Towards net-zero shipping: Sustainable energy and power in future marine vessels

Techno-economic assessment

Mika Lehmusto

Aalto University

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ABSTRACT

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Towards net-zero shipping: Sustainable energy and power in future marine vessels

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Keywords Marine decarbonisation, circular economy, second-life batteries, alternative marine fuels, icebreaker

Global shipping is undergoing a critical transition as it strives to meet the International Maritime Organization’s target of reaching net-zero greenhouse gas emissions by 2050. Achieving this ambition requires a coordinated transformation of energy technologies, powertrain architectures, and circular economy practices. As the maritime sector advances toward electrification, choices in propulsion, energy-storage, and fuel systems will determine both environmental performance and long-term economic viability.

This research explores the techno-economic and environmental feasibility of sustainable energy pathways for marine vessels, focusing on alternative fuels for high-power ships and on circular economy strategies for large-scale lithium-ion batteries. It integrates three complementary areas: sustainable fuel options for icebreakers, experimental analysis of first- and second-life battery performance, and life-cycle cost modelling of marine energy storage systems. The investigation integrates laboratory-scale ageing experiments, life-cycle and total cost-of-ownership modelling, and ship-level techno-economic simulations based on operational data from the *Polaris* icebreaker and *Ellen* e-ferry. Comparative assessments encompass fossil fuels, electrofuels, and nuclear energy systems, while the circular economy framework quantifies the reuse and salvage value of propulsion batteries across diverse market and cost conditions.

The results identify small modular reactors and renewable methanol and ammonia as the most promising long-term energy solutions for icebreakers. The Small Modular Reactor (SMR) offers near-zero operational emissions and approximately €15 million lower life-cycle costs than the next best alternative. In the energy storage studies, retired electric vehicle batteries retained substantial capacity for reuse in lower-stress stationary applications, with first-life cycling intensity having only a limited effect on second-life degradation once repurposed at approximately 80% state of health. Second-life batteries can achieve payback periods between three and six years in frequency control or stacked grid services when procured at half the cost of new systems. Battery reuse and material circulation further reduce ferry life-cycle costs by 1–2%, improving battery capital efficiency by about 20%.

Future research should focus on optimising hybrid fuel–battery configurations, conducting more comprehensive techno-economic analyses of small modular marine reactors, developing policy-driven life-cycle models to refine decarbonisation pathways for a broader range of vessel types, and enhancing the logistics of large-scale battery repurposing.

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TIIVISTELMÄ

Tekijä
Mika Lehmusto

Väitöskirjan nimi
Kohti nollapäästöistä merenkulkua: Kestävät energia- ja voimansiirtoratkaisut

Artikkeliväitöskirja

Sivumäärä 57

Avainsanat Merenkulun hiilidioksidipäästöjen vähentäminen, kiertotalous, toisen käyttöiän akut, vaihtoehtoiset meripolttoaineet, jäänmurtaja

Kansainvälinen merenkulku on käännekohdassa pyrkiessään saavuttamaan Kansainvälisen merenkulkujärjestön (IMO) asettaman nollapäästö tavoitteen kasvihuonekaasujen osalta vuoteen 2050 mennessä. Tämän tavoitteen saavuttaminen edellyttää kokonaisvaltaista muutosta energiantuotantoteknologioissa, voimansiirtojärjestelmissä ja kiertotalouden käytännöissä. Merenkulun edetessä kohti sähköistymistä ratkaisut propulsioenergian varastoinnissa ja polttoainejärjestelmissä ja merimoottoreissa määrittävät sekä ympäristösuorituskyvyn, että pitkän aikavälin taloudellisen kestävyyden.

Tässä tutkimuksessa tarkastellaan kestävien energiavaihtoehtojen teknistaloudellista ja ympäristöön liittyvää toteuttamiskelpoisuutta meriliikenteessä keskittyen suuritehoisten alusten vaihtoehtoisiin polttoaineisiin sekä suurten litiumioniakkujen kiertotalousratkaisuihin. Tutkimus yhdistää kolme toisiaan täydentävää osa-aluetta: jäänmurtajien kestävät polttoainevaihtoehdot, ensimmäisen ja toisen elinkaaren akkujen kokeellisen suorituskykyanalyysin sekä meriliikenteen alusten energiavarastojen elinkaarikustannusmallinnuksen. Menetelmällisesti tutkimus yhdistää laboratoriomittakaavan ikäännytyskokeita, elinkaari- ja omistuskustannusmallinnusta sekä alustason teknistaloudellisia simulointeja, jotka perustuvat operatiivisiin mittausaineistoihin Polaris-jäänmurtajasta ja Ellen-sähkölautasta. Vertailuanalyysit kattavat fossiiliset, synteettiset ja ydinvoimapohjaiset energiavaihtoehdot, ja kiertotalouskehikko arvioi propulsioakkujen uudelleenkäytön ja jäännösarvon eri markkina- ja kustannusskenaarioissa.

Tulokset osoittavat, että pienet modulaariset reaktorit (SMR) sekä uusiutuva metanoli ja ammoniakki ovat lupaavimmat pitkän aikavälin energiaratkaisut jäänmurtajille. SMR mahdollistaa lähes nollapäästöisen käytön ja noin 15 miljoonaa euroa pienemmät elinkaarikustannukset verrattuna seuraavaksi parhaaseen vaihtoehtoon. Energiavarastotutkimuksissa havaittiin, että käytöstä poistetuilla sähkökäyttöisen liikkuvan kaluston akuilla on edelleen merkittävästi jäljellä olevaa kapasiteettia, kun niitä hyödynnetään matalampaa kuormitusta vaativissa kiinteissä sovelluksissa. Ensimmäisen elinkaaren kuormituksella todettiin olevan vain rajallinen vaikutus toisen elinkaaren vanhenemiseen, kun akut otetaan uudelleen käyttöön noin 80 %:n kuntoasteella. Toisen elinkaaren akut voivat saavuttaa 3–6 vuoden takaisinmaksuajan kantaverkon taajuuden säätöreservinä tai yhdistetyissä sähköverkon palveluissa, kun ne hankitaan puolella uuden järjestelmän hinnasta. Akkujen uudelleenkäyttö ja materiaalien kierrätys alentavat lisäksi sähkölauttojen elinkaarikustannuksia 1–2 % ja parantavat akkuinvestointien pääomatehokkuutta noin 20 %.

Jatkossa tutkimuksen tulisi keskittyä hybridialusten polttoaine ja akkujärjestelmien optimointiin, pienten modulaaristen merireaktoreiden syvempään teknistaloudelliseen analyysiin, politiikkaperusteisten elinkaarimallien kehittämiseen eri alusten päästövähennyspolkujen tarkentamiseksi sekä laajamittaisen akkujen uudelleenkäytön logistiikan tehostamiseen ja prosessien automatisointiin.

Preface

This thesis has been carried out through fruitful research collaboration and contributions within the Energy Conversion and Systems Research Group and the Marine and Arctic Technology Research Group at the Department of Mechanical Engineering, Aalto University.

First and foremost, I would like to express my deepest gratitude to my main supervisor, Professor Annukka Santasalo-Aarnio, for providing me with this research opportunity, and for her patience, trust, and continuous support throughout the entire process, which was not always as straightforward as initially anticipated. I have greatly valued her positive, encouraging, solution-oriented, and innovative guidance, as well as her ability to provide a broader perspective and inspire creative thinking during this research journey.

I am also sincerely thankful to Professor Osiris A. Valdez Banda and Dr. Victor Bolbot for their excellent collaboration and valuable contributions to the marine and Arctic technology aspects of this research. This work would not have been possible without their expert supervision, insightful discussions, and guidance.

Furthermore, I would like to acknowledge Professor Juhani Hyvärinen from the Nuclear Energy Laboratory, School of Energy Systems, Lappeenranta–Lahti University of Technology (LUT), for his inspiring collaboration. His extensive experience in nuclear power plants offered invaluable perspectives when evaluating the feasibility of small modular reactors for icebreaker applications.

My sincere thanks also go to my research colleagues for their flexible, proactive, and productive collaboration. In particular, I would like to thank Dr. Neha Garg, BSc Ella Koivisto, and MSc Aravindda Venkatesh for their contributions to the energy storage research, as well as to Umair Khalid, Max Cobben, and Mia Elg for their work and cooperation in the field of marine technology.

Finally, I owe my deepest appreciation to my wife and family for their patience, understanding, and unwavering support. Thank you for standing by me whenever “father had some writing work on the table” yet again. My heartfelt thanks also go to my parents, parents-in-law, and relatives for their continuous encouragement throughout this five-year research journey.

Espoo, October 15, 2025

Mika Lehmusto

Contents

Publications

List of Publications

This doctoral thesis is based on the following publications:

I. **Lehmusto, Mika**; Santasalo-Aarnio, Annukka; 2022. Mathematical framework for total cost of ownership analysis of marine electrical energy storage inspired by circular economy. Elsevier. Journal of Power Sources, 528, pages 231164-231174. ISSN 0378-7753. DOI: 10.1016/j.jpowsour.2022.231164.

II. **Lehmusto, Mika**; Santasalo-Aarnio, Annukka; 2025. Impact of first-life usage on second-life performance of lithium-ion batteries. Elsevier. Next Energy, 9, pages 100385-100398. ISSN 2949-821X. DOI: 10.1016/j.nxener.2025.100385

III. **Lehmusto, Mika**; Khalid, Umair; Cobben, Max; Bolbot, Victor; Elg, Mia; Hyvärinen, Juhani; Santasalo-Aarnio, Annukka, Osiris A. Valdez Banda; 2025. Techno-economic analysis of alternative energy sources for icebreakers in the Baltic Sea. Elsevier. Renewable and Sustainable Energy Reviews, 224, pages 115963-115981. ISSN 1364-0321. DOI: 10.1016/j.rser.2025.115963.

Author's Contribution

Article I: Mathematical framework for total cost of ownership analysis of marine electrical energy storage inspired by the circular economy.

> The author conceptualised and carried out the research, including the literature review, methodological development, mathematical modelling, preparation and visualisation of results, as well as sensitivity and economic analyses. Professor Annukka Santasalo-Aarnio provided support with article structuring, figure preparation, and the review of the manuscript.

Article II: Impact of first-life usage on second-life performance of lithium-ion batteries.

> The author conceptualised and carried out the research, including the literature review, methodology development, data collection, preparation and visualisation of results, economic analyses, and manuscript writing. Valuable support in the execution of practical test runs using the Arbin cycler was provided by BSc Ella Koivisto and MSc Aravindda Venkatesh. Professor Annukka Santasalo-Aarnio provided support with article structuring, results assessment, test environment funding, and the review of the manuscript.

Article III: Techno-economic analysis of alternative energy sources for icebreakers in the Baltic Sea.

> The author conceptualised the study design with the assistance of Dr. Victor Bolbot, Professor Juhani Hyvärinen, and co-authors Umair Khalid and Max Cobben. Engine data from the Polaris icebreaker were obtained from Arctia and Marfle at the request of the main author and Dr. Victor Bolbot. The initial draft was written by the main author with support from the co-authors. The analyses and visualisations were generated by the main author with support from co-authors Umair Khalid, Max Cobben, Juhani Hyvärinen, and Mia Elg. Writing, review, and supervision were provided by Dr. Victor Bolbot, Professor Osiris A. Valdez Banda, and Professor Annukka Santasalo-Aarnio.

List of Abbreviations

AC	alternating current
ACIR	alternating current internal resistance
BESS	battery energy storage system
CAPEX	capital expenditure
CE	circular economy
DC	direct current
DoD	depth of discharge
DCIR	direct current internal resistance
E/F	electric ferry
EIS	electrochemical impedance spectroscopy
FC	fuel cell system
FCR	frequency containment reserve
GHG	greenhouse gas
GWP	global warming potential
ICE	internal combustion engine
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LCA	life-cycle assessment
LCC	life-cycle cost
LCOE	levelised cost of energy
LDT	light displacement tonne (hull, superstructure, machinery, equipment)
LF	load factor
LIB	lithium-ion battery

LNG	liquefied natural gas
ME	main engine
NCA	lithium nickel cobalt aluminium oxide
NMC	lithium-nickel manganese cobalt oxide
O&M	operation and maintenance
OPEX	operating expenditure
PEMFC	proton exchange membrane fuel cell
PWR	pressurised water reactor
SEI	solid electrolyte interphase
SFOC	specific fuel oil consumption
SOFC	solid oxide fuel cell
TCO	total cost of ownership - LCC plus costs or revenues associated with the asset
TTP	tank-to-propulsion
WTT	well-to-tank
WTW	well-to-wake
WTP	well-to-propeller

List of Figures

1 Introduction

The Intergovernmental Panel on Climate Change (IPCC) has warned that the goal of limiting global warming to 1.5 °C is at risk due to significant gaps between projected emissions and the current policies and legislation intended to meet climate targets across all sectors and regions [1]. In the future, goods and services must be produced and transported using more sustainable methods supported by coherent policies. Parallel efforts across all sectors will be essential to achieving global sustainability goals and securing benefits for future generations [2].

Accordingly, the maritime transportation sector, which plays a critical role in global trade and the world economy, must take strong and tangible steps towards cleaner and more energy-efficient operations to support international climate and sustainability objectives. The International Maritime Organization (IMO) and the Organisation for Economic Co-operation and Development (OECD) estimate that the maritime sector emits nearly 1,000 million tonnes of CO_{2e} annually, accounting for approximately 3% of global greenhouse gas (GHG) emissions [3-4]. In response, the IMO has defined a concrete GHG-reduction strategy and long-term action plan aimed at achieving net-zero GHG emissions from international shipping by or around year 2050 [5-6].

In the marine industry, there are significant opportunities to reduce emissions both during the operational phase and through sustainable material circulation throughout a vessel's life cycle [8], [10]. Achieving net-zero emissions in shipping is a complex, multidimensional challenge that involves a variety of factors from regulatory frameworks, requirements, and performance indicators related to energy efficiency and carbon intensity, to the selection of energy sources and power-plant technologies. These choices must consider the evolution of fuel technologies over a lifetime of the vessel, to ensure compatibility with propulsion systems, alignment with emission-reduction targets, and overall fuel affordability. Furthermore, ship design must align with the specific operational missions of different vessel segments. For example, coastal ferries, RoPax ships, and icebreakers each have distinct operational requirements that influence design decisions. Factors such as fuel consumption, tank size, fuel weight, bunkering options, and safety must be harmonised with the operational and power profiles of the ship.

Additionally, the design phase should incorporate foresight into the end-of-life stage of the vessel. This includes understanding material flows and selecting materials that support sustainable recycling and disposal. Integrating circular-economy principles early in the design process is essential for minimising environmental impacts over the full life-cycle of the ship and beyond.

1.1 Electric powertrains

The maritime industry is undergoing a profound transformation as it seeks pathways toward sustainable propulsion and reduced greenhouse gas emissions. A central element in this transition is the adoption of electric powertrains, which provide a highly flexible platform for integrating diverse energy sources into ship propulsion and onboard power systems. By decoupling the generation of electrical energy from its use in propulsion, vessels can draw power from multiple sustainable technologies, whether rotational energy produced by engines running on low- or zero-emission fuels, electrochemical conversion in fuel cells, or energy storage systems such as batteries. This flexibility not only enables the incremental adoption of cleaner energy sources but also supports a future-proof approach to ship design in an era of rapidly evolving regulations and technologies.

The core of an electric propulsion system in a marine vessel is the electric powertrain, which links the energy source to the propulsion units and auxiliary loads through electrical conversion and distribution. At its simplest, an electric powertrain consists of a prime mover or energy source, an electric generator, a power electronic converter, and propulsion motors that drive the propellers or thrusters [9], as shown in Figure 1. Depending on the vessel design, additional components such as batteries, fuel cells, and energy management systems may be integrated to enhance efficiency, flexibility, and sustainability.

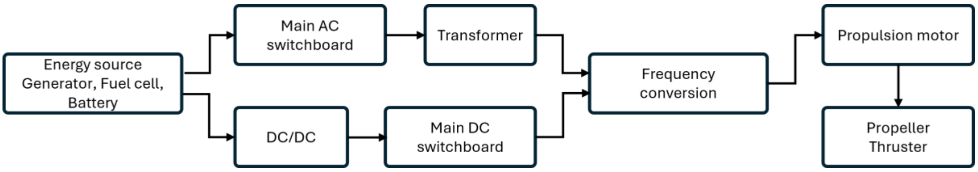


Figure 1. Conceptual schematic diagram of marine electric powertrain.

A key feature of marine electric powertrains is the electrical grid architecture that connects the various power generation and consumption units. Traditionally, marine vessels employ alternating current (AC) distribution systems, which are well established, robust, and compatible with a wide range of equipment. AC grids serve as the electrical backbone in many large ships, including cruise vessels and icebreakers, where high levels of installed power and long operating times demand proven reliability [10]. The use of synchronous or induction machines as generators and motors fits naturally within an AC framework, and the existing body of standards and operational experience provides confidence in its continued application.

In recent years, however, direct current (DC) grids have attracted growing interest, particularly in smaller vessels and hybrid designs. One of the principal advantages of DC distribution is the ease with which it accommodates non-synchronous power sources such as batteries and fuel cells. By removing the need for frequency synchronization, DC systems allow multiple energy sources and storage units to be connected flexibly while reducing conversion losses and improving overall system efficiency. This makes DC grids particularly suitable for battery-electric ferries and vessels with frequent load variations [11]. Furthermore, the lower component count in some DC architectures can reduce both weight and space requirements — factors of high importance in passenger and short-sea shipping.

Hybrid AC/DC configurations are also emerging, combining the strengths of both approaches. In such systems, an AC backbone may be retained for high-power distribution and compatibility with established equipment, while local DC subsystems are introduced to integrate batteries, fuel cells, or renewable inputs. These hybrid solutions provide operational flexibility, redundancy, and pathways for the incremental adoption of new technologies without discarding established infrastructure.

The selection of grid type is therefore not merely a technical detail but a strategic design choice that influences vessel performance, fuel flexibility, and future adaptability. AC systems remain the standard for large-scale, high-power applications due to their maturity and robustness, while DC grids are increasingly chosen for smaller, innovative, or zero-emission vessels where the integration of storage and fuel cells is central. Hybrid AC/DC solutions provide an intermediate step, allowing operators to balance reliability with innovation. In all cases, the overarching trend is clear: electric powertrains and modern grid architectures are reshaping the foundations of ship design and enabling sustainable propulsion concepts that can evolve with emerging energy sources.

The adoption of electric propulsion in shipping is no longer limited to specialised applications but is becoming a defining feature across a wide spectrum of vessel types. Different ship categories have embraced electric powertrains for distinct operational and environmental reasons, reflecting the versatility of this technology.

