward hydrogen or methanol, pending the development of global supply chains and infrastructure preparedness, combined with safety certification pathways.

Answer to the central research question: Estonia can phase in coastal-ferry decarbonization by pairing immediate operational and digital optimization with phased hybridization and targeted fuel switching on routes where energy profiles, winter operations, safety certification, and charging/bunkering readiness make these options technically credible and economically sound, sequenced under EU instruments (ETS, FuelEU Maritime, EEXI/EEDI).

Of note, the real-time operational modeling results underscore the considerable short-term mitigation opportunities that can stem from non-technology measures. For example, data-driven seasonal control adaptations to propulsion-load distribution optimization can yield fuel and emission savings of up to 25% without significant capital expenditures. This finding reinforces the importance of operational and technological digital refinements in decarbonization strategies, especially for countries with multidecade fleet renewal cycles.

Additionally, Estonia is expected to create new regulations with its Climate Resilient Economy Act, which could act as a legislative lever towards the domestic maritime sustainability pivot. It also underscores that regulatory alignment should not be regarded as mere compliance, but as an enabler of strategic innovation blueprints, which drive creativity. By aligning EU policy frameworks with national instruments and accommodating pathways to novel fuel alternatives, the state can position itself as a continental leader on sensitive region-context adjustable seamark transitions.

In light of recent shifts in technology, economics, or policy, these works frame evolution in predefined adaptive trajectories instead of relying on fixed, prescriptive roadmaps framed within stringent boundaries defined by policies set in stone, timetable systems. In this way, the proposed approach supports system transformation while still achieving near-term emissions reduction goals.

Assimilating the findings reveals that Estonia's maritime decarbonization is not only attainable, but key from a strategic standpoint. It does, however, need to adhere to local realities, which respect operational information, policy guesswork, and well-informed pragmatic tiered methodologies. Port logistics, coupled with hydrogen uptake or integrating electrified national ferry systems with renewable energy planning, are examples where further research on cross-sectoral synergies could be pursued.

It is important to emphasize that the proposed decarbonization framework, including the transition phases and institutional recommendations, is presented as a conceptual and analytical tool. It does not constitute an operational or policy prescription, but is intended to inform strategic thinking under uncertainty. Future empirical validation, stakeholder engagement, and context-specific analyses will be necessary to adapt and apply these pathways in practice.

This dissertation has been framed alongside climate-responsive policies for geographically small and dispersed regions with covenants that reinforce, prompt, and advocate for data-based modular transitions informed by consistent policy dynamics on maritime energy systems, typically stressing ferries. Therefore, strengthening the literature through foresight ascertained guidance provided by actionable frameworks deepens complexity-strategic interplay, actively engaging stakeholders, which extends beyond theory.

Importantly, the thesis situates ferry decarbonization within the broader framework of Estonia's national energy and climate strategies (Government of Estonia, 2024;

Government of Estonia, 2025). By aligning operational strategies, fuel transitions, and digital optimization with the goals set out in ENMAK 2035 and the Climate-Resilient Economy Act, the research offers a ready-made sectoral contribution to Estonia's path towards climate neutrality.

5 Recommendations for Policy and Industry

This chapter distils the results into actions for Estonia's policy-makers and operators. The recommendations follow the thesis' phasing logic: start with low-hanging operational improvements and hybridization where grid access allows; scale port electrification to support repeatable short-route charging; and time large fuel shifts with the maturation of safety codes and bunkering logistics. The intent is not to prescribe a single pathway, but to give decision-makers a robust sequence of steps that can be adapted route by route.

5.1 Recommendations for Policy and Industry

In the context of this study, the following considerations are derived from the findings above, aiming to inform policy development while accounting for unpredictability. Because decarbonization pathways depend heavily on regional circumstances and no single solution works everywhere, the framework described here gives decision-makers a nimble, scenario-driven instrument that can be fine-tuned as transport corridors, capital limits, and shifting regulations change, thereby underscoring the importance of adaptive, forward-looking planning. These recommendations are intended primarily to support discussion and planning processes, and do not constitute prescriptive instructions.

- Enhancing public procurement policies could evaluate grant applications using carbon costing throughout the project life cycle, alongside traditional price metrics, which would motivate lower emissions technologies.
- One possible starting point could be the retrofitting of short-haul routes, where preliminary analyses suggest that investment returns may materialize more quickly.
- Crew training aids and telemetry systems may improve real-time data monitoring, responsiveness, and optimize propulsion load adjustments, dynamically adjusting operational loads in real time.
- Electrification of ports (mainly for state-owned terminals), where integration of intermittent renewable sources is technically possible, could be implemented first.
- Collaboration between other public or private stakeholders might help share the risk associated with financing, charging, or bunkering infrastructure deployment.

As ENMAK transitions from draft to law and the Climate-Resilient Economy Act is finalized, continued dialogue between the maritime sector, policymakers, and energy planners will be critical (Government of Estonia, 2024; Government of Estonia, 2025). This collaboration can ensure that ferry decarbonization efforts are fully embedded in Estonia's formal climate and energy governance frameworks, maximizing synergies and minimizing policy gaps.

Estonia should deliberately tie its own plans for new maritime fuels to existing, regionally ambitious initiatives. Although flagship programmes such as the Green Shipping Corridors and BalticSeaH2 focus initially on long-haul routes (including the Southern Finland-to-Estonia link), they matter for the coastal ferry network in an important, if indirect, way.

By serving as nationwide living laboratories, these endeavors spur the construction of bunkering facilities for hydrogen and methanol at major ports. That infrastructure then acts as an anchor supply point from which greener fuels can trickle out to the smaller regional harbours serving coastal vessels. At the same time, the certification and regulatory work needed for the first alternative-powered megaships builds local know-how, writes safety standards, and thereby eases the future arrival of zero-emission ferries on shorter runs. Investing in the large corridors thus becomes a forward-looking step toward the post-2035 decarbonization target of Estonia's public ferry fleet.

5.1.1 Relevance of International Benchmarking for Estonia's Policy Choices

As stated in Section 3.6, the international benchmarking comparison conducted has relevance to this thesis and provides further reasoning towards the identified plausible decarbonization pathways for Estonia's ferry fleet. Having Finland and Sweden as reference countries due to their comparable climate, geography, and operations allows drawing strategic lessons that would validate the recommendations posed in this thesis.

The case of Finland and the hybrid-electric ferry Elektra is pertinent, especially with its deployment since 2017. The ferry operates on a short 1.6 km route between Parainen and Nauvo in the Turku archipelago. Elektra features a large battery bank paired with a diesel-electric backup system. During frequent 5–7 minute stops to load and unload passengers, batteries are recharged via shore power, showcasing efficient integration between vessel propulsion systems and port infrastructure that enables low-emission operations with minimal emissions. Elektra is kept in year-round service despite harsh ice conditions during winter, because the diesel generators provide necessary redundancy as well as ice navigation support. Publicly available technical descriptions and case materials report substantial operational CO_2 reductions for Elektra relative to conventional diesel configurations, attributable to shore-powered battery operation with diesel-electric redundancy. The magnitude of reduction is route- and method-dependent, and should be interpreted with the stated assumptions on load, ice conditions, and grid electricity mix (Deltamarin, n.d.; Finferries, 2017; Danfoss, 2020). From a Nordic perspective, electrical propulsion with backup engines has proven operational reliability and technical viability, demonstrated by the ferry's performance. The case of Sweden continues to build the evidence base. There, Trafikverket, the national ferry operator, has undertaken a multi-year project to transition domestic ferry routes toward electric and hybrid-electric propulsion, retrofitting or replacing vessels in line with sustainability goals. Their approach emphasizes not only decarbonization of vessel propulsion, but also smart port infrastructure automation that includes automated shore-charging systems, battery storage integrated with renewable energy sources, and grid optimization for charging renewables. The Swedish strategy showcases the interplay between essential elements needed for successful maritime decarbonization: "Ship systems synchronization," development of port-side assets, and regulations all need simultaneous advancement.

From an Estonian vantage point, both Finland and Sweden provide important comparative insights. These countries share extreme geographical challenges, sub-zero temperatures, sea ice, and complex multi-island logistics. Their ability to implement hybrid-electric solutions under such conditions confirms that Estonia's cautionary/progressive approach, prioritizing hybridization supported by batteries and gradual port electrification, is indeed widely documented. Certainly, the benchmarks justify assigning foremost importance to plug-in hybrid options for near-term new builds and mid-life retrofits to the state fleet. These approaches present a transitional pathway balancing technical maturity and degree of decarbonization impact, while reducing service disruption risk during ice-prone months.

In addition, international benchmarking highlights the gaps in alignment with a policy. Finland and Sweden have both gained from the strong public funding systems and national policies that enable the renewal and innovation of fleets. In Estonia's case, achieving similar outcomes would require designing the forthcoming Climate Resilient Economy Act to actively subsidize not just the construction of low-emission vessels, but also cold ironing, port energy retrofits, hydrogen-ready designs, as well as other ancillary investments.

Encouragingly, benchmarking reinforces conclusions drawn about LNG rapidly losing favor as a transitional fuel for electric or hybrid-electric alternatives. This is largely attributed to the growing availability of advanced battery systems, more stringent GHG regulations, and increasing scrutiny on methane slip. Estonia's current strategic decision to refrain from sustaining any major investments in new ferry construction aligns with the global trend that justifies opposing large-scale LNG infrastructure development.

In summary, it was noted once again that overseas studies furnish ample evidence to support the central premise of the Estonian thesis: The decarbonization effort on Estonia's coastal ferry fleet is best achieved through an adaptive incremental approach.

5.1.2 Strategic Considerations Regarding Hybrid-Electric Systems for Estonian Coastal Ferries

According to the international experience presented in this thesis, hybrid-electric propulsion systems, especially plug-in systems, can significantly reduce emissions from Estonia's coastal ferry operations. These systems are operationally reliable and ease the adoption of dual-fuel options, where vessels that rely solely on batteries would be seasonally restricted due to ice and cold weather.

In addition to mainline ferry routes, the strategic role of hybrid-electric systems is particularly relevant for small island services analyzed in Article IV. Routes such as Munalaid-Kihnu and Laaksaare-Piirissaar exhibit operational profiles that differ significantly from the larger inter-island corridors. These routes typically involve lower passenger volumes, shorter sailing distances, and more constrained port infrastructure. As shown in the operational model developed in Article IV, decarbonization strategies for such routes must integrate service-level flexibility, seasonal demand variability, and port-level grid constraints. Therefore, the adoption of scalable hybrid systems (especially those with modular battery configurations) offers a technically and economically feasible pathway to extend decarbonization benefits beyond mainline services, while respecting the unique constraints of Estonia's peripheral maritime regions.

There is potential for existing diesel-powered vessels to be converted into hybrids during benchmarks, like mid-life upgrades or tonnage renewal cycles. Likewise, incentivising new builds to integrate prospective hybrids into design specs would ensure compatibility with shore power systems. This supports overarching EU policies and aligns with Estonia's climate goals under the intended climate energy initiatives.

Given the direct nature of many Estonian ferry lines, such as Virtsu-Kuivastu or Rohuküla-Sviby, these routes have potential as initial deployment test beds, tempered by attractive fundamentals for immediate implementation. However, overarching vessel duty cycles, energy price dynamics, port electricity access, and others must be considered in detailed cost-benefit analyses beforehand. It cannot be assumed that hybrid systems are a one-size-fits-all solution, but they can be implemented in the short term to enable operational flexibility while achieving significant reductions in GHG emissions. Innovations in zero-emission fuels or storage technologies could provide more advanced alternatives in the future.

5.1.3 Supporting Role of Port Electrification and Cold Ironing Infrastructure

To properly implement low-emission ferry systems, adequate ferry shore-side infrastructure must be developed, and proper vessel technologies must also be deployed. Without sufficient port-side electricity capacity, the potential benefits of hybrid or electric propulsion cannot be fully realized. Hence, cold ironing and similar infrastructures should be prioritized within Estonia's maritime spatial planning frameworks.

Gradually outfitting key ferry terminals with cold ironing connections can maximize environmental benefits while minimizing emissions at heavily utilized environmental hotspots. In some cases, grid-constrained islands may obtain greater resilience and emissions benefits through renewable energy or battery-buffered systems at ports during peak demand periods.

Consideration could be given to implementing automated charging systems, which are already operational in several Nordic Ports as part of infrastructure development in Estonia. Similar to these systems, existing EU funding mechanisms or frameworks based on carbon revenue might partially cover the costs of such investments.

As stated in the first section, no one solution fits all cases; hence, a flexible approach will yield better results than inflexible adherence to a set plan. As for Estonia, there is a high possibility that solutions leveraging emerging technologies would enhance cost performance much more than traditional approaches focused on full compliance with predetermined criteria for infrastructure development.

Electrification of ports should be understood as part of an overarching decarbonization strategy supporting the evolution of vessel technology and regulatory frameworks alongside energy systems planning.

Port and grid readiness assessments were conducted at a general level, drawing on national reports and sector overviews. A detailed site-specific engineering analysis for individual Estonian ports was beyond the scope of this thesis and remains a task for infrastructure owners and operators.

5.2 Future Research and Development Needs

This section is intended for academic and applied research teams, national and EU funding bodies, the Estonian contracting authorities, publicly owned or contracted ferry operators, port and terminal authorities, shipyards, classification societies, and technology suppliers considering pilots on domestic routes.

The following areas are identified for future research and development:

- Complete life-cycle emissions analysis. Regional, scenario-specific well-to-wake LCA models for hydrogen and ammonia should be developed (e.g., Estonian wind vs. imported green ammonia pathways).
- Battery system innovation. Solid-state and cold-climate-optimized lithium-ion systems should be investigated for sub-Arctic ferry operations.
- Resilience and safety in ice conditions. Hybrid-electric propulsion solutions should be designed and tested to address hull-ice interaction challenges, with initial trials conducted in the Gulf of Riga.

- Monitoring of carbon capture and storage (CCS). Although CCS is currently unfeasible for small coastal ferries, technological progress should be monitored for potential long-term applicability if onshore CO_2 handling infrastructure emerges.
- Human-machine systems. Ergonomic aspects of decision aids and telemetry interfaces should be evaluated, and operator interaction protocols refined to support the uptake and efficiency of these systems.

Furthermore, future research activities should be strategically aligned with existing European Union programs that support maritime decarbonization and the deployment of clean technology. The Horizon Europe Mission "Restore our Ocean and Waters by 2030" promotes large-scale demonstrators in the Baltic Sea region, focusing on innovations in coastal transport and port electrification (European Commission, 2023a). In parallel, the FuelEU Maritime Regulation provides a binding legal framework and financial mechanisms for implementing renewable and low-carbon fuels, while reinforcing lifecycle-based compliance structures (FuelEU Maritime, 2023). Estonia's participation in the BalticSeaH2 hydrogen valley initiative establishes a cross-border platform for piloting hydrogen applications in maritime settings, including port-to-vessel integration, energy storage, and regulatory coordination (BalticSeaH2, 2024; BalticSeaH2, 2025). Aligning national-scale experimentation with these EU-level initiatives will enhance Estonia's research visibility, facilitate access to co-funding opportunities, and expedite the validation of scalable, low-emission solutions.

5.3 Indicative Transition Phases for Maritime Decarbonization in Estonia

The inclusion of time-bound phases in this doctoral thesis is both methodologically deliberate and strategically aligned with the real-world context in which maritime decarbonization is expected to unfold. It is crucial to emphasize that these indicative transition phases for maritime decarbonization in Estonia are flexible and adaptive frameworks, rather than rigid prescriptions. While it is correct that any attempt to forecast future developments in a fixed, deterministic way carries risk (especially in a dynamic and uncertain policy and technology landscape), these indicative timelines serve a different and necessary function in this research.

In the context of maritime policy, fuel technology readiness, and public-sector investment cycles, time phasing is not merely a speculative exercise but a core tool of scenario-based planning and feasibility structuring. It provides both a strategic logic and a practical anchor to interpret complex decisions over time. The inherent flexibility of these phases, particularly when adapting them to other regions, necessitates the explicit consideration and integration of local parameters. This includes, but is not limited to, region-specific environmental conditions (e.g., severe ice conditions, shallow waters), port infrastructure particularities (e.g., shore power availability and grid capacity), local regulatory nuances, and economic factors. Therefore, the framework's adaptation necessitates the input of these specific data points into the decision-making process to ensure the feasibility and relevance of the proposed solutions within a given context.

First, these time horizons are directly derived from binding national and international policy instruments, including the EU's Fit for 55 climate package (targeting 55% emissions reduction by 2030), the FuelEU Maritime Regulation (entering into force in 2025), and the IMO's Revised Greenhouse Gas Strategy (targeting net-zero emissions by or around 2050). Estonia's draft Climate Resilient Economy Act adds national sectoral milestones, including a 70% transport sector reduction target by 2040 and net-zero by 2050. These legal and regulatory frameworks create hard milestones that ferry operators, infrastructure planners, and policymakers must work toward. Designing a decarbonization roadmap without reference to these enforced time anchors would significantly diminish the relevance of the proposed framework.

Second, indicative phasing enables effective differentiation of technological maturity. Near-term deployable options (such as HVO, battery-electric hybrids, and compressed biomethane) are technically viable today and align with the infrastructure and safety standards already in place. Conversely, zero-carbon fuels like green hydrogen and ammonia, though promising in terms of lifecycle GHG potential, still face substantial barriers related to bunkering safety, vessel retrofitting, fuel cost, and regulatory clarity. These fuels are therefore positioned in a later phase (post-2035), contingent upon further technological and institutional development. Without temporal separation, there is a risk of presenting all options as equally viable today, which misrepresents practical constraints.

Third, public procurement processes, especially in small-state contexts such as Estonia, require long-term planning horizons. Infrastructure projects related to electrified ports, bunkering upgrades, and vessel retrofits must be integrated into multi-year budget cycles. The use of indicative timelines, therefore, facilitates investment pacing, risk mitigation, and alignment with EU funding instruments (e.g., CEF, Horizon Europe), making the proposed roadmap not only technically coherent but also financially actionable.

The use of year ranges such as 2025–2035 or 2035–2050 is explicitly not meant to imply strict deadlines or immutable predictions. Rather, these phases are conceived as scenario-based planning windows – adaptive frameworks that reflect today's best-available knowledge and allow decision-makers to sequence investments in accordance with evolving conditions. This approach also corresponds with methodologies used in strategic foresight, where horizon scanning and milestone mapping are common tools to guide transition management under uncertainty.

