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Applying Multi-Objective Robust Decision-Making to Decarbonisation Strategies in Research Vessels

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Abstract

This paper applies a Multi-Objective Robust Decision-Making framework, combined with an Epoch-Era Analysis, to evaluate decarbonisation strategies for ocean- and global-class research vessels. The method incorporates deep uncertainties across technological, operational, regulatory, and economic aspects and compares configurations based on technical feasibility, greenhouse gas emissions, and lifecycle costs. The analysis covers conventional and alternative fuels, energy converters, and energy-reduction technologies. Methanol-based concepts emerge as robust low-carbon options across all operational profiles, while ammonia shows additional potential for lower-demand vessels. Iterative analyses of blended fuels and hull-form variations further demonstrate the approach's flexibility for exploring adaptive design strategies and highlight the potential of transitional fuels.

1. Introduction

The maritime sector faces growing pressure to reduce greenhouse gas (GHG) emissions in line with international and regional climate objectives. While commercial shipping is increasingly subject to carbon-intensity and efficiency regulations, research vessels remain largely exempt despite their high energy demand and global operations. Their complex and mission-dependent operating profiles make strategic decisions on propulsion and fuel systems particularly challenging.

Future developments in alternative fuels, converter technologies, and regulatory frameworks are characterised by deep uncertainty. Key factors such as fuel availability, cost, energy density, and emission performance remain difficult to predict, as do potential policy extensions, such as the inclusion of non-commercial ships in carbon-pricing schemes.

This study addresses this gap by proposing a combined Multi-Objective Robust Decision Making and Epoch-Era Analysis framework to explore decarbonisation strategies. The case study is applied to ocean- and global-class research vessels, which represent the most energy-intensive and operationally demanding categories. The framework integrates technological, operational, economic, and policy uncertainties, linking short-term operational variability with long-term contextual change. It enables the identification of propulsion concepts that remain technically feasible, cost-effective, and low-emission across a wide range of plausible futures, providing a structured basis for decision-making in the decarbonisation of research vessels.

2. Background

2.1. Regulatory Context for Maritime Decarbonisation

The maritime industry faces increasing pressure to decarbonise, with policy levers driving reductions in GHG emissions. In recent years, both international and national frameworks have strengthened their focus on the energy transition in shipping. At the international level, the International Maritime Organization (IMO), *IMO (1997)*, has introduced several regulatory measures, including the Energy Efficiency Design Index (EEDI) and the Carbon Intensity Indicator (CII). However, research vessels are exempt from both, as these apply to ships engaged in the transport of goods or passengers. Their operational profiles are highly variable, which further complicates the application of standard efficiency metrics.

In 2025, the IMO approved a Net-Zero Framework, aiming for net-zero GHG emissions from international shipping by or around 2050, introducing a global GHG pricing mechanism, *DNV (2025a)*. Additionally, the FuelEU Maritime Regulation and the extension of the EU Emissions Trading System (ETS) to shipping establish incentives to reduce lifecycle emissions and encourage the use of renewable and zero-carbon fuels, *EU (2023a)*, https://climate.ec.europa.eu/eu-action/eu-emissions-trading-system-eu-ets/about-eu-ets_en. The ETS, in particular, applies a carbon price to emissions. At present, in the maritime sector, the system is restricted to transport vessels and does not cover research and non-commercial ships. Thus, decarbonisation efforts for research vessels typically depends mainly on institutional and national initiatives, such as voluntary emission-reduction targets.

2.2. The Special Case of Research Vessels

Research vessels represent a distinct category within the maritime sector, characterised by specialised missions and highly variable operating profiles. Unlike commercial ships that follow predictable trade routes and operate under market incentives, research vessels are designed to support diverse scientific activities that can change over time. This creates significant operational uncertainty. In general, research vessels can be divided into four main operational classes according to their area of operation and endurance requirements, *Nieuwjaar and Mazauric (2019)*:

- Global-class operates worldwide, often in remote regions, supporting diverse scientific missions with extensive deck space, advanced laboratory facilities, and specialized equipment.
- Ocean-class shares many features with the global-class, but are typically confined to a single ocean, and accommodate fewer scientists.
- Regional-class operates in a specific geographic region, close to the coast and in deep waters.
- Coastal-class and local-class conduct research close to the coast. Local-class vessels typically return to port daily.

The differing operational range, endurance, and mission type influence fuel storage capacity, crew size, and the level of onboard scientific infrastructure. This study focuses on global- and ocean-class vessels, as they represent the most energy-demanding and logistically complex categories, making them particularly relevant for evaluating alternative fuels and propulsion systems. Research vessels exhibit complex operational profiles, typically combining transit, research, and stand-by modes. E.g., the German research vessel ‘Sonne’, <https://briese-research.de//research-department/research-vessels/rv-sonne>, requires a large amount of electrical power during research operations, particularly during precise research that requires enhanced dynamic positioning capability, L. Meinders in personal communication. During transit, power demand is somewhat lower but remains significant due to propulsion power. The vessels ‘Sonne’ and ‘Maria S. Merian’ indicate that research vessels spend ~40% of their mission time in transit, ~45% in research activities, and ~15% in ports or yards.