Battery-electric ferries are among the most visible examples, particularly on short-distance routes where predictable schedules and charging opportunities enable fully zero-emission operations. These vessels typically employ DC-based grids that facilitate direct integration of large-scale battery storage, offering both efficiency gains and reduced local pollution in sensitive coastal areas.

Offshore support vessels, by contrast, have adopted hybrid-electric architectures to enhance dynamic positioning and optimise fuel consumption. Here, AC backbones are commonly complemented by energy storage systems, allowing operators to balance fluctuating load demands and achieve both cost savings and emission reductions.

In large cruise ships, the motivation for electric propulsion lies in power scalability, redundancy, and passenger comfort. These vessels often rely on podded propulsion units integrated into AC grids, providing excellent manoeuvrability while meeting stringent environmental regulations in coastal and port areas.

Icebreakers and Arctic vessels represent another category where electric propulsion has become indispensable. With Azipod systems and robust AC grids, these ships gain the high torque and manoeuvrability needed in challenging ice conditions.

Taken together, these examples highlight how electric propulsion is transitioning from niche to mainstream, positioning it as a cornerstone of future marine energy systems.

1.2 Sustainable ways to power a marine vessel

Over the past few decades, multiple pathways towards low- and zero-emission marine transportation have been explored and trialled through both privately and publicly funded initiatives [12]. These efforts have aimed to transition the marine power plant landscape from traditional fossil diesel engine-based systems toward alternative energy solutions [11][13]. Emerging technologies have incorporated energy sources such as liquefied natural gas (LNG), methanol, hydrogen, and, more recently, ammonia. To accommodate varying operational profiles and economic constraints, dual-fuel engines have been developed, offering the flexibility to optimise both performance and cost. Proton exchange membrane fuel cells (PEMFCs) [14][15] and solid oxide fuel cells (SOFCs) [16][17] have also emerged as promising technologies, attracting increasing interest for use in maritime applications and power generation systems [18][19] due to their potential for low-or zero-emission energy production. In addition, small modular nuclear reactors are increasingly being considered as a potential option for achieving zero-emission marine propulsion [20].

Although modern and more environmentally sustainable power-plant technologies are already in commercial use, over 99% of the global shipping fleet remained dependent on conventional fossil fuels as of 2022 [21].

In evaluating sustainable marine fuels, it is crucial to consider not only tank-to-propulsion (TTP) emissions but also emissions arising from well-to-tank (WTT) stages, which can contribute significantly to the overall environmental footprint. A comprehensive assessment of sustainability must account for fuel consumption patterns across different power ranges, as well as the impact of undesirable side reactions, such as methane slip from LNG-fuelled engines operating outside their optimal performance zones.

Furthermore, the sustainability of a given fuel depends substantially on its production pathway: for example, whether methanol is produced using fossil sources such as coal (brown methanol) or natural gas (grey methanol), or through processes involving captured CO_2 (blue methanol) or biomass feedstocks (bio-methanol). Green e-fuels (electrofuels) are produced by utilising renewable electricity to generate hydrogen via electrolysis, which is subsequently combined with nitrogen to form ammonia or with captured carbon dioxide to form methanol or methane. When produced using carbon-neutral pathways, these fuels offer a viable route to achieving net-zero greenhouse gas (GHG) emissions [22].

Both the CO_2 emissions and production costs of these different methanol types, similar to those of other alternative fuels, exhibit considerable variation, as illustrated in Figure 2.

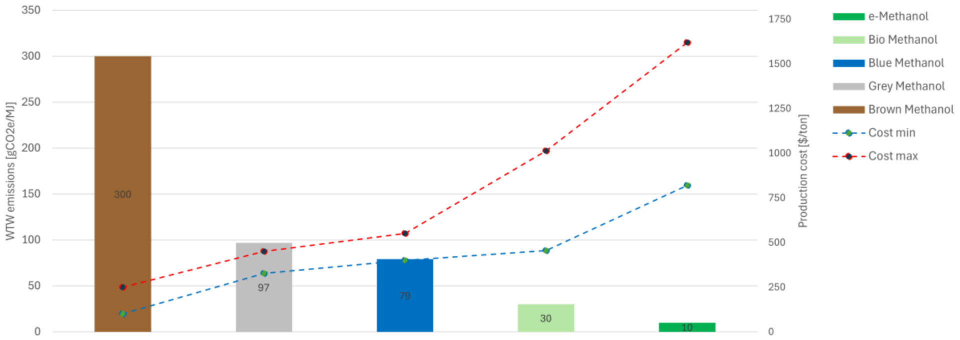


Figure 2. Cost range and well-to-propeller emissions. Unpublished image, data from [22-24].

Figure 2 shows a clear inverse relationship between production cost and CO_2 emissions among different types of methanol. Brown methanol, while the least expensive, exhibits the highest emissions, whereas e-methanol, although the most costly, achieves the lowest emission levels. This trade-off between cost and emissions presents a key challenge for ship designers and owners aiming to transition their fleets towards net-zero targets. A critical consideration is determining the appropriate timing for adopting lower-emission fuels. The uptake of low-carbon fuels is shaped by multiple factors, including regulatory incentives, carbon pricing mechanisms, technological advancements in fuel production, production volumes of the particular fuel, and the evolution of engine technologies, all of which influence the market dynamics of alternative fuels. At present, the high cost of zero- and low-carbon fuels primarily stems from their limited production volumes. Looking ahead, it is expected that as renewable energy becomes more accessible and carbon-reduction technologies continue to advance, the production costs of low- or zero-fossil fuels will decrease. This, combined with the necessary scaling-up of production capacity, is anticipated to enhance the competitiveness of sustainable fuels relative to fossil-based alternatives.

The operational and power profiles of a vessel are critical determinants of fuel consumption and the overall efficiency of its propulsion system. The fuel demand of an engine and its associated energy losses are directly influenced by prevailing load conditions [25]. Ideally, operating an engine consistently near its optimal power output minimises both fuel consumption and CO_2 emissions per nautical mile. In addition to operational optimisation, designing ships with a focus on high fuel efficiency represents an important strategy for further reducing greenhouse gas (GHG) emissions. Detailed analyses of power and load profiles can reveal opportunities for optimising energy usage, leading to reductions in both emissions and operational costs. Figure 3 presents the annual power profile of an icebreaker, illustrating the variations in power demand across mild, average, and severe winter conditions. The frequency of occurrence represents the number of samples recorded during the analysed season for each power range. The interval between consecutive sensor measurement samples is 30 seconds; therefore, the total operating time is defined by the number of samples and their duration. In this study, all calculations are performed separately for each main engine using individual 30-second sensor sample sets, which enables a high level of accuracy in the results.

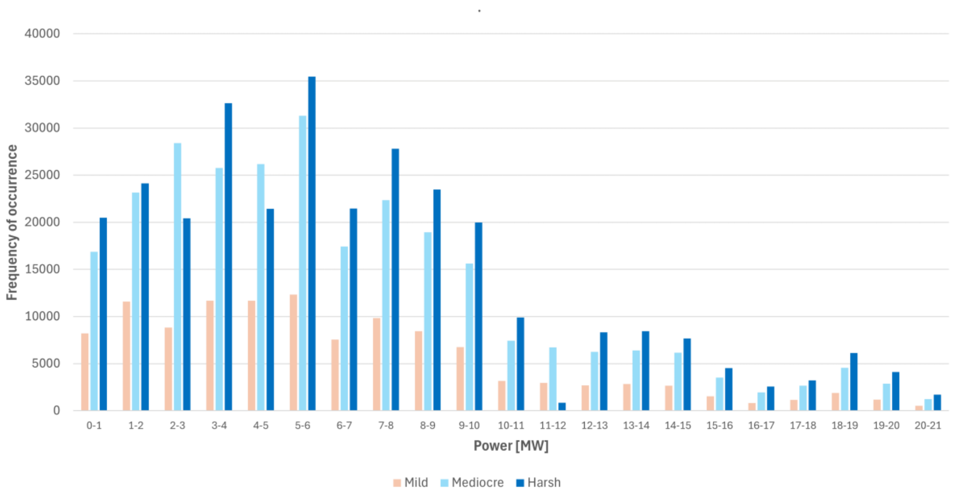


Figure 3. Annual power profile of an icebreaker for different winter conditions. *Publication III*.

As illustrated in Figure 3, the annual power profiles of operational vessels often exhibit significant periods of low power demand and substantial power fluctuations. These dynamic profiles present greater challenges for achieving high operational efficiency compared with profiles that have relatively constant power requirements.

To address these challenges in traditional vessels, engine sizing and operational strategies must be optimised to ensure that engines operate as close as possible to their optimal efficiency ranges. One effective approach involves integrating additional power sources, such as auxiliary battery energy storage systems (BESS), into the design of the vessel. Batteries can supply power during periods of low demand, such as overnight layovers or idle times between active operational phases, allowing diesel engines to be shut down and thereby reducing idling losses.

Moreover, energy storage systems in vessels generally offer multiple operational advantages: they can rapidly provide peak-power shaving, deliver fast power boosts, support zero-emission operations during port approaches and departures, and enhance resilience by mitigating the risk of power outages. Implementing these strategies contributes significantly to reducing the CO_2 emissions associated with diesel engine operation. In addition, operational cost savings can be achieved through reduced energy losses, lower emission-related costs, decreased diesel-engine maintenance requirements, and lower fuel consumption.

Furthermore, the integration of energy storage is particularly beneficial for vessels employing fuel-cell power systems with hydrogen as the primary fuel, as these systems typically exhibit limited dynamic response capabilities. In such cases, energy storage can support peak power demands and store excess energy generated during periods of low load, thereby enhancing the overall efficiency, flexibility, and fuel economy of the power system.

2 Research objectives

This thesis explores the pathways towards achieving net-zero emissions in the marine sector, with a specific focus on alternative energy sources and shipboard powerplant technologies. The research concentrates on two key life-cycle phases: the operational use phase and the end-of-life phase—the latter particularly concerning decommissioning and disposal. The overall objective is to evaluate the potential for improving sustainability by assessing technological, economic, and environmental viability in an integrated manner.

The study adopts a multidisciplinary approach, combining practical case studies with analytical comparisons to support robust conclusions. Two representative use cases—namely, a zero-emission electric ferry and the *Polaris* icebreaker—serve as real-world examples for examining the applicability and performance of selected energy technologies. These cases provide a valuable framework for exploring the practical implementation of sustainable solutions and highlight differences in environmental impact and energy-system design. The inclusion of real applications also strengthens the reliability of the economic feasibility analysis.

This chapter introduces the core research questions (RQ1-RQ8) addressed in the thesis. In addition, the data sources, collection and analysis methods, and applied research methodologies are summarised in Table 1.

1. Which energy technologies and fuels offer the greatest potential to decarbonize the marine industry under projected regulatory, economic, and technological constraints?

2. Which fuels and technological pathways are most viable for enabling environmentally sustainable maritime operations when transition risks related to fuel cost trajectories, infrastructure readiness, and technological maturity are considered?

3. Are low- and zero-emission energy sources economically viable over the operational lifetime of icebreakers in the coming decades? To what extent can these conclusions be generalised to other types of marine vessels?

4. To what extent does first-life cycling intensity affect the technical suitability of EV batteries for second-life applications?

5. To what extent is the reuse of marine or EV batteries economically justified, and which second-life use cases present the highest commercial value?

6. Under what conditions can second-life batteries achieve an economically viable payback period and generate net positive returns?

7. What is the expected economic salvage value of large marine propulsion batteries at the time of a BESS retrofitting?

8. What is the potential reduction in the life-cycle cost of electric ferries resulting from the reuse of propulsion batteries?

Table 1: Methodology and research questions addressed in the articles.

Article number	**Data source**	**Data collection**	**Data analysis**	**Research questions addressed**	**Theoretical framework**
1	Electric-Ferry project	E-Ferry validation report	Mathematical modelling	RQ1, RQ2, RQ5, RQ7, RQ8	Life-cycle cost modelling grounded in empirical data from a real-world e-ferry prototype.
2	Empirical data from cell-cycle testing (2023-2024)	Cell-cycler test logs over a one-year period	Experimental, data-driven techno-economic analysis	RQ4, RQ5, RQ6	Capacity and electrochemical-impedance-spectroscopy measurements conducted over second-life cycling periods across four cell-sample groups.
3	*Polaris* icebreaker sensors and counters (2022-2023)	Icebreaker log files for over a one-year period	Data-driven techno-economic analysis	RQ1, RQ2, RQ3	Quantitative assessment of the viability of alternative fuels across technical, economic, and environmental dimensions.

3 Research background

3.1 Net-zero-emission designs in marine transport

Today, shipowners and naval architects are presented with a broad range of technological alternatives as they seek to renew and future-proof their fleets in alignment with global decarbonisation targets [6]. The selection of propulsion and energy systems is a critical strategic decision that will significantly influence the environmental, economic, and operational sustainability of maritime operations. However, numerous questions arise in this process: Which energy technologies hold the greatest promise for enabling long-term sustainability in the marine sector? Are these options viable not only from an environmental perspective but also in terms of economic feasibility, infrastructure readiness, and supply-chain resilience? What are the key technical and financial risks associated with each pathway, and how can they be effectively mitigated? Figure 4 outlines a set of candidate energy technologies that merit consideration as part of the transition towards zero-emission maritime operations.

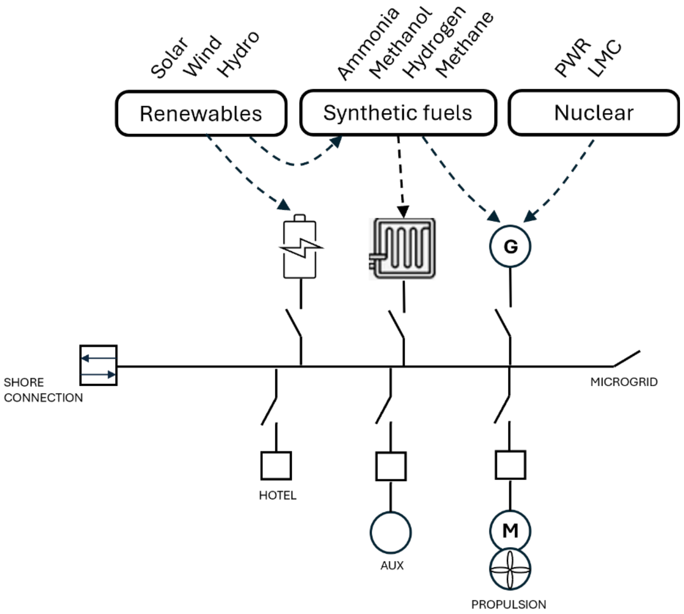


Figure 4. Zero-emission energy sources and power conversion in a marine microgrid supplying grid-connected loads.

The feasibility of alternative energy technologies in maritime applications is highly dependent on the mission profile of the vessel and associated operational requirements. For instance, fully electric ships powered by battery energy storage systems (BESS) and charged with renewable electricity represent a compelling solution for short- to medium-range coastal routes [11], [26]. In such contexts, charging infrastructure can be strategically implemented at the origin, destination, or both ports. However, operational constraints, such as tight turnaround schedules, may impose limitations on charging durations and necessitate high-power charging capabilities, thereby placing significant demands on the electrical infrastructure of the port. In areas with limited grid capacity, such as archipelagic regions, hybrid propulsion systems may offer a more practical solution [27]. For example, integrating hydrogen-fuelled fuel cells alongside BESS can extend the operational range and provide additional energy for both propulsion and onboard charging, thereby enhancing flexibility while supporting decarbonisation objectives [28].

For long-distance maritime routes and vessels operating under heavy-duty cycles, the capacity to store substantial amounts of energy is critical, similar to the energy-storage strategies employed in conventional diesel propulsion systems [29-33]. One promising solution lies in the use of synthetic fuels, or e-fuels, which can be stored in onboard fuel tanks designed to align with standard bunkering strategies for a given mission [34], [35]. Although current dominant production methods are not yet entirely fossil-free, they provide a more cost-effective option while the industry scales up. Importantly, synthetic fuels are compatible with both internal combustion engines (ICEs) and high-temperature fuel cell (FC) systems, though their energy-conversion efficiencies and technical integration characteristics vary depending on the fuel type and engine technology employed.

Nuclear power represents another promising alternative for maritime propulsion, particularly in applications requiring extended endurance and high power output. With its ability to operate without producing direct greenhouse gas emissions, nuclear propulsion aligns well with long-term decarbonisation goals in the marine sector. Its viability has been demonstrated in naval vessels and Arctic operations, where energy density and reliability are critical. Hirdaris et al. [20] reviewed the deployment of nuclear power in naval fleets, Russian icebreakers, and selected Western merchant vessels. The International Atomic Energy Agency's (IAEA) Advanced Reactors Information System (ARIS) highlights eight maritime applications of small modular reactors (SMRs) based on pressurised water reactor (PWR) technology, including one currently operational as a floating nuclear power plant [36]. Vergara and McKesson [37] found nuclear propulsion to be competitive for high-power, long-haul cargo vessels. In terms of capital expenditure, Moon and Kim [38] investigated the investment requirements for SMR integration, while the Canadian Economic and Finance Working Group (EFWG) roadmap estimated the levelised cost of electricity (LCOE) for SMRs. Notably, a 20 MWe off-grid SMR was shown to be cost-competitive with diesel generation at 6% and 9% discount rates [39]. Although regulatory, safety, and public-acceptance challenges persist, nuclear energy could play a vital role in enabling sustainable, long-range, and high-capacity maritime operations.

In summary, net-zero ship design entails balancing multiple criteria: technological maturity, operational feasibility, life-cycle emissions, safety, and cost. These vessel-level design considerations form part of the broader maritime transition discussed in Section 3.2, where policy, infrastructure, and market dynamics are examined as enabling factors for the large-scale adoption of sustainable energy technologies.

3.2 Transition to sustainable energy technologies and fuels in the maritime sector

The maritime energy transition and the circular economy in shipping are not only matters of technical change and innovation but are also strongly and bidirectionally linked to politics, regulation, supply chains, processes, economics, and the environment. The maritime energy transition refers to the shift from conventional fossil fuels to low- and zero-emission energy sources to decarbonise shipping. The circular economy (CE) in shipping entails designing and operating vessels, ports, and supply chains in ways that minimise waste, extend the lifetime of materials and components, and promote reuse and recycling throughout the maritime sector. Consequently, the assessment of new solutions for clean shipping requires transformation not only within the technical design of vessels but also across all stakeholders in the maritime ecosystem.

International organisations such as the European Union (EU), the Intergovernmental Panel on Climate Change (IPCC) [1], the Organisation for Economic Co-operation and Development (OECD) [3], and the International Maritime Organization (IMO) have established directives, strategies, and regulatory frameworks aimed at reducing greenhouse gas (GHG) emissions globally [6]. These efforts are intended to maintain atmospheric CO_2-equivalent (CO_2e) concentrations at levels consistent with limiting the rise in global average temperature to 1.5 °C.