In sum, the phased timeline model used in this thesis serves four core functions:

- Anchoring technology adoption to legally binding climate targets;
- Differentiating between mature and emerging solutions;
- Supporting structured investment and infrastructure planning; and
- Maintaining flexibility through scenario-based rather than deterministic framing.

It is acknowledged that future conditions may diverge from current expectations; however, omitting timelines altogether would undercut the operational realism and policy alignment of the decarbonization framework. The inclusion of indicative years is therefore not only justified but necessary for building a strategy that is at once forward-looking, policy-aware, and pragmatically staged.

The following phases are presented as possible development pathways, not as fixed or predetermined action plans.

5.3.1 Phase 1: 2025–2035 – Tactical Integration of Hybrid Systems, Biofuels, and Port Electrification

This phase focuses on low-hanging technologies that can be implemented with minimal system changes and provide significant reductions in GHG emissions. Diesel vessels currently operating on Estonian routes can be upgraded to plug-in hybrid systems with battery modules and diesel or biodiesel generators, which would serve as supplemental power sources. Considering Estonia's short (typically 5–20 km) inter-port distances and frequent servicing, lines like Virtsu-Kuivastu and Rohuküla-Heltermaa would greatly benefit from partial or full sea-route electrification.

Alongside runoff reduction strategies, HVO and biomethane enable emission reduction in the exhaust stream, while maintaining existing fueling infrastructure. Even though they are not zero-emission solutions, these fuels work on current engines, which makes them appealing transitional options for maritime cofferdams.

This phase has concentrated objectives limited to maintenance crew training, where energy management systems will be introduced along with digital propulsion monitoring tools, telemetry-based maintenance optimization schedules, and advanced remote diagnostics powered by IoT devices, while focusing on state-controlled ports for charging system construction.

Strategic Objectives for Phase 1:

- Initiate a phased retrofitting program for the active coastal ferry fleet, with a strategic target of upgrading a significant portion of vessels with battery-diesel hybrid propulsion systems, contingent on ongoing technical and economic feasibility assessments.
- Promote the integration of biofuels, such as HVO and biomethane, into the existing supply chains, prioritizing short- to mid-range ferry routes for initial adoption.
- A key objective would be the development of a charging infrastructure, with an initial focus on key mainland ports like Rohuküla, Virtsu, and Munalaid.
- Establish a comprehensive telemetry data harvesting program across all vessels on public transport routes to create a robust baseline for ongoing optimization.
- Develop and implement digital training modules for crews, focusing on fuel optimization and load management, particularly for cold-weather operations.
- Foster collaboration with classification societies to develop and formalize a national standard for hybrid retrofitting, ensuring safety and interoperability.

5.3.2 Phase 2: 2035–2050 – Strategic Adoption of Hydrogen and Methanol Technologies

This phase initiates a shift to next-generation fuels that promise full decarbonization. Although currently limited by infrastructure and regulation, these fuels hold substantial long-term promise. With advancements in the production of green hydrogen, fuel cell systems, and renewable methanol synthesis, it appears early adopters may be able to integrate these solutions into purpose-designed vessels by 2035. The inclusion of hydrogen and ammonia in this strategic deployment phase (2035–2050) reflects the political ambition to achieve full decarbonization, acknowledging the need for significant advancements in R&D, the establishment of robust safety standards, and extensive infrastructure development. This timeline is thus a vision guiding long-term investments and scientific efforts, rather than a fixed, predictive roadmap. Pilot projects and scientific advancements are already underway, demonstrating early feasibility, such as the MF Hydra in Norway, the world's first hydrogen-operated ferry. Similarly, Maersk's ECOETA design in the cargo sector sheds light on emerging marine technologies that could be adapted for passenger ferries in the future.

For Estonia, this could mean the employment of newbuild ferries intended for hydrogen or methanol use on longer or less infrastructure-constrained routes. This would necessitate phased investments toward bunker infrastructure, revised safety regulations, and cooperation with class societies for alternative fuel system certification under ice-class operational conditions.

These considerations will likely coincide with some revisions to EU or IMO policy instruments designed to enable further adoption alongside stricter emissions caps, cap-and-trade systems, or even carbon intensity limits. Regulatory foresight combined with fiscal flexibility will be crucial to capitalize on opportunity space while fully mitigating risk during implementation.

Strategic Objectives for Phase 2:

- Plan for the strategic introduction of zero-emission newbuilds, with a plausible target of commissioning up to three vessels utilizing compressed hydrogen or methanol, focusing on longer-range routes as technology matures.
- Support the development of dedicated bunkering infrastructure, with a long-term goal of establishing terminals in key hubs like Saaremaa and Tallinn by 2040.
- Integrate zero-emission thresholds into public procurement, making them a mandatory criterion for all new ferry tenders issued after 2035.
- Implement mandatory lifecycle assessment (LCA) certification for all fuel supply chains and propulsion systems to ensure genuine sustainability.
- Set a strategic target to transition a majority of the fleet to technologies meeting or exceeding Tier III emission standards.
- Actively pursue and promote participation in EU-funded pilot projects (e.g., Horizon Europe) to accelerate the integration of advanced technologies like fuel cells.

As posited by Balci et al. (2024), Estonia might consider a phased approach towards ammonia adoption that includes (1) ammonia pilot testing on a small auxiliary vessel, followed by (2) crew training alongside safety system implementation, and finally (3) gradual incorporation into medium-sized ferry engines after 2040. This pathway underscored the importance of technical readiness, in terms of infrastructure and safety pedagogy, prior to widespread implementation. Emphasizing early-stage ammonia deployment, Balci et al. underscored the need for modular retrofitting kits and dual-fuel engines to enable risk mitigation along with operational adaptability.

5.3.3 Phase 3: 2025–2050 – Ongoing Operational Optimization and Digital Integration

Enhanced operational efficiency represents another area where targeted work during previous phases could yield significant improvements to ferry efficiency and emissions through advanced practices such as real-time load balancing for propulsion using predictive analytics, machine learning driven weather routing, scheduling in accordance with renewables availability, among others, and adaptive scheduling aligned with renewable electricity supply.

The implementation of SCADA (supervisory control and data acquisition) systems along with interoperable port-vessel communication systems can facilitate intelligent dispatching, aid in minimizing idling emissions, and optimize charging periods in congruence with grid requirements. Furthermore, seasonal modifications such as hull load forecast algorithms and ice-drag estimation algorithms can assist in improving efficiency during the harsh winters of the Baltic region.

Although these digital systems might not be alternatives to structural propulsion changes, they greatly improve multi-dimensional system effectiveness while achieving environmental and economic benefits. Additionally, data collection frameworks allow ferry operators to embed routine operations that foster long-term environmental decisions that promote sustainable innovation.

Strategic Objectives for Phase 3:

- Integrate predictive maintenance platforms across all retrofitted and new vessels to enhance reliability and efficiency.
- Establish continuous monitoring of key performance indicators (including propulsion load, wind resistance, and hull condition) using advanced telemetry.
- Develop dynamic operational templates for summer and winter seasons based on historical telemetry and Automatic Identification System (AIS) data to standardize best practices.
- Create a framework for coordinated emissions and energy reporting to provide transparent data for port authorities and regulators.
- Set a long-term ambition for AI-driven route and logistics optimization by 2045 to maximize system-wide efficiency.

For clarity, Phase 3 is a recent operational/digital workstream that runs in parallel with Phases 1–2 over 2025–2050, supporting both with monitoring, optimization, and risk management.

5.4 Institutional and Regulatory Recommendations for Estonia

Based on the previous analysis alongside Nordic countries and European Union regulatory frameworks, there are several institutional strategies that will allow Estonia to aid the decarbonization of maritime emissions more effectively from a technical and legal perspective. The following institutional recommendations are presented as research-based insights intended to inform policy dialogue and practical discussions. Any real-world implementation would require further study and close consultation with relevant stakeholders.

Estonia might look into formalizing delegation agreements with classification societies such as DNV or Lloyd's Register. Although collaborations with Recognized Organizations are in place, resolving transparent EU-compliant 'delegation' frameworks (per Directive 2009/15/EC) could augment legal certainty and streamline processes. This would allow classification societies to perform technical evaluations over hydrogen propulsion systems, ammonia fuel storage, battery electric systems, and shore-side charging infrastructure, among others, while guaranteeing the Estonian Maritime Administration's jurisdiction over the final certification and enforcement decision.

As a flag state, Estonia could consider focusing more on the flag-state surveyor and inspector's specialized technical training. An unconventional propulsion system assessment features non-conventional propulsion systems, such as fuel management safety in cryogenic temperatures, ammonia handling, thermal battery management in frigid climates, and high-voltage charging systems, which require specialized skills. Cooperation with authorities like the Norwegian Maritime Authority or the Swedish Transport Agency could provide learning opportunities through joint audits or knowledge transfer that improve Estonia's competence in regulatory development for these matters.

There is also room for contextual policy and technical work within the establishment of multi-stakeholder technical working groups. Representatives from ferry operators, port authorities, energy companies, and classification societies can work together to write operational protocols suitable for Estonia's geography and infrastructure. This might include procedures like shore-charging in ice-class ports and retrofit procedures for hybrid vessels geared towards winter operations.

Fourth, Estonia stands to gain from participating in international forums that deal with maritime regulations, such as the International Maritime Organization (IMO), as well as the European Commission's FuelEU working groups on alternative fuels and regulatory meetings. By actively participating in rulemaking processes, Estonia would assist in meeting the operational requirements of short-distance ice-class ferry systems in global decarbonization policies.

To conclude, the advancement of technology certainly accelerates the process of decarbonizing maritime operations and activities; however, it needs to be matched by a worldview shift. Estonia will be able to utilize sustainable maritime technologies while ensuring safety and effectiveness compliant with EU and IMO goals if it adapts its policies and administrative structures to evolving regulations and country practices among peers.

These institutional recommendations are also intended to inform the forthcoming Climate Resilient Economy Act and ENMAK 2035, currently under development in Estonia. The phased transition model, policy-technology alignment principles, and public procurement considerations outlined in this thesis provide a ready-to-use foundation for drafting the implementing provisions of the Act. Specifically, the framework supports integration of technological feasibility assessments, fuel lifecycle criteria, and infrastructure dependencies into national-level regulatory instruments. By aligning academic insights with legislative design, the recommendations facilitate a more coherent and adaptive decarbonization pathway for Estonia's public ferry fleet, while ensuring compliance with EU maritime directives.

While this dissertation offers practical insights tailored to Estonia's public ferry fleet, it is essential to frame these recommendations within a broader academic and exploratory context. It is important to emphasize that the proposed decarbonization framework, including the transition phases and institutional recommendations, is presented as a conceptual and analytical tool. It does not constitute an operational or policy prescription, but is intended to inform strategic thinking under uncertainty. Future empirical validation, stakeholder engagement, and context-specific analyses will be necessary to adapt and apply these pathways in practice.

While this framework is tailored to Estonia's state-run ferry context, the underlying methodology and MCDA structure can be adapted for use in other small and medium-sized ferry systems, particularly in Northern Europe and North America, where similar climatic and operational conditions apply.

Estonia's forthcoming fairway dues reform represents an important policy tool for incentivizing decarbonization in the commercial shipping sector; however, it does not apply to public-service coastal ferries, which operate under specific exemptions granted by the Ports Act. This limitation highlights the need for complementary public mechanisms, such as targeted investment support, environmentally conditioned procurement rules, and dedicated retrofitting programs, to ensure that national and EU decarbonization goals are effectively implemented across all segments of the maritime sector.

6 Conclusions and Future Work

This thesis addressed the question of how Estonia's coastal ferry fleet can be decarbonized in a technically credible and cost-effective manner, navigating the constraints of existing infrastructure, regulatory uncertainty, and the demanding operational environment of the Baltic Sea. The research was guided by a sequential mixed-methods framework that integrated regulatory mapping, techno-economic modelling, and empirical analysis of high-frequency vessel telemetry data. The core finding is that a successful transition depends not on a single technological solution, but on a portfolio approach that is sequenced over time and tailored to the specific profiles of different routes.

Positioning against prior research
A key contribution of this dissertation is to present route-specific results alongside earlier comparative work. Prior reviews have found that several fuels can be viable in principle, with rankings being sensitive to methane slip, upstream emissions, and infrastructure path dependency (Brynolf et al., 2014; Bouman et al., 2017; Balcombe et al., 2019; DNV, 2023; EMSA, 2023). The present evidence supports that picture, but reorders priorities for Estonian coastal ferries: battery-electric and hybrid, where quay power and lay-time allow; a cautious view on LNG for small, ice-class routes; and targeted methanol pilots where space and class constraints can be met. Telemetry-informed optimization provides measurable reductions now and prepares the system for higher electric shares, while hydrogen and ammonia remain longer-term options pending safety and bunkering maturity (Johnson et al., 2013; EMSA, 2023).

The results indicate that the most immediate and cost-effective emission reductions can be achieved through operational and digital optimization, such as data-driven propulsion load management, which can lower fuel consumption without requiring significant capital investment (Johnson et al., 2013; EMSA, 2023). For the medium term, the analysis supports a phased introduction of hybrid-electric systems and the use of sustainable biofuels, with biomethane being particularly notable due to its local production potential in Estonia, alongside readily available drop-in fuels such as Hydrotreated Vegetable Oil (HVO). Looking toward the post-2035 horizon, the framework identifies green hydrogen and methanol as viable long-term candidates, contingent on crucial developments in bunkering infrastructure, safety protocols, and regulatory frameworks. This phased strategy provides an adaptive roadmap that aligns with the evolving timelines of international (IMO), European (EU ETS, FuelEU Maritime), and national (Climate Resilient Economy Act, ENMAK 2035) climate policies, offering a practical pathway for Estonia to meet its decarbonization targets while ensuring the continued reliability of its essential island transport services.

Principal Findings and Contributions
This thesis was structured to answer four specific questions, the answers to which form the principal contribution of this thesis.

The first research question (RQ1) asked: What regulatory drivers from the International Maritime Organization, the European Union, and Estonian climate and energy initiatives shape the transition pathways for Estonia's public ferry fleet? The analysis revealed that while Estonia's coastal ferries often fall below the tonnage thresholds of major international regulations, they are indirectly but powerfully influenced by them through fuel costs, funding criteria, and public procurement standards. Furthermore, national legislation, including the forthcoming Climate Resilient Economy Act, creates a direct mandate for decarbonization. A key finding is that high-level policy ambition is insufficient on its own; its success hinges on the alignment of procurement logic, port readiness, and safety certification at the operational level, highlighting a critical gap between policy goals and practical implementation.

The second research question (RQ2) was: What are the comparative techno-economic and operational trade-offs of key alternative fuel options under Estonian conditions? Through a multi-criteria decision analysis (MCDA) tailored to the Baltic context, the thesis determined that battery-electric propulsion is the optimal solution for short, high-frequency routes with access to shore power. For the existing fleet, HVO and biomethane present the most feasible near-term options due to their compatibility with current engines and infrastructure. Methanol is identified as a viable mid-term fuel, while hydrogen and ammonia are positioned as long-term strategic options, pending significant advances in technology and infrastructure. This context-specific ranking, which accounts for cold-climate performance and TRL, is a central contribution to the literature on short-sea shipping.

The third research question (RQ3) asked: How can real-time operational optimization improve energy efficiency and enable low-emission technologies? The analysis of high-resolution telemetry data from an Estonian ferry demonstrated conclusively that data-driven practices (such as balanced engine loading and seasonal tuning) yield measurable reductions in fuel consumption and GHG emissions without requiring hardware modifications. This finding validates operational optimization as a rapid and low-cost initial step in any decarbonization strategy, serving as a critical bridge that allows for immediate action. At the same time, longer-term investments in new fuels and technologies mature.

Finally, the fourth research question (RQ4) aimed to develop an integrated strategic framework for phased decarbonization that supports context-sensitive decision-making for public ferry operations. By synthesizing the findings from the regulatory, technological, and operational analyses, the dissertation delivered a phased and route-specific roadmap for 2025–2050. This framework sequences actions logically: beginning with operational gains, progressing to hybridization and shore power investments, and culminating in the adoption of zero-emission fuels as the necessary supporting ecosystem develops. This integrated plan serves as a practical decision-support tool for policymakers and fleet managers, providing a playbook that aligns technological feasibility with procurement cycles and port development realities.

Limitations and Future Research

This thesis was deliberately scoped to ensure focus and feasibility, and it is important to acknowledge its boundaries, which in turn highlight productive avenues for future research. The empirical analysis relied on telemetry data from a limited portion of the fleet, and the MCDA weightings were assigned by the researcher, although tested for robustness through sensitivity analysis. Furthermore, the economic assessments focused on technical costs, excluding dynamic market factors like carbon pricing or subsidies, and performance estimates for future fuels in cold climates were based on simulations rather than local pilot trials.

These limitations highlight the need for future research. First, there is a clear need for pilot-scale demonstration projects in the Baltic Sea to test hybrid, battery, and, eventually, methanol and hydrogen systems under real-world winter conditions. Such trials would provide invaluable data to validate models and inform the development of safety protocols and classification standards. Second, future work should involve participatory MCDA processes, engaging stakeholders from government, industry, and civil society to develop a shared understanding of priorities and criteria weights. Third, expanding the operational dataset to include multi-year telemetry from the entire fleet would enable more robust validation of the optimization models across different vessel types and routes. Finally, future research should develop integrated techno-economic models that incorporate market mechanisms and policy incentives to provide a more comprehensive assessment of the total cost of ownership for different decarbonization pathways.

In conclusion, this dissertation argues for a pragmatic and sequenced transition toward a decarbonized coastal ferry fleet. By starting with operational efficiencies, leveraging readily available biofuels like biomethane and HVO, strategically deploying hybrid and electric technologies where infrastructure permits, and phasing in next-generation fuels as they mature, Estonia can create a clear and actionable path forward. This approach transforms the complex challenge of decarbonization from an abstract technological debate into a manageable program of actions that can be implemented, monitored, and adapted over time.

List of Tables

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Abstract

Decarbonization Framework of Estonian Coastal Ferries

This dissertation examines how a medium-sized public ferry fleet operating in a cold-climate coastal environment can decarbonise credibly and cost-effectively under evolving EU regulation. This thesis expands on related articles co-authored by Laasma and colleagues (2022, 2024, 2025) by applying multi-criteria decision analysis to maritime fuel choice and by analyzing vessel telemetry datasets to quantify the emission-reduction potential of the identified strategies. The empirical backbone combines multi-year operational and telemetry data with modelling and life-cycle considerations to compare the technical and policy feasibility of alternative fuel and retrofit pathways. The work situates fleet-level choices – fuels, hybridization, and digital/operational optimization – within constraints specific to northern waters (ice conditions, short routes with tight turn-arounds, reliability and safety) and the European rule set (ETS, FuelEU Maritime, EEXI/EEDI).