2.3. Alternative Fuels and Technologies

Decarbonisation of shipping depends on the gradual replacement of fossil fuels with low- and zero-carbon alternatives and the integration of energy-saving technologies. Energy conversion can be achieved through internal combustion engines (ICEs) or fuel cells (FCs). ICEs are well established and capable of operating on a wide range of liquid and gaseous fuels, but efficiency improvements are reaching physical limits, *Klein Woud and Stapersma (2019)*. Moreover, the installation costs of ICEs remain uncertain for emerging fuels, as these systems are not yet widely adopted at a commercial scale. FCs, conversely, offer higher electrical efficiency and near-zero local emissions but remain expensive and largely untested for marine applications. The efficiency and cost of FC stacks represent major technological and economic uncertainties for their future deployment. Other converter types, such as steam turbines and electric propulsion, were also assessed. Steam turbines, interesting in combination with iron powder, were excluded due to low technological readiness of the fuel, *De Kwant et al. (2023)*, while direct battery-electric systems were considered infeasible for ocean- and global-class ships because of limited energy density, *MAN (2019)*. Electric propulsion, however, is already incorporated through ICE-electric systems.

The most relevant fuels include hydrogen, ammonia, methanol, liquefied natural gas (LNG), and hydrotreated vegetable oil (HVO). Other potential carriers, such as liquefied petroleum gas, sodium borohydride, and iron powder, are at a very low technological readiness level for marine applications. Their energy conversion technologies, storage methods, and safety systems remain largely experimental, and they are therefore not yet considered feasible for near-term vessel integration (*de Kwant et al. (2023)*, *MAN (n.d.)b*, *Kaya (2024)*).

Ammonia eliminates carbon emissions, and if produced green becomes carbon neutral, *Bora et al. (2024)*. It acts as a hydrogen storage medium, offering a higher volumetric energy density than hydrogen, but is toxic and corrosive, *Chai et al. (2021)*, *IRENA (2024)*. The absence of bunkering infrastructure and operational experience adds technological uncertainty. HVO is a renewable fuel compatible with existing marine diesel oil (MDO) engines and infrastructure, *Laurson et al. (2023)*. It enables immediate emission reductions but is constrained by feedstock availability and uncertain long-term price and supply, *DNV (2019)*. Hydrogen enables carbon-free operation when produced green but requires high-pressure or cryogenic storage, *EU (2023b)*, *Center for Sustainable Systems (2024)*. Handling and safety challenges, together with limited port infrastructure, make its large-scale adoption uncertain, *MAN (n.d.)a*. LNG is a transitional fuel that reduces CO₂ emissions compared to MDO and pollutant emissions, but it remains fossil-based and subject to methane slip, *Fun-sang Capeda (2019)*. Although infrastructure is available and ICEs are commercially available and introduced, their long-term regulatory acceptance is unclear under tightening emission limits, <https://sea-lng.org/why-lng/availability/>, *DNV (2025b)*. Methanol can be stored at ambient conditions and produced from the gasification of biogas. Its lower energy density compared to conventional fuels increases storage requirements, and the future availability of sustainably produced methanol remains uncertain, *DNV (2023)*.

Complementary energy-saving technologies can significantly reduce fuel consumption and improve overall system efficiency. The most relevant options for research vessels are wind-assisted ship propulsion (WASP) and exhaust heat recovery (EHR). Other options, such as solar photovoltaic systems, were not considered, as deck space is needed for research purposes. WASP can provide auxiliary thrust during transit phases, but its effectiveness depends on route, weather, and technological progress, *Chica et al. (2023)*. EHR systems capture waste heat from engines and transform it to electrical energy, but their performance depends on stable exhaust temperatures, *Mondejar et al. (2018)*. Both WASP and EHR involve significant performance uncertainty and installation cost uncertainties.

Overall, developments in fuel, technology, and infrastructure remain deeply uncertain. Consequently, identifying a single optimal solution is unrealistic. The diversity of possible pathways underscores the need for a robust decision framework to evaluate options across a wide range of future conditions.

2.4. Decision Making under Deep Uncertainty

The decarbonisation of research vessels is characterised by multiple layers of uncertainties. Following the classification proposed by *Terüin et al (2022)*, these include technological, regulatory, and economic uncertainties, while operational uncertainty is introduced here as a specific characteristic of research vessel operations. Technological uncertainty relates to the performance of converters and energy-saving technologies. Regulatory uncertainty arises from evolving international and regional emission frameworks and the potential inclusion of research vessels in future policies. Economic uncertainty concerns fuel prices and technology costs. In contrast, operational uncertainty reflects the mission-dependent nature of research vessels – their irregular routes, variable power demand, transit speeds, and number of personnel on board.

These factors constitute deep uncertainty, in which neither the probabilities of future developments nor the relationships among the influencing factors can be reliably predicted, *Marchau et al. (2019)*. In such an environment, the use of deterministic design approaches is limited. To address these limitations, this study proposes a robust decision-making approach that prioritizes solutions that perform satisfactorily across a wide range of plausible futures rather than those optimized for a single expected scenario.

3. Methods

3.1. Framework Overview

The applied framework combines Multi-Objective Robust Decision Making (MORDM) with Epoch Era Analysis (EEA), enabling systematic exploration of uncertainties and assessment of the robustness of alternative design strategies. Within this framework, the MORDM supports the generation and evaluation of large ensembles of design alternatives and uncertain futures. To capture uncertainty specific to research vessels, EEA is integrated into the MORDM process. EEA is used to link mid-term operational epochs to long-term mission eras, representing how research activities and technologies may evolve over a vessel's life, *Gaspar et al. (2015)*. Each epoch represents a set of operational factors, namely research intensity and operational range, while epochs change over a vessel's lifetime.