Extensive research has focused on alternative marine fuels and energy sources. Techno-economic studies compare their technical and economic characteristics, as well as their suitability for specific route types and duty cycles [20], [29], [40-43]. In addition, environmental factors such as well-to-propeller (WTP) and tank-to-propeller (TTP) CO_2e emissions have been frequently addressed in the literature [44], along with life-cycle assessment (LCA) studies that compare different fuel options [30], [31], [45-47] and examine the LCA benefits of using second-life batteries as part of the CE [48-51]. Moreover, the challenges of Arctic shipping are occasionally addressed in the literature, though relatively rarely with specific reference to icebreakers [52-56].

Across the maritime domain, these initiatives have stimulated extensive research and technological innovation aimed at adopting alternative energy carriers and fuels with lower carbon intensity, such as liquefied natural gas (LNG, CH_4), methanol (CH_3OH), and hydrogen (H_2), in comparison with conventional marine diesel oil [25], [57-62]. Furthermore, carbon-free energy carriers that contain no carbon—such as ammonia (NH_3), hydrogen, and nuclear power are increasingly being considered as potential long-term solutions [20], [63-66]. The technical feasibility of these alternative energy sources is analysed in *Publication III*, using the *Polaris* icebreaker as the reference vessel.

According to the latest data from DNV's Alternative Fuels Insight (AFI) platform, orders for vessels powered by alternative fuels increased by 38% year-on-year in 2024 compared with 2023, reaching a total of 515 vessels [67]. The majority of these orders were for ships powered by LNG, methanol, and ammonia. This growth trend is notable; however, when placed in context, the penetration of alternative fuels within the active fleet remains limited. In 2022, only 1.2% of the global fleet operated on alternative fuels, with the following distribution: LNG (68.4%), battery/hybrid systems (29.4%), methanol (0.8%), and liquefied petroleum gas (LPG) (1.4%). By contrast, the order book for newbuild vessels in 2022 presents a more optimistic outlook, as alternative-fuelled ships accounted for 21.1% of total orders. Within this segment, the breakdown was as follows: LNG (52.1%), battery/hybrid systems (39.9%), LPG (5.5%), methanol (3.4%), and hydrogen (0.3%) [68]. While these market statistics illustrate the growing adoption of alternative fuels, the selection of an energy source for a new vessel remains a complex design decision influenced by multiple factors.

A key question then arises: which fuel represents the most suitable choice for a new vessel, and which option provides the greatest potential at both the ship and fleet level? When evaluating the feasibility of alternative fuels, several aspects must be taken into account. These include: (1) the purpose and operational profile of the vessel; (2) applicable regulations and environmental requirements; (3) technical feasibility; (4) economic considerations; (5) the planned lifetime of the vessel; and (6) future development projections.

Figure 5 illustrates one of the key drivers in ship design: the power demand. It presents the cumulative distribution of main-engine load levels across different operating conditions during the icebreaking season. The analysed icebreaking period spans from 1 March 2023 to 15 May 2023, which represents a mild winter.

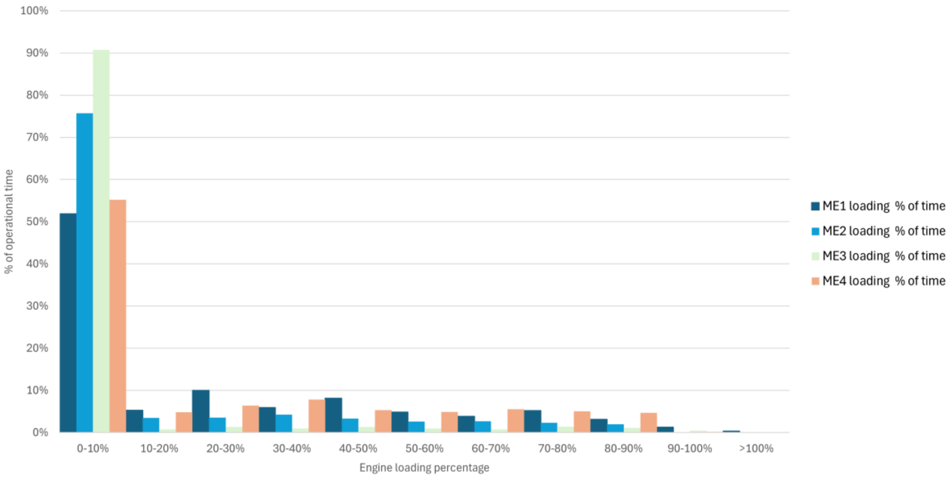


Figure 5. Engine load scatter of the icebreaker throughout the icebreaking season. *Publication III*, supplementary.

When considered over an annual timescale, the power profiles of icebreaker main engines exhibit significantly greater statistical variability than those of merchant vessels, which arises from fundamental differences in operational modes, mission profiles and loading conditions. Icebreaker operation is characterised by rapid and large-amplitude power fluctuations, in which the main engine load varies from partial load to near-rated power and subsequently to almost zero load. The instantaneous loading is governed by real-time interactions with the ice, including ice thickness and mechanical properties, the structure of the ice field, and the operational state of the assisted vessel. Seasonal variation further accentuates the dispersion of icebreaker load profiles, as summer operations are largely limited to harbour duties and transit voyages associated with low average power levels. In contrast, merchant vessels operate with largely uniform power profiles throughout the year, with variations in route and environmental conditions exerting only a marginal influence on main engine loading. During the studied mild ice breaking season in 2023, the main engines 1 and 4 were predominantly in use whereas engines 2 and 3 were used only to a limited extent.

In addition to power demand and engine usage profiles, factors such as the vessel's mission, ship type, route length, and operational profile, port-visit frequency, and allowable refuelling times have a significant impact on the selection of the energy source, as reflected in *Publication III*. These aspects influence the technical design, as the energy density of different fuels affects storage requirements and vessel weight. For instance, LNG requires cryogenic tanks, hydrogen storage is even more technically demanding, and batteries are heavy and require considerable space.

Furthermore, stringent safety requirements have a strong influence on ship design, and the technical specifications vary considerably between fuels.

Regulatory and environmental requirements also play a crucial role. These include international emission limits for sulphur, nitrogen oxides (NOx), and carbon dioxide (CO2). In addition, regional regulations, such as the EU FuelEU Maritime initiative, must be considered. Given the long service life of ships, it is essential that the chosen energy solution remains compliant with both current and future emission standards.

From an economic perspective, factors such as fuel price, price volatility across different markets, global availability, and the distribution and bunkering infrastructure must be assessed. Maintenance costs also vary depending on the machinery and fuel type employed.

A ship designer faces the challenge of identifying a fuel that is both suitable and optimal to meet the key requirements of the vessel throughout its operational lifetime. Different fuels and energy sources show distinct strengths and weaknesses, as well as varying levels of maturity in terms of machinery technology and supply-chain development [69]. Table 2 provides an overview of their key characteristics [70-71].

Table 2. Comparison of alternative fuels and energy sources

Fuel/Energy Source	Pros	Cons	Technology Readiness Level (TRL)
HFO Heavy Fuel Oil	High energy density; widely available; existing infrastructure and engines.	High sulphur and CO_2 emissions; increasingly restricted by IMO and regional regulations; negative public and environmental image.	9
LSFO / MGO Low-Sulphur Fuel Oil/Marine Gas Oil	Complies with sulphur caps; mature technology; globally available; established infrastructure.	More expensive than HFO; still fossil-based; CO_2 emissions remain high.	9
LNG Liquefied Natural Gas	Lower SOx, NOx, and particulate emissions; reduces CO_2 by ~20% vs HFO; growing global infrastructure	Methane slip (GHG concern); cryogenic storage required; large tanks reduce cargo space; not fully carbon neutral.	9
LBG Liquefied Biogas	Renewable; circular economy compatible; much lower net CO2 footprint.	Limited availability; high production costs; infrastructure still developing.	6-7
Methanol Conventional/ Green	Liquid at ambient conditions (easy storage and handling); can be produced from renewable sources (green methanol); flexible retrofitting potential.	Lower energy density (requires larger fuel volume); toxic and flammable; infrastructure still limited.	7-8
Ammonia Conventional/ Green	Zero CO_2 emissions at use; can be renewable (green ammonia); high potential as a long-term fuel.	Toxic and corrosive; low energy density; combustion challenges (NOx formation); infrastructure immature.	5-6
Hydrogen compressed/ Liquid	Zero emissions at point of use; high energy potential; flexible applications (fuel cells, ICEs).	Very low energy density (especially compressed); cryogenic or high-pressure storage required; infrastructure very limited; safety concerns (flammability, leakage).	5-6
Batteries Electric Propulsion	Zero local emissions; high efficiency; quiet, low-maintenance; ideal for short-sea shipping and ferries.	Very low energy density compared with fuels; heavy and bulky; charging infrastructure required; not feasible for long voyages.	8-9
Hybrid Fuel + Batteries	Combines flexibility of liquid fuels with emission-free port operations; reduced fuel consumption; proven in ferries	Higher capital cost; system complexity; still dependent on fossil or alternative fuels.	8-9

SMR Small Modular Reactor	Zero direct CO2 emissions; very high energy density; long fuel cycles; potential cost savings over life cycle.	Public-acceptance challenges; regulatory complexity; high upfront CAPEX; long approval times.	3-4

Consequently, the choice of energy source during the concept phase of ship design represents a compromise between regulatory compliance, cost, technical and operational feasibility, and emission-reduction objectives. Detailed calculations and comparisons of fuel characteristics are presented in *Publication III*, while battery-electric propulsion is addressed in *Publication I*.

Up to this point, this chapter has focused on the operational phase of the ship. However, when considering decarbonisation and sustainable industries more broadly, it is equally important to account for the end-of-life phase of the ship and its equipment. Given the expected lifetime of a vessel—typically 30 to 50 years—propulsion batteries must be retrofitted three to five times. This raises concerns that the use of batteries as the primary energy source may be both costly and materially intensive. However, waste generation can be mitigated through circular-economy strategies that emphasise reuse, recycling, and energy recovery [72-77]. *Publications I and II* demonstrate that battery-material circulation is technically feasible through repurposing by deploying retired batteries in second-life applications for less demanding stationary storage. This approach has been shown to be not only technically achievable but also economically viable.

The eco-design of battery systems aims to minimise environmental impacts throughout their life cycle by selecting sustainable materials, improving efficiency, and ensuring components can be easily disassembled for future reuse or recycling. After first use, many batteries can be repurposed in less demanding applications, such as stationary energy storage, thereby extending their service life and improving overall resource efficiency [77]. Ultimately, when batteries reach end-of-life, recycling processes recover critical materials such as lithium, cobalt, nickel, copper, and aluminium through safe collection, dismantling, and mechanical, thermal, or chemical treatment [74], [78]. Together, these steps establish a circular approach in which eco-design facilitates easier reuse, reuse postpones decommissioning, and recycling closes the loop by returning valuable resources to the supply chain while minimising environmental harm.

A particularly promising option, and almost “low-hanging fruit”, is the re-use of end-of-life (EOL) batteries. This approach can significantly delay recycling, depending on the use case, while saving large amounts of energy and virgin resources by avoiding new battery production. Understanding the remaining lifetime of second-life batteries is essential for ensuring their reliable use in stationary storage applications [79-82], which is examined experimentally in *Publication II*. The main challenge lies in predicting how much additional service can be extracted once batteries are retired from mobility, typically at around 80% state-of-health [83-84]. Recent research has addressed this by simulating less stressful operating conditions representative of stationary use, such as partial cycling with lower currents and smaller depths of discharge. These conditions not only reduce capacity-degradation rates but may even trigger stabilisation or partial recovery in performance. To evaluate this potential, capacity retention is monitored alongside diagnostic measurements of internal resistance. Direct-current internal-resistance (DCIR) testing provides insight into ohmic losses, while electrochemical-impedance spectroscopy (EIS/ACIR) reveals deeper ageing mechanisms linked to electrode and electrolyte changes. Together, these methods clarify how partial cycling extends useful life and quantify the available energy throughput for second-life applications.

3.3 Environmental approaches for the maritime sector

The maritime sector is entering a decisive phase of transformation driven by environmental imperatives and tightening regulations. Achieving net-zero shipping requires a life-cycle perspective that integrates design, operation, and end-of-life material recovery into a unified sustainability framework. Each stage of a vessel's life cycle offers opportunities to reduce emissions, conserve resources, and enhance overall environmental performance.

Cradle-to-grave perspective - Environmental benefits originate at the design stage, where architecture, energy systems, and material choices largely determine lifetime emissions. Holistic optimisation—incorporating modular propulsion layouts, hybrid readiness, and fuel flexibility—reduces fuel demand and operational emissions. At the end of life, regulated recycling and decommissioning processes ensure safe dismantling and maximise material recovery [85]. A cradle-to-grave perspective highlights that sustainability cannot be achieved through operational efficiency alone. Instead, a systems approach is required in which design for reuse, energy-storage replacement, and responsible recycling work in concert with fuel innovation and operational measures [72].

Alternative fuels and emission-reduction potential - Replacing fossil marine diesel oil (MDO) with low-carbon or carbon-free fuels yields immediate environmental benefits. Liquefied natural gas (LNG) offers an immediate reduction of approximately 20-25% in CO_2 emissions compared with diesel, while cutting nitrogen oxides (NOx) by up to 95% and nearly eliminating sulphur oxides (SOx) and particulate matter [86-87]. However, the methane slip during combustion reduces its overall climate benefit, indicating that fossil LNG cannot serve as a long-term solution for deep decarbonisation.

Methanol is gaining rapid traction, as evidenced by the growing number of methanol-fuelled vessel orders. While fossil-based methanol currently dominates, its renewable variant can significantly cut greenhouse gas emissions (by 70-90%), although its lower energy density requires larger storage volumes [88-89].

Green ammonia (NH_3) provides a zero-carbon combustion pathway that benefits from established global production and transport infrastructure. Being carbon-free, it eliminates CO_2 at the point of use [90] and can deliver up to a 79% well-to-wake (WTW) GHG emission reduction compared with conventional marine fuels [91]. Its toxicity and low energy density remain challenges, yet it offers one of the clearest routes toward deep decarbonization of long-distance shipping.

Hydrogen (H_2), when used in fuel cells, is operationally zero-carbon; at the tank-to-propeller (TTP) stage, CO2 emissions are eliminated. On a well-to-propeller (WTP) basis, green H2 fuel-cell pathways reduce CO_{2e} emissions by approximately 94% compared with MDO [92].

Nuclear energy, particularly via small modular reactors (SMRs), represents an unconventional but technically viable option. Recent analyses for icebreakers suggest that SMRs can achieve the lowest life-cycle costs among the fuels studied while providing near-zero operational emissions.

Each of these options contributes differently to lowering well-to-propeller CO_2e emissions. Transitioning from grey to green production pathways (e.g., green methanol or ammonia) can almost eliminate life-cycle emissions, highlighting the importance of decarbonizing the entire supply chain.

Energy storage and circular economy - Circular strategies of lithium-ion batteries (LIBs) include direct onboard reuse of ageing batteries in less demanding roles, second-life applications in stationary systems such as shore-side storage, and material recycling with recovery efficiencies of 89–99% for critical metals [74]. Life-cycle assessment studies show that manufacturing a new 50 kWh EV-type battery produces between 2.8 and 24.7 tonnes of CO_2e, depending on chemistry and production route [93]. By repurposing such batteries for second-life maritime or stationary use, up to 56% of these emissions can be avoided [51]. Studies indicate that repurposed batteries can extend usable lifespans by 50–65% and generate up to 20% life-cycle cost savings for shipowners [Publication I]. In addition to cost benefits, these strategies prevent unnecessary mining of scarce resources, reduce waste volumes, and avoid emissions from manufacturing new cells.

These closed-loop pathways align with the EU waste hierarchy and circular-economy directives, minimising waste and supporting net-zero targets under the European Climate Law and FuelEU Maritime regulation.

3.4 Economic assessment

This chapter provides the background for the economic assessments discussed in the publications, addressing both the operational and end-of-life phases of ships and their equipment within the broader context of energy sources and power generation.

3.4.1 Economic assessment of alternative energy sources

The economic dimension constitutes a central component in evaluating alternative energy sources for icebreakers and, more broadly, for ships across different segments [25]. Investment decisions in the maritime sector are influenced not only by technical feasibility and compliance with environmental regulations but also by their long-term economic implications. Techno-economic assessments provide a structured framework for comparing fuels and propulsion technologies across their life cycle, enabling decision-makers to balance capital expenditure (CAPEX), operational costs (OPEX), decommissioning requirements, and potential revenue streams [17], [42]. For icebreakers—highly specialized vessels with demanding operational profiles—demonstrating economic viability is particularly important to justify a transition away from conventional fossil-based systems.

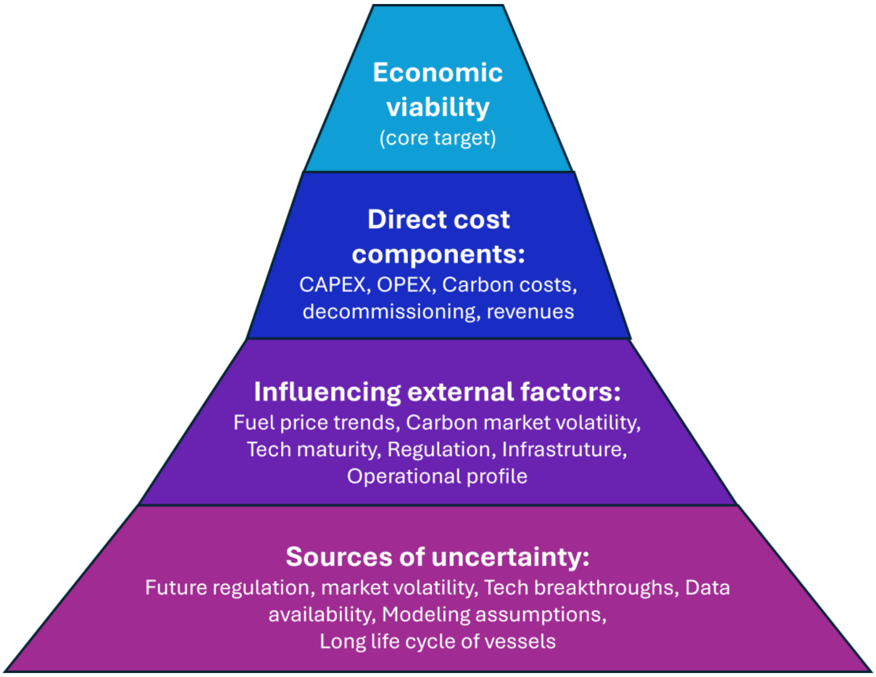


Figure 6. Economic assessment framework for alternative energy sources in icebreakers.