Findings show that decarbonization is a portfolio problem: near-term reductions are delivered primarily through operational and digital measures (e.g., propulsion control and scheduling that cut fuel use without compromising service). In contrast, fuel switching and hybrid retrofits can be phased on routes whose energy profiles and supply chains allow. The analysis clarifies trade-offs between climate benefits, costs, technical risks, and regulatory compliance. It explains when options that look promising on paper become impractical aboard smaller vessels in winter operations. Theoretically, it contributes a decision-analytic framework that integrates life-cycle climate performance, operational feasibility, and regulatory compliance, formalizing a portfolio view of decarbonization and specifying boundary conditions for small, cold-climate ferry operations. Beyond the Estonian case, the framework generalizes to similar public fleets in northern Europe and informs procurement and policy sequencing.

Lühikokkuvõte

Eesti rannasõidu parvlaevade dekarboniseerimise raamistik

Käesolev doktoritöö otsib vastust lihtsale, kuid sama keerukale küsimusele: kuidas saab keskmise suurusega rannasõidu parvlaevandus külma kliimaga rannikuvetes vähendada oma kliimamõju nii, et teenuse kvaliteet ja töökindlus ei kannataks ning kulud püsiksid mõistlikud? Fookuses on Eesti riigi parvlaevad ja nendega sarnased alused Põhja-Euroopas, mida korraga mõjutavad nii tegevuskeskkonna iseärasused (lühikesed liinid, lühikesed peatusajad sadamas, talvine jää) kui ka kiiresti arenev EL-i regulatsioon (ETS, FuelEU Maritime, EEXI/EEDI).

Töö laiendab autori ja kaasautorite 2022., 2024. ja 2025. aasta artikleid kahel viisil. Esiteks rakendatakse mitmekriteeriumilist otsustusanalüüsi (MCDA) merenduse kütusevalikule, hinnates alternatiive mitte ainult kliimamõju, vaid ka ohutuse, tarneahela, tehnilise valmisoleku ja kulude vaates. Teiseks ühendatakse laevade telemeetria- ja operatiivandmestikud (sh AIS ja pardamõõtmised) modelleerimise ja elutsüklilise vaatega (LCA), et kvantifitseerida tuvastatud strateegiate tegelik heitevähenduspotentsiaal. Empiiriline selgroog on andmepõhine: vaadeldakse nii liinide energiaprofiile kui ka laiemat mustrit ning seotakse see otsustuspõhise raamistikuga.

Peamised järeldused on kahetised. Esiteks on dekarboniseerimine portfelliprobleem: lühikeses plaanis annab suurima ja kiireima mõju operatiivne ja digitaalne optimeerimine – eeskätt propulsiooni ja kiiruse juhtimine, täpsem graafik, manööverdamise harjumused ja muu töökorraldus, mis langetab kütusekulu teenust ohverdamata. Teiseks on alternatiivkütused ja hübriidlahendused realistlikud etapiviisiliselt nendel liinidel, kus energia- ja tarneahela profiil seda lubab (nt laadimistaristu, ohutusriskid talvetingimustes, hooldusvõimekus). Analüüs selgitab kompromisse kliimamõju, kulu, tehnilise riski ja regulatiivse vastavuse vahel ning toob esile piirtingimused, mille juures „paberil hea" lahendus osutub väiksematel alustel talvel ebapraktiliseks. Kokkuvõtlik vastus kesksele uurimisküsimusele on järgmine: Eesti saab liikuda edasi astmeliselt, ühendades viivitamatud operatiivsed ja digitaalsed täiustused etapiviisilise hübridiseerimise ja sihitud kütusevahetusega nendel liinidel, kus energiaprofiil, talvetingimused, ohutusnõuded ning laadimis- või tankimistaristu valmisolek seda võimaldavad, ning ajastades investeeringud ja hanked kooskõlas EL-i raamistikuga (ETS, FuelEU Maritime, EEXI/EEDI).

Teoreetiline panus on otsustus-analüütiline raamistik, mis seob elutsüklilise kliimatulemuse, operatiivse teostatavuse ja regulatiivse vastavuse. Raamistik formaliseerib portfellivaate väikese ja keskmise mastaabiga rannasõidu parvlaevanduse dekarboniseerimisele ning täpsustab piirtingimused (jää, peatusaeg sadamas, ohutus), mille raames tehnoloogiad on päriselt rakendatavad. See aitab vältida nii alainvesteerimist (liiga vähe, liiga hilja) kui ka üleinvesteerimist (valesse tehnoloogiasse valel liinil).

Praktilise rakenduse mõttes pakub töö otsustuste jadasid: alustada andmepõhise operatiivoptimeerimisega (telemeetria, KPI-d, meeskondade koolitus, töökorralduse täpsustused), jätkata liinipõhiste hübriidide ja laadimislahenduste katsetustega seal, kus profiil seda soosib, ning ajastada suuremad kütuse- või mootoriümberehitused koos taristu ja tarneahelate arendusega. Raamistik on välja töötatud Eesti juhtumist, kuid üldistub Põhja-Euroopa rannasõidu parvlaevandusele, kus keskkonna- ja töökindlusnõuded on sarnased.

Appendix 1 (Publication I)

Publication I
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sustainability

Article

Evaluation of Alternative Fuels for Coastal Ferries

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Abstract: The International Maritime Organization (IMO) and European Union (EU) have set targets to reduce greenhouse gas (GHG) emissions. Focusing on ships above 5000 GT, their measures exclude several ship types, such as fishing vessels, offshore ships, and yachts. However, smaller ships generate 15–20% of the total GHG emissions. Multiple potential fuel alternatives are already in use or have been investigated to minimize carbon emissions for coastal ferries. This study evaluates the possibility of using alternative fuels for small ferries by seven different parameters: technical readiness, presence of regulations, GHG emission reduction effectiveness (with two different criteria), capital expenditure (Capex), operating expenditure (Opex), and ice navigation ability. The assessment is based on an evaluation of state-of-the-art literature as well as second-hand statistics and press releases. The study also reports the most recent implementations in each alternative technology area. As a result, it was found that although there are several measures with high potential for the future, the most feasible fuel alternatives for coastal ferries would be fully electric or diesel-electric hybrid solutions.

Keywords: GHG emission reduction; coastal ferries; alternative fuels; low carbon

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1. Introduction

The IMO has set a target to reduce total GHG emissions from shipping by 50% worldwide, and the EU is aiming to achieve carbon neutrality in Europe by 2050 [1]. The current focus is on measures such as carbon pricing schemes (ETS) and low GHG fuel standards (FuelEU Maritime) that target ships above 5000 GT. The IMO and EU measures exclude several ship types, such as fishing vessels, tugs, offshore ships, and yachts. However, according to Armstrong [2], smaller ships generate 15–20% of total GHG emissions. This is a significant amount of CO_2 for a carbon-neutral future that should not be kept unregulated.

From a wider perspective, the IMO and EU have similar main goals, but regionally, the EU is aiming for significantly tighter regulations and span. The European Parliament's environmental committee (ENVI) voted in May 2022 to include ships of 400 GT and above in the Emissions Trading System (ETS) [3]. With this implementation, European waters are heading towards maritime decarbonization on a wide scale and the limitations also affect the coastal ferry industry.

Ferry production and operational changes are already being implemented by ship owners all over the world. It should be noted that although there are no valid requirements for smaller vessels, there is currently a need to review the requirements [4] since the market is guiding coastal ferries towards becoming carbon neutral. It can be claimed that in the coastal ferry industry, there is a chance to reduce GHG emissions and a desire and initiative is also in place. The market and trends are changing, and many potential fuel alternatives are under development or already in use by smaller crafts.

Apart from alternative fuels, other measures, including slow steaming, main engine derating, waste heat recovery, and changes in operational patterns, can be applied to decrease

CO_2 emissions. These measures are not new in the shipping industry and were initially implemented to reap benefits such as minimized operational costs and fuel consumption [5]. In addition to low GHG emissions, slow steaming has drawbacks for political reasons and its direct impact on trade [6]. Similarly, main engine de-rating has been offered by most engine producers, but also has limited use depending on the climate and ice conditions. On the other hand, engine de-rating in certain regions with warm climates creates additional GHG emission reduction possibilities [7].

In order to achieve climate goals, it is necessary to make immediate decisions when planning policies to retrofit existing fleets and build new ships.

Since the most significant effect on reducing emissions is provided by using alternative fuels, this study aims to answer the following significant research questions: What are the current alternative fuel systems for new coastal ferries in planning and under construction? Which of these systems has the most significant potential for use considering today's technical developments, legislation, ability to reduce GHG emissions, and the economic environment?

The goal of this work was to study the usability of various present-day alternative fuel systems with existing technologies or technologies in high R&D stages. The focus of the study is to analyze GHG emission reduction directly related to the ship's energy use. The origin of the fuel is not considered in this study.

Section 2 presents the work of Lindstad et al. [8], which is the basis for our analysis of coastal ferries. Section 3 presents a general overview of the ages of the vessels and possibility of using alternative fuels or other GHG emission reduction measures, as well as an overview of different alternative fuel pilot projects and an evaluation of the potential technologies that could be applied to coastal ferries. Future developments and how they can be predicted and summarized based on the ratings are discussed in Section 4. The conclusions of the study are presented in Section 5.

2. Assessment of Alternative Fuels

When comparing alternative fuels, recent studies have mainly assessed the entire life cycle of an energy carrier using the LCA (life cycle assessment) method, which covers the whole chain of use starting from fuel extraction and ending with combustion in the internal combustion engine of the ship. In the past, studies investigating the use of fuels have mainly dealt with three different stages: Well-to-Tank (WTT), Tank-to-Wake (TTW), and Well-to-Wake (WTW), the latter of which combines the first two.

Unlike the WTW method, the full LCA method also includes the construction and decommissioning of the fuel production chain. Lindstad et al. [8] mapped 22 alternative pathways for using fuels in the maritime sector and compared the qualitative and quantitative factors. Aspects were weighted based on their impact, considering that they have complex relationships with GHG emissions, technical readiness, economic profitability, safety, and industry regulations. As a result of the study, they concluded that in the short term, the most economically efficient energy usage model for reducing GHG emissions was the use of fossil fuels in combination with CCS (carbon capture system) installation, which increased costs by approximately 18% compared to conventional marine fuels. Additionally, conventional fuels with CCS and biodiesel required fewer volumes than the other alternatives and required minimal modification to the existing infrastructure. The most energy-efficient option was using electricity, which would reduce energy consumption by 27–50%. Hydrogen and ammonia needed the highest energy for production but emitted zero carbon and particulate emissions [9].

Lindstad et al. [8] used the concept of E-fuels (electro-fuels) in categorizing an emerging class of carbon-neutral fuels that are produced by storing electrical energy from renewable sources in the chemical bonds of liquid or gas fuels. For shipping, liquid hydrogen and ammonia are the two main E-fuels generated from the same starting point: water electrolysis into hydrogen and oxygen. Hydrogen and ammonia manufacturing is feasible for shipping, but the fuels must be liquefied. However, liquid hydrogen needs cryogenic conditions and liquid ammonia needs low-temperature storage at −33 °C, or alternatively, both require pressurization to 350–700 bars, which are too space demanding for most shipping applications. Thus, the use of these fuels doubles or triples the maritime sector's energy consumption in a Well-to-Wake context.

The second entry in this category is synthetic E-fuels (synthetic electro-fuels), gaseous or liquid fuels produced from hydrogen and carbon captured from the air using renewable electricity. Having high energy efficiency, synthetic E-diesel is fully compatible and blendable with MGO (Marine Gasoil), and synthetic E-LNG (Electric-liquefied natural gas) is fully compatible and blendable with E-diesel or LNG and E-LNG. Additionally, these fuels do not require new infrastructure or bunkering facilities in ports, unlike ships fueled on hydrogen or ammonia [8].

According to McKinlay et al. [10], hydrogen has more potential than ammonia and methanol because its green production process has fewer losses. Additionally, hydrogen production requires less upscaling (171%) of manufacturing to meet the global fleet's energy demands. Unlike other modes of transport, shipping inherently operates with more fuel on board than is ever likely to be used for a single voyage; this is especially true for HFO (heavy fuel oil) storage. Therefore, reducing storage levels closer to the expected output can reduce mass and volume requirements and make alternative fuels significantly more viable.

Since short-distance shipping journeys are naturally shorter, and it is possible to switch to energy supply chains in at least one port, local shipping is also moving without existing regulations to energy solutions with low GHG emissions, such as electricity and hydrogen.

3. Decarbonizing Coastal Ferries

According to Equasis [11], the world's passenger ship fleet consisted of 7567 vessels in 2020.

The age composition of the fleet in Table 1 indicates that 53% of all passenger ships are 25+ years old and should be replaced soon. For this research, it is essential to look at small and medium-sized ships, where decisions will be made shortly to replace nearly 3900 vessels aged 25+ years as the time resources of the ship begin to be exhausted. It is estimated that these ships account for up to 20% of the global GHG emissions attributed to shipping.

Table 1. World passenger fleet size in 2020. Source: Authors' own compilation, based on data from Equasis [11].

Age/Size	Small (1)		Medium (2)		Large (3)		Very Large (4)		Total	
0–4 years old	348	9%	371	9%	32	2%	32	2%	783	10%
5–14 years old	595	5%	559	4%	58	1%	66	2%	1278	17%
15–24 years old	778	9%	555	7%	100	3%	75	5%	1508	20%
+25 years old	2491	8%	1405	8%	91	16%	11	6%	3998	53%
Total	**4212**	**56%**	**2890**	**38%**	**281**	**4%**	**184**	**2%**	**7567**	**100%**

(1) GT < 500; (2) 500 ≤ GT < 25,000; (3) 25,000 ≤ GT < 60,000; (4) GT ≥ 60,000.

Det Norske Veritas (DNV) has created the Alternative Fuels Insight platform [12], according to which the total number of existing and ordered new passenger ships (including cruise ships, RoPax, and car/passenger ferries) using alternative fuel solutions or GHG emission reduction devices (CCS) is 788 (see also Table 2).

Table 2. Passenger ships in service and on order. Source: Authors' own compilation, based on data from DNV [12].

Vessel Type	LNG	LNG-Ready	Scrubber	Battery	Hydrogen	Methanol	Total
Ferries	53	4	13	289	4	0	**363**
RoPax	33	9	95	7	0	1	**145**
Cruise ships	35	0	223	21	1	0	**280**
Total	**121**	**13**	**331**	**317**	**5**	**1**	**788**

Comparing the Equasis [11] and DNV [12] databases, 10.4% of the existing passenger ships and vessels that will be built soon already use or will use alternative fuels. The focus of this study is smaller (less than 5000 GT) car/passenger ferries, which account for nearly 50% of all vessels with alternative fuel use.

There is a clear trend in the energy use of smaller passenger ferries. In newly built vessels, the focus is on electricity use in cooperation with electricity storage technologies. Figure 1 shows the precise distribution of alternative energy solutions among car/passenger ferries. The data reflected in the figure is derived from the DNV Fuel Insight [12] portal as of June 2022 and includes both ships in operation and those to be built in the future.

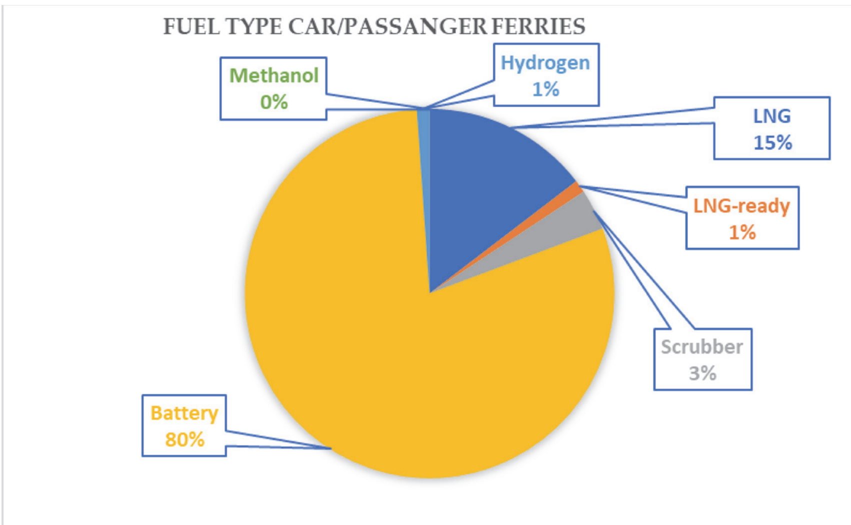

Figure 1. Car/passenger ferries in operation and on order [12].

My Word displays percentage sum 100% as follows: battery 80%, LNG 15%, scrubber 3%, hydrogen 1%, LNG-ready 1%. For clearance, Figure 1 in picture format is added.

Different battery solutions are used in 289 out of 363 ships, i.e., nearly 80% of cases. Approximately 15% of vessels use LNG as the primary energy source, and the remaining 5% of ships use other energy sources (see details in Table 3).

In 2022 and later, batteries will be installed on 69 ships as a retrofit or new construction. In terms of energy use, there are 30 hybrids, 15 plug-in hybrids, and 24 fully electric ships. They are geographically divided, with 6 ships in the USA, 35 ships in Asia, 26 ships in Europe, and rest are in unknown locations.

Table 3. Energy solutions for Car/passenger ferries in operation and order. Source: Authors' own compilation, based on data from DNV [12].

Type	In Operation	In Order
LNG	46	7
Scrubber	13	0
Hydrogen	2	2
Batteries	220	69
Pure electric		24
Hybrid		30
Plug-in hybrid		15

3.1. Fuel Alternative Pilot Projects with the Most Potential

A literature review and analysis of various low-emission alternatives was conducted for this study. Despite the lack of environmental regulations for coastal ferries, there are abundant modifications available on the market for vessels to lower their emissions. The development and interest in carbon-free ferries are apparently rising, and each sector of the maritime industry can contribute, from leisure yachts to large cargo vessels (without exemptions).

3.1.1. Diesel-Electric Hybrid

The highest number of newbuilt or retrofit examples currently have diesel-electric hybrid systems. Examples of newbuilt coastal ferries include the Uber Boat [13] in the UK; the Arlau, Alster, and Stecknitz in Germany [14]; and the Ibestad in Norway, which is a retrofit motor ferry (MF) [15].