Together, MORDM and EEA enable the identification of design concepts that remain robust, meaning technically feasible and comparatively stable in performance across diverse futures. The framework is implemented using the "XLRM"-structure, which organises the analysis into exogenous uncertainties (X), policy levers (L), relationships (R), and performance metrics (M).

3.2. Exogenous Uncertainty (X)

The X-dimension of the framework describes uncertainties external to the vessel design itself that influence its long-term performance. Regulatory uncertainty is treated separately as part of the decision lever (L), since it represents policy settings that can be intentionally varied rather than purely exogenous factors. The remaining technological, economic, and operational uncertainties constitute the X-dimension and define the conditions under which vessel concepts are evaluated.

Operational uncertainty is particularly relevant to research vessels and is therefore structured using the EEA approach. In this study, EEA is used to combine the two most influential operational drivers – operational range and share of precise research – into distinct epochs. Each epoch, therefore, reflects a representative combination of mission characteristics that determine the vessel's power and energy demand, while transitions between epochs capture the evolution of operational requirements throughout the vessel's lifetime. In addition, further operational parameters were varied independently. These include the transit speed and the number of personnel on board, which directly affect propulsion power, hotel load, and space demand. Technological uncertainty refers to the unknowns associated with the development of alternative propulsion technologies, as reflected in variations in converter efficiencies and the performance of WASP and EHR. Lastly, economic uncertainty reflects the variability of cost parameters, including fuel prices, carbon costs, and capital expenditures.

3.3. Policy Lever (L)

The L-dimension represents variables that decision-makers can intentionally adjust. In this study, an ETS is considered as the sole policy lever. Since research vessels are exempt from the major international emissions regulations, a zero-carbon mandate is considered unlikely. The extension of the EU ETS to research vessels or a global GHG pricing mechanism introduced by the IMO, however, represents a plausible and policy-relevant scenario that could directly affect operational costs and investment decisions. Accordingly, two policy cases are considered in the model:

1. ETS applied, where emissions are subject to carbon pricing and the resulting costs are included in total operational expenditures. Carbon costs are subject to economic uncertainty.
2. ETS not applied, representing the current exemption of research vessels from EU emission regulation.

This differentiation enables the framework to explore the economic implications of potential ETS inclusion and assess how such a policy change could affect the robustness and competitiveness of alternative vessel designs under uncertainty.

3.4. Relationships (R)

The R-dimension defines how design inputs, X-, and L-levers are linked to resulting performance measures. These relationships are implemented within a parametric model combining the vessel's energy demand, emissions, and cost structure. Together, these relationships describe how changes in technology, operation, and regulatory context affect the vessel's overall performance.

Energy demand is derived from the vessel's operational profile and propulsion configurations to estimate fuel consumption, emissions, and cost. Emissions are estimated on a well-to-wake (WtW) basis using fuel-specific emission factors, allowing consistent comparison between design alternatives. The cost relationship expresses costs related to the propulsion system, including potential carbon costs where the ETS applies. By linking these relationships, the model provides a coherent representation of how design and policy decisions influence economic and environmental performance.

3.5. Performance Measures (M)

The M-dimension defines the indicators used to evaluate the performance of each vessel concept under the combinations of L and X. These measures represent the most relevant aspects of vessel performance in the context of decarbonisation, addressing both environmental and economic objectives. Two key indicators are applied in this study:

1. GHG emissions, expressed on a WtW-basis, capture the vessel concept's environmental impact. They depend on the selected fuel, energy converter, and energy-reduction devices, and operational and technological uncertainties.
2. Expenses related to a propulsion strategy over the vessel's lifecycle represent the economic performance of the concept, including investment, maintenance, and fuel expenditures, as well as potential carbon costs if the ETS applies, and depend on all uncertainties combined.

3.6. Analysis of Scenarios

Following the definition of the framework elements, the analysis proceeds through four main steps:

- Step 1 established the decision context via the XLRM matrix. The subsequent steps correspond to steps 2-5 of the MORDM process as proposed by *Marchau et al. (2019)*.
- Step 2 (Simulation of Configurations) - All combinations of propulsion configurations, X-, and L- are simulated using a parametric model. Each combination represents one plausible future in which a specific vessel configuration operates. The simulation generates vessel concept data – including geometric characteristics, installed power, and system configurations – together with corresponding propulsion-related costs and GHG emissions. The resulting dataset forms an ensemble of design and performance outcomes across the uncertainty ranges.
- Step 3 (Vulnerability Analysis) - The generated dataset is analysed to identify vulnerabilities of vessel concepts to changes in uncertain parameters. Changes in the relative ranking of fuels and technologies indicate the vulnerabilities of individual configurations to varying operational, technological, or economic conditions.
- Step 4 (Trade-off Analysis) - A multi-objective comparison of lifecycle GHG emissions and configuration-related expenses is conducted. The relationship between both objectives is visualised to illustrate trade-offs and possible synergies between economic and environmental performance. Configurations that achieve balanced results across most uncertainty settings are considered robust.
- Step 5 (New Futures and Strategies) - Findings from the analyses are used to guide iterative refinements of the design space. New strategies, such as blended low-carbon fuels or modified vessel parameters, can be re-evaluated under the same uncertainty framework to test their consistency and robustness.

4. Case Study

4.1. Case Description

The case is based on the German research vessel ‘Sonne’, selected for its suitability as a benchmark for energy-intensive scientific operations and for the data available. The ‘Sonne’ operates worldwide, primarily in the Indian and Pacific Oceans, supporting multidisciplinary research missions. Its operations combine long-range transits with energy-demanding research activities under dynamic positioning. The vessel serves as a baseline configuration from which design variants are generated. It provides the physical, operational, and functional reference for the parametric model developed in Section 4.2.