Figure 6 illustrates the proposed economic assessment framework, highlighting the interplay between cost components, external factors, and sources of uncertainty. The pyramid visualises how broad uncertainties (e.g., regulatory changes, market volatility, data limitations) and external influencing factors, including fuel price trajectories, carbon markets, technological maturity, and infrastructure availability, converge through direct cost elements (CAPEX, OPEX, carbon costs, decommissioning, and potential revenues) toward the ultimate evaluation of economic viability [69, 94-95]. The framework emphasises both the principal drivers of economic assessment and the key sources of uncertainty that must be explicitly acknowledged in techno-economic studies.

A wide range of factors shape the economic assessment of alternative energy options [96-97]. These include the capital costs of power plants and storage systems, fuel price levels and projected trends, and applicable carbon taxation schemes. Additional considerations involve maintenance requirements, decommissioning and recycling costs, and, in certain cases, the potential for off-season revenue generation (for example, electricity sales to the grid). Regulatory developments—such as the tightening of International Maritime Organization (IMO) and European Union (EU) emission frameworks—further influence the relative financial attractiveness of different fuel pathways. In the case of icebreakers, vessel-specific aspects such as long duty cycles, limited storage capacity, and seasonal variability in operating conditions also substantially affect cost structures.

Despite their importance, economic evaluations are subject to notable limitations. Cost projections for emerging fuels (such as green hydrogen and ammonia) remain uncertain due to evolving production technologies and limited production volumes [98]. Likewise, volatility in carbon pricing complicates life-time cost modelling. Nuclear-based solutions face additional uncertainties related to high capital intensity, regulatory approval processes, and end-of-life disposal challenges [99-100]. More broadly, techno-economic analyses are constrained by assumptions regarding operational profiles, fuel availability, and price evolution, which may not fully reflect real-world variability [101]. The accuracy of such assessments also depends strongly on the availability of high-quality operational data, which is frequently restricted due to confidentiality requirements or technical barriers to data collection.

In summary, economic assessment represents an indispensable tool for evaluating the feasibility of sustainable energy sources for icebreakers. However, it remains inherently subject to uncertainties related to costs, regulatory frameworks, and technological maturity. Recognising these limitations is crucial for contextualising the results of techno-economic studies and for supporting robust, evidence-based decision-making.

3.4.2 Economic assessment in the context of battery circular economy

The accelerating electrification of transportation and other end-use sectors has led to unprecedented deployment volumes of LIBs, which in turn raises critical questions regarding their sustainable management at end-of-life (EOL). In this context, the adoption of circular-economy (CE) principles—comprising reuse, repurposing, and recycling—has emerged as a promising strategy to mitigate environmental impacts while simultaneously generating economic value [73], [102]. A rigorous economic assessment is therefore indispensable in this regard, as decisions concerning second-life applications of batteries must be supported not only by technical feasibility but also by robust evaluations of long-term cost-effectiveness and resource efficiency.

From an economic perspective, CE pathways create opportunities to extend the value of batteries beyond their first life. Residual performance can be harnessed through direct reuse in less demanding applications, repurposing into stationary energy-storage systems, and recovering valuable raw materials through recycling [102-105]. Each of these strategies has the potential to reduce capital expenditure (CAPEX) associated with new energy-storage systems, defer replacement investments, and lower decommissioning-related costs. In maritime and other industrial applications, where battery retrofits are often required during the long operational lifetime of assets, the residual value of second-life batteries can partially offset the high cost of new installations, as demonstrated in *Publication I*. More generally, repurposed batteries are typically available at a significant discount compared to new ones, thus improving the economic attractiveness of stationary storage across multiple sectors, as analysed in *Publication II*. These dynamics underscore the importance of life-cycle cost (LCC) and total cost of ownership (TCO) models that explicitly incorporate CE principles. Figure 7 illustrates the CE pathways of end-of-life batteries.

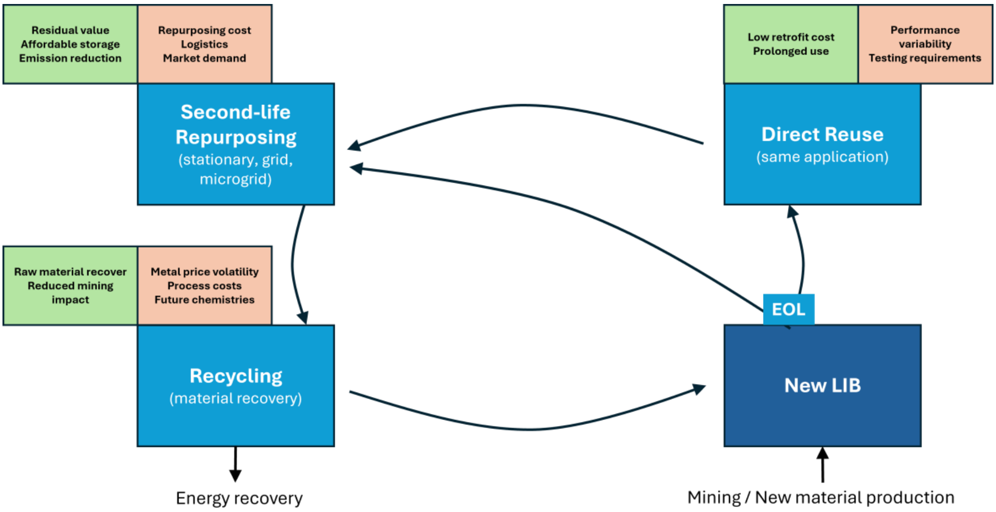


Figure 7. Circular economy pathways for end-of-life batteries.

As illustrated in Figure 7, end-of-life (EOL) batteries can follow multiple circular-economy pathways, including direct reuse, second-life repurposing, recycling, or energy recovery. Each pathway offers distinct opportunities but is also subject to various uncertainties [82,106-111]. The economic viability of second-life batteries is shaped by several interrelated factors. Foremost, the technical condition and residual state of health at the end of first-life use largely determine repurposing costs and the duration of second-life service. In addition, market dynamics, including long-term trajectories of new LIB prices, volatility of raw-material markets, and prospective shifts in battery chemistries, influence competitiveness and resale value. Equally important are the costs of repurposing and logistics, which encompass inspection, disassembly, refurbishment, transport, and quality assurance. These costs remain highly case specific and are sensitive to the level of industrial standardisation and scale. Moreover, policy and regulatory frameworks—such as extended producer responsibility schemes, recycling mandates, and incentives for energy-storage integration—play a decisive role in shaping cost-benefit structures. For maritime applications in particular, vessel-specific constraints, including long design lifetimes, operational profiles, and spatial limitations, further complicate the evaluation of second-life pathways.

Despite these evident opportunities, economic assessments of second-life batteries are characterised by substantial uncertainties and limitations. Estimates of residual value depend on accurate predictions of degradation behaviour, which vary across chemistries, first-life usage patterns, and operating conditions. Industrial processes for repurposing and certification remain under development, adding uncertainty to both cost and performance. Furthermore, the future competitiveness of second-life batteries is sensitive to the rate of declining costs of new LIBs and to evolving electricity-market conditions, such as tariff structures and ancillary-service markets. Finally, the scarcity of standardised long-term field data on degradation and second-life performance constrains the precision of current economic modelling efforts.

In conclusion, the economic assessment of circular-economy strategies, and second-life applications in particular, represents an essential analytical dimension for evaluating the feasibility of sustainable energy-storage systems. Such assessments elucidate the principal cost drivers, contextual factors, and sources of uncertainty, thereby providing a necessary foundation for interpreting subsequent findings and supporting evidence-based decision-making across both industry and policy contexts.

4 Research Methods

This chapter outlines the research approach and methodological steps applied in this thesis. The overall aim of the study is to investigate pathways towards a cleaner maritime industry by examining multiple perspectives, scales, and system aspects. Two primary lines of inquiry are pursued. First, the operational phase of ships is analysed to determine the extent to which alternative fuels can reduce CO_2e emissions and influence life-cycle costs compared with conventional marine diesel. Second, the study evaluates the feasibility and economic implications of adopting circular-economy practices in relation to marine energy-storage systems. A central foundation of all analyses is the use of empirical evidence, drawing on real operational data from vessels in service as well as results from extensive battery-cycling experiments. Accordingly, the methodological framework of this research is grounded in an empirical approach designed to ensure that the findings are directly connected to practical, real-world conditions.

4.1 Investigated ships

This section elaborates on the principal methodological considerations applied in the analysis of the reference vessels.

4.1.1 *Polaris* icebreaker

The *Polaris*, a 110-meter Finnish icebreaker built in 2016, served as the reference vessel. Equipped with a dual-fuel propulsion system comprising four main engines (2 × 6000 kW, 2 × 4500 kW) and one auxiliary unit, it can operate on both ultra-low-sulphur diesel and liquefied natural gas (LNG). This study contributes to the currently limited body of research on icebreakers by employing an extensive one-year dataset of real operational engine-power, energy, and fuel-consumption data from all four engines, covering the period from November 2022 to October 2023. It also uniquely assesses a comprehensive set of energy sources, including marine diesel oil (MDO), LNG, methanol, ammonia, hydrogen, and small modular reactors (SMRs).

Publication III and its supplementary material provide a detailed description of the ship-level parameters, power-profile details, fuel-specific consumption factors, and the calculation steps adopted in the assessment.

4.1.2 *Ellen* electric car-passenger ferry

The second reference case concerns the *E/F Ellen*, the world’s first fully electric ROPAX ferry, developed within the EU Horizon 2020 *E-Ferry Project* and in operation since 2019 on the route between Fynshav (Als) and Søby (Ærø), Denmark [11]. Designed to carry about 30 vehicles and 200 passengers, *Ellen* is powered by a 4.3 MWh LIB system (NMC111 chemistry), divided between the bow and stern compartments in 840 modules across 80 energy racks and 20 control racks, with a total mass of 57 tonnes.

The battery system enables sailing distances of up to 21.4 nautical miles (≈38 km) on a single charge, representing the largest-capacity installation of any ferry worldwide at the time of commissioning. The novelty of this research lies in linking detailed vessel-level technical specifications and operational data with a comprehensive circular-economy perspective across the ship’s lifetime, thereby quantifying how battery reuse, second-life applications, and recycling can mitigate both economic costs and environmental impacts.

4.2 Investigated battery energy storage systems

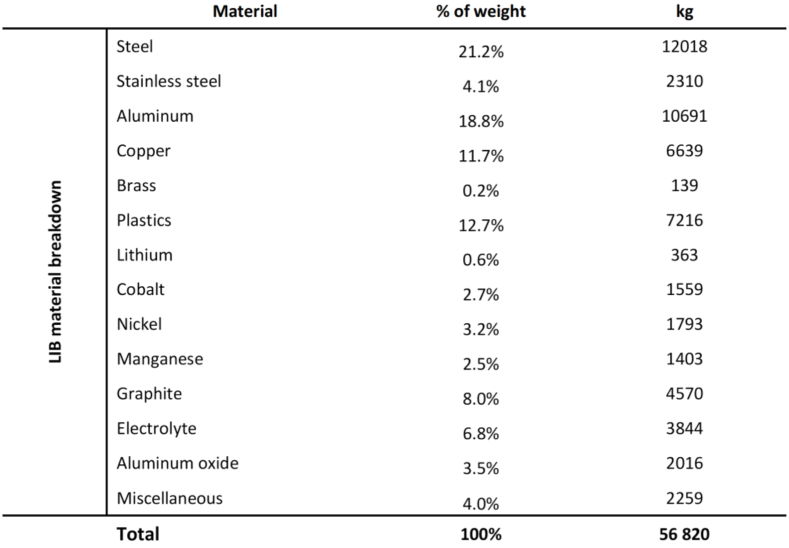
This research aims to generate new knowledge on the feasibility of applying circular-economy principles to marine battery systems. Interest in battery-assisted propulsion is driven by multiple factors, including high energy efficiency, improved ship-system architectures, operational advantages such as faster response times and reduced noise and vibration, lower tank-to-wake emissions, and the potential for component recycling [112]. The number of vessels employing batteries as part of their propulsion system has more than tripled over the past five years, increasing from a few dozen to 1,045 vessels in operation as of March 2025 [112-113], and this growth is expected to continue. Consequently, the technical and economic feasibility of circular-economy solutions for marine batteries is of critical importance both now and in the coming decades. Equally significant are the environmental benefits, particularly in terms of avoided CO2e emissions.

In this research, two LIB chemistries were investigated. At the vessel level, the case study focused on lithium-nickel manganese cobalt oxide (NMC) batteries, which represent one of the most common chemistries used in electric ferries, as elaborated in *Publication I*. In *Publication II*, laboratory cycling experiments examined nickel cobalt aluminium oxide (NCA) cells, enabling detailed analysis of degradation, second-life performance, and economic feasibility.

4.2.1 Battery energy storage system (BESS) of the electric car-passenger ferry

The vessel-level battery energy storage system (BESS) is based on lithium-nickel manganese cobalt oxide (NMC) pouch cells of the NMC111 type. In this cathode composition, nickel, manganese, and cobalt are present in approximately equal molar ratios (1:1:1), providing a balance between high energy density, stability, and cost. The cathode consists of layered $LiNiO_2$, $LiMnO_2$, and $LiCoO_2$ structures that together enhance both capacity and structural stability. The anode is graphite-based, allowing efficient lithium intercalation and contributing to high cycle life when operated within controlled depth-of-discharge and thermal conditions. In addition to the active materials, Table 3 presents the complete material composition of the studied marine battery pack.

Table 3. Marine BESS material breakdown, *Publication I*.



	Material	% of weight	kg
LIB material breakdown	Steel	21.2%	12018
	Stainless steel	4.1%	2310
	Aluminum	18.8%	10691
	Copper	11.7%	6639
	Brass	0.2%	139
	Plastics	12.7%	7216
	Lithium	0.6%	363
	Cobalt	2.7%	1559
	Nickel	3.2%	1793
	Manganese	2.5%	1403
	Graphite	8.0%	4570
	Electrolyte	6.8%	3844
	Aluminum oxide	3.5%	2016
	Miscellaneous	4.0%	2259
	Total	**100%**	**56 820**

As indicated in Table 3, a substantial amount of material remains available for circulation at end-of-life (EOL), in addition to the active materials contained in the cell electrodes.

4.2.2 NCA battery used in experimental laboratory tests

The laboratory-level cycling experiments were conducted using cylindrical Samsung INR18650-35E cells employing lithium-nickel-cobalt aluminium oxide

(NCA) chemistry. In this cathode composition, nickel provides the primary capacity contribution, cobalt enhances structural stability and electronic conductivity, and aluminium doping improves thermal stability and cycle life. The cathode has a layered oxide structure, while the anode is graphite-based, enabling efficient lithium intercalation and high specific energy. NCA cells typically deliver specific energies in the range of 230–260 Wh/kg, with a nominal voltage of 3.6 V, making them well suited for applications requiring long runtimes, although they are relatively more sensitive to cycling and temperature conditions. The datasheet specifications of the tested battery cells are presented in Table 4.

Table 4. Key characteristics of Samsung INR18650-35E cell. *Publication II*, data from References [114-115].

Characteristic	**Value**
Cell format	Cylindrical, 50 g (max.)
Positive electrode/cathode	NCA
Negative electrode/anode	Graphite
Rated energy	12.24 Wh
Rated capacity	3.4 Ah (min 3.350 mAh)
Nominal voltage	3.60 V
Voltage range	2.65 V - 4.2 V
Charge current	Standard 1.7 A, Max 2.0 A
Discharge current	Initial 3.4 A, Max 8.0 A
Initial internal impedance	<35 mΩ
Cycle life	SoH 60% after 500 cycles

In this study, Samsung NCA cells that had reached the end of their first life in e-mobility applications were utilised. However, the cells had not yet declined to 80% state of health (SOH), which is commonly regarded as the end-of-life threshold in electric-vehicle applications.

4.3 Technical evaluation of the ship operational phase

A central aspect of the analysis is the calculation of annual fuel and energy demand. The required fuel quantity is determined as the sum of the instantaneous load levels of each engine. Based on the power profiles, the fuel demand is then estimated using the specific fuel oil consumption (SFOC) curves corresponding to each fuel type. To ensure a complete representation, the consumption of both the main fuel and the pilot fuel must be considered separately. The pilot fuel is typically marine diesel oil (MDO). The subsequent section outlines the key methods, while the complete methodological framework is detailed in *Publication III*.

The ship power profile was calculated from the engine-specific load factors (*LF%*) and the rated power (P_{DGme}) of each engine at 30-second intervals, as described in Eq. (1), where index me=1-4 indicates main engine number . This calculation forms the basis for analysing the annual power profile, as illustrated in Figure 3. The dataset representing a mild winter was further used to estimate the power demand under moderate and severe winter conditions.

$$Power\ [kW] = \sum_{me=1}^{4} \left(P_{DGme,rated}[kW]\ *\ LF_{me}(t)\ *\ 10^{-2}\right) \tag{1}$$

Annual fuel consumption (W_{fuel}) for each engine was calculated using the detailed load-profile dataset (LF), the specific fuel-oil-consumption (SFOC) profile, the instantaneous engine power, and the time-step intervals over the full year, as shown in Eq. (2). The total ship-level fuel consumption was then obtained by summing the annual fuel mass of the four main engines (ME1–ME4). It is worth noting that during the operating season the engines are utilized at their recommended power levels. During the periods of lower demand only a subset of the engines is in use, which is also reflected in the dataset. The sampling interval, t, is 30 seconds.

$$W_{fuel}\ [t] = \sum_{n=1}^{year} \left(SFOC(LF) \left[\frac{g}{kWh}\right] *\ P(n)[\mathrm{kW}] * t[\mathrm{s}] * \frac{10^{-6}}{3600} \right) \tag{2}$$

SFOC profiles express fuel consumption in grams per kilowatt-hour (g/kWh) for each fuel at different engine load factors (LF). *Publication III* and its supplementary material present the fuel-specific SFOC curves derived for both the main and pilot fuels. As an example, the SFOC equation for ammonia as the main fuel is presented in Eq. (3), expressed as a quadratic (second-degree) polynomial. For the fuels analysed (MDO, LNG, methanol, ammonia and hydrogen), the fitted polynomials range from first to fourth degree. In the case of methanol and hydrogen, the SFOC curve for full load range of 0-100% is constructed from two polynomial functions, whereas the other fuels a single polynomial function covers the entire range.

$$\mathrm{SFOC_{Ammonia}} = 0.0172 \times \mathrm{LF}^2 - 3.840 \times \mathrm{LF} + 617.53 \qquad (3)$$

Input data for SFOC curves often cover only a portion of the engine loading range, typically between 50% and 100% load. In such cases, additional reference data are required to extend the curve across the full operating range. In *Publication III*, supplementary input data were obtained from engine manufacturers (Wärtsilä, MAN) and research articles [35,60-61,95,98,116]. Figure 8 illustrates the resulting SFOC curve for ammonia.