Another significant aspect for fully electric coastal ferries in northern areas of the Baltic Sea is the ice conditions and cold temperatures [16]. This challenge is only met by the Elektra in Finland (a hybrid electric ferry) through the use of supportive diesel engines in winter conditions, which serve the vessel in cases of traveling through the ice. Therefore, it should be noted that diesel-electric hybrids are most likely the best alternative for cold conditions.

While assessing the current use of fully electric and diesel-electric hybrid alternatives, it is essential to clarify the geographical location [17], infrastructure of ports, and the electrical supply's limitations. In several cases of finalized newbuilt vessels, the port's readiness to supply the vessel with electricity is insufficient. A similar issue is a concern for remote areas and smaller islands, where the electrical supply and infrastructure are outdated and capacities are not built to fulfill the demands of sizeable external electricity users. For those cases, it is essential to evaluate the life-span of a vessel and assess the risks of using only fossil fuels if the infrastructure is not ready to supply electricity. Having onboard electrical batteries is another factor that raises fuel consumption, first due to the extra weight and second due to limited cargo or passenger capacity on board for the exact dimensions of the ship.

3.1.2. Fully Electric

Fully electric, battery-powered systems are an excellent option for shorter distances and milder climates. The first fully electric car and passenger ferry was the MF Ampere in Norway [18]. This ferry a remarkable example of not emitting greenhouse gases and having exceptionally low noise levels during operation. The first large e-ferry, the Ellen [19], operates in Denmark and should be noted for the same benefits.

Similar innovative developments have been carried out to build the first high-speed craft with zero emissions. The TrAM project [20] vessel, the Medstraum, began its operation in Norway in 2022.

When focusing on fully electric fuel options, the biggest challenge is currently the battery's physical size, capacity [21], and price [22]. For leisure vessels, battery price is also a disadvantage, but it is expected that price reduction will take place with technology development in time and significant changes in battery innovations [23]. On the other hand, a great advantage for such vessels is their operational noise levels.

3.1.3. Hydrogen

Norway has taken the lead in hydrogen use in transportation; therefore, it is not a surprise that they have also built and put into operation the first hydrogen MF, the Hydra [24].

The first hydrogen-powered commercial ferry, the Sea Change [25] (Projects—SW/TCH Maritime, n.d.), was launched and operates in San Francisco Bay. Moreover, with similar characteristics, the first CTV (crew transfer vessel), the Hydrocat 48 [26], is operating in the UK.

It also must be noted that the future is promising for the current storage and infrastructure issues [27]. Other means of transportation are interested in hydrogen use, which helps to develop areas that still lack opportunities and cost-effectiveness. As for other fuel alternatives, use of hydrogen as a fuel varies in countries and regions. Hence there are several promising methods of hydrogen production. For example, in specific locations in Canada, hydrogen is produced from the waste heat of nuclear power plants [28].

3.1.4. Methanol

For longer distances and larger vessels, the focus seems to be heading towards methanol. In 2015, the Stena Germanica was a hybrid of diesel or methanol fuel use, but the vessel has run on recycled methanol since 2021 [29].

Although methanol has a lot of potential, the current significant issue is that it is widely dependent on price dynamics in different regions, according to Masih et al. [30]. On the other hand, it is also essential to include that several large shipping companies, such as Maersk [31] and Cosco [32], have found methanol as a key factor for minimizing GHG emissions.

3.1.5. Liquefied Natural Gas

Another fuel alternative that has gained wide popularity for longer distances and larger ferries is liquified natural gas (LNG). With this alternative, it is essential to note that the use of LNG itself does not decrease GHG emissions [33] and there is no significant CO_2 reduction. Nevertheless, it is considered to be the cleanest fossil fuel.

An example would be the RoPax Salamanca [34], the first LNG-fueled passenger ferry to operate from the U.K. Successful LNG retrofit examples include the German ferries MS (motor ship) Ostfrieslan and MS Münsterland [35]. There are also diesel-LNG hybrids, such as the MS Megastar [36].

The hybrid solution enables a reduction in operating costs while gas pricing and availability are unstable. LNG use greatly depends on the region and regional policies [37]. The instability of gas prices was one of the most significant benefits of LNG usage before Europe's energy crisis in 2022. Among the disadvantages of LNG usage, an essential factor to consider is the risk of methane leakage and methane slip [38]. Similar to electric batteries, there are several technical and dimensional implementation issues with using LNG as fuel oil [39].

3.2. Evaluation of Potential Technologies

This research assessed the possibility of using alternative fuels on small coastal ferries by evaluating seven parameters, as shown in Tables 4 and 5. The assessment's color scale is divided into five parts (see rating map). Red indicates a rating of 0, meaning a situation that essentially excludes the use of the solution, whereas green indicates a rating of 4, which means that full readiness already exists for the solution. The sum of the ratings indicates the success of the technology's usability. Table 5 shows the numerical values, including the average, median, and standard deviation.

Table 4. The potential of alternative fuels in coastal shipping. Source: Authors' composition.

	Technical Readiness	Regulations	Zero Emission		Capex	Opex	Ice	Rating
			Well-to-Tank	Tank-to-Wake				
Plug-in hybrid			If non fossil source					26
Hybrid			If non fossil source	No grid energy				25
LNG	Methane slip		Fossil	Methane slip				23
Pure electric			If non fossil source		Bat. cost			23
Scrubber	CO_2; CH_4; N_2O		Fossil	CO_2; CH_4; N_2O				20
Methanol	Safety	Passenger	If non fossil source					19
Hydrogen			If non fossil source					18
Ammonia	Poisonous	Passenger	If non fossil source					16
Rating map								
	0							
	1							
	2							
	3							
	4							

Table 5. Numeral ratings of alternative energy systems in coastal shipping. Source: Authors' composition.

	Technical Readiness	Regulations	Zero Emission		Capex	Opex	Ice	Rating (Total)	Average	Median	St. Deviation
			Well-to-Tank	Tank-to-Wake							
Plug-in hybrid	4	4	3	3	4	4	4	26	3.71	4.00	0.49
Hybrid	4	4	3	2	4	4	4	25	3.57	4.00	0.79
LNG	2	4	2	3	4	4	4	23	3.29	4.00	0.95
Pure electric	4	4	3	4	2	4	2	23	3.29	4.00	0.95
Scrubber	2	4	0	2	4	4	4	20	2.86	4.00	1.57
Methanol	2	2	3	4	2	2	4	19	2.71	2.00	0.95
Hydrogen	4	4	3	4	0	1	2	18	2.57	3.00	1.62
Ammonia	0	0	3	4	2	3	4	16	2.29	3.00	1.70

The different parameters are described as the following:

- Technical Readiness: Evaluates the existence and use of relevant technologies in commercial use now. For example, manufacturers do not offer solutions without methane emissions for LNG systems. Scrubber technologies have been designed to reduce SO_2 and are not currently optimized to catch GHG, such as carbon dioxide, methane, and laughing gas, nitrous oxide. In the case of methanol, there are no workable solutions for the safe storage of fuel onboard passenger ships. In the case of ammonia, human safety due to the extreme toxicity of the gas needs to be addressed.
- Regulations: Assesses the current situation regarding the regulatory status of the use of the technology and the possibility of use with passengers on board the ship (IMO, [40]).
- Zero emission Well-to-Tank: Assesses the production process and supply of the fuel used by the ship based on the GHG emissions of the cycle and its compliance with the agreed climate targets. As many fuels can use both fossil fuels and renewable energy sources, the technology depends on the fuels available in the region and the choice of ship operator [9].
- Zero emission Tank-to-Wake: Illustrates the impact of the ship's potential GHG emissions and compliance with agreed climate goals.
- Capex (Capital Expenditure): Indicates the estimated size of the investment compared to the share of today's usual assets in the business model [41].
- Opex (Operative Expenditure): Estimates the running costs of the technology, such as fuel and technical maintenance, compared to today's habitual costs as a share of the business model [42].
- Ice: Appreciates the possibility of using the technology in more severe ice conditions, which need remarkably more propulsion power and onboard energy storage.

The option with the highest rating (26 points) was the plug-in hybrid system. The range of fuels in this system is diverse, and shipping will move in this direction regardless of the development activities that take place in the future. The system earned the maximum results (see Table 5) both in the "Technical Readiness" and "Regulations" categories because this solution is already in actual use. Smaller battery systems of up to 1000 kWh are already being installed quite widely today, and shore-based automatic charging systems are also in commercial use. The maximum results in the "Capex" and "Opex" categories were based on the fact that the costs of the system are already approaching market conditions (covering peak loads) compared to fossil fuels, and the system in this form can be successfully used in winter ice conditions.

The system allows for full carbon-free energy use when e-fuels or synthetic e-fuels are used as fuels in internal combustion engines. The electricity produced from renewable energy is also used in shore-based electricity systems. Nevertheless, lower scores (3 points) were achieved in both "Zero emission" categories because e-fuel production opportunities are lacking or are economically uncompetitive for commercial use today [43]. Additionally, the onshore electricity supply is based mainly on non-GHG emission-free sources.

A hybrid system achieved the second highest rating result (25 points). Like the plug-in hybrid system, there is an opportunity to achieve carbon neutrality using e-fuels with existing technology. At the same time, a lower rating (2 points) was achieved in the "Tank-to-Wake" category because it misses the charging option offered by advanced power grids from shore-side systems. Therefore, more considerable bunker reserve or denser bunkering is required by land transport, which raises the traffic load of fuel trucks on port roads.

In the evaluation model, LNG (23 points), as a low-carbon energy solution, achieved identical results as the pure electric solution. However, current market trends (see Tables 2 and 3) clearly show that problems with the use of LNG (methane slip as reported by Gronholm et al. [44] and Seithe et al. [45]) have significantly reduced the usage of LNG in new construction projects. Therefore, the system earned 2 points in the "Technical Readiness" category. The lower result in the "Well-to-Tank" category (2 points) was caused by the fossil fuel nature of the system and that in the "Tank-to-Wake" category (3 points) was because the system is not completely emission-free in its current development.

In contrast, fully electric solutions achieved the same result as LNG in the total ratings (23 points). Unfortunately, as a large part of light transport moves in the direction of electricity use, there may be a significant shortage of electricity supply, especially in remote areas and islands where mainland electricity connections are built without sufficient capacity reserves. The lower result for the "Capex" category (2 points) indicated the high installation cost for a sufficient battery capacity on board. The same result in the "Ice" category (2 points) reflected current difficulties using the system in harsh ice conditions, where the energy reserve on board with existing battery systems is insufficient for safe navigation.

The scrubber, a currently widely used cleaning system combined with HFO, received 2 points in the "Technical Readiness" and "Tank-to-Wake" categories because this technology is mainly optimized for reducing air pollutants such as SOx and NOx emissions and not for GHG such as CO_2 (carbon dioxide), CH_4 (methane), and N_2O (nitrous oxide "laughing" gas). Since these systems are commonly built to collaborate with fossil fuels, the results in the "Well-to-Wake" category were the lowest possible—0 points.

Methanol, as a fuel, achieved a total score of only 19 points, even though it is generally considered promising as a marine fuel. Although there are technical solutions for using methanol as fuel, the system requires almost 2.5 times more ship space for both fuel storage and technical handling [46]. In addition, in today's solutions, methanol is not used as the only fuel, which means that two alternative systems are needed on board small coastal ferries, which reduces the useful space. Although the IMO has regulated fuel use, systems have not yet been installed on smaller passenger ferries, and domestic regulations do not yet favor relatively toxic fuel in passenger shipping. Partly due to the reasons above and based on the fact that there is no ground-based methanol infrastructure for scaled fuel production, the system received only 2 points in the "Technical Readiness," "Legislation," "Capex," and "Opex" categories. The "Well-to-Tank" category received 3 points because currently, methanol is mainly produced from fossil fuel-based feedstocks [10].

The main reasons for the low overall result for hydrogen (18 points) as a fuel were the low points received in the "Capex" (0 points) and "Opex" (1 point) categories. At today's prices, the system cost (Capex) of various solutions used with hydrogen fuel is 2 to 2.5 times higher than that of a diesel system. According to forecasts, hydrogen (Opex) will not become price competitive with diesel until 2050 [47]. The low result in the "Ice" category (2 points) was based on the fact that the most significant critical factor for hydrogen systems is the space required for fuel storage [48]. When navigating difficult marine conditions, the amount of fuel stored would be unreasonably high for coastal ferries.

In median terms (see Table 5), the first five options performed equally well (from plug-in hybrid to scrubber). However, the scrubber displayed considerable variation (st. dev.) and should not be considered in this high-performing group. Despite this, the scrubber should not be excluded either; it was between the lowest three groups and the highest group (and very close to the latter).

Each of the lowest three solutions are troublesome in some respects. For example, the methanol option had a high average performance and slight variation. However, its median performance was the lowest in this evaluation (it received ratings of 2 in many aspects, and only a few high ratings of 4).

Hydrogen and ammonia had standard deviations in their performance that were too high, very low ratings (with ratings of 0 in many aspects), and they do not seem feasible or they have apparent weaknesses.

At the high end of this evaluation, it could be said that the plug-in solution was the highest performing in the group, even considering the average and standard deviation. However, the hybrid solution followed it very closely.

4. Discussion

Currently, the market, and not legislation, is indicating that coastal ferries should become carbon neutral, and the market is heading towards minimizing GHG emissions. Statistics on newly built and under-construction vessels show that each fuel has several alternatives with specific advantages and disadvantages. Nevertheless, the coastal ferry business is generally heading towards diesel-electric hybrids and fully electric energy solutions.

There are multiple potential alternative fuels to decrease the GHG emissions of coastal ferries (see e.g., Balcombe et al. [49]; Bouman et al. [50]; and Korberg et al. [51]). There are options for using LNG, batteries, methanol, LPG (liquefied petrol gas), hydrogen, and ammonia. In addition, there are other alternatives to reduce GHG emissions in ferries, for example, slow speeding, main engine de-rating, waste heat recovery, and changes in operational patterns. Lindstad et al. [8] evaluated their costs and emissions.

Statistics [12,52] on newbuilt and under-construction vessels and ratings obtained in this research showed that the ferry business is mainly heading towards diesel-electric hybrids, plug-in hybrids, and fully electric energy solutions. The range of usable fuels in these systems is diverse.

A coastal ferry with a diesel-electric propulsion system is the most attainable alternative with minor requirements for the operator and infrastructure. Diesel is necessary for emergencies and more challenging conditions, such as ice and low temperatures.

Regardless of what will be the fuel solution of the future, it can already be estimated that shipping will move to zero-carbon energy use when (1) e-fuels or synthetic e-fuels are used as fuels in internal combustion engines, and (2) electricity produced from renewable energy is supplied to ships from shore-based electricity loading systems.

It is essential that existing solutions also allow Nordic countries to ensure necessary navigation in difficult ice conditions. Despite achieving a high rating by LNG as a low-carbon energy solution, current market trends show that problems with methane slip have significantly reduced the usage of this solution in new ship building projects.

In contrast, all-electric solutions have become prevalent on smaller passenger ferries in inland waters and navigation areas without ice conditions. It is also essential to consider the following: as a large part of light transport moves in the direction of electricity use, there may be a significant shortage of electricity supply, especially in remote areas and islands where mainland electricity connections are built without sufficient capacity reserves.

It was found in this study that hydrogen, methanol, and ammonia are very promising fuels in shipping. However, the technical solutions and regulatory framework for passenger transport using ammonia as fuel are currently lacking. In addition, using methanol is in the developing stage, primarily for cargo shipping. In contrast, in the case of hydrogen, the biggest obstacle is the system's construction and operating costs. Additionally, ignorance of future tax levels for grey or green hydrogen significantly increases investment risks in hydrogen systems. For these various arguments, it was found that at this point, the most feasible solutions for coastal ferries in the near future would be fully electric- or diesel-electric hybrid-powered solutions.

Compared to earlier studies of alternative fuels, this study provides new information about smaller coastal ferries operating on short routes and near external energy sources, which means less need for onboard fuel storage. In addition, the usability of alternative energy systems in conditions of ice navigation is assessed.

The limitation of this work was the availability of technical data. Due to large-scale innovations in the field, market participants hide accurate technical information due to competition or share generalized information, which complicated the analysis. The implementers of different fuel technologies narrowly exchange information with organizations in their field, and so-called information in energy research is not found in any database. Therefore, essential arguments may have been sufficiently overlooked in the analysis. Research for finding measures to decarbonize coastal ferries continues. In further research, case studies of more specific environments will be carried out with more apparent solutions and actions that could be taken to achieve carbon neutrality in the region.

5. Conclusions

Lowering GHG emissions for small vessels and coastal ferries in European navigating areas is currently being initiated by shipbuilders, shipowners, and operators. The development and interest in carbon-free ferries are apparently rising, and there will be more feasible solutions in the future.

This study assessed the possibility of using alternative fuels on small ferries by seven different parameters, including technical readiness, presence of regulations, GHG emission reduction effectiveness (with two different criteria), Capex (capital expenditure), Opex (operative expenditure), and ice navigation ability.

There are several fossil fuel alternatives. As a result of this study, it was found that currently, the most suitable solution would be to use fully electric or diesel-electric hybrid solutions. The use of heavier fossil fuels, such as Low-Sulfur Residue Marine Fuel, in cooperation with scrubbers has clear potential, but the impact of asphaltenes on fuel stability [53], their potential for use in emission control areas [54], and their impact on lubrication systems must be taken into account in future studies.

In the near future, it is expected that changes in logistics, infrastructure, and science will offer alternatives that are more competitive in the market. It is also evident that the availability of different fossil fuel alternatives varies in different regions. While focusing on the ferry industry, it is essential to consider regional peculiarities and opportunities for specific lines. This study aimed to provide a general perspective, and research should focus on specific regions, fleets, and ferry lines and their best-suited fossil fuel alternatives in future studies.

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Appendix 2 (Publication II)

Publication II
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7. Decarbonising coastal ferries: case of the Estonian state fleet ferry

Andres Laasma, Riina Otsason, Ulla Tapaninen and Olli-Pekka Hilmola

1. INTRODUCTION

In early 2022, the Estonian government requested the Estonian Transport Administration to initiate the design and procurement of a new vessel for the coastal ferry service operating between the major Estonian islands Hiiumaa and Saaremaa and the mainland. The ship's commissioner is the state agency Estonian State Fleet, and upon completion, the ship will be handed over for use to a line operator selected through a competitive process.

Before the vessel can be ordered, several studies have been carried out concerning the concept, structure, size, speed, etc. One of the aims of the vessel was to become zero- or low-carbon. This chapter presents the alternatives studied for the energy source for the vessel, the evaluation process, and the final solution for which the study could be used.