4.2. Model Setup and Assumptions

4.2.1. Model Structure

Building on the XLRM framework, a parametric model quantifies the relationships between design choices, operational conditions, and performance outcomes. The parametric model developed represents a baseline vessel, the ‘Sonne’, through a set of principal parameters describing hull geometry, propulsion power, energy demand, and system integration. The model incorporates a range of alternative propulsion strategies combining different fuels, energy converters, and energy-saving technologies. The fuels include MDO (reference case), HVO, LNG, methanol, ammonia, and hydrogen. Each fuel is evaluated with ICE and FC configurations, where technically feasible. In addition, two energy-reduction technologies – WASP and EHR – are included as optional components. Together, these parameters define the design space explored within the uncertainty framework and determine the configuration-specific relationships between energy demand, emissions, and lifecycle costs.

4.2.2. Vessel Definition and Geometric Constraints

The vessel has a $L_{BP} = 104\text{ m}$, $B = 20.6\text{ m}$, and a $T = 6.4\text{ m}$. It has a $V_s = 12\text{ kn}$, with a range of 7500 nm and an endurance of about 50 days. Accommodation is provided for up to 80 persons, including crew and scientific staff. The vessel operates under a mixed mission profile comprising ~40% transit, ~45% research, and ~15% port or yard time.

Within the parametric model, the baseline geometry is used to determine displacement, resistance, and power requirements for each operational mode. To maintain technically realistic proportions when varying hull length, a geometric constraint is imposed on the L/B ratio:

$$\frac{L_{BCV} + \Delta L}{B_{BCV}} \leq 7.0 \quad (1)$$

L_{BCV} and B_{BCV} denote the baseline vessel dimensions, and ΔL is the additional length required to accommodate alternative fuel or converter systems.

4.2.3. Operational Profiles

The operational behaviour is structured into three modes reflecting the typical activity of ocean-going research vessels: transit, research, and port or yard time. Power demand varies considerably between operational modes, from 3200 kW during normal research to 4000 kW during transit to 6000 kW during precise research operations. To define the vessel’s operational profile, variations in operational range and research intensity are structured into a set of epochs, each representing a specific combination of the two, which together describe the vessel’s overall operational profile, Fig. 1.

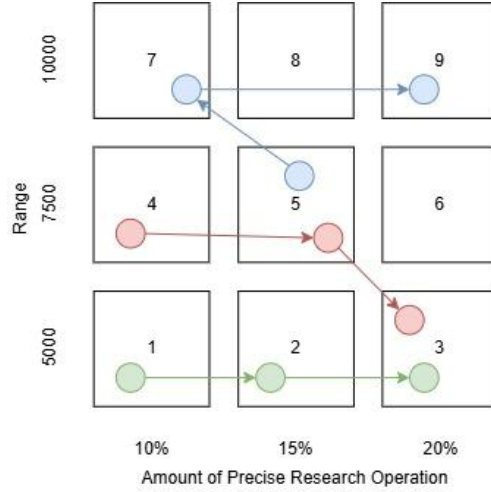


Fig. 1: Epoch-Era diagram

Together, the three eras form a set of representative operational profiles used in the uncertainty analysis. The total mission energy demand, E , is obtained by summing the power demands of all operational modes multiplied by their corresponding durations of operation:

$$E = \sum P_i t_i \quad (2)$$

P_i denotes the power needed and t_i the time spent in that specific mode i . Based on operational modes, the total mission energy demand, E , serves as the baseline for assessing fuel consumption, additional vessel length, emissions, and cost.

4.2.4. Space Requirements

The introduction of alternative fuels and converters, together with variations in the number of persons onboard, alters the vessel's internal arrangement. Space requirements are assessed for three components: fuel storage, machinery installation, and accommodation. Fuel storage varies considerably with the properties of the energy carrier. For each configuration, the required tank volume is determined from the total mission energy and the fuel's volumetric energy density. Cryogenic or pressurised fuels such as LNG, ammonia, or hydrogen are modelled as cylindrical tanks arranged in the midship section with structural clearances. The resulting volume increase is expressed as an additional hull length.

Machinery space is defined by the power density of the respective converter type. The model aggregates the volumes of converters, electric components, and auxiliary systems into a single machinery volume, ensuring consistent integration across propulsion concepts. Accommodation is independent of the energy system but varies with the number of personnel onboard. Required accommodation is obtained linearly. All additional volumes are translated into an equivalent length extension of the baseline hull using available midship areas for below- and above-waterline spaces. Where feasible, superstructure volume can partially offset below-deck demand. The added length is included in the displacement and resistance calculations.

4.2.5. Resistance and Power Estimates

Propulsive power is evaluated from the baseline vessel and adjusted for additional length or depth, variations in service speed, and efficiencies of the converters. The resistance model follows empirical relations by *Schneekluth (1988)*, scaled with wetted surface and the cubic relation between power and service speed. This approach allows consistent updates of resistance and required power when hull length or displacement changes. The influence of WASP is represented as a fractional reduction of the propulsion demand, while converter efficiency accounts for differences between ICE and FC systems.