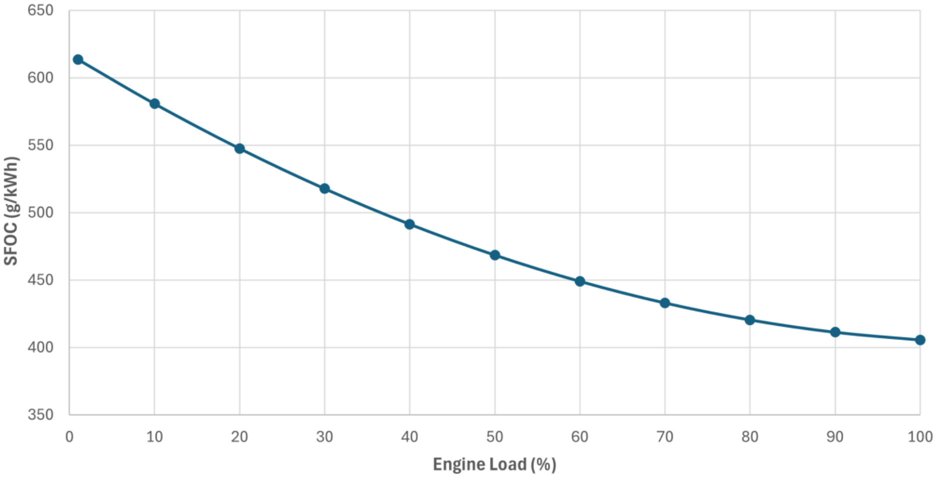


Figure 8. Ammonia main fuel SFOC curve. *Publication III*.

Figure 9 illustrates the pilot-fuel SFOC applied in conjunction with ammonia as the main fuel. In ammonia-fuelled engines, a small proportion of pilot fuel is required to initiate stable combustion, as ammonia exhibits poor ignition properties and a high autoignition temperature. As shown in the supplementary material of Publication III, also LNG and methanol require the use of pilot fuel. The pilot fuel, typically marine diesel oil (MDO), plays a critical role in enabling reliable ignition, ensuring combustion stability, and maintaining safe engine operation across the entire load range.

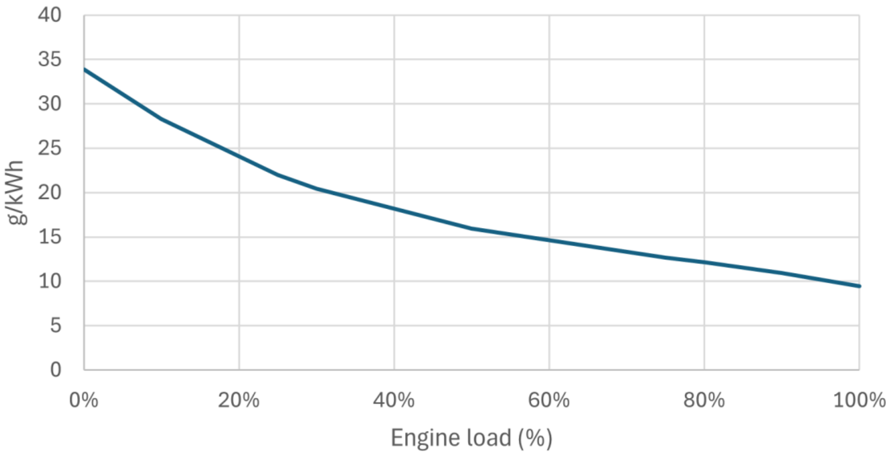


Figure 9. SFOC curve for pilot fuel of ammonia (MDO). *Publication III*.

Once the masses of the main and pilot fuels required for the year have been calculated, the corresponding fuel volumes and the required main-fuel tank capacity were determined. The fuel tank volume for all considered fuels was calculated using the formula presented in Eq. (4). The factor B_n represents the number of bunkering operations per year, which was kept constant for all of fuels under study to enable a fair comparison. A safety factor 1.3 was applied to provide an additional margin that ensures compliance with the selected bunkering policy. The densities used in the calculations are specific to each alternative fuel at its respective temperature in the tank.

$$V_{fuel}[\mathrm{m}^3] = 1.3 * \frac{W_{fuel}[\mathrm{t}]}{\rho\left[\frac{\mathrm{t}}{\mathrm{m}^3}\right] B_n[-]} \tag{4}$$

In the emissions assessment, the contributions of both the main and pilot fuel to CO_2e emissions are included. For a comprehensive assessment, it is essential to distinguish between the well-to-tank (WTT) and tank-to-propulsion (TTP) components for each fuel, as well as to account for methane slip in the case of LNG. The coefficients required for these calculations are provided in Appendix A, and Section 3.2.3 of *Publication III*.

Annual CO_{2e} WTT emissions are calculated according to the formula presented in Eq. (5). Emissions are based on the fuel mass, expressed in tonnes (t), and fuel specific WTT emission factor C_W.

$$W_{CO2}^{W} = C_W[-] * W_{fuel}[\mathrm{t}] \tag{5}$$

Annual CO_{2e} TTP emissions by fuel are estimated using the formula presented in Eq. (6). Emissions are based on the fuel mass and fuel specific TTP emission factor C_F.

$$W_{CO2}^{OP}[\mathrm{t}] = C_F[-] * W_{fuel}[\mathrm{t}] \tag{6}$$

For LNG, the TTP emissions include the methane slip component (MS), whose magnitude is influenced by the engine load factor (LF) and is estimated according to the formula presented in Eq. (7). The GWP factor represents the global warming potential of methane compared with CO_2, and a value of 28 is adopted in accordance with the literature [117]. P(n) represents the engine power at the discrete time index, and t denotes the sampling interval.

$$W_{CO2}^{MS}\,[t] = \sum_{n=1}^{year} MS(LF)\left[\frac{g}{kWh}\right] * P(n)[kW] * t(n)[s] * GWP * \frac{10^{-6}}{3600} \tag{7}$$

4.4 Experiments on lithium-ion battery ageing

The objective of this research was to evaluate the potential residual value of second-life battery (SLB) cells, therefore requiring an estimation of their expected remaining lifetime. To enhance understanding of lifetime behaviour, real degradation data were generated by experimentally cycling NCA cells under controlled, less demanding second-life operating profiles.

The experimental work was conducted in a controlled laboratory environment designed for long-term cycling and characterisation of lithium-ion cells. The setup included a control PC, a cell cycle tester (Arbin BT2000), and an auxiliary electrochemical impedance spectroscopy (EIS) tester (Camry), integrated, and managed through the cycle tester. Temperature and safety parameters were continuously monitored to ensure stable operation during both high-current cycling and extended low-current tests. This setup enabled accurate replication of stress conditions typical of mobility applications, followed by less demanding regimes representative of stationary energy-storage use. Figure 10 illustrates the laboratory test environment.

Figure 10. Laboratory test environment.

The study focused on assessing how first-life cycling histories influence the subsequent second-life performance of NCA cells. Cells retired from electric-mobility applications with a state of health (SoH) of approximately 87–91% were selected and further cycled close to the USABC-defined end-of-life threshold of 80% SoH, achieving an average final SoH of 78%. Two current levels were applied during first life: a high-current profile (1.18C discharge and 0.58C charge) and a low-current profile (0.58C discharge and 0.29C charge), thereby creating distinct degradation pathways.

For the second life, cells were cycled under stationary-storage conditions with a depth of discharge (DoD) of 30%, centred around 50% state of charge (SoC), at current rates of either 0.25C or 0.5C. This yielded four test groups (HC-HC, HC-LC, LC-HC, LC-LC), allowing systematic analysis of the combined effects of high- and low-stress regimes in both life phases. All cells were subjected to 600 cycles.

Characterisation was performed periodically to monitor capacity retention, DCIR, ACIR, and EIS, thereby providing detailed insight into capacity fade and electrochemical degradation during cycling. This methodology enabled a structured comparison of how mobility-induced ageing affects the technical feasibility of second-life applications, as well as an estimation of the remaining lifetime of the cells across the different test groups.

Figure 11 illustrates the cycle types used in cell aging tests. Figure 11a shows the first ten first-life cycles, followed by capacity characterization. Figure 11b shows a batch of 100 second-life cycles, followed by capacity and DCIR characterization.

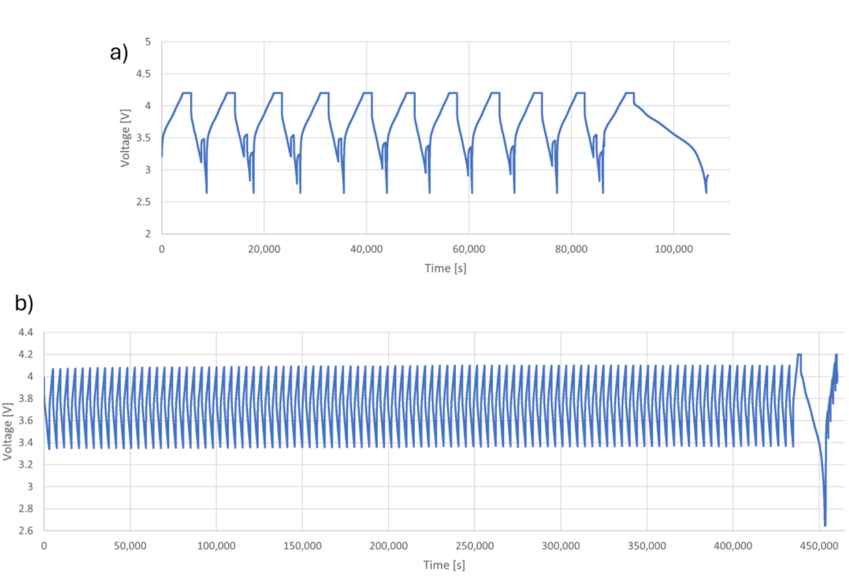


Figure 11. Diagrams introducing the used cycle profiles: a) first-life cycles and b) second-life cycles.

4.5 Methods for economic evaluation

This section provides a summary of the economic evaluation methods applied throughout the research. *Publications I–III* contain the detailed methodological descriptions and the parameterisation employed.

4.5.1 Economic evaluations of the operational phase

The principal measure used to assess the economic competitiveness of alternative fuels in this research is the life-cycle cost (LCC). LCC encompasses capital expenditure (CAPEX), operational expenditure (OPEX), and costs associated with retrofits and end-of-life. For the icebreaker case, a service lifetime of 50 years is assumed, reflecting the traditionally long operational lifetime of such vessels in Finland. For the electric ferry, a shorter service lifetime of 36 years is adopted, corresponding to typical expectations for this vessel type. These assumptions provide a consistent basis for comparing alternative fuel pathways across different ship categories.

OPEX comprises variable costs such as annual maintenance, fuel, and CO_2e-emission costs. Depending on the case study and comparison, OPEX may also include labour, insurances, taxes, and fees. In addition, potential service benefits that reduce overall OPEX are considered, for example, revenue generated from selling electricity to the national grid during the icebreaker's off-season. The carbon-emission cost calculation utilises three carbon cost trajectories: the EU ETS price as of June 2024, and Bloomberg's *EU ETS market outlook for years 2030 and 2035* [118-119]. The calculation of operating expenses is presented in Eq. (8).

$$Opex[€] = C_{maint}[€] + C_{CO2}[€] + C_{fuel}[€] + C_{service}[€] \tag{8}$$

The annual maintenance cost for the ICE and FC is determined based on the actual utilization of the propulsion system, as shown in Eq. (9). The maintenance cost factors (C_M) for engine technologies are obtained from the literature and are provided in Appendix A of Publication III. P(n) represents the engine power at the discrete time index and t denotes the sampling interval.

$$C_{maint}[\text{€}] = \sum_{n=1}^{year} C_m \left[\frac{\text{€}}{\text{kWh}}\right] * P(n)[\text{Kw}] * t(n)[\text{s}]/3600 \tag{9}$$

The estimated annual carbon tax cost for the well-to-propulsion path is calculated as presented in Eq. (10). The factor C_T is the carbon cost according to the scenarios described in the literature for years 2024, 2030 and 2035 [119].

$$C_{CO2}[\text{€}] = C_{CT}\left[\frac{\text{€}}{\text{t}}\right] * (W_{CO2}^{OP}[\text{t}] + W_{CO2}^{MS}[\text{t}] + W_{CO2}^{W}[\text{t}]) \tag{10}$$

The annual fuel cost is estimated using the formula presented in Eq. (11). The factor C_{FO} represents the cost of the fuel type per tonne.

$$C_{fuel}[\text{€}] = C_{FO}\left[\frac{\text{€}}{\text{t}}\right] * W_{fuel}[\text{t}] \tag{11}$$

The service benefit arises during the icebreaker's off-season, when the market price of electricity (C_e) exceeds the onboard electricity production cost (C_x). This potential revenue stream is further elaborated in *Publication III*, Sections 3.3.4 and in 4.2.4, and is expressed in Eq. (12).

$$C_{service}[\text{€}] = -\sum_{n=1}^{year} (C_e - C_x)\left[\frac{\text{€}}{\text{kWh}}\right] * P_e(n)[\text{Kw}] * t(n)[\text{s}]/3600 \tag{12}$$

CAPEX consists of the investment costs associated with the vessel's installed power and the energy-storage system. It is calculated as the sum of the installed-power cost and energy-storage costs, as expressed in Eq. (13). The installed power (C_{IP}) and energy storage (C_S) cost factors are derived from the literature and are presented in Appendix A of Publication III.

$$Capex[\text{€}] = C_{IP}[\text{€/kW}] * IP[\text{kW}] + C_S\left[\frac{\text{€}}{\text{kWh}}\right] * E_S[\text{kWh}] \tag{13}$$

The LCC calculation includes, in addition to CAPEX and OPEX, potential retrofit and disposal costs, as depicted in Eq. (14). It is worth noting that the disposal of equipment—such as marine batteries—or even the dismantling of the ship itself may generate revenue for the owner. For example, in 2022, the scrap price for tanker recycling ranged from USD 500 to 750 per light displacement tonne (LDT) [85]. A discount (interest) rate (r) of 5% is applied in the life-cycle cost (LCC) calculations.

$$\mathrm{LCC}\,[€] = Capex[€] + \sum_{N=1}^{\infty} \frac{\mathrm{Opex}\,[€]}{(1+r)^N} + \sum_{N=1}^{\infty} \frac{C_{IP}\left[\frac{€}{\mathrm{kW}}\right] * IP[\mathrm{kW}]}{(1+r)^N} + \frac{C_{Disposal}}{(1+r)^{50}} \tag{14}$$

4.5.2 Economic evaluation methods of second-life batteries

In *Publication I*, the focus is on analysing the life-cycle cost (LCC) impact of battery-energy storage in a marine application, which typically has a longer lifetime than an individual BESS.

Generally, LCC analysis evaluates the total cost of ownership of an asset over its lifetime and enables comparisons between alternative options. The main cost components include acquisition (CAPEX), recurring operating and maintenance costs (OPEX), and end-of-life disposal costs, which may be offset by residual value [120]. Conventional LCC models discount future costs to present value using the capital discount rate (r) and time (t). In this research, the model is extended to explicitly include energy-storage system (ESS) retrofit costs, disposal costs, and residual-value calculations, with particular attention to the multiple replacements required in marine applications. The following equations are introduced to analyse the impact of circular-economy considerations on the LCC of marine batteries.

The life-cycle cost of the ESS can be expressed as depicted in Eg. (15):

$$LCC_{ess} = C_{Cap,ess} + PV_{RC} - PV_{RV} =$$

$$\sum_{n=0}^{T} \frac{C_{Cap,n\cdot Ty}}{(1+r)^{n\cdot T_y}} + \sum_{t=1}^{(T+1)\cdot T_y} \frac{C_{O\&M} + C_{CH}}{(1+r)^t} - \sum_{t=1}^{T+1} \left(\frac{V_{ce,t}}{(1+r)^{t\cdot T_y}} - \frac{C_{dr,t}}{(1+r)^{t\cdot T_y}} \right) \tag{15}$$

The ESS acquisition component ($C_{cap,ess}$) accounts for the initial investment cost and multiple upgrades of the traction battery, typically three to four retrofits over the vessel’s lifetime. The middle component (PV_{RC}) represents the present value of recurring operating costs, including maintenance ($C_{O\&M}$) and daily charging (C_{CH}) of the energy storage system (ESS). Finally, the disposal cost component (PV_{RV})

incorporates the benefit of the ESS resale value (V_{CE}), reduced by the cost of disassembly, removal, transportation, and validation testing at end-of-life (C_{dr}).

In addition to LCC estimation, complementary economic analyses can be employed to quantify the potential benefits of each business opportunity or scenario. The following section presents the calculation of payback time, together with the revenue models for an ESS providing frequency containment reserve (FCR) services [121] to the national grid (Fingrid) and for energy arbitrage (EA). These equations have been applied in *Publication II*.

Payback time - For each potential use case, the payback time is estimated using Eq. (16). The initial investment includes the second-life battery (SLB) energy-storage system and installation costs, with the latter assumed at 10% of the BESS price. The mean annual cash flow equals annual revenue minus trading fees and fixed operation and maintenance (O&M) costs . In this analysis, the price of a new BESS is assumed to range between 400 and 450 €/kWh *(Publication II).* The SLB BESS price assumes a residual value of 50% of a new battery. Trading fees are set at 20% of revenue, and fixed O&M costs at 3.5% of the BESS price, consistent with literature values of approximately 2.5% per kilowatt [122]

$$PBT = \frac{C_{\mathrm{BESS}} + C_{\mathrm{inst}}}{CF_{\mathrm{ann}}} \tag{16}$$

where PBT means payback time (years), C_{BESS} is the SLB BESS investment cost, C_{inst} denotes installation cost, and CF_{ann} represents mean annual cash flow.

FCR Revenue - The revenue from Frequency Containment Reserve services is calculated by multiplying the annual number of bids by the average FCR-N bid price set by the national grid operator. Each bid represents 1 MW of capacity offered for one hour, available to provide either upward or downward reserve to support grid-frequency stability. The FCR revenue is calculated using Eq. (17).

$$R_{\mathrm{FCR}} = N_{\mathrm{bids}} \cdot P_{\mathrm{avg}} \tag{17}$$

where R_{FCR} denotes FCR Revenue (€), N_{bids} indicates the annual number of bids, and P_{avg} represents the average bid price (€) during the year. For the year 2024, the average FCR-N bid price set by the national grid operator, reported in the literature as 25.39 €/MW for a one-hour reserve (*Publication II*).