The International Maritime Organization (IMO) has established a goal to cut overall greenhouse gas emissions from shipping by 50 percent across the globe, and the European Union (EU) has set a target date of 2050 for reaching carbon neutrality across Europe. At the moment, attention is being paid to programs such as carbon pricing schemes (ETS) and low GHG fuel requirements (FuelEU Maritime), both of which are directed toward vessels with a gross tonnage of more than 5,000.

In July 2023 the IMO made a significant tightening to its targets. The revised IMO GHG Strategy includes an enhanced common ambition to reach net-zero GHG emissions from international shipping close to 2050, a commitment to ensure the uptake of alternative zero- and near-zero GHG fuels by 2030, as well as indicative checkpoints for 2030 and 2040.[1]

[1] IMO, 'Revised GHG reduction strategy for global shipping adopted' (07 July 2023) <www.imo.org/en/MediaCentre/PressBriefings/pages/Revised-GHG-reduction-strategy-for-global-shipping-adopted-.aspx> accessed 17 June 2023.

The IMO and the EU share many of the same primary objectives, although the EU's focus is on achieving substantially more stringent laws and a greater range of authority. In May 2022, the environmental committee of the European Parliament (ENVI) resolved to incorporate ships with a gross tonnage (GT) of 400 or more in the Emissions Trading System (ETS).[2] As a result of its implementation, European seas are moving in the direction of maritime decarbonisation on a broad scale, and the limitations impact the coastal ferry business as well.

However, the rules enacted by the IMO and the EU do not apply to a number of different kinds of ships, including yachts, fishing vessels, tugs, and offshore ships. Armstrong[3] claims that smaller ships are responsible for 15–20% of the total greenhouse gas emissions. In other words, there is a significant amount of CO2 that should not be left unregulated for a future that will be carbon-free.

Alterations to the production of ferries and their methods of operation are currently being made by ship owners all around the world. It is important to highlight that even while there are no valid standards for smaller vessels, there is currently a need to evaluate the requirements.[4] This is because the coastal ferry industry has both the desire and the initiative necessary to make progress towards the reduction of greenhouse gas emissions. Both the market and the trends are in the process of shifting, and numerous viable fuel alternatives are either in the process of being developed or are already in use by crafts of a lesser size.

Other methods—in addition to new fuels—such as slow steaming, main engine de-rating, waste heat recovery, and alterations in operational patterns, can also be utilised to bring a reduction in CO2 emissions in addition to the use of alternative fuels.[5] In the shipping industry, these techniques are not new; in fact, they were initially put into place to reap benefits such as minimising oper-

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2 European Parliament, Report—A9-0162/2022 (Brussels, Belgium, 2022) <www.europarl.europa.eu/doceo/document/A-9-2022-0162_EN.html> accessed 5 May 2022.

3 Jacob Armstrong, 'Climate Impacts of Exemptions to EU's Shipping Proposals Shipping Laws' (Transport & Environment, Brussels, Belgium, 2022) <www.transportenvironment.org/wp-content/uploads/2022/01/Climate_Impacts_of_Shipping_Exemptions_Report-1.pdf> accessed 2 August 2022.

4 Jonathan Saul, and Kate Abnett, 'EU Shipping Plan Leaves Millions of Tonnes of CO2 Unregulated—Study' (*Reuters*, 13 January 2022) <www.reuters.com/world/europe/eu-shipping-plan-leaves-millions-tonnes-co2-unregulated-study-2022-01-12> accessed 6 May 2022.

5 Julio Barreiro, Sonia Zaragoza, and Vicente Diaz-Casas, 'Review of ship energy efficiency' (2022) 257 Ocean Engineering 111594.

ational expenses and reducing fuel usage.[6] However, slow steaming can also have direct repercussions on commerce.[7] Similarly, main engine de-rating has been made available by most engine manufacturers. However, its application is restricted depending on the weather and ice conditions. On the other hand, the de-rating of engines in particular areas that have warm climates creates further opportunities for reducing greenhouse gas emissions.[8]

This research work is a continuation of the previously published work of the authors, "Evaluation of Alternative Fuels for Coastal Ferries."[9] In this work, we studied the various alternative fuel systems that are currently available for new coastal ferries. The primary objective of the study was to investigate potential methods for decreasing the amount of greenhouse gas emissions that are caused by the ship's consumption of energy. This study did not take into consideration where the gasoline came from.

After this work, the studies have gone further, and now a new vessel has been designed. Due to clarity, we will start this chapter by presenting the main outcomes of the previous work, and thereafter present how this analysis has been used in this case under study.

The work that Lindstad and colleagues[10] have done is presented in section 2 (Evaluation of Alternative Fuels), and it served as the foundation of our examination of coastal ferries. In section 3 (Reduce the Carbon Footprint of Coastal Ferries), a general overview of the ages of the vessels and the possibility of using alternative fuels or other GHG emission reduction measures is presented. Additionally, an overview of the various alternative fuel pilot projects and an evaluation of the potential technologies that could be applied to coastal ferries are presented in this section. In section 4 (Analysis of Possible Technological Solutions), we talk about potential future developments, as well as how they might be anticipated and described based on the ratings. Section 5 presents the

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6 Nastia Degiuli and others, 'The impact of slow steaming on reducing CO2 emissions in the Mediterranean Sea' (2021) 7 Energy Reports 8131.

7 James J Corbett, Haifeng Wang, and James J Winebrake, 'The effectiveness and costs of speed reductions on emissions from international shipping' (2009) 14(8) Transportation Research Part D: Transport and Environment 593.

8 Kræn V Nielsen and others, 'Marine diesel engine control to meet emission requirements and maintain maneuverability' (2018) 76 Control Engineering Practice 12.

9 Andres Laasma and others, 'Evaluation of Alternative Fuels for Coastal Ferries' (2022) 14 Sustainability 2022 16841.

10 Elizabeth Lindstad and others, 'A Reduction of maritime GHG emissions and the potential role of E-fuels' (2021) 101 Transportation Research Part D: Transport and Environment 103075.

new vessel that has been ordered after the previous analysis. The findings and interpretations of the study are discussed in section 6 (Discussion).

2. EVALUATION OF ALTERNATIVE FUELS

When comparing alternative fuels, recent research has primarily focused on evaluating the entire life cycle of an energy carrier using the LCA (life cycle assessment) method. This method examines the entire chain of use, beginning with the extraction of the fuel and ending with its combustion in the ship's internal combustion engine. Studies that have been conducted in the past on the utilisation of fuels have mostly focused on three distinct stages: well-to-tank (WTT), tank-to-wake (TTW), and well-to-wake (WTW), the latter of which combines the first two stages.

In contrast to the WTW method, the full life cycle assessment (LCA) method takes into account both the construction and decommissioning of the fuel production chain. Lindstad and others[11] explored 22 potential pathways for utilising fuels in the maritime sector and evaluated the qualitative and quantitative parameters. Aspects were given a weighting depending on their influence, taking into consideration the fact that they have intricate linkages with greenhouse gas emissions, economic profitability, technical readiness, and safety standards within the industry. As a result of the research, the researchers came to the conclusion that in the short term, the most economically efficient energy usage model for reducing greenhouse gas emissions was the use of fossil fuels in combination with the installation of CCS (carbon capture system), which resulted in an increase in costs of approximately 18 percent when compared to conventional marine fuels. In addition, conventional fuels combined with carbon capture and storage (CCS) and biodiesel required significantly less volume than the other alternatives and required just a modest amount of change to the infrastructure that was already in place. Using electricity was the most energy-efficient choice since it would cut the amount of energy used by between 27 and 50 percent. The synthesis of hydrogen and ammonia required the greatest amount of energy, but did not result in any emissions of carbon or particulate matter.[12]

E-fuels, also known as electro-fuels, were categorised by Lindstad and others[13] as a developing class of carbon-neutral fuels. These fuels are created by storing electrical energy from renewable sources in the chemical bonds of

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[11] ibid.

[12] Li C Law and others, 'A comparison of alternative fuels for shipping in terms of lifecycle energy and cost' (2021) 14 Energies 8502.

[13] Lindstad and others (n 10).

liquid or gas fuels. The electrolysis of water, which produces hydrogen and oxygen, is the initial step in the production of the two primary E-fuels used in the transportation industry: liquid hydrogen and ammonia. It is possible to manufacture hydrogen and ammonia for shipment, but the fuels will first need to be liquefied. Nevertheless, liquid hydrogen needs cryogenic temperatures, and liquid ammonia needs low-temperature storage at 33°C, or alternatively, both require pressurisation to 350–700 pressures, which is too space-demanding for most transportation uses. Ammonia also needs storage at a temperature lower than 33°C. In a scenario of Well-to-Wake, the usage of these fuels causes the sector of the marine economy's energy consumption to either double or triple.

The second type of fuel in this category is known as synthetic E-fuel (synthetic electro-fuels), and it can either be a gas or a liquid. It is made by combining hydrogen and carbon dioxide that has been extracted from the atmosphere with electricity that comes from renewable sources. Synthetic E-diesel has high energy efficiency and is entirely compatible and blendable with MGO (Marine Gasoil). Similarly, synthetic E-LNG (Electric-liquefied natural gas) is totally compatible and blendable with E-diesel or LNG and E-LNG. Both of these fuels come from natural gas. In addition, ships powered by these fuels do not require new infrastructure or bunkering facilities in ports, which is not the case with ships powered by hydrogen or ammonia.[14]

According to McKinlay and others,[15] hydrogen has a greater potential than ammonia and methanol since its production process is more environmentally friendly and results in fewer losses. In addition, the generation of hydrogen requires less of an increase in the scale of manufacturing—171 percent less, to be exact—in order to fulfil the energy requirements for the world fleet. Shipping, in contrast to other forms of transportation, always requires a larger quantity of fuel to be carried on board than is ever expected to be consumed for a single journey. This is notably the case with regard to the storage of HFO, which stands for heavy fuel oil. As a result, bringing storage levels closer to the output that is anticipated can minimise the amount of mass and volume that is required, making the use of alternative fuels substantially more feasible.

Local shipping is also transitioning, without existing regulations, to energy solutions that produce low levels of greenhouse gas emissions, such as electricity and hydrogen. This is possible because short-distance shipping journeys

[14] ibid.

[15] Charles J McKinlay, Stephen Turnock, and Dominic A Hudson, 'Route to zero emission shipping: Hydrogen, ammonia or methanol?' (2021) 46 International Journal of Hydrogen Energy 28282.

are naturally shorter, and it is possible to switch to energy supply chains in at least one port.

2.1 The Most Promising Alternative Fuel Pilot Projects

Throughout the course of this research, a comprehensive literature search and an investigation of a wide range of emission-reducing options were carried out. Although there are no environmental rules governing coastal ferries, there is a large selection of equipment that may be retrofitted into vessels in order to reduce the amount of pollution they produce. There is an apparent increase in both the development of an interest in carbon-free ferries and each sector of the maritime industry that may contribute, from leisure yachts to large-scale cargo vessels (without exemptions).

2.1.1 Diesel-electric hybrid

Currently, diesel-electric hybrid systems are being installed in the greatest number of newly built or retrofitted instances. MV Tellus was the first diesel-electric plug-in hybrid road ferry that came into service in 2019 in Sweden.[16] The Uber Boat in the UK, the Arlau, Alster, and Stecknitz in Germany,[17] and the Ibestad in Norway, which is a retrofit motor ferry (MF),[18] are all examples of newly constructed coastal ferries.

Ice conditions and low temperatures present an additional challenge for completely electric coastal ferries operating in northern regions of the Baltic Sea.[19] Elektra, a hybrid electric ferry in Finland, was also able to operate in winter-time by employing auxiliary diesel engines. These engines are there to assist the vessel in the event that it must sail through the ice. Because of this, it is important to point out that diesel-electric hybrids are most likely the best solution for driving in cold temperatures.

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16 Corvus Energy, 'Project Tellus' (2022) <https://corvusenergy.com/projects/tellus/> accessed 15 April 2023.

17 Binnenschifffahrt, 'Hybridfähren: Dreifachtaufe am NOK' (Free Translation to English: 'Hybrid Ferries: Triple Christening on the NOK') (29 October 2022) <https://binnenschifffahrt-online.de/2021/10/featured/22736/hybridfaehren-dreifachtaufe-am-nok-%E2%80%A8%E2%80%A8/> accessed 23 September 2022.

18 Baird Maritime, 'Norled Ferry to Undergo Hybrid Electric Refit' (8 March 2022) <www.bairdmaritime.com/work-boat-world/passenger-vessel-world/ro-pax/norled-ferry-to-undergo-hybrid-electric-refit/> accessed 23 September 2022.

19 Yazan Al-Wreikat, Clara Serrano, and José Ricardo Sodré, 'Effects of ambient temperature and trip characteristics on the energy consumption of an electric vehicle' (2022) 238 Energy 122028.

2.1.2 Fully electric

Systems that are completely electric and run on batteries are a good choice for more moderate temperatures and shorter distances. The MF Ampere, which operated in Norway,[20] was the world's first automobile and passenger ferry to be powered entirely by electric propulsion. This ferry is a noteworthy example because it does not emit any greenhouse gases and has extraordinarily low noise levels while operating. It is important to remember that the Ellen,[21] the world's first major electric ferry, which serves in Denmark, has the same advantages.

Innovations along these lines have been put into place in order to construct the world's first high-speed vessel that produces no pollution. In 2022, the vessel known as the Medstraum, which is part of the TrAM project,[22] began its operations in Norway. In the southern hemisphere (New Zealand), in 2022, the fully electric catamaran ferry Ika Rere[23] started operation.

Focusing on totally electric fuel options presents a number of challenges, the most significant of which are the physical size, capacity, and cost of the battery.[24,25] The cost of the batteries is another drawback associated with leisure vessels; however, it is anticipated that this drawback will be mitigated as a result of the progression of technology through time and the substantial shifts in innovation associated with batteries.[26] On the other hand, the low levels of noise that these vessels produce while operating are a significant benefit.

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20 Corvus Energy, 'MF Ampere' (2022) <https://corvusenergy.com/projects/mf-ampere/> accessed 23 September 2022.

21 Ship Technology, 'Ellen E-Ferry: World First a Glimpse of the Future of Ferries' (2022) <www.ship-technology.com/analysis/ellen-e-ferry/> accessed 23 September 2022.

22 TrAM, 'About the Project' (2022) <https://tramproject.eu/about/> accessed 23 September 2022.

23 McKay Group, 'Ika Rere' (2022) <www.mckay.co.nz/news/project/ika-rere-electric-ferry/> accessed 15 April 2023.

24 Monaaf D A Al-Falahi and others, 'Power management optimization of hybrid power systems in electric ferries' (2018) 172 Energy Conversion and Management 50.

25 Jessica Kersey, Natalie D Popovich, and Amol A Phadke, 'Rapid battery cost declines accelerate the prospects of all-electric interregional container shipping' (2022) 7 Nature Energy 664.

26 Mika Naumanen and others, 'Development strategies for heavy-duty electric battery vehicles: Comparison between China, EU, Japan, and USA' (2019) 151 Resources, Conservation and Recycling 104413.

2.1.3 Hydrogen

Because Norway is already at the vanguard when it comes to the utilisation of hydrogen in transportation, it should not come as a surprise that they have also constructed and put into service the very first hydrogen MF, which is known as the Hydra.[27] The Sea Change[28] (Projects—SW/TCH Maritime, n.d.), the world's first hydrogen-powered commercial ferry, was just launched and is currently operating in San Francisco Bay. In addition, the first crew transfer vessel (CTV) in the UK, the Hydrocat 48,[29] has similar characteristics and is currently in operation there.

2.1.4 Methanol

The use of methanol appears to be gaining popularity as a fuel option for longer routes and larger vessels. In 2015, the Stena Germanica could run on either diesel or methanol as its fuel. However, as of 2021, the ship only uses regenerated methanol as its power source.[30] According to Masih and others,[31] despite the fact that methanol has a great deal of untapped potential, the major challenge it faces right now is the fact that its price is very susceptible to fluctuations in a variety of places. On the other hand, it is vital to mention the fact that a number of significant maritime firms, such as Maersk[32] and Cosco,[33]

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[27] FuelCellWorks, 'Norway: MF "Hydra", The World's First Hydrogen Operated Ferry, Wins Ship of The Year 2021' (28 December 2021) <https://fuelcellsworks.com/news/norway-mf-hydra-the-worlds-first-hydrogen-operated-ferry-wins-ship-of-the-year-2021/> accessed 23 September 2023.

[28] Switch Maritime, 'Projects—SW/TCH Maritime' (2022) <www.switchmaritime.com/projects> accessed 23 September 2022.

[29] CMB TECH, 'First hydrogen-powered CTV: Hydrocat 48 | CMB TECH' (10 May 2022) <https://cmb.tech/news/windcat-workboats-cmb-tech-present-the-first-hydrogen-powered-crew-transfer-vessel-ctv-the-hydrocat-48-ready-for-immediate-operation> accessed 23 September 2022.

[30] Jasmina Ovcina Mandra, 'Stena Germanica Runs on Recycled Methanol' (*Offshore Energy*, 24 June 2021) <www.offshore-energy.biz/stena-germanica-runs-on-recycled-methanol/> accessed 23 September 2022.

[31] A Mansur M Masih, Khaled Albinali, and Lurion DeMello, 'Price dynamics of natural gas and the regional methanol markets' (2020) 38 Energy Policy 1372.

[32] Maersk, 'A.P. Moller-Maersk Engages in Strategic Partnerships Across the Globe to Scale Green Methanol Production by 2025' (10 March 2022) <www.maersk.com/news/articles/2022/03/10/maersk-engages-in-strategic-partnerships-to-scale-green-methanol-production> accessed 23 September 2022.

[33] Sam Chambers, 'Methanol Backers Including COSCO and Bill Gates Show Their Hands' (*Splash 247*, 31 August 2022) <https://splash247.com/methanol-backers-including-cosco-and-bill-gates-show-their-hands/> accessed 23 September 2022.

have discovered that methanol is an important element in reducing their greenhouse gas emissions.

2.1.5 Liquefied natural gas

Liquefied natural gas is a fossil fuel, that should—in principle—not be taken into account in this study. There is considerable methane slip in its usage, which can make it an even more harmful greenhouse gas than a traditional bunker. However, it is often mentioned as an alternative fuel, so we also took it into account in the analysis.