In research modes, propulsion loads are largely governed by dynamic positioning and scientific equipment requirements. The base value of 3200 *kW* and 6000 *kW* for normal and precise research, respectively, are maintained and only scaled with converter efficiency. Hotel load increases linearly with the number of persons onboard, using a representative factor of 16 *kW* per person. It remains dependent on converter choice and is scaled accordingly. The total mission energy is obtained by multiplying the energy requirements by the time spent in that specific mode. When an EHR is installed, the overall energy demand is reduced proportionally, as waste heat is available in all combustion-driven operating modes.

4.2.6. Energy-Reducing Technologies

Within this model, both WASP and EHR are represented as reduction factors applied to energy consumption. WASP affects only the propulsion share of the transit power and is implemented as a fractional reduction ranging from 5% to 15%, depending on the applied uncertainty factor. EHR, in contrast, acts on the total required energy, reducing the required fuel input by an equivalent factor. EHR is only applicable to ICE configurations. Both technologies are included as optional parameters in the design space, allowing the framework to assess their contribution to overall performance and to test their robustness under varying operational and economic conditions.

4.2.7. Iteration

The model operates as an iterative loop to ensure internal consistency between geometry, displacement, resistance, and power demand. Each configuration starts from the baseline geometry and initial displacement. Based on the defined fuel, converter, and operational profile, the required power is estimated. The corresponding energy demand and masses determine changes in displacement, which in turn affect resistance and power. After each cycle, the displacement and wetted surface are updated, and the resistance and propulsive power are recalculated. This process continues until convergence, defined as a variation of less than 1 square meter of wetted surface area between iterations. The iterative procedure ensures that each configuration represents a physically consistent vessel concept. The resulting dataset provides comparable outputs for installed power, energy demand, fuel consumption, and added length of the hull. Configurations that exceed the geometric constraint are excluded from the feasible design set.

4.2.8. Greenhouse Gas Emissions

GHG emissions are assessed on a WtW basis, combining Well-to-Tank (WtT) and Tank-to-Wake (TtW) calculations:

$$GHG = \sum GHG_{WtT} + GHG_{TtW} \quad (3)$$

The WtT component represents upstream emissions associated with fuel production, processing, and transport and is derived from the mission energy demand and the fuel-specific WtT emission factor:

$$GHG_{WtT} = CO_{2eqWtT} * E \quad (4)$$

The TtW component accounts for on-board combustion and slip emissions and depends on the mass of fuel, and fuel-specific emission factors for CO₂, CH₄, and N₂O, and their global-warming multiplier (1, 25, and 298, respectively):

$$GHG_{TtW} = m_{fuel} * \sum (C_{f,GHG} * f_{GHG}) + C_{slip} * C_{fCH_4} * f_{CH_4} \quad (5)$$

All emissions are expressed as CO₂-equivalents on a WtW basis. The resulting total lifetime emissions per configuration form one of the two primary performance measures within the XLRM frameworks.

4.2.9. Expenses

Lifecycle expenses are evaluated to represent the economic performance of each propulsion concept. The calculation combines capital, operational, and fuel-related costs over a 30-year design lifetime and discounts them to present value. Capital costs comprise the cost for the initial machinery system, fuel storage, steel for the greater hull, and energy-saving technologies. Cost factors for converters and tanks are derived from recent market data or literature and scaled with installed power or required volume. Additional allowances are included for auxiliary systems and installation.

Operational costs include fuel, maintenance, and carbon costs. Fuel costs are calculated from fuel demand and the projected fuel price, which varies over time and within the economic uncertainty ranges defined in the XLRM matrix. Maintenance requirements vary depending on the propulsion system. FCs, in particular, have a limited service life and require periodic stack replacement. A FC lifetime of 25000 hours is assumed, *Mylonopoulos et al. (2024)*. WASP installation also requires maintenance; the associated expenses are included in the cost factor. For policy scenarios where the ETS applies, carbon costs are added proportionally to the WtW emissions using the corresponding carbon price. All cost components are discounted to their present value using a constant real discount rate, and the sum represents the total lifecycle expenses. Together with the GHG emissions described above, these expenses form the second performance measure of the framework.

4.3. Application of the MORDM Framework

Following the establishment of the decision context through the XLRM matrix in combination with the EEA framework (Step 1), the MORDM framework is applied to the data generated by the parametric model. The aim is to identify propulsion strategies that remain technically feasible, cost-effective, and low-emission across a wide range of uncertain future conditions.

- **Step 2 (Simulation of Configurations)** - All plausible combinations of design parameters are simulated within this framework. Configurations that are technically not plausible – such as FC-EHR or LNG/MDO/HVO-FC combinations – are excluded from the analysis. In total, 102,528 scenarios are evaluated, each representing one possible future in which a specific vessel configuration operates under defined uncertainty settings.
- **Step 3 (Vulnerability Analysis)** - The simulation results are analysed to identify the sensitivity of each configuration to changes in uncertainty parameters. Variations in fuel price, WASP and EHR efficiencies, and epochs are compared to reveal which concepts maintain stable performance and which are highly affected by specific uncertainties. Performance stability is visualised through box plots of lifecycle costs and GHG emissions. A widespread indicates strong sensitivity (see Figs.2 and 3 as an example). Changes in the relative ranking of configurations between epochs or uncertainty settings are used to identify vulnerability patterns – for example, when a concept is competitive only under specific economic or technological conditions. This step highlights the parameters that most influence the competitiveness of each propulsion strategy and provides the basis for the subsequent trade-off analysis.
- **Step 4 (Trade-off Analysis)** - The trade-off analysis compares lifecycle GHG emissions and total expenses as the two primary performance measures to examine how economic and environmental objectives interact under deep uncertainty. For each combination, the results from all uncertainty combinations are evaluated if feasible. The two performance indicators are plotted against each other in scatter plots to visualize their relationship across the simulated futures. This step assesses the overall balance between environmental and economic performance.
- **Step 5 (New Futures and Strategies)** - Based on the insights from the previous steps, new strategies can be introduced and re-evaluated within the same framework. Adjustments include modified vessel parameters and the introduction of blended fuels. Each revised configuration is simulated across the same uncertainty space to test its consistency and robustness. This iterative procedure enables continuous refinement of the design pace.