EA revenue - The revenue from energy arbitrage (EA) is determined by the difference between the electricity selling price and the electricity purchase cost, multiplied by the effective amount of discharged energy over all cycles. The energy-arbitrage revenue can be estimated as defined in Eq. (18).

$$R_{\mathrm{EA}} = \left(P_{\mathrm{sell}} - P_{\mathrm{buy}}\right) \cdot N_{\mathrm{cyc}} \cdot E_{\mathrm{DoD}} \tag{18}$$

where R_{EA} denotes EA revenue (€), P_{sell} is the electricity sales price (€/kWh), P_{buy} indicates the electricity purchase cost (€/kWh), N_{cyc} defines the number of cycles used in EA revenue forecasting, and E_{DoD} represents the average depth of discharge (kWh) per individual transaction.

5 Research findings

5.1 Powering an icebreaker

Despite the critical role of icebreakers in maintaining maritime operations in harsh Arctic and sub-Arctic conditions, research on low- or zero-emission energy alternatives for these vessels remains limited. In particular, there is a lack of comprehensive assessments addressing their technical feasibility, operational implications, and life-cycle cost differences compared with conventional fuel options.

Examining a ship's fuel consumption and fuel economy in relation to ship design is fundamental for assessing the technical feasibility of alternative solutions and for establishing a factual basis for comparison at the concept-design stage. To conduct such an evaluation, key input data are required, most notably, the power profile of a ship (ideally encompassing all main engines), voyage or operational duration (indicating the time between bunkering or refuelling events), and the characteristics of each alternative fuel. These parameters enable the estimation of annual fuel consumption, quantities required between bunkering intervals, and, consequently, the necessary fuel tank volume, associated annual emissions, and both operational and investment costs. *Publication III* presents a detailed assessment of the required fuel mass and tank capacity, complemented by a sensitivity analysis that accounts for varying severities of winter conditions and economic indicators across all analysed energy sources. In all comparisons, the reference fuel is conventional marine diesel oil (MDO), the most commonly used fuel today.

Figure 12 demonstrates that pilot fuel represents only a minor fraction of total annual fuel consumption, though the share differs by main fuel: approximately 5% for LNG, 8% for methanol, and 3% for ammonia. The results further show that ammonia and methanol require nearly twice the overall fuel mass compared with MDO, and that all three alternatives (LNG, methanol, and ammonia) depend on pilot fuel in addition to the main fuel, unlike hydrogen fuel cells or conventional MDO. Hydrogen is found to require only 29% of the mass of MDO for equivalent energy demand, whereas the SMR option shows the lowest requirement, less than 0.1 tonne annually. The findings presented in *Publication III* align with previous research [69] on relative fuel needs, while this study further extends the analysis to include ammonia and SMR options and uniquely employs a full operational-year power profile from an actual icebreaker.

In Figure 13, the sensitivity of fuel mass to different winter scenarios is analysed. The results show that annual fuel consumption is highly sensitive to winter severity, with requirements in harsh winters reaching up to three times those in mild conditions. While SMR fuel demand remains low and stable across all scenarios, ammonia consumption can rise to about 9,000 tonnes, with significant implications for tank sizing and bunkering strategy.

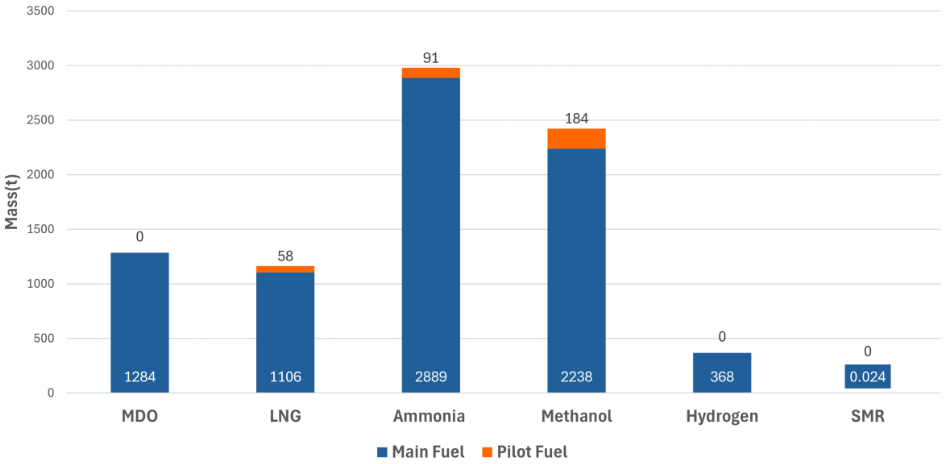
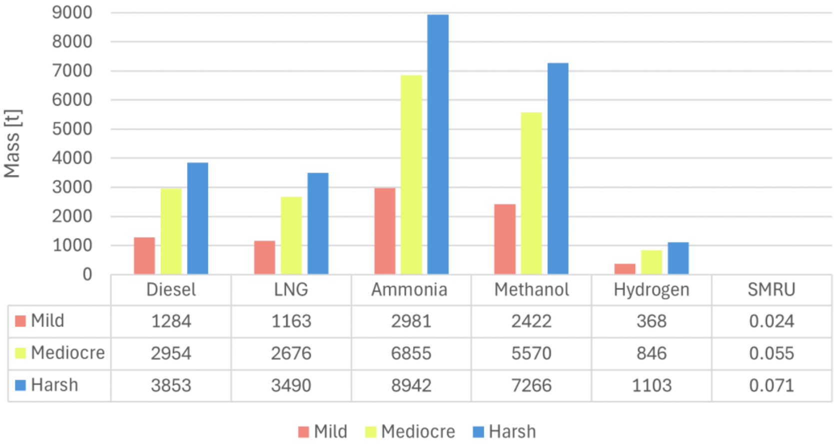


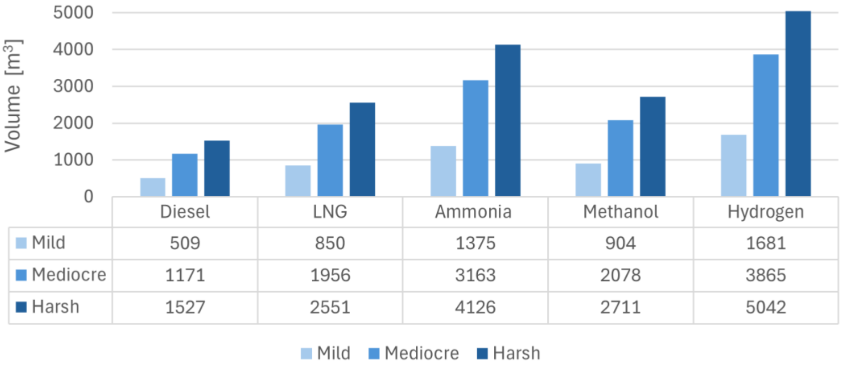
Figure 12. Annual consumption of main and pilot fuels under mild winter conditions. *Publication III*.



	Diesel	LNG	Ammonia	Methanol	Hydrogen	SMRU
Mild	1284	1163	2981	2422	368	0.024
Mediocre	2954	2676	6855	5570	846	0.055
Harsh	3853	3490	8942	7266	1103	0.071

Figure 13. Annual fuel mass for different winter conditions. *Publication III*.

Figure 14 illustrates the comparative tank-volume requirements of the examined fuel options. The findings highlight that although hydrogen exhibits the lowest fuel-mass requirement, its low density results in by far the largest tank-volume demand. LNG also requires a larger storage volume than MDO, despite its lower fuel mass. Ammonia and methanol impose substantially greater tank-volume requirements relative to MDO, with ammonia necessitating nearly threefold and methanol nearly twofold greater capacity, consistent with the higher fuel-mass needs identified earlier. Seasonal variation further amplifies these differences: harsh winter conditions markedly increase the required tank sizes, particularly for ammonia and hydrogen. A 2,000 m³ tank is sufficient to accommodate LNG and methanol in mild and average winter scenarios, and diesel across all conditions. By contrast, hydrogen and ammonia can only be stored within this capacity under mild winters, necessitating more frequent bunkering during harsher conditions. The existing 3,043 m³ tank capacity of the *Polaris* icebreaker is sufficient for all options except ammonia and hydrogen in severe winters, and hydrogen also under average conditions. Notably, SMR operation does not require annual refuelling.



	Diesel	LNG	Ammonia	Methanol	Hydrogen
■ Mild	509	850	1375	904	1681
■ Mediocre	1171	1956	3163	2078	3865
■ Harsh	1527	2551	4126	2711	5042

Figure 14. Fuel tank volume requirements under different winter severity scenarios. *Publication III.*

Figure 15 compares the annual CO2 emissions of the fuel options, including well-to-tank (WTT), tank-to-propeller (TTP), and methane-slip contributions. The calculations are based on annual fuel masses from Figure 11, with emission factors provided in *Publication III*; the SMR case follows the IPCC factor [84], while LNG accounts for methane slip. Among the fuels, LNG exhibits the highest emissions, primarily due to methane slip, followed by methanol and MDO. Without methane slip, LNG emissions would decrease by approximately 1,400 tonnes annually. The lowest emissions are observed for SMR, green hydrogen, and green ammonia. These results are consistent with previous research [69] on tank-to-propeller emissions, while also extending the analysis to include well-to-wake and methane-slip effects, thereby highlighting the importance of full life-cycle assessment.

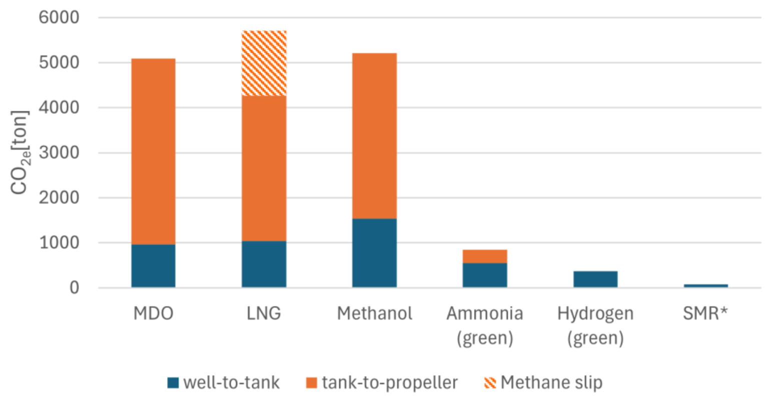


Figure 15. Annual CO2*e* emissions, mild winter. *Publication III*.

Figure 16 presents the sensitivity of annual well-to-propulsion emissions to different winter conditions. Across all fuels, emissions during harsh winters are approximately three times higher than in mild winters, reflecting the strong influence of seasonal severity [123-124]. Non-carbon fuels—ammonia, hydrogen, and nuclear—exhibit markedly lower sensitivity, with even their harsh-winter emissions remaining below 50% of the mild-winter levels of MDO, LNG, and methanol. These results indicate that average winter conditions provide the most representative basis for long-term emission estimates. In addition, the share of methane slip in the CO2e emissions for LNG is illustrated in Figure 14 for all weather conditions.

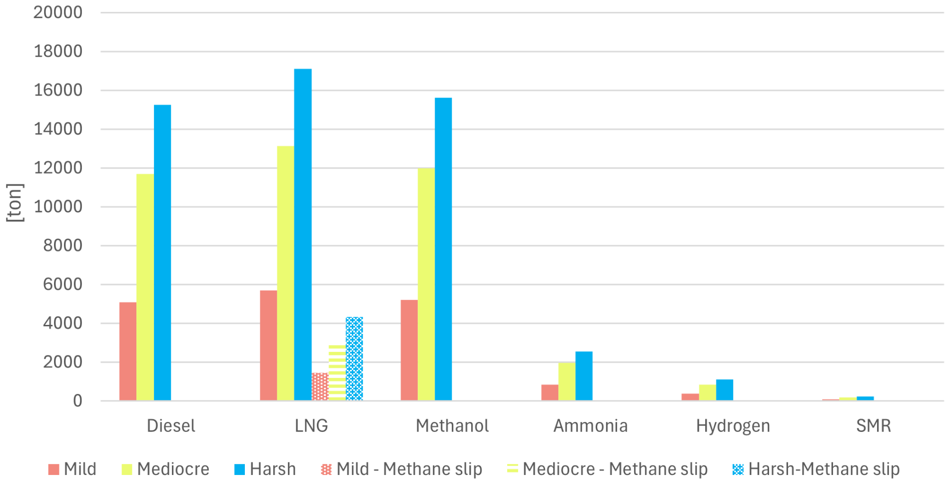


Figure 16. Annual CO2*e* emissions for different winter severity scenarios. Modified from *Publication III*.

5.2 Ageing of lithium-ion batteries

The technical performance of the NCA cells was evaluated in a temperature-controlled container equipped with a cycle tester and 12 cells under test, as described in *Publication II*. The studied NCA cells showed first-life degradation during electric-vehicle (EV) use, with state of health (SoH) declining to 88.17–90.27% in high-current (HC) cells and 87.09–90.27% in low-current (LC) cells. Additional cycling resulted in further capacity losses of 11.26–13.89% (HC) and 7.16–12.09% (LC), reflecting higher stress under HC operation.

Figure 17 presents the second-life cycling results for all four cell groups from the perspective of capacity degradation. During second-life cycling (600 cycles, 30% depth of discharge), degradation was strongly governed by cycling conditions. Under HC profiles, cells degraded at approximately 2% per 1,000 cycles, projecting about 5,000 cycles to reach 70% SoH, irrespective of first-life history. Under LC conditions, HC-LC cells degraded much more slowly (0.6% per 1,000 cycles), extending useful life beyond 10,000 cycles. Interestingly, LC-LC cells exhibited slight capacity recovery (0.8% per 1,000 cycles), indicating highly stable behaviour under mild cycling.

These findings emphasise that remaining lifetime in second-life applications is determined primarily by second-life cycling conditions rather than first-life usage. In particular, shallow depth of discharge and low current levels significantly mitigate degradation, thereby extending useful service life. This provides a reliable basis for projecting the available partial-cycle lifetime of repurposed EV batteries in stationary energy-storage applications.

These results align with previous findings on NMC-LMO and NMC811 chemistries, confirming that low C-rates and shallow DoD sustain capacity retention in second-life applications [125-127].

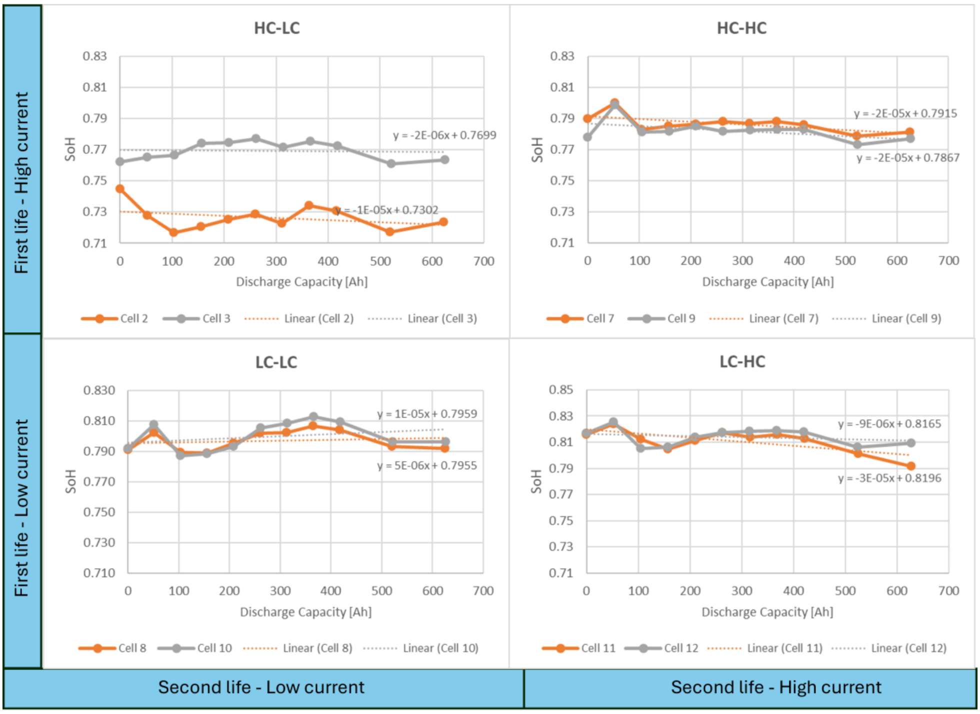


Figure 17. Cell capacity degradation profiles as a function of cycled capacity. *Publication II*.

The next assessment method used to investigate cell ageing was electrochemical impedance spectroscopy (EIS), which provides detailed insights into the electrochemical reactions and degradation mechanisms occurring within a battery cell. A key diagnostic parameter obtained from EIS is the alternating-current internal resistance (ACIR), which serves as an indicator of state of health and overall ageing progression. Figure 18 presents the evolution of ACIR values throughout the test campaign for all four cell groups. The EIS results revealed that ACIR evolved distinctly under different cycling conditions. During the early stages of second-life operation, ACIR remained stable; however, gradual increases were observed with ageing, reflecting processes such as solid-electrolyte interphase (SEI) thickening, electrolyte depletion, lithium plating, and electrode degradation.

Comparative analysis showed that second-life high-current cases (HC-HC and LC-HC) exhibited minor ACIR decreases of 1–4 mΩ per 1,000 cycles, indicating limited resistance change. In contrast, the HC-LC condition displayed more pronounced degradation, with an 8 mΩ per 1,000 cycles decrease(~15%). Interestingly, the LC-LC case demonstrated the most significant resistance decrease, with 15 mΩ per 1,000 cycles, and consistently exhibited higher ACIR values than the other groups. Despite these trends, overall ACIR behaviour remained relatively stable, with impedance plateauing near 50 mΩ. This suggests that major degradation mechanisms have not yet become dominant, and the cells still retained substantial cycle life, supporting their suitability for partial-depth second-life applications.

These findings align with previous research showing minimal resistance growth over 10,000 second-life cycles when operating within a reduced voltage range [128]. Furthermore, other studies suggest that adopting mild load profiles, such as reduced charge rates and limited voltage windows, can effectively extend the lifespan of lithium-ion cells [127].