The RoPax Salamanca,[34] which was the first LNG-fuelled passenger ferry to operate from the UK, is a good example of this. Examples of LNG retrofits that were carried out successfully are the German ferries MS Ostfrieslan and MS Münsterland.[35] There are also diesel-LNG hybrids, such as the MS Megastar[36] and MS Mystar,[37] to be found.

2.2 Analysis of Possible Technological Solutions

The viability of employing alternative fuels on smaller coastal ferries was analysed by using nine parameters, the results of which are presented in Table 7.1a/b. There are five grade ratings (from 0 to 4) that are used for the evaluation. The ratings have been based on expert insights from the Estonian Maritime Academy and the Estonian State Fleet. As there are many factors to be taken into account, and they are not numerically comparable, the exact figures should be merely taken indicatively.

A rating of 4 shows that there is already full readiness for the solution, whereas a rating of 0 indicates a circumstance that practically precludes the application of the solution. The overall number of ratings (Total) provides an indication of how well the technology may be utilised. The numerical values, including the mean, the median, and the standard deviation, are also presented

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34 Sanja Pekic, 'Wärtsilä to Support Brittany Ferries' LNG-Fueled Salamanca' (*Offshore Energy*, 25 March 2022) <www.offshore-energy.biz/wartsila-to-support-brittany-ferries-lng-fueled-salamanca/> accessed 23 September 2022.

35 NOW, 'LNG Conversion of the RoRo Ferry MS "Münsterland"—NOW GmbH' (2022) <www.now-gmbh.de/projektfinder/lng-umruestung-der-roro-faehre-ms-muensterland/> accessed 23 September 2022.

36 Ship Technology, 'Tallink's Megastar LNG-Fuelled Fast Ferry' (23 February 2018) <www.ship-technology.com/projects/tallinks-lng-fuelled-fast-ferry/> accessed 23 September 2022.

37 Ajsa Habibic, 'Tallink takes delivery of LNG-fueled shuttle ferry' (Offshore Energy, 7 December 2022) <www.offshore-energy.biz/tallink-takes-delivery-of-lng-fueled-shuttle-ferry/> accessed 16 April 2023.

Table 7.1a *Numeral ratings of alternative energy systems in coastal shipping*

	Technical Readiness	**Regulations**	**Zero Emission**		**Capex**	**Uncertainty of Capex**
			Well-to-Tank	**Tank-to-Wake**		
Plug-in hybrid	4	4	3	3	4	3
Hybrid	4	4	3	2	4	3
LNG	2	4	2	3	4	4
Pure electric	4	4	3	4	2	3
Methanol	2	2	3	4	2	3
Hydrogen	4	4	3	4	0	3
Ammonia	1	0	3	4	2	2

Note: Authors' own composition.

Table 7.1b *Numeral ratings of alternative energy systems in coastal shipping*

	Opex	Uncertainty of Opex	Ice	Rating (Total)	Average	Median	St. Deviation
Plug-in hybrid	4	4	4	33	3.67	4.00	0.50
Hybrid	4	3	4	31	3.44	4.00	0.73
LNG	4	2	4	29	3.22	4.00	0.97
Pure electric	4	3	2	29	3.22	3.00	0.83
Methanol	2	2	4	24	2.67	2.00	0.87
Hydrogen	1	3	2	24	2.67	3.00	1.41
Ammonia	3	2	4	20	2.22	2.00	1.48

Note: Authors' own composition.

in Table 7.1a/b. “Uncertainty” parameters have been added due to the major changes in global supply chains caused by the Covid-19 pandemic and the war in Ukraine.

The following is an explanation of each of the available parameters:

- Technical Readiness: This evaluates the existence of important technologies that are currently being used in commercial applications. As an illustration, producers of LNG systems do not offer any alternatives that do not produce methane emissions. When it comes to the safe storage of methanol on passenger ships, there are no practical options that can be implemented at this time, but the first methanol solutions are already in cargo vessels. In the case of ammonia, it is necessary to address concerns regarding the extreme toxicity of the gas to human beings.
- Regulations: Assesses the current situation surrounding the regulatory status of the use of the technology and the potential of using it with passengers while the ship is in port or at sea.[38]
- Zero emission Well-to-Tank: Evaluates the production process and supply of the fuel used by the ship based on the GHG emissions of the cycle and its compliance with the agreed-upon climate targets. Because there are numerous fuels that can use both fossil fuels and renewable energy sources, the technology relies on the fuels that are readily available in the location as well as the ship operator that is selected. This analysis is based on work of Lindstadt.[39]
- Zero emission Tank-to-Wake: This metric illustrates the impact of the ship’s potential greenhouse gas emissions and demonstrates compliance with the agreed-upon climate goals.
- Capex (Capital Expenditure): Shows the estimated size of the investment in comparison to the share of today's normal assets in the business model.[40]
- Uncertainty of Capex: basically, inflation and limited availability of raw materials for ship constructions caused by disruptions to supply chains.

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38 IMO, ‘Maritime Safety Committee (MSC 105), 20–29 April 2022’ (2022) <www.imo.org/en/MediaCentre/MeetingSummaries/Pages/MSC-105th-session.aspx> accessed 24 September 2022.

39 Lindstad and others (n 10).

40 Yifan Wang and Laurence A Wright, ‘A Comparative Review of Alternative Fuels for the Maritime Sector: Economic, Technology, and Policy Challenges for Clean Energy Implementation’ (2021) 2 World 456.

- Opex (Operational Expenditure): Estimated running expenses of the technology, such as fuel and technical maintenance, in comparison to today's typical costs as a proportion of the business model.[41]
- Uncertainty of Opex: a hard-to-estimate trend of changes in fuel prices and availability.
- Ice: Appreciates the possibilities of deploying the technology in more severe ice conditions, which require substantially more propulsion power and onboard energy storage than other environmental situations.

The plug-in hybrid system was the one that received the highest rating (33 points). The variety of fuels that can be used within this system is extensive, and regardless of the research and development that may take place in the years to come, the shipping industry will continue decarbonisation. Due to the fact that this particular solution is already being put to use, the system was awarded the highest possible score (refer to Table 7.1a/b) in both the "Technical Readiness" and "Regulations" categories. Today, smaller battery systems with capacities of up to 1,000 kilowatt hours (kWh) are already being installed on a large scale, and shore-based automated charging systems are already in use in commercial applications. The fact that the costs of the system are already approaching market conditions (covering peak loads) in comparison to fossil fuels was the primary factor that determined the maximum results in both the "Capex" and "Opex" categories. Lower results in "Uncertainty of Capex" were caused by fluctuation of battery prices and availability. Additionally, the fact that the system in its current configuration is able to be successfully used in winter ice conditions also played a role in these maximum results.

When e-fuels or synthetic e-fuels are used as fuels in internal combustion engines, the system enables the use of energy that is completely free of carbon emissions. The electricity that is generated from renewable sources is also utilised in the generation of electricity by shore-based systems. However, lower scores for three points were reached in both of the categories labelled "Zero emission". This is due to the fact that options for the generation of e-fuel are either non-existent or are not economically competitive for usage in commercial settings today.[42] In addition, the supply of electricity generated on land derives from non-GHG-emitting sources for the most part.

[41] Lara Pomaska and Michele Acciaro, 'Bridging the maritime-hydrogen cost-gap: Real options analysis of policy alternatives' (2022) 107 Transportation Research Part D: Transport and Environment 103283.

[42] Tomi Solakivi, Aleksi Paimander, and Lauri Ojala, 'Cost competitiveness of alternative maritime fuels in the new regulatory framework' (2022) 113 Transportation Research Part D: Transport and Environment 103500.

The second-highest rating result was reached by a hybrid system (31 points). With the technology that is now available, it is possible to attain carbon neutrality by using e-fuels, just like with the plug-in hybrid system. At the same time, a lower rating of two points was attained in the “Tank-to-Wake” category since it does not make use of the charging option that is made available by sophisticated power grids that are shore-side based. As a result, land transport must either maintain a larger bunker reserve or bunker at a higher density. This results in an increase in the number of fuel trucks that use the port roads. Lower results in uncertainty factors are caused by the fluctuation of battery prices and availability, as well as lack of access to low-cost grid energy.

In the evaluation model, the outcomes that LNG (29 points) achieved as a low-carbon energy source were identical to those that the pure electric solution attained. However, there are problems with the utilisation of LNG (methane slip, as reported by Gronholm and others[43] and Seithe and others[44]). As a consequence of this, the system was awarded 2 points in the category of “Technical Readiness.” The lower result in the “Well-to-Tank” category (2 points) was caused by the fossil fuel nature of the system, and the lower result in the “Tank-to-Wake” category (3 points) was caused by the fact that the system is not completely emission-free in its current development. Both results were due to the fact that fossil fuels were used in the system. Low results (2 points) “Uncertainty of Opex” resulted, as the LNG market highly depends on sanctions on Russia. In addition, EU ETD (Energy Taxation Directive) may equal LNG taxation with HFO in 2033.[45]

On the other hand, totally electric solutions were able to attain the same outcome as LNG in terms of the total ratings (29 points). Unfortunately, as a significant proportion of light transportation moves toward the use of electricity, there may be a significant shortage of electricity supply. This is especially likely to occur in remote areas and on islands, where mainland electricity connections are constructed without sufficient capacity reserves. The low score of two points obtained in the “Capex” category revealed the large

43 Tiia Grönholm and others, ‘Evaluation of methane emissions originating from LNG ships based on the measurements at a remote marine station’ (2021) 55 Environmental Science and Technology 13677.

44 Grusche J Seithe and others, ‘Maritime transport in a life cycle perspective: How fuels, vessel types, and operational profiles influence energy demand and greenhouse gas emissions’ (2020) 13 Energies 2739.

45 Anastassios Adamopoulos, Michelle Wiese Bockmann, and Declan Bush, ‘EU proposes tax on all shipping emissions and to limit polluting fuels’ (*Lloyd’s List*, 14 July 2021) <https://lloydslist.maritimeintelligence.informa.com/LL1137545/EU-proposes-tax-on-all-shipping-emissions-and-to-limit-polluting-fuels> accessed 23 April 2023.

initial investment required to install a battery capacity that was adequate for the vessel. Lower results in uncertainty factors were caused by the fluctuation of battery prices and availability and potential limitations for shore grid power. The identical result in the "Ice" category, which was two points, reflected the challenges that are currently encountered when attempting to use the system in severe ice conditions. In these situations, the energy reserve on board with existing battery systems is insufficient for safe navigation.

Although it is usually regarded as having great potential as a marine fuel, the overall score that methanol received for its use as a fuel was only 24. Even if there are technological methods for using methanol as fuel, the system requires roughly 2.5 times more ship area for fuel storage in addition to the space required for technical handling.[46] Only two points were awarded to the system in each of the categories of "Technical Readiness", "Legislation", "Capex", "Opex", and "Uncertainty of Opex." This was in part because of the reasons that were listed above, but it was also due to the fact that there is no ground-based methanol infrastructure for large-scale fuel production. Because fossil fuels are the primary feedstocks used in the production of methanol at the present time,[47] the "Well-to-Tank" category resulted in three points.

The low scores obtained in both the "Capex" (0 points) and "Opex" (1 point) categories were the primary contributors to the disappointingly low overall result for hydrogen as a fuel, which was 24 points. The capital expenditure (Capex) cost of various solutions that employ hydrogen fuel is two to two-and-a-half times greater than the cost of a diesel system at the current time. It is not expected that hydrogen (Opex) will reach a pricing point that is competitive with diesel until the year 2050.[48] The low score of two points achieved in the "Ice" category can be attributed to the fact that the amount of space necessary for fuel storage is the most major crucial factor for hydrogen systems.[49]

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46 William Stoichevski, 'Future Fuels: The Pros and Cons of Methanol' (*Maritime Logistics*, 16 May 2022) <www.maritimeprofessional.com/news/future-fuels-pros-cons-methanol-376525> accessed 23 April 2023.

47 McKinlay and Turnock (n 15).

48 Simona Di Micco and others, 'Feasibility analysis of an innovative naval on-board power-train system with hydrogen-based PEMFC technology' (2021) 312 E3S Web Conf. 07009.

49 Mariagiovanna Minutillo and others, 'Hydrogen-based technologies in maritime sector: Technical analysis and prospective' (2022) 334 E3S Web Conf. 6011.

3. THE NEW VESSEL

Based on the analysis presented above, the Estonian state fleet will order a new vessel in 2024. The new zero-emission ferry will arrive on the traffic between the islands of Saaremaa and Hiiumaa and mainland routes in the first half of 2026.[50] There are two alternative routes it will operate, either mainland—Saaremaa 6.5 km that would take 27–33 minutes or Hiiumaa—mainland 22.3 km that would take 75–88 minutes.

The ferry can accommodate 700 passengers and up to 200 cars and will have two car decks. The details of the vessel are:

Length: 118m
Width: 20m
Height: 8.3m
Draught: 3.5m
Passengers: 700 persons
Lane metres: 1,000m
Max speed: 14 knots

Note: ibid.

Figure 7.1 The picture of the planned new vessel

[50] Riigilaevastik, 'Tulevikumeri' <https://riigilaevastik.ee/tulevikumeri> accessed 18 July 2023.

While the analysis of the most potential fuel showed very high uncertainties, it was decided not to only rely on one fuel solution. Therefore, the ship will run on both batteries and fuel cells. It will use green fuel, compressed hydrogen, and renewable shore electric charging (internal combustion engines only as a backup). In addition, a special focus on automatic work functions and cyber security is planned for the ferry. The ferry will have automated port-to-port navigation and docking and will be future-ready for remote control.

4. DISCUSSION

At this time, it is also the market, not only regulation, that is signalling that coastal ferries should become carbon neutral, and the market is moving in the direction of lowering greenhouse gas emissions.[51] There is a wide variety of potential alternative fuels that could lower the greenhouse gas emissions of coastal ferries (see, e.g., Korberg and others;[52] Bouman and others;[53] and Balcombe and others.[54]). It is possible to make use of liquefied natural gas (LNG), batteries, methanol, liquefied petroleum gas (LPG), hydrogen, and ammonia. In addition, there are further approaches that may be taken to reduce the amount of GHG emissions produced by ferries. These include traveling at a slower speed, de-rating the main engine, recovering waste heat, and altering the routines under which the ferry operates. Lindstad and colleagues[55] analysed the expenses as well as the emissions.

A coastal ferry equipped with a diesel-electric propulsion system is the most practicable solution, because it places minimal demands on the infrastructure and the operator. Diesel fuel is essential for dealing with unexpected events as well as more difficult situations, such as ice and cold temperatures.

It is already possible to estimate that shipping will transition to zero-carbon energy use when: (1) e-fuels or synthetic e-fuels are used as fuels in internal

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51 The Maritime Executive, 'Study: Customer Demand Will Drive Decarbonization' (8 July 2020) <www.maritime-executive.com/article/study-customer-demand-will-drive-decarbonization> accessed 28 April 2023.

52 Andrei D and others, 'Techno-economic assessment of advanced fuels and propulsion systems in future fossil-free ships' (2021) 142 Renewable and Sustainable Energy Reviews 110861.

53 Evert A Bouman and others, 'State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping—A review' (2017) 52 Transportation Research Part D: Transport and Environment 408.

54 Paul Balcombe and others, 'How to decarbonise international shipping: Options for fuels, technologies and policies' (2019) 182 Energy Conversion and Management 72.

55 Lindstad and others (n 10).

combustion engines, and (2) electricity produced from renewable energy is supplied to ships from shore-based electricity loading systems. This will happen regardless of what the fuel solution of the future will be.

It is of the utmost importance that the current solutions enable Nordic countries to maintain vital navigation even in tough ice conditions. Despite receiving a high rating from LNG as a solution for a low-carbon energy source, current market trends show that problems with methane slip have significantly reduced the usage of this solution in new ship-building projects.

On the other hand, the use of solutions that are powered solely by electricity has become increasingly common on smaller passenger ferries operating in inland waters and navigation areas that are free of ice conditions. It is also essential to keep the following in mind: As a large proportion of light transportation moves toward the use of electricity, there may be a significant shortage of electricity supply, particularly in remote areas and islands where mainland electricity connections are built without sufficient capacity reserves.

Based on research, the Estonian State Fleet has developed a plan for a new ferry that will serve the large islands of Saaremaa and Hiiumaa, as well as the mainland. The ferry will utilise three types of potential energy sources: batteries charged from the shore grid, fuel cells, and diesel engines as a backup.

This chapter gives fresh information regarding smaller coastal ferries that operate on shorter trips and are located near external energy sources, which means that there is less of a need for onboard fuel storage than there was in past studies of alternative fuels. In addition, an analysis is performed to determine whether or not alternative energy systems may be utilised under conditions of ice navigation. Finally, it presents a coastal ferry that is already in the process of being ordered in early 2024 and should be in operation in 2026.

The accessibility of technical data posed a challenge for this particular project. The study was made more difficult as a result of the widespread advances that have taken place in the industry. As a result of this competition, market participants either conceal precise technical knowledge or share broad information. The implementers of various fuel technologies only share information with other organisations working in their particular field, and the so-called information in energy research cannot be located in any database. As a result, vital points of the debate may have been neglected in the investigation. Research into methods to reduce the carbon footprint of coastal ferries is still ongoing. Case studies of more specific environments will be carried out as part of subsequent research, and the solutions and actions that may be implemented to attain carbon neutrality in the region will become more evident as a result.

5. CONCLUSION

Shipbuilders, shipowners, and operators in European navigating zones are now taking action to reduce the amount of greenhouse gas emissions that are produced by coastal ferries and smaller vessels. There appears to be a rise in both the development of an interest in carbon-free ferries and the future will see an increase in the number of viable alternatives.

The work presented in this chapter evaluates the feasibility of using alternative fuels on smaller ferries based on nine distinct criteria, including technical readiness, the existence of regulations, the effectiveness of reducing greenhouse gas emissions (based on two distinct criteria), the amount of capital expenditure and its uncertainty, the amount of operational expenditure and its uncertainty risks, and the capability of navigating ice.

There is more than one alternative for using fossil fuels. As a consequence of this investigation, it was discovered that, at this time, the solution that would be best suited to use would be hybrid diesel-electric solutions or solutions that were completely electric. However, as the aim of the Estonian government was to support totally emission-free shipping, hydrogen was also taken into account. Based on the analysis of this work, the Estonian State Fleet is in the process of ordering a new vessel and the vessel will be using three types of fuel: hydrogen, electricity and diesel as a backup. It is planned that the vessel will be in operation between the large Estonian islands of Saaremaa and Hiiumaa as well as the mainland in 2026.