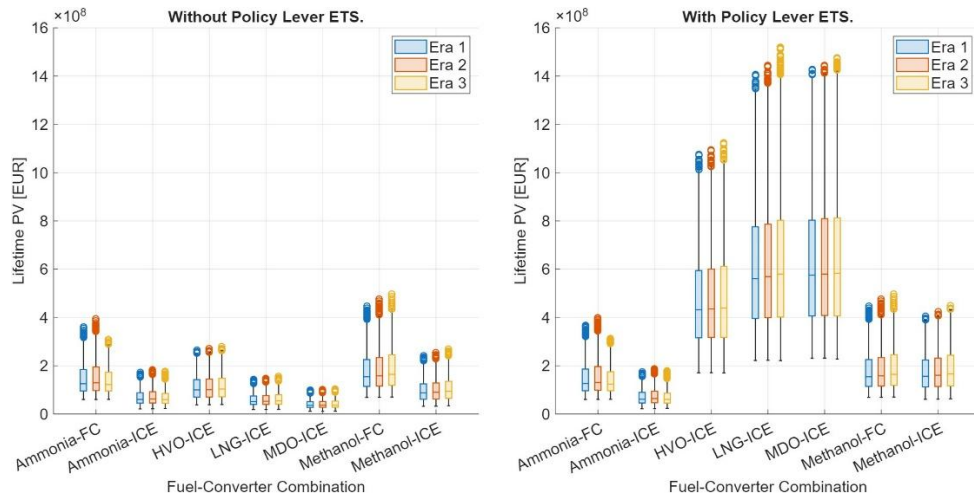


Fig.2: Lifecycle PV, visualised by fuel-converter combinations and eras

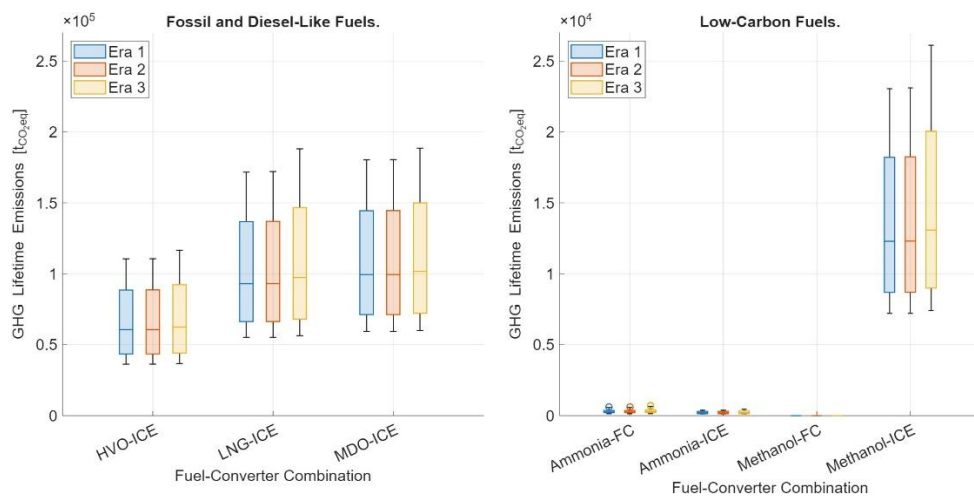


Fig.3: Lifecycle GHG emissions, visualised by fuel-converter combinations and eras

5. Evaluation of Propulsion Strategies for Deep-Sea Research Vessels under Uncertainty

Before assessing the performance, all concepts are evaluated for technical feasibility based on the geometric constraints. Configurations unable to meet the permitted hull proportions or that fail to meet endurance or safety requirements are excluded from further evaluation. The subsequent analysis examines the remaining propulsion strategies with respect to lifecycle GHG emissions and expenses.

5.1. Technical Feasibility

Feasibility is assessed based on the geometric constraint defined in Section 4.2, where configurations are deemed infeasible if the required hull extension triggers a $L/B > 7$. The analysis is applied across all fuel-converter combinations, operational eras, and optional technologies, such as EHR and WASP. Three groups are identified:

- **Robust fuels** are feasible in 100% of scenarios. This applies to HVO, LNG, MDO, and methanol in combination with an ICE.
- **Borderline fuels** achieve high feasibility fractions from 95 to 99%. Borderline configurations are ammonia and methanol-FC configurations.
- **Highly infeasible fuels** reach feasibility in less than 60%. This is the case for hydrogen configurations.

Auxiliary technologies improve feasibility, for instance, ammonia-ICE systems increased from 89% feasibility without auxiliaries to 97% when both EHR and WASP are integrated. Ammonia and methanol-FC configurations benefit slightly from WASP, whereas hydrogen options remain largely infeasible. These results indicate that while auxiliary systems enhance robustness, they cannot fully offset geometric limitations inherent to low-density fuels.