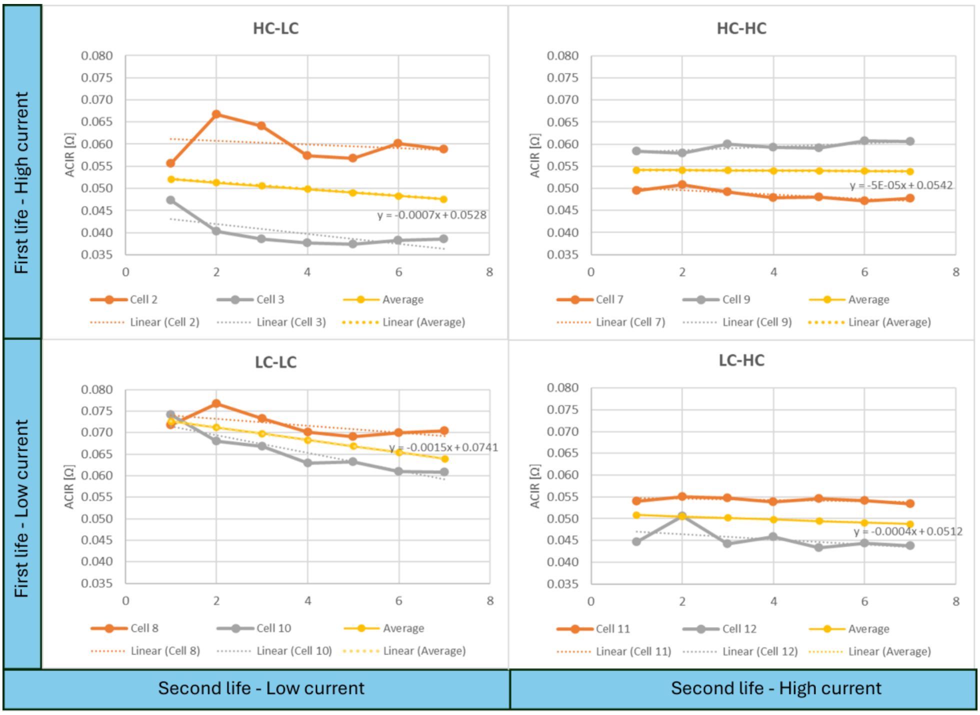


Figure 18. ACIR profiles based on EIS measurement data as a function of cycle number (100 cycles). *Publication II.*

Figure 19 presents the EIS measurement results for the studied cell groups. Electrochemical impedance spectroscopy (EIS) analysis revealed distinct patterns of internal resistance growth across different usage phases and cycling conditions. The original rated internal impedance of the cells was 35 mΩ. During EV use, HC-cycled cells exhibited an average increase of 9 mΩ, with an additional 10.9–14.9 mΩ increase during first-life (FL) HC cycling, confirming that laboratory HC cycling imposed greater stress than EV operation. In contrast, LC cycling resulted in milder resistance growth: cell 11 showed a 13.3 mΩ increase during EV use and only 5.9 mΩ during FL cycling, consistent with reduced current stress.

Interestingly, cell 10 demonstrated anomalous behaviour, showing a 19.3 mΩ increase during EV use and a further 19.8 mΩ increase under LC cycling. However, during second-life LC cycling, the cell exhibited a notable “healing” effect, with internal resistance decreasing by 13.2 mΩ after 600 cycles. This reduction is attributed to lower cycling stress, solid-electrolyte interphase (SEI) restructuring, electrolyte redistribution, and lithium rebalancing.

At end-of-life (EOL), impedance values converged across cells, ranging from 54 to 61 mΩ, indicating stable and consistent degradation behaviour. These results, consistent with previous studies, demonstrate that moderate load profiles and restricted cycling ranges can mitigate resistance growth and extend useful lifetime, reinforcing the viability of partial-cycle second-life applications [127].

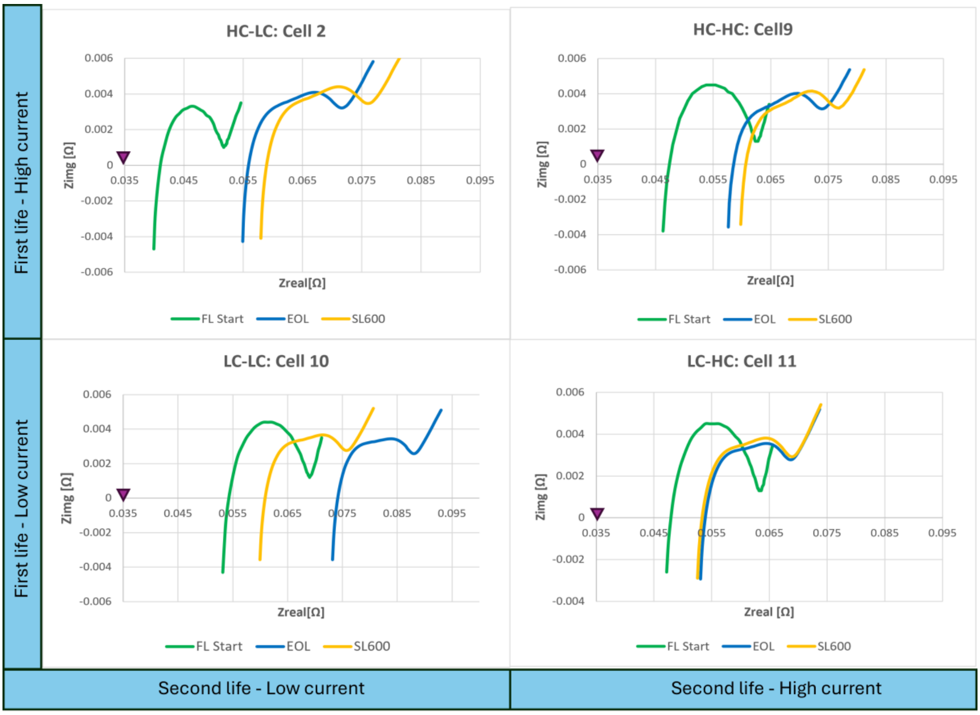


Figure 19. Nyquist plots of electrochemical impedance spectra. *Publication II*.

Note: Internal impedance from datasheet (BOL). FL Start = start of FL cycling; EOL= end of FL cycling; SL600 = after 600 SL cycles.

Direct current internal resistance (DCIR) measurements, conducted after each 100-cycle batch using pulse current tests, provided critical insights into cell health and degradation. Unlike AC impedance, DCIR reflects resistance changes under steady-state or pulse load conditions and is closely associated with mechanisms such as electrolyte decomposition, SEI layer growth, electrode porosity loss, and current-collector corrosion. These processes contribute not only to increased resistance but also to power fade, directly influencing overall performance.

The results in Figure 20 indicate that DCIR remained largely stable under partial DoD cycling in the HC-HC, LC-HC, and HC-LC test cases, demonstrating limited internal resistance growth under these conditions. Interestingly, in the LC-LC case, DCIR decreased by approximately 10 mΩ, although resistance values remained consistently higher than in the other groups. This reduction may be linked to stress-relaxation effects, consistent with earlier observations of ACIR “healing.”

A strong correlation between DCIR and ACIR was observed across all conditions, validating measurement reliability and confirming the absence of anomalies. Importantly, the combination of stable DCIR behaviour and low-capacity fade highlights the suitability of these cells for second-life applications in partial-cycle operation, where extended lifetime and high energy throughput outweigh the need for maximum power delivery.

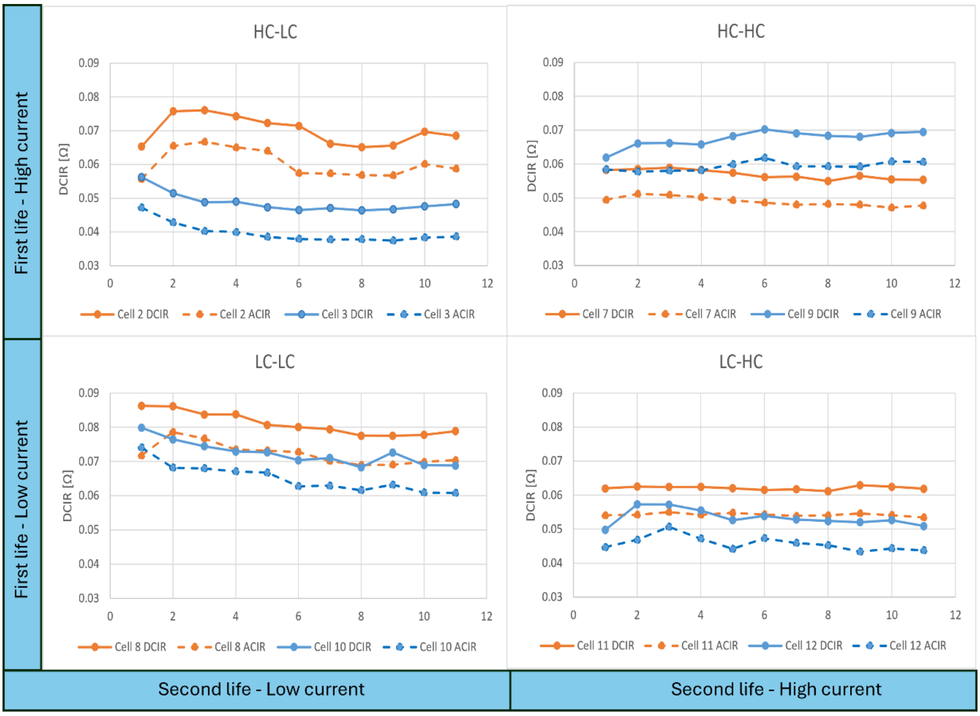


Figure 20. DCIR profiles from DC pulse measurements compared with ACIR profiles. *Publication II*.

5.3 Results of economic assessments

5.3.1 Economic assessment of the icebreaker

The following results are discussed in detail in *Publication III*. Figure 21 summarises the estimated carbon costs for different fuels under three carbon price trajectories, starting from the EU ETS 2024 baseline [118]. Under average winter conditions, the annual well-to-propeller carbon costs for fossil fuels (MDO, LNG, and methanol) range between €770,000 and €870,000, while ammonia (~€130,000), green hydrogen (~€56,000), and SMR (~€11,000) exhibit substantially lower values. The results indicate that fossil fuels incur around five times higher carbon costs than green ammonia, whereas green hydrogen and SMR remain by far the least costly options. Bloomberg's EU ETS projections [119] suggest that by 2035, carbon prices could more than triple, significantly increasing operational expenditures, particularly for fossil-fuel-based shipping. These findings align with previous assessments [129] and reinforce the importance of transitioning to low- and zero-carbon fuels to mitigate long-term economic risks.

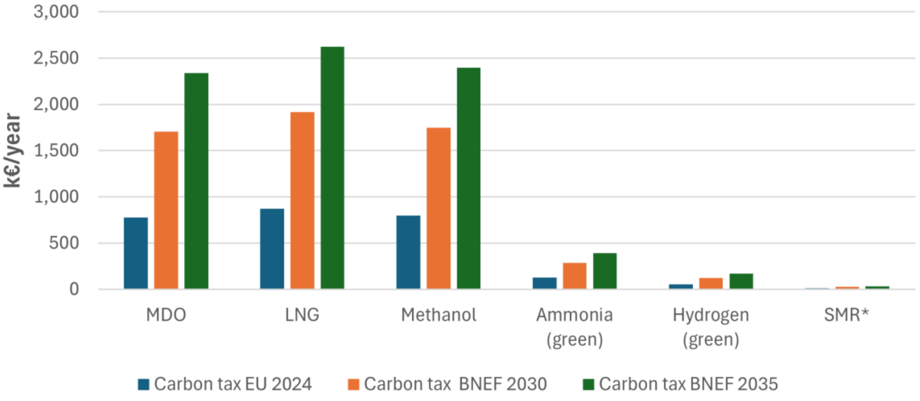


Figure 21. Annual carbon tax cost trajectories, well-to-propeller. *Publication III*.

Figure 22 illustrates the effect of carbon costs on total fuel exenditure, defined as the sum of basic fuel costs and carbon-related charges. For conventional fuels (diesel, LNG, methanol), market prices from Rotterdam [130] were applied, while cost estimates for green ammonia and hydrogen are derived from large-scale production scenarios involving renewable electricity, electrolysis, and ammonia synthesis [131]. The analysis indicates that, on a fuel-cost-only basis, SMR, LNG, and methanol appear the most economical. However, when carbon costs are incorporated, the relative advantage of fossil fuels diminishes, with diesel, LNG, and methanol approaching the cost levels of the green alternatives. SMR remains the lowest-cost option overall, even when accounting for spent-fuel disposal. The sensitivity analysis further highlights the variability of green-fuel production costs. Green ammonia ranges from €355–822 per tonne, potentially undercutting fossil fuels at the lower end of this range but becoming the most expensive option at the upper end. Green hydrogen, by contrast, ranges from €3,400–7,800 per tonne, positioning it competitive only at its lowest cost projections. These results underscore the decisive role of carbon pricing in narrowing the cost gap between fossil and renewable fuels, thereby reinforcing the long-term competitiveness of low-carbon alternatives.

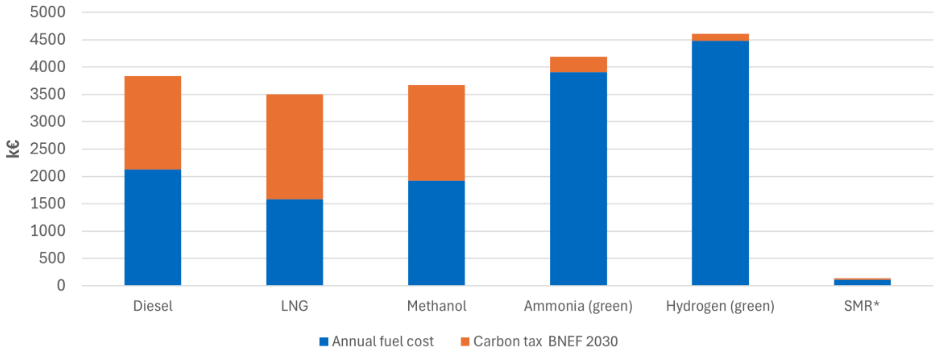
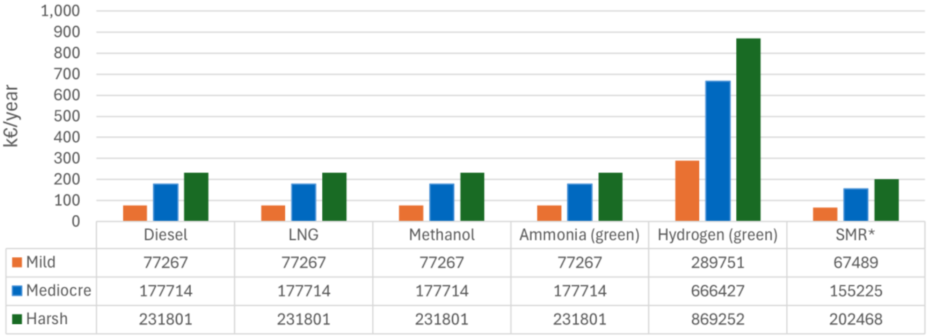


Figure 22. Annual fuel and carbon tax costs. BNEF 2030 carbon costs, mediocre winter. *Publication III.*

Figure 23 compares the annual maintenance costs for different fuel options under mild, average, and harsh winter conditions. The estimates were derived using the methodologies and cost factors outlined in *Publication III*, applied to the vessel's annual engine-load profile. SMR-based power plants exhibit the lowest maintenance costs, whereas combustion-engine systems operating on diesel, LNG, methanol, or ammonia are approximately 15% higher. Fuel-cell systems show the highest costs—around 3.7 times those of internal combustion engines—primarily due to the multiple fuel-cell replacements required over the vessel's lifetime.



	Diesel	LNG	Methanol	Ammonia (green)	Hydrogen (green)	SMR*
🟧 Mild	77267	77267	77267	77267	289751	67489
🟦 Mediocre	177714	177714	177714	177714	666427	155225
🟩 Harsh	231801	231801	231801	231801	869252	202468

Figure 23. Annual maintenance costs. *Publication III*.

Figure 24 presents a comparison of power-plant disposal costs, estimated using the methodology and parameters described in *Publication III*. The results indicate that SMR plants incur substantial end-of-life (EOL) costs due to decommissioning requirements and the safe disposal of radioactive materials. In contrast, the disposal of combustion-engine and fuel-cell systems can generate modest revenues through the recovery of scrap value, thereby partially offsetting the overall life-cycle costs.

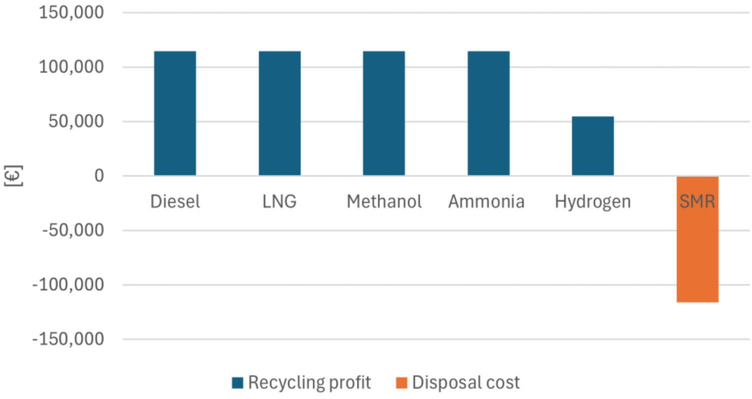
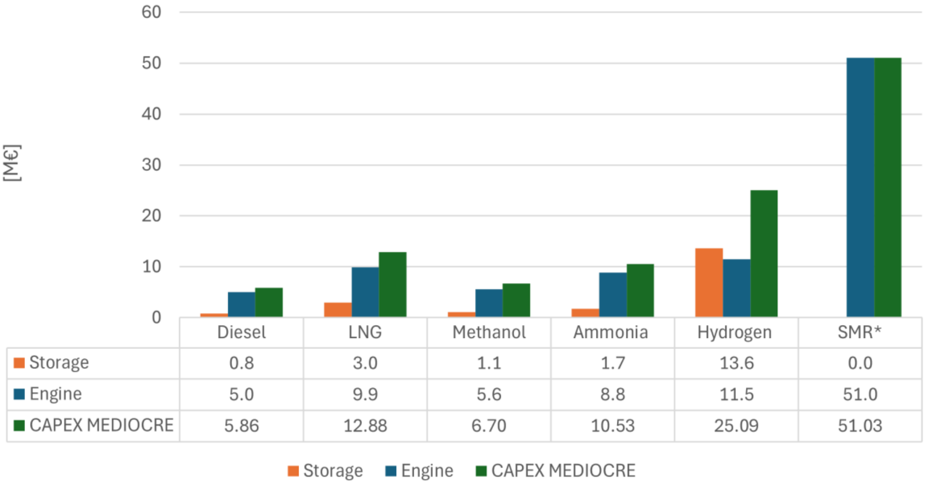


Figure 24. Recycling and disposal cost estimation. *Publication III*.

Figure 25 compares the capital expenditures (CAPEX) of different power-plant and storage configurations across various fuel options, with estimates derived from Eq. (6) and storage requirements sized for average winter conditions. The results highlight marked differences between the options: diesel exhibits the lowest CAPEX

(~€5.9 million) owing to its low capital and storage costs per kilowatt, followed closely by methanol (~€6.7 million). At the opposite extreme, SMR presents the highest CAPEX (~€51.0 million), nearly ten times greater than that of diesel, reflecting its substantially higher unit capital costs despite requiring no storage capacity. Storage-related costs are shown to be highly sensitive to winter severity, particularly for hydrogen, where CAPEX varies by up to €13 million depending on storage-sizing assumptions. In contrast, the influence of storage on CAPEX for other fuels is comparatively modest.