Appendix 3 (Publication III)

Publication III

Laasma, A, Aiken, D., Kasepõld, K., Hilmola, O.-P., Tapaninen, U. (2025). Data-Driven Propulsion Load Optimization: Reducing Fuel Consumption and Greenhouse Gas Emissions in Double-Ended Ferries. Journal of Marine Science and Engineering, 13 (4), #688. DOI: 10.3390/jmse13040688

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Data-Driven Propulsion Load Optimization: Reducing Fuel Consumption and Greenhouse Gas Emissions in Double-Ended Ferries

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Abstract: As the focus on climate action and sustainable development of the shipping industry intensifies, the maritime sector has intensified its focus on decarbonization. Although the ferry sector accounts for a small part of the global fleet, it plays a crucial role in specific regions. This study examines data from an energy monitoring system installed on a double-ended Estonian ferry over the period from 2022 to 2024. The empirical results clearly show that targeted adjustments can lead to substantial fuel consumption reductions as the optimal operation of the vessel requires equal power from the aft and fore engines particularly when operating under cold or icy conditions. Additionally, the research finds that real-time energy monitoring together with integrating environmental factors supports energy efficiency and fulfilling regulatory requirements. The analysis reveals that environmental corrections and balanced decision-making can generate fuel savings and extended emission reductions. The suggested framework offers ferry operators practical and economical ways of meeting sustainability requirements.

Keywords: maritime transportation; energy efficiency; GHG emissions; ferry operations; data-driven optimization; propulsion load

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1. Introduction

The maritime sector has intensified its decarbonization efforts over the past decade since the introduction of the Initial Greenhouse Gas (GHG) Strategy in 2018 by the International Maritime Organization (IMO) [1]. The strategy has undergone revisions, the most recent of which is the 2023 IMO Strategy on Reduction of GHG Emissions from Ships, which includes a target of reaching net-zero emissions by 2050 [2]. Meeting this target necessitates the widespread adoption of innovative strategies and practices across all shipping industry segments, including large vessels, as well as smaller ones such as ferries. While representing a relatively minor fraction of the global fleet in total tonnage, ferries play a vital role in regional transport systems, particularly in the European island and coastal regions where they serve as vital links in the transportation network [3]. The special operational characteristics of ferries, which include fixed routes, shorter voyages, and frequent docking operations, present an opportunity to implement energy efficiency improvements on these vessels [4].

The Baltic Sea region facilitates an array of continuous ferry traffic connecting at least ten countries along its coastline [5,6]. It is reported that approximately 3500 to 5000 ships navigate through the Baltic Sea per month [7]. In addition to being the site of the most intensive shipping activity globally accounting for approximately 15% of global trade, the Baltic Sea experiences large seasonal variations ranging from a low of zero to −5 °C to a high of 15 °C to 20 °C [7,8]. This fluctuation in the operating environment ultimately affects the efficiency of the vessels traversing the region. Studies have highlighted that the presence of sea ice can affect the maneuverability of vessels, leading to slower speeds and higher fuel consumption [9]. Fuel consumption tends to increase under severe weather conditions and higher cargo levels when the ship maintains constant speed [10]. Advancements in technologies such as onboard data systems have significantly improved the capabilities for the real-time monitoring of ferry operations; however, the effective conversion of raw operational data into actionable insights that can inform and guide fuel-efficient practices and emissions reductions is still minimally explored and adopted [11,12].

Despite IMO's ambitious 2050 zero carbon targets, the poor availability and high price of cleaner fuels and technologies push operators to find alternative energy efficiency measures [13]. One such interim measure involves finding new operational strategies to reduce fuel consumption on vessels. Previous studies have discussed power management strategies for ferries as well as the potential of data-driven approaches to optimize maritime operations [14–17]. Whilst these studies have provided sufficient insight, very few of them address the nuances of energy efficiency approaches for double-ended ferries. In fact, Balestra and Schjølberg [18] highlighted the need for differing approaches to the optimization of operations when considering the double-ended ferries. Double-ended ferries are characterized by their bidirectional travel capabilities and are most prevalent in regional maritime networks, particularly for high-frequency, short sea routes. Their unique design enables efficient operations and minimal terminal time through a specific symmetric hull form and propulsion system, allowing for equally efficient sailing ahead and astern [19]. Double-ended ferries generally operate on fixed schedules. Their design and operational characteristics pose energy management challenges in optimizing their performance as they frequently encounter highly variable environmental conditions that directly impact their energy efficiency. Despite this, the actual performance of double-ended ferries remains under-researched [20].

While previous studies [21,22] have looked into predictions of power requirements of ships, data-driven methods have emerged as key components of energy efficiency strategies. These methods rely on machine learning techniques to analyze ship energy performance [23,24]. It has been reported that these models are useful in predicting the power demand and energy consumption of ships [25,26]. Prior approaches to energy management have rarely captured the nuances of dual-propulsion configurations, where optimizing fuel consumption necessitates balancing engine loads. Existing studies have highlighted the use of regression models in predicting fuel consumption using artificial neural networks [27]; meanwhile, others have explored machine learning and optimization algorithms, revealing their effectiveness in dynamically adjusting revolutions per minute (RPM) configurations to achieve optimal performance under varying conditions [28,29]. These methodologies represent a broader industry trend toward leveraging data-driven approaches for maritime energy management. Despite the technological advancements, there remains a heavy reliance on human expertise for effective energy management. Operators play a key role in interpreting system outputs and making real-time decisions that account for situational variables not fully captured by automated systems. Agand et al. [30] outlined that earlier studies focused on the vessel's operational performance, overlooking the operator's perspective and environmental factors. They emphasized the lack of research on developing a systematic approach for selecting and analyzing tailored datasets.

Using data-driven methodology, this paper analyzes sensor data alongside operational characteristics and environmental conditions. This study examines a double-ended ferry operating in the Baltic Sea and demonstrates how optimizing propulsion loads combined with strategic operator decisions can reduce fuel consumption and lower GHG emissions. Although this case study is specific to the Baltic Sea region, the findings and methods are broadly applicable to the wider maritime industry, offering valuable recommendations for ferry operators and policymakers. This study is centered on the following two research questions:

(1) How can ferry operators effectively utilize operational and environmental data to reduce fuel consumption and emissions without compromising performance?
(2) In what ways do operator decisions and seasonal variations impact propulsion efficiency in double-ended ferries?

Understanding the dynamics of ferry operations requires addressing these critical questions, as they uncover actionable strategies for enhancing sustainability performance.

This study offers suggestive findings on how to minimize fuel consumption on ships but acknowledges some important limitations. The regression models were developed for a specific route in Estonia and may not be entirely applicable to other geographical areas with differing environmental conditions. Future research could expand the analysis to include diesel fuel consumption as well as other fuel types and explore the impacts of various propulsion systems. Additionally, the quantitative nature of the regression models does not account for all factors influencing fuel consumption. Other studies could incorporate other operational parameters including crew behavior, scheduled maintenance, and hull integrity as these have been known to impact vessel efficiency. Furthermore, while seasonal adjustments took into account the effects of the winter months, more detailed data on ice conditions, sea state, and wind patterns could enhance the models' precision.

This research provides two main contributions. First, it shows that real-time monitoring combined with data-driven propulsion load strategies can reduce fuel consumption. Second, it emphasizes the need for an even split in using the fore and aft engines for optimal efficiency in double-ended ferries. These findings assist ferry operators and guide primary research geared towards modifying operational goals to increase fuel savings and achieve sustainability in maritime shipping.

This paper is structured as follows: Section 2 outlines the data sources used in this study and the methodological framework, which includes the application of regression models, wind influence corrections, and seasonal performance adjustments to assess the variability in operational conditions. In Section 3, the data analysis demonstrates that balanced propulsion loads and informed operator decisions result in reduced fuel consumption. Section 4 interprets the findings, while Section 5 details the study's conclusion, summarizes the key insights, and offers practical recommendations for ferry operators and suggestions for future research.

2. Data and Methodology

Data for this study were obtained from the Vessmon (v. 300-05.000.01) Energy Monitoring System (EMS) data from the double-ended ferry MV Soela. This system was developed and installed by the Estonian shipbuilder Baltic Workboats (Nasva Harbor, Saaremaa, Estonia). The platform is integrated, collecting and analyzing real-time data (see Figure 1) using multiple variables and inputs. It monitors fuel flow, engine load, and environmental conditions to compile and assess high-resolution energy usage profiles for each subsystem. Additionally, performance alerts are recorded to improve the system's analysis.

	Max	Min	Avg	Median	Std.Dev
Fuel used (AUX) (L)	7.486	0	3.818	3.843	2.193
Fuel used (PROP) (L)	110.07	0	58.83	59.615	32.624
Fuel used (L)	117.55	0	62.643	63.455	34.816
Engine speed (AFT) (rpm)	955	0	84.668	0	219.108
Fuel rate (AFT) (L/h)	31.1	0	1.992	0	5.864
Fuel used (AFT) (L)	2.15	0	0.19	0.08	0.362
Engine speed (FORE) (rpm)	1461	504	1248.848	1301	177.293
Fuel rate (FORE) (L/h)	170.5	13.3	97.167	102.2	23.957
Fuel used (FORE) (L)	107.92	0	58.636	59.53	32.458
Wind angle	231	126	198.998	200	16.259
Wind speed (kn)	21.5	1.9	13.245	13.85	3.509
Trip economy (l/nm)	52.742	0	16.761	15.421	4.609
Ground speed (kn)	9.11	0.02	8.093	8.61	1.656

Trip data

Route: **Triigi - Sõru**
Captain: **Captain 4**
Duration: **01:07:00**
Total distance (water): **7.88 Nm**
Total distance (ground): **8.96 Nm**
Ground speed: **8.05 Kn**

Trip economy: **16.81 l/nm**
Fuel used: **117.84 L**
Fuel used (AFT): **2.26 L**
Fuel used (FORE): **108.05 L**
Fuel used (AUX): **7.53 L**
Fuel used (PROP): **110.31 L**

Wind angle: **198.78**
Wind speed: **13.21 Kn**
Fuel rate (AFT): **2.04 L/h**
Fuel rate (FORE): **96.78 L/h**
Engine speed (AFT): **86.30 rpm**
Engine speed (FORE): **1246.10 rpm**

Figure 1. Sample of collected trip data.

The system interface is accessible both on board (see Figure 2) and on shore and uses predictive algorithms for optimizing the vessel's speed, path, and use of equipment to enhance fuel efficiency. Other elements, such as trip data over past periods and comparisons across the fleet, also provide for further strategic planning and decision-making.

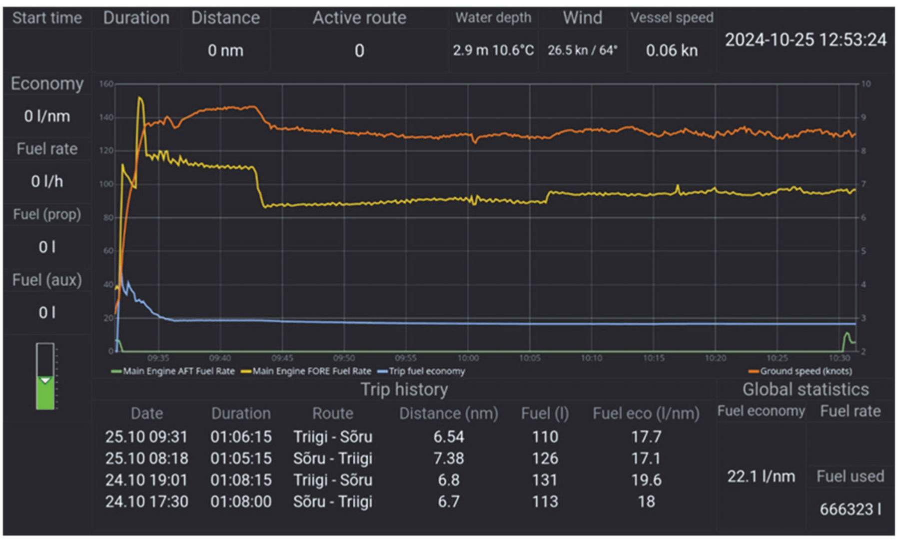

Figure 2. Decision support system display.

This vessel, detailed in Table 1, operates a nine nautical mile (NM) route in the Baltic Sea between the Estonian islands of Hiiuma (Sõru Harbor) and Saaremaa (Triigi Harbor). The data, which include fuel consumption, engine load (both AFT and FORE), the distance travelled, speed, and wind conditions, were collected between June 2022 and September 2024. The selected route for comparison was Sõru to Triigi, chosen to assess the impact of wind on fuel consumption. Reversing the route would alter the wind effects, complicating the comparison. The ferry is operated by four different captains, who work in two-captain shifts for two weeks each, ensuring continuous and varied operational data. This operational structure provides a range of practices that can be analyzed to study the effects of human factors on fuel efficiency [31].

Table 1. MV Soela particulars.

Particulars	Information/Value	Unit
Vessel type	RoRo cargo/Passenger	-
Vessel speed	12	kn
Engine type	MTU 8V 4000 M63	-
Engine power (N.C.R.), Pe	2000	kW
Length overall, L	45	m
Breadth, B	12	m
Deadweight, DWT	131, 863	t

To ensure accuracy of the data, these data first underwent a validation process as shown in Figure 3. Outliers were detected and removed, and inconsistencies in vessel speed and fuel consumption were flagged. After flagging the outliers and inconsistencies, the remaining dataset was then compared to manual crew logs and weather data to verify variables such as wind speed and directions, and environmental conditions. This is an important step when working with large maritime datasets [32]. Following the cross-referencing of data, anomalies were resolved through a systematic process of data removal, correction, and verification. Inconsistencies in vessel performance metrics were adjusted, and wind and environmental data were aligned with recorded observations. Additionally, discrepancies in timestamps and sensor readings were corrected to maintain consistency across all data points. The dataset was then rechecked for correctness before resulting in a cleaned and validated dataset for detailed analysis.

To handle missing or incomplete data, we used an interpolation method which involves predicting the values of missing point from the trends observed in the dataset. Through this method, we preserved the continuity of the dataset so that our analysis could accurately capture as close as possible to actual scenarios. We explored the relationship between wind conditions and fuel consumption by performing regression analysis. Regression models serve as powerful tools for exploring and quantifying relationships between variables and examine the effects of one or more explanatory variables on another, such as in the case of fuel consumption and its relationship with other factors like distance travelled [23].

Within this study, the regression model incorporated variables such as wind speed and direction, operational practices, and engine load to provide a more detailed analysis of factors influencing fuel consumption. We developed two regression models to allow for a more in-depth analysis. First, an unadjusted model, referring to straightforward fuel consumption without comparisons to wind conditions; and second, a corrected model, with comparisons to wind speed, angle and direction. This second model required an assessment of as many factors that may affect fuel consumption as possible. The corrected model showed that there was some variation in the fuel consumption adjustments as seen in Figure 4. For example, in headwind conditions, the corrected consumption values were higher by as much as 30 L. Alternatively, when tail winds were used, the corrected values were lower by as much as 30 L. Nevertheless, when it came to the general impact of the correction on the dataset, the impact was rather faint. The average fuel consumption of the dataset was lower by 1.62% from 140.6 L to 138.4 L.

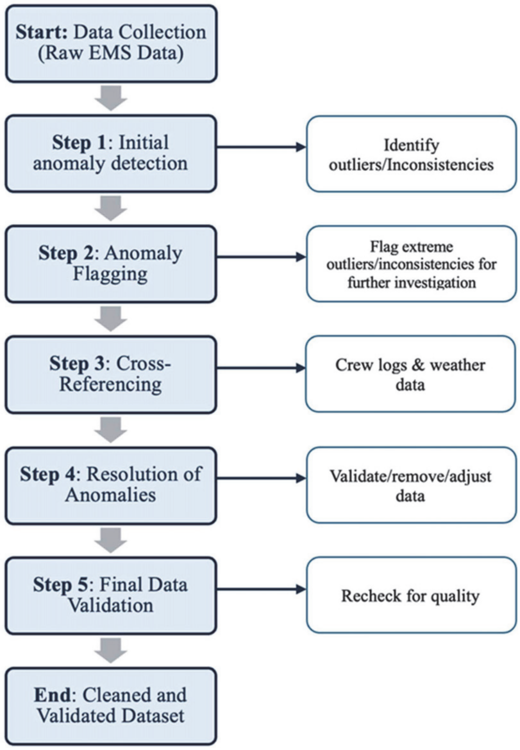

Figure 3. Data cleaning process.

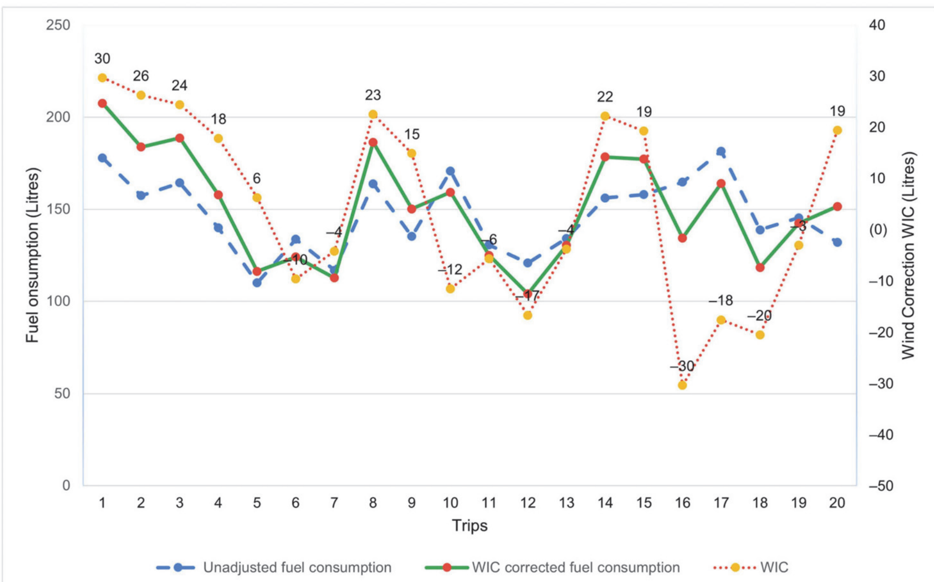

Figure 4. Comparison of unadjusted vs. corrected fuel consumption in ice-free period from 25 October until 5 November 2023.