Operational profiles also influence technical feasibility. The three operational eras, representing progressively more energy-intensive operations, are analysed with respect to feasibility. Naturally, feasibility decreased with increasing operational demand. Methanol-FC and ammonia combinations remain fully feasible in era 1 and 2 configurations, but hydrogen configurations failed to achieve robustness under any operational profile. Given the low feasibility, hydrogen was excluded from further consideration.

Overall, the results demonstrate that the feasibility of decarbonisation strategies for research vessels depends strongly on the volumetric energy and power density of fuel and converter, and the operational intensity of the missions. Auxiliary energy-reduction technologies further enhance feasibility but cannot fundamentally change these underlying relationships.

5.2. Sensitivity Analysis

The sensitivity analysis evaluates how uncertainty parameters and policy parameters affect the performance measures of the feasible propulsion concepts. Variations in emissions and expenses are assessed to identify which uncertainties exert the strongest influence. The assessment covers economic, technological, operational, and policy-related uncertainties as defined in the XLRM framework.

5.2.1. Greenhouse Gas Emissions

The sensitivity of GHG emissions is investigated by analysing the influence of operational profiles, efficiency levels of EHR and WASP. Operational profiles exert a measurable, but secondary influence on total lifecycle emissions. Across three operational eras, GHG emissions increased stepwise with mission demand. Era 1 vessels, with relatively short-range missions, exhibited the lowest emissions, while Era 3 vessels produce the highest due to greater energy requirements. However, this variation remains smaller than the differences between fuel types. Between era 1 and 2, the difference is negligible for all fuel types. Hence, while operational conditions affect absolute emission levels, they do not alter the relative ranking of fuel-converter options. The efficiencies of EHR and WASP are modeled as reductions in propulsion or total energy demand of 5%, 10%, and 15%. Both systems demonstrate a consistent, stepwise reduction in GHG emissions with increasing efficiency. In absolute values, the sensitivity is more pronounced for fossil and diesel-like fuels; higher EHR and WASP efficiencies substantially reduce lifetime emissions. For low-carbon fuels, the impact was minor due to the already low baselines. Overall, these results confirm that auxiliary technologies can enhance decarbonisation potential but remain subordinate to the choice of fuel and converter. In summary, GHG emissions exhibit limited sensitivity to operational profile and auxiliary efficiency uncertainties compared with the dominant influence of fuel type and conversion technology.

5.2.2. Expenses

The sensitivity of lifecycle expenses to uncertainty parameters is assessed similarly to GHG emissions, but extended to include economic and policy-related uncertainties and levers. The evaluation, therefore, covers variations in operational profiles, the efficiency levels of energy-saving technologies, uncertainty in fuel and capital costs, and the inclusion or exclusion of an ETS. Variations in operational demand across mission eras exert a moderate influence on total lifecycle costs. Longer, more energy-intensive missions increased fuel consumption and operational expenditures; however, their impact on emissions remains smaller than that of fuel types.

Efficiency variations in EHR and WASP affect lifetime PV marginally. For most fuels, the variation in costs between efficiencies is small relative to the overall spread of the results. Notably, for EHR and without ETS, costs without auxiliaries appear slightly lower, since the additional capital investment is apparently not offset by fuel savings. Under ETS conditions, however, their economic relevance increases, as reductions in fuel consumption also lower carbon-related costs. For low-emission fuels such as ammonia and methanol, the effect remains minor, especially for ammonia EHR does not deliver a positive economic case.

Among the examined economic uncertainties, fuel prices are the dominant driver of lifecycle expenses. A $\pm 40\%$ change in fuel price produces higher cost variations, whereas capital expenditure changes $\pm 25\%$ has limited impact. However, both uncertainties affect costs only slightly and do not influence the hierarchy determined by fuel and converter.

The introduction of carbon pricing fundamentally alters the cost hierarchy. Under market conditions, MDO, LNG, and HVO remain the least expensive options. When accounting for ETS, these fuels become the most costly, while ammonia- and methanol-based systems achieve cost competitiveness. Ammonia-ICE configurations emerge as the most economical option under regulated conditions. In summary, policy levers dominate the uncertainty sensitivity on lifecycle expenses. Carbon pricing reshapes the cost hierarchy, while other uncertainties affect the outcomes only slightly.

5.3. Trade-off Analysis

The trade-off analysis compares lifecycle GHG emissions and total expenses as the two performance measures of the framework. It aims to identify configurations that achieve balanced performance across both environmental and economic objectives under uncertainty. Because the inclusion of an ETS has the strongest influence on the economic outcome, results are presented separately with and without ETS. This separation allows the effect of carbon-pricing to be clearly distinguished.

Fig.4 illustrates the relationship between emissions and expenses for all feasible configurations. Each point represents one configuration under a specific uncertainty setting. Under present conditions without carbon pricing (left panel), MDO- and LNG-ICE configurations remain the most cost-efficient, but also the highest in lifecycle emissions. HVO provides moderate emission reductions at higher costs. Methanol- and ammonia-based concepts achieve substantially lower emissions, with methanol remaining roughly competitive to HVO, while ammonia requires higher expenses. FCs show a greater spread at higher average costs but are carbon-neutral. The trade-off surface, therefore, extends from low-cost/high-emission fossil configurations to high-cost/low-emission alternatives.