	Diesel	LNG	Methanol	Ammonia	Hydrogen	SMR*
🟧 Storage	0.8	3.0	1.1	1.7	13.6	0.0
🟦 Engine	5.0	9.9	5.6	8.8	11.5	51.0
🟩 CAPEX MEDIOCRE	5.86	12.88	6.70	10.53	25.09	51.03

Figure 25. CAPEX total, power conversion, and energy storage. *Publication III*.

Figure 26 presents the life-cycle cost (LCC) comparison of different fuel options, including sensitivity analyses for the most cost-effective alternatives. The LCC estimates are derived using Eq. (7), which incorporates CAPEX, OPEX, retrofit, and disposal costs over the vessel's lifetime. A specific scenario (SMR^E) includes the service benefit of electricity sales during off-season operation, as defined by Eq. (17) in *Publication III*. The results indicate that, while combustion-engine options (diesel, LNG, methanol, ammonia) are the most economical at the investment stage, their LCC increases steeply over time due to rising fuel and emission expenses. Fuel-cells systems emerge as the least economical option, with lifetime costs surpassing those of SMR after six years. In contrast, SMR becomes competitive after 22 years, owing to its low fuel, maintenance, and emission costs, while the SMR^E variant achieves the lowest overall LCC, attaining cost leadership by year eight as a result of electricity sales. Sensitivity analyses confirm the robustness of these findings: SMR and SMR^{E} remain the most economical options even when CAPEX varies by ±10% and fuel or disposal costs by ±20%. Carbon-tax scenarios further reinforce the competitiveness of green fuels, as fossil-fuel LCCs increase by €9–12 million under the 2035 BNEF forecast, whereas SMR, SMR^{E}, ammonia, and hydrogen remain largely unaffected. Overall, the ranking of the most economical long-term options is led by SMR^{E}, followed by SMR, LNG, and methanol.

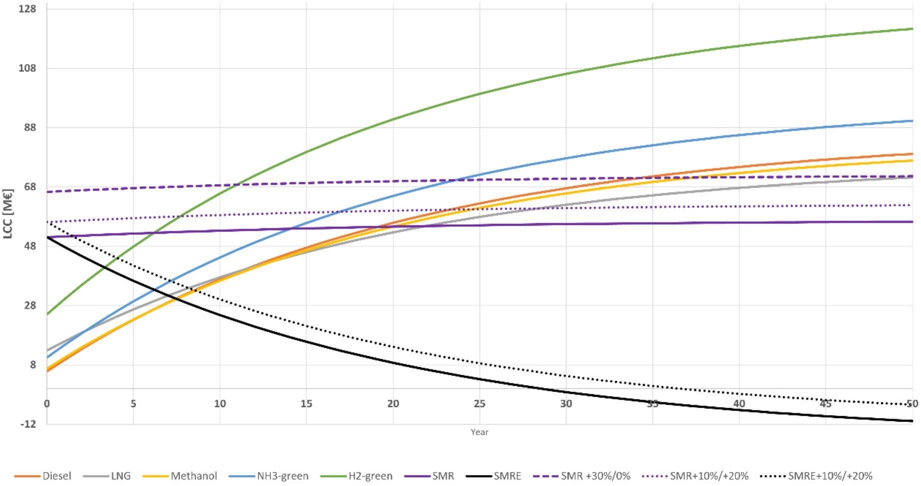


Figure 26. Life-cycle costs, baseline scenario, well-to-propeller, mediocre winter. *Publication III*. Note: Sensitivity scenario legends indicate changed parameter: SMR +Capex%/+Fuel costs%.

5.3.2 Economic evaluation of lithium-ion battery-based systems

Fully electric car-passenger ferry

Publication I develops a mathematical framework for assessing the total cost of ownership (TCO) of marine LIB systems while incorporating circular-economy principles. As LIB deployment accelerates in transport and shipping, sustainable reuse and recycling become essential for cost efficiency and environmental impact reduction. Figure 27 illustrates that marine batteries typically require several retrofits (one to three) during a vessel's 30-year lifetime, making second-life use and material circulation economically significant. A case study analysis of a fully electric ferry shows that reusing retired LIBs in second-life applications or through recycling can lower retrofit costs by up to 35% and reduce the life-cycle capital expenditure of batteries by approximately 20%. These results align with previous studies [102][132]. Figure 28 presents the economic impact of battery circular-economy strategies at ship level, demonstrating a 1.3% reduction in total life-cycle cost compared with conventional disposal and an €8.6 million LCC advantage relative to a modern diesel ferry after a 36-year lifetime. This finding aligns with the results of a study comparing the economic performance of diesel and electric ferry [133] . In addition to reducing ownership costs, circular strategies decrease greenhouse gas emissions and create opportunities for new revenue streams. The study concludes that efficient reuse, recycling, and energy recovery of LIBs can significantly enhance the commercial viability of marine electrification. However, further technological and industrial innovation is needed to optimise circular material flows.

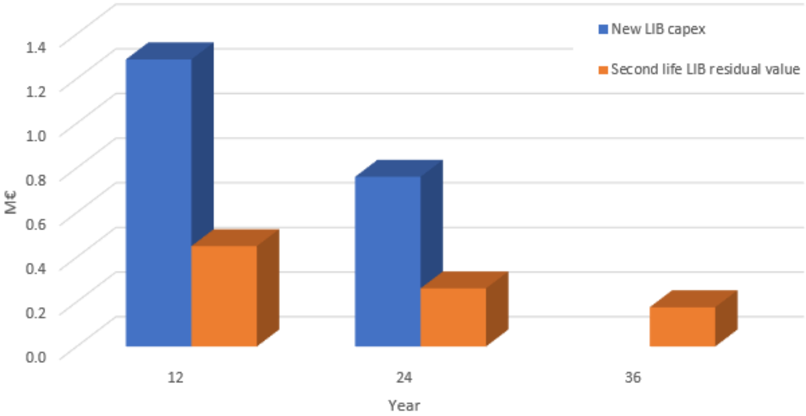


Figure 27. Marine BESS capital expenditure and residual value over the lifetime of a ship. *Publication I.*

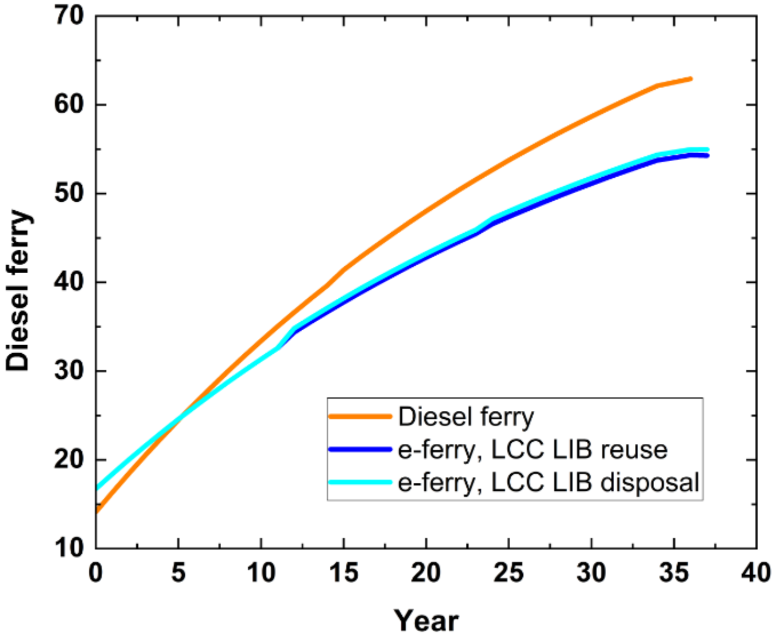


Figure 28. Ferry life-cycle cost over 36 years for two electric ferry scenarios compared with a diesel ferry. *Publication I*.

Second-life battery economic opportunities

Figure 29 presents a comparative analysis of four different use cases in which second-life batteries (SLBs) are employed for value creation. The complete analysis is presented in *Publication II*. The results demonstrate that the economic viability of SLB energy-storage systems is strongly dependent on application type, investment costs, and revenue models. Market immaturity results in high price variability for SLBs, creating both risk and opportunities. A baseline assumption was made that an SLB energy storage system, including installation, costs 50% of a new battery, with sensitivity ranging from 30% to 70%.

Among the assessed applications, frequency control proved most profitable. Offering 1 MW capacity for upward and downward reserves generated an estimated annual revenue of €222,000, leading to a payback period of 2.9 years, with variability of −1.2 to +1.4 years. The electric vehicle (EV) charging arbitrage case also showed favorable economics, with annual revenue of approximately €108,000 and a payback period of 5.1 years. In contrast, the solar PV storage provided limited economic benefit, producing annual savings of only €46,000 and an estimated payback of 15.4 years—longer than the expected system lifetime, making this case commercially unattractive as a stand-alone service. The power-booster case achieved annual savings of around €52,000 with a payback of 11.9 years, although performance improved significantly when SLB costs were reduced to 30–40% of new battery costs. Importantly, combining multiple applications, such as solar PV and power booster, shortened the payback period to 5.3 years, improving overall feasibility.

These findings underscore that business opportunities for SLBs are highly application-specific. While frequency-control and arbitrage applications offer the strongest returns, PV-only cases are less likely to be economically viable. Multi-use strategies appear most robust, particularly when paired with favourable SLB pricing.

The results also highlight the critical influence of battery lifetime on economic potential. Accurate estimation of remaining useful life requires consideration of degradation drivers such as charge-discharge currents, depth of discharge, average state of charge (SoC), temperature, and cycling patterns. Sensitivity analyses are essential to account for uncertainties in SLB pricing, frequency market revenues, electricity price dynamics, and advances in diagnostics and industrialisation. Ultimately, while SLBs can deliver competitive returns in specific applications, their commercial success depends on carefully-designed business models, reliable lifetime forecasting, and proactive risk mitigation.

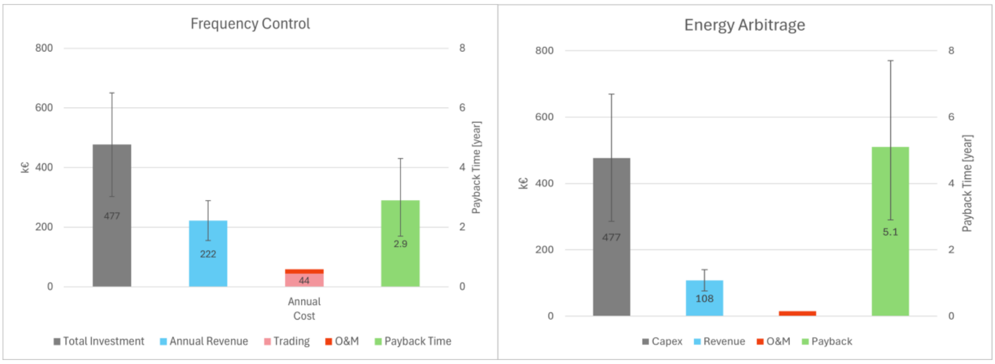


Figure 29. Economic comparison of second-life BESS for two promising use cases. Adapted from *Publication II*.

In summary, the research findings demonstrate that the transition towards low- and zero-emission fuels can substantially reduce operational greenhouse gas emissions while offering long-term economic advantages compared with conventional marine fuels. Among the assessed alternatives, SMR, methanol, and LNG exhibit strong potential for lowering life-cycle costs, particularly under evolving carbon pricing frameworks. Moreover, green ammonia is projected to reach competitive cost levels as production volumes scale up towards 2040–2050. Complementary studies on battery degradation and recycling further confirm that circular-economy strategies and second-life applications can deliver both emission reductions and tangible economic gains. Collectively, these findings suggest that maritime operations can achieve significant decarbonisation while optimising life-cycle costs and enhancing overall resource efficiency.

6 Conclusions

The objective of this research has been to analyse and compare alternative marine fuels, propulsion technologies, and material-circulation pathways to support the transition towards greener and more sustainable operations within the maritime sector.

Since 2020, when this doctoral research commenced, substantial developments have occurred in the marine industry, global energy technologies, and the broader domains of environmental and energy policy. Owing to an increasingly unstable geopolitical environment, both nationally and across Europe, there has been a strong call to reduce dependency on fossil energy suppliers, enhance energy self-sufficiency, and strengthen the overall security of supply under all circumstances.

This overall transition has been driven by the long-term strategic framework of EU climate and energy policy, including the Emissions Trading System (ETS) and the implementation of renewable energy directives. At the global level, the International Maritime Organization (IMO) has adopted its 2023 strategy aimed at achieving net-zero greenhouse gas emissions from international shipping by or around 2050, further aligning the maritime energy transition with broader decarbonisation goals. The continuous expansion of fossil-free electricity generation reflects a profound structural transformation of the EU energy system towards decarbonisation, reinforcing system resilience and supporting the Union's carbon neutrality target for 2050. A core element of the green transition is the circular economy, promoted through the European Commission's *Circular Economy Action Plan* (2020) as part of the European Green Deal. *The Waste Framework Directive* (EU 2008/98/EC) underpins EU waste policy by mandating waste reduction, recycling, and product design for resource efficiency. Complementing this, the *Waste Electrical and Electronic Equipment (WEEE) Directive* regulates the collection and recycling of electronic devices, further advancing circularity in this sector.

Within the maritime domain, a gradual transition towards alternative propulsion systems is underway, including the adoption of LNG, methanol, ammonia, and hydrogen as marine fuels. Consequently, ship power plants are evolving towards more sustainable configurations, as reflected in recent vessel deliveries and order statistics. The environmental performance of marine fuels is projected to improve further with the increasing use of renewable energy in their production and the integration of carbon capture and storage technologies. Owing to their significant potential advantages, such as competitive life-cycle costs and long refuelling intervals, small modular reactors are also expected to become a viable option for marine applications in the coming decades.

The techno-economic evaluation of alternative fuels for icebreakers, as presented in the Baltic Sea case study, demonstrates that the small modular reactor (SMR) represents the most promising long-term solution for high-power, high-endurance vessels. SMRs offer the lowest life-cycle emissions and overall costs, combined with operational autonomy unmatched by combustion-based systems (RQ1). The absence of onboard fuel storage requirements provides significant space savings and potential for profitable electricity generation during non-ice-icebreaking seasons. However, the immaturity of marine-certified SMR technology, the absence of a comprehensive regulatory framework, and public acceptance challenges remain key barriers to near-term implementation. Among chemical fuels, green methanol and ammonia have emerged as feasible alternatives, balancing environmental performance, energy density, and technical integration feasibility (RQ1). Methanol's liquid-handling characteristics and potential for carbon-neutral synthesis make it particularly attractive for retrofitting and hybridisation, while ammonia offers a zero-carbon combustion pathway when produced from renewable hydrogen. A significant strength of methanol and ammonia is their ability to enable a gradual transition pathway from low-carbon fossil fuels (grey and blue) to green alternatives, thereby supporting alignment with environmental and economic objectives (RQ2). Liquefied natural gas, although lower emissions than diesel, faces long-term limitations due to methane slip and continued fossil dependency; nonetheless, it yet remains a cost-effective transitional fuel within the 2030 horizon.

For ships in general, the findings align with global fleet trends indicating a gradual diversification of energy carriers. The uptake of LNG, methanol, and ammonia is accelerating, supported by shipyard orders and the expansion of fuel infrastructure. According to DNV's 2024 data, vessels using alternative fuels represented over 20% of new orders, with methanol and ammonia showing the strongest relative growth. However, penetration in the active fleet remains below 2%, reflecting long vessel lifetimes and capital lock-in. Feasibility is highly dependent on vessel type, operational profile, and refuelling logistics: short-sea ferries increasingly adopt hybrid and battery systems, while long-haul vessels transition towards scalable low-carbon options such as methanol, LNG, and ammonia (RQ3).

Looking ahead, the future outlook indicates a multi-fuel transition converging towards a portfolio of complementary solutions rather than a single dominant fuel. Between 2030 and 2050, green hydrogen and ammonia are expected to achieve greater commercial maturity, supported by large-scale renewable electricity deployment and declining electrolyser costs. Simultaneously, the development of SMR propulsion may redefine energy autonomy for ice-class and specialised vessels, provided that safety and governance frameworks evolve accordingly. The increasing reliance of e-fuels on fossil-free electricity strengthens the overall sustainability of marine energy chains, progressively decoupling maritime operations from fossil carbon. Collectively, these trends signal an irreversible structural transformation of the maritime energy system—towards diversified, electrified, and circular energy flows—aligning the sector with global decarbonisation pathways and the IMO's net-zero target for 2050.

Circular-economy principles have emerged as an essential framework for advancing environmental and economic sustainability in the maritime sector. This research and the associated publications demonstrate that systematic material circulation, reuse, and recycling can substantially reduce both life-cycle emissions and total ownership costs of marine technologies, particularly in battery-electric propulsion systems. The analysis of large-scale marine LIB systems revealed that efficient circular material flows can lower battery life-cycle capital expenditure by up to 20% and retrofit costs by as much as 35% (RQ7). This is especially relevant for vessels requiring multiple battery replacements during a 30-year lifespan, such as ferries and icebreakers. By integrating reuse, second-life, and recycling pathways, ship operators can not only mitigate environmental impacts but also generate new revenue streams from recovered materials and residual value. Battery reuse and material circulation were found to yield a further 1-2% reduction in ferry life-cycle costs (RQ8). The mathematical framework for total cost of ownership developed in the thesis quantifies these benefits, providing a replicable model for assessing the economic feasibility of CE-based energy storage solutions in marine applications.

The experimental study on second-life batteries complements this systems-level analysis by providing empirical evidence that first-life usage has limited influence on degradation rates in controlled second-life conditions (RQ4). Under moderate cycling, retired NCA batteries retained 98% of their post-first-life capacity after 1,000 cycles. These findings validate the technical viability of reusing traction batteries in less demanding stationary or auxiliary maritime applications (RQ6), such as port energy storage, grid frequency containment, onshore charging infrastructure, and stacked energy services combining multiple services (RQ5). From an environmental perspective, repurposing end-of-life batteries can reduce CO_2 emissions by over 50% compared with manufacturing new battery systems, while offering a payback period of less than three years in frequency-control services (RQ6). Overall, the results indicate that the circular economy of LIBs can generate additional economic value not only for shipowners but also for the end users of repurposed marine battery systems.

In summary, the maritime sector stands at the intersection of technological innovation and systemic transformation, where clean-energy adoption and circular-design principles jointly define a sustainable path forward. Continued collaboration across policy, industry, and research will be essential to accelerate this transition—

reminding us that through science, innovation, and responsibility, we are working towards a better tomorrow.

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