Wind Influence Correction

Wind conditions significantly affect a ship's operational efficiency. To understand impacts on fuel consumption we developed a wind influence coefficient (WIC), defined as: WIC = cos(θ)·WS, where theta represents the angle between wind direction and the ship's course and WS is wind speed in knots. The use of the cosine function enables a more precise assessment of wind direction effects on ship propulsion. Typically, headwinds correspond to an angle of 130 degrees, while tailwinds are associated with 310 degrees. The WIC serves as a parameter which evaluates wind impact on fuel consumption based on wind speed and direction. Specifically, the cosine function accounts for wind directional effects: cos (130°) produces a negative value, indicating increased resistance and a fuel penalty during headwind conditions, whereas cos (310°) yields a positive value, reflecting reduced resistance and fuel savings in tailwind conditions.

The corrected fuel consumption (CFC) is derived from the initial fuel consumption (FC) by incorporating the WIC, represented as follows: CFC = FC + k·WIC. In this equation, FC represents the baseline fuel consumption for the voyage, while k is the scaling factor that determines the sensitivity of fuel consumption to the wind influence coefficient. Although k can be adjusted based on vessel-specific performance data, for this analysis, it is set to 1, assuming a direct proportionality between WIC and its impact on fuel consumption. Adjustments to k can be made based on vessel-specific performance data [33]. This methodology enhances the evaluation of maritime fuel efficiency by isolating the effects of wind conditions, allowing for the analysis of fuel consumption trends independent of external wind influences resulting in a clearer assessment of operational parameters.

3. Results

Both regression models (Tables 2 and 3) resulted in relatively similar outcomes (using linear regression as non-linear regression did not perform well). Generally, using the rear engine (AFT) will increase lower co-efficient diesel fuel consumption compared to the front engine (FORE)—these are both highly statistically significant. The ratio between AFT and FORE is also similarly statistically significant, and it reveals that if the front engine is not used at all (or on a very minor scale), and the power weight is essentially only on the rear engine, then consumption will increase. The regression model also argues that usage of the front engine consumes more diesel fuel (compared to the rear), the vessel needs to apply some reasonable area of power for the front engine and not remove from it too significant a quantity of overall power.

Table 2. Regression model parameters for raw fuel consumption.

	Coefficient	***p*-Value**
Fixed term	−130.285	***
Engine speed (AFT)	0.106	***
Engine speed (FORE)	0.153	***
AFT/FORE	6.861	***
R^2	0.458	

*** statistically significant at level of <0.001.

3.1. Seasonal Adjustments (Winter Effect)

Regression models were able to forecast 45.8% (see Table 2 and R^2) and 43.7% (see Table 3 and R^2) out of the diesel fuel consumption with data consisting of all seasons of the year (from June 2022 to September 2024). In Table 2, the explanation power of the three variables are reduced somewhat, even if weather conditions are better considered.

The data are from the Estonian route, located in Northern Europe, where winter is expected to occur with snow, ice, and low temperatures (especially in January and February) every year. The seabed occasionally freezes, and vessels operating in sea ice conditions require high power usage from both engines.

Based on the data, we identified December, January, and February as winter months (higher than average diesel fuel consumption compared to other months), and these were assigned with number one (1) as the rest of the months in the data were marked with zero (season is a binary variable, 0 or 1). As Tables 4 and 5 illustrate, enlarged regression models show increased explanation power (R^2) close to 50% or above. Adding winter months as a variable to the model is also justified as its statistical significance is very high. Winter months increase diesel fuel consumption per journey by 35–36 L. Other regressors have a similar order of importance in coefficients, and all have very high statistical significance. Incorporating the winter months appears to reduce these coefficients, but only minimally.

Table 3. Regression model parameters for wind-corrected fuel consumption.

	Coefficient	*p*-Value
Fixed term	−145.178	***
Engine speed (AFT)	0.115	***
Engine speed (FORE)	0.154	***
AFT/FORE	6.612	***
R^2	0.437	

*** statistically significant at level of <0.001.

Table 4. A regression model including the winter effect for raw fuel consumption.

	Coefficient	*p*-Value
Fixed term	−93.862	***
Engine speed (AFT)	0.087	***
Engine speed (FORE)	0.131	***
AFT/FORE	6.203	***
Winter month	35.781	***
R^2	0.529	

*** statistically significant at level of <0.001.

Table 5. A regression model including the winter effect for wind-corrected fuel consumption.

	Coefficient	*p*-Value
Fixed term	−109.043	***
Engine speed (AFT)	0.097	***
Engine speed (FORE)	0.132	***
AFT/FORE	5.960	***
Winter month	35.498	***
R^2	0.499	

*** statistically significant at level of <0.001.

3.2. Identifying Optimal Engine Speed Combinations

This study evaluates the improvement in the fuel economy of dual engine vessels that operate over a range of engine speeds. In the process of identifying the optimal RPMs that would result in the lowest fuel consumption, the impacts of AFT and FORE engine speeds on fuel use were assessed. The approach integrates statistical analysis and data visualization to derive meaningful findings. The dataset consists of vessel operational data including AFT RPM, FORE RPM, and fuel consumption in liters.

To quantify the impact of RPM on fuel consumption, multiple linear regression (MLR) was employed. MLR is a statistical technique that models the relationship between multiple independent variables and a single dependent variable by fitting a linear equation. In this analysis, MLR was used to examine how variations in AFT and FORE RPM influence fuel consumption, providing a quantitative assessment of their effects.

The regression equation is formulated as follows:

$$\text{Fuel Consumption} = \beta 0 + \beta 1 \times \text{AFT\_RPM} + \beta 2 \times \text{FORE\_RPM} + \epsilon$$

where

- $\beta 0$ is the intercept;
- $\beta 1$ and $\beta 2$ are the regression coefficients for AFT and FORE RPM, respectively;
- ϵ represents the residual error.

This approach is in line with the methodologies applied in maritime studies to predict fuel consumption as a function of operational parameters. Percentile-based filtering was used to determine engine speed combinations that are linked with percentiles of fuel consumption lower than or equal to 0.10. The most fuel-efficient operations were identified at the 10th percentile of fuel consumption data. This subset highlights the optimal AFT and FORE RPM combinations that contribute minimal fuel usage. To visualize these relationships, a 3D scatter plot was generated using Python 3.13, illustrating the interaction between AFT engine speed, FORE engine speed, and fuel consumption. In Figure 5, the AFT RPM (*X*-axis), FORE RPM (*Y*-axis), and fuel consumption (*Z*-axis) are depicted through the plotted data points. Data points are color-coded based on fuel consumption levels, with the most efficient operating conditions distinctly highlighted for clarity.

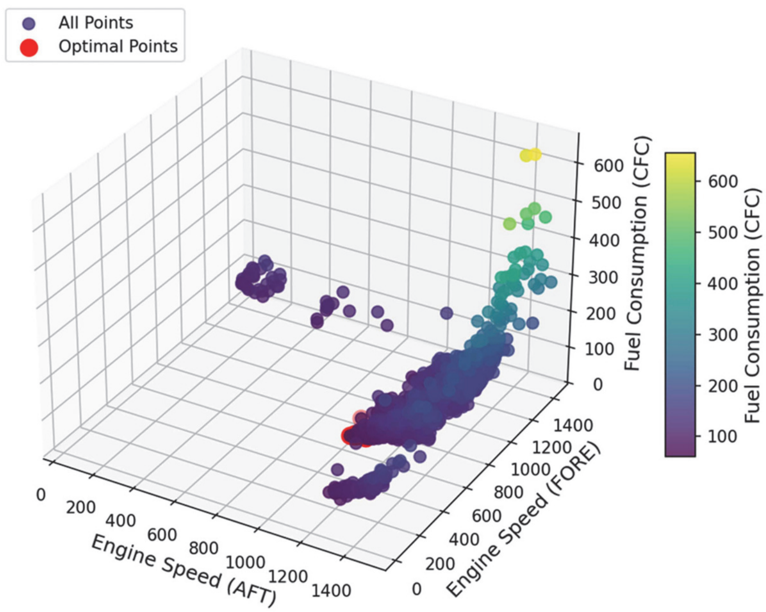

Figure 5. The 3D scatter plot depicting the relationship between AFT RPM, FORE RPM, and fuel consumption. Clusters of low-consumption data points highlight optimal RPM ranges.

The color gradient (see Figure 5) (from purple to yellow) indicates fuel consumption levels, with purple representing lower fuel consumption and yellow representing higher fuel consumption.

3.3. Optimal Cluster

The highlighted red points represent the most fuel-efficient operation ranges where fuel consumption is at its lowest. These points correspond to specific AFT and FORE engine speed ratios that minimize fuel usage. The red points are positioned in the lower section of the Z-axis and form a cluster, indicating that the optimal fuel consumption is achieved at moderate engine speed levels for both the AFT and FORE engines. This clustering provides valuable insights for operators to identify the ideal RPM ranges that enhance fuel efficiency. In contrast, the yellow points, which represent higher fuel consumption, are positioned further along the Z-axis, illustrating that increased RPMs result in higher fuel consumption. The non-optimal zones can be avoided during regular vessel operations to improve fuel economy. This visualization technique enables the identification of optimal engine speed ratios and is commonly used in maritime research. To facilitate data analysis and visualization, the following libraries were employed:

- pandas (v.2.2.3) for data manipulation;
- NumPy (v.2.1.3) for numerical computations;
- Matplotlib (v.3.9.3) for plotting.

3.4. Trend

The relationship between engine speeds and fuel consumption is non-linear. At lower and moderate engine speeds, fuel consumption remains relatively stable, but at higher engine speeds, it increases at a higher rate, indicating reduced efficiency. The results highlight specific AFT and FORE engine speed settings that yield the lowest fuel consumption. The 3D scatter plot effectively visualizes these optimal ranges, providing insights that can inform operational adjustments to enhance fuel efficiency. As shown in Figure 5, it is evident that reducing AFT RPM while increasing FORE RPM does not always lower fuel consumption. In fact, excessive increases in FORE RPM lead to higher fuel usage due to its impact on overall fuel burn. On the other hand, significantly lowering the FORE RPM while over-relying on the AFT engine is also inefficient. This suggests that both engines should be operated in a moderate range, with the AFT set slightly higher than the FORE. This configuration balances both engines within a more optimal operating range. Table 6 presents the ten most optimal FORE-AFT RPM combinations.

Table 6. Most optimal FORE-AFT RPM combinations.

Engine Speed (AFT) RPM	Engine Speed (FORE) RPM	Fuel Used (CFC) Liters per Trip
1043	688	60
1074	539	64
1100	543	65
1086	537	65
1097	539	66
1101	537	68
1094	542	71
1151	537	71
1111	542	72
1108	541	73

This approach provides a comprehensive method for enhancing fuel efficiency by optimizing vessel engine operations through the use of multiple linear regression analysis and enhanced visualization techniques.

4. Discussion

The regression analyses conducted in this study provide valuable insights into the key factors influencing fuel consumption in short sea shipping, with a particular focus on engine design, operational parameters, and environmental factors such as wind and seasonal variations. The regression models consistently demonstrated that fuel consumption is closely linked to the choice of operating the AFT or FORE engine. Notably, the findings indicate that using the AFT engine results in relatively lower fuel consumption as compared to the FORE engine and this difference is statistically significant. Further, the relationship between the two engines revealed that reducing or completely shutting down the FORE engine results in a slight increase in overall fuel consumption, emphasizing the importance of maintaining a balanced power distribution between the two engines.

An important aspect of this study is the evaluation of engine load management, and particularly, the most optimal usage of the AFT and FORE engines in hybrid systems. The findings indicate that effectively managing both engines simultaneously, and ensuring proper load distribution, significantly reduces the fuel consumption. The results suggest that vessel operators avoid shutting off the FORE engine, as doing so negatively impacts fuel efficiency. To enhance the regression models, an additional variable was introduced to account for winter months (December to February), improving model accuracy, and capturing the seasonal effects on fuel consumption. This indicates the impact of factors on fuel consumption trends. Adverse weather conditions, including high winds and low temperatures, have been seen to increase resistance and propulsion demands, and therefore fuel consumption [10]. In comparison to the results illustrated in Figure 6, where seasonal consumption seems to be greater in winter, our linear regression analyses (refer to Tables 4 and 5) suggest that the average difference is only around 35 to 36 L more fuel utilized per trip in freezing settings. This "winter penalty" while insignificant is understated, highlighting the fact that working under low temperature conditions requires extra energy.

It is important to note that while incorporating winter conditions enhanced the dataset's explanatory power, the overall impact on fuel consumption across the sample remained relatively minor. Although winter weather affects efficiency to some extent, it does not significantly alter overall fuel consumption trends. This suggests that while seasonal variations are important for operational planning, they may not require major adjustments to fuel consumption strategies.

One of the key contributions of this study is the identification of optimal engine speed combinations that minimize fuel consumption. Through a linear regression analysis, certain configurations of AFT and FORE engine speeds were linked to variations in fuel usage. The 3D scatter plots (Figure 5) visually depict the relationship between AFT RPM and FORE RPM, and fuel consumption, while higher RPMs lead to excessive fuel usage. These findings align with previous research on fuel efficiency, which often highlights the non-linear relationship between engine speeds and fuel consumption.

Table 6 presents the most effective AFT and FORE RPM combinations for fuel optimization. Based on these findings, vessel operators can alter engine speeds to enhance fuel efficiency, lower operational costs, and reduce environmental impact. This study suggests that the frequent use of the FORE engine leads to increased fuel consumption, making it more advantageous to limit its use when possible. However, the optimal strategy is not to over-rely on either engine but to operate both in a balanced manner. Figure 5 highlights specific RPM ranges where fuel consumption is minimized, offering clear guidance for operators on propulsion adjustments. Notably, the findings align with Al-Falahi et al. [15] who emphasized that optimizing engine performance will support fuel efficiency. In addition, the identification of specific RPMs that are linked with lower fuel consumption gives practical advice for ferry operators. In this way, with such data-driven approaches, operators can improve the operational efficiencies and decrease the environmental impacts that are relevant to the increased regulatory pressures on emissions. Additionally, the research underscores the importance of combining technical optimizations with crew training to maximize fuel savings.

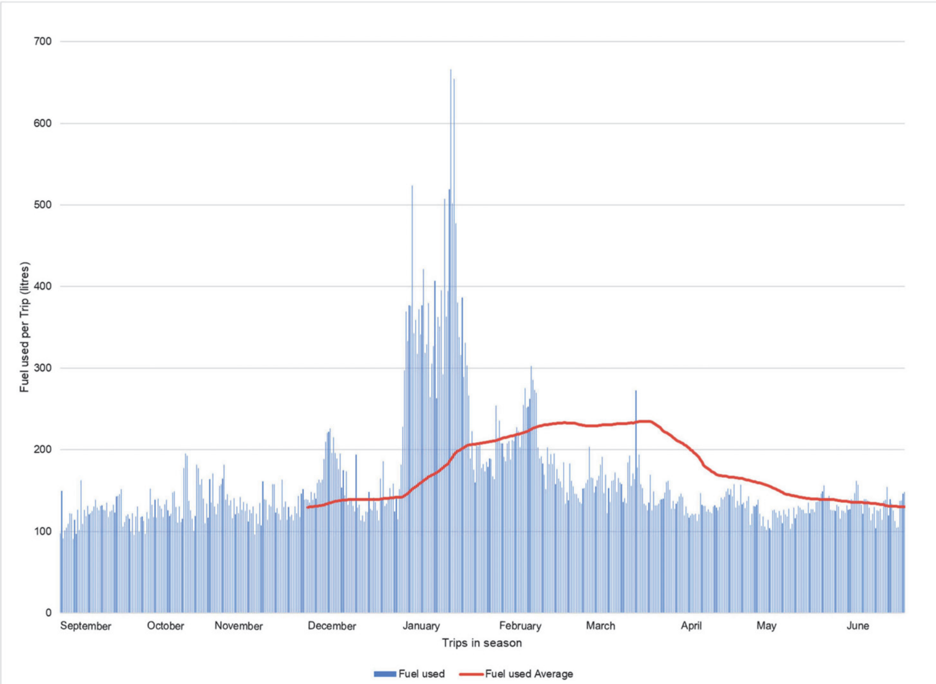

Figure 6. Monthly and 120 days period average fuel consumption from September 2023 until June 2024.

Optimized engine use in maritime transportation presents unique challenges. Stoumpos et al. [34] concluded that advanced knowledge of engine functionality is essential for efficiency improvements. This study further clarifies the complexity highlighting that reducing reliance on one engine may initially appear beneficial but can introduce inefficiencies that increase fuel consumption. These insights underscore the need for more advanced engine management systems. Furthermore, the integration of modern technologies like machine learning and big data analytics can enhance the operational efficiency of the vessel. Machine learning techniques, in particular, could be applied to real-time fuel consumption forecasting, providing critical decision support for maritime operations [35].

5. Conclusions

This study applies regression modelling to study how fuel consumption is affected by certain operational and environmental characteristics of a double-ended ferry in Estonia. The findings of this study agree with the idea that engine configuration, operational strategies, and environmental conditions are critical in determining fuel efficiency. Finding the best combinations of engine speeds is helpful in terms of practicality to the marine operators and aids in making sustainable marine transportation. Furthermore, applying seasonal modifications increases the accuracy of the fuel consumption estimates of specific regions, especially in the colder areas.

This study builds on previous works [10,36,37] and shows that incorporating operational data with wind corrections, seasonal shifts, and human adjustments improves the energy efficiency of double-ended ferry operations in terms of GHG emissions. The findings of this study can serve as a useful reference for operator training, route planning, and fleet management to identify the ideal RPM settings and to consider the ship state and importance of balanced propulsion. This study agrees with previous works which have noted that wind corrections, seasonal components, and proper engine loading are factors to be considered for maximizing the energy efficiency of double-ended ferry operations. Our regression analyses also supported previous findings that winter conditions raise average fuel consumption by approximately 35–36 L per trip. Although the general change is small, winds can change consumption as much as $\pm$35 L.

The core contribution of this research lies in the detailed analysis of engine load combinations, examined through ordinary regression and the 10th percentile approach. The findings indicate that reducing the use of the FORE engine can actually lead to an overall increase in fuel consumption. Consequently, the most effective strategy is to maintain a balanced operation of both AFT and FORE engines. These results align with existing theories on energy management, reinforcing current human-centered approaches while introducing new, actionable methods for adjusting propulsion based on specific environmental conditions. Rather than contradicting established principles, this study provides data-driven insights that enhance operational decision-making.

Future research could explore the impact of incorporating additional parameters into efficiency projections, potentially refining fuel optimization strategies. Additionally, studies could examine how incentives and crew training programs influence adherence to fuel-efficient operational practices. Such initiatives will become increasingly relevant in the context of regulatory compliance and sustainability, particularly as the maritime industry moves toward decarbonization.

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