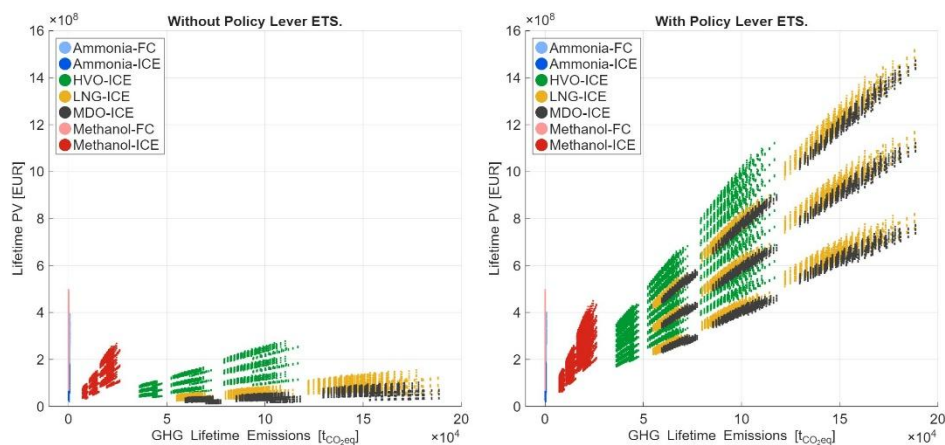


Fig.4: Lifecycle PV against GHG emission, by fuel-converter options

When carbon costs are included, the trade-off scatter changes significantly. The costs of fossil fuels increase in proportion to their emissions, and low-carbon carbon fuels are competitive. Ammonia

visibly improves its performance compared to methanol, while MDO, HVO, and LNG lose competitiveness.

A closer look at the role of converter choice shows that for ammonia, ICE and FC configurations overlap strongly in both cost and emissions. FCs achieve lower emissions in some cases, but in many scenarios, they perform worse than ICEs due to higher space requirements. At the same time, ICEs are systematically cheaper. This means that FCs do not provide a robust advantage and cannot be considered a clearly superior option.

The combined analysis indicates that economic and environmental objectives are not inherently conflicting. Instead, policy mechanisms such as the ETS can realign incentives, enabling low-carbon fuels to perform competitively on both axes. Robust solutions are identified for methanol-ICE configurations across all operational demands and for ammonia-ICE configurations in vessels with lower operational demand, both achieving a favourable balance between cost and emissions even under varying uncertainty conditions.

5.4. Iterations of Design Parameters and Blended Fuels

Step 5 of the framework applies the iterative element of the MORDM to explore new futures and strategies derived from the preceding analyses. In the present study, two iterations are conducted: one testing blended fuels as transitional options, and another assessing the effect of hull form modifications.

5.4.1. Blended Fuels

In this iteration, methanol and ammonia are assessed as grey/green blends with an 80%/20% composition. Physical and technical properties remain identical to the pure fuels, while prices and emission factors were mixed proportionally. Fig.5 visualises the trade-off between lifecycle GHG emissions and expenses for all blended-fuel configurations under uncertainty.

Under market conditions without an ETS, the lowest median lifecycle cost is for the MDO configuration, followed by the ammonia-ICE and LNG-ICE configurations. Methanol-ICE is slightly more expensive, while HVO and FC configurations remain cost-intensive with the widest spreads. When carbon pricing is included, this order changes only moderately: fossil fuels and HVO remain the cheapest options, while blended fuels fall into a middle-cost range, only marginally more expensive than MDO and LNG. Methanol becomes somewhat cheaper than ammonia. In terms of emissions, methanol FC configurations achieve the lowest values, followed by HVO, LNG, and MDO. The highest emissions occur for ammonia and methanol-ICE configurations.

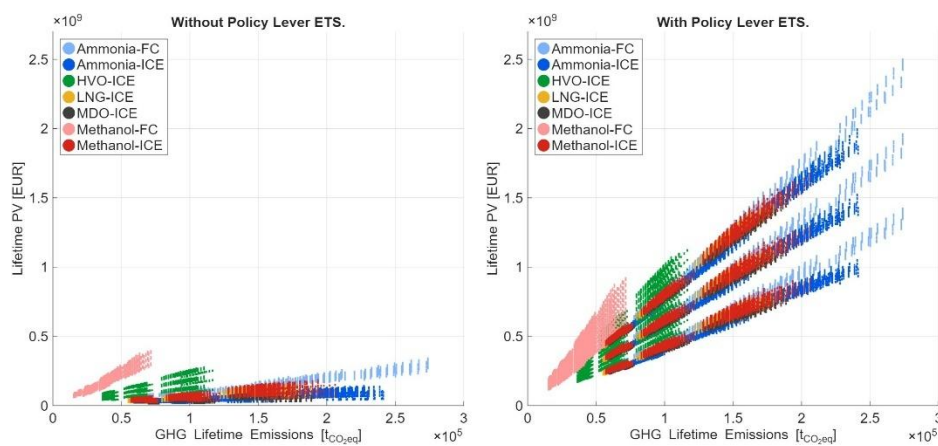


Fig.5: Lifecycle PV against GHG emissions, by fuel-converter combinations with ammonia and methanol as blended fuels with 80% grey and 20% green composition.

Overall, the blended-fuel iterations demonstrate that partial substitution of green content can substantially improve economic viability. When economic performance is prioritised over emission minimisation, blended configurations may remain temporarily preferable under market conditions without ETS. Conversely, when carbon pricing is applied, the use of fully green fuels becomes the preferred and most straightforward option, as only the fuel composition needs to be adapted while the propulsion setup remains unchanged.

5.4.2. Design Parameters

A second iteration investigated the impact of increasing the block coefficient (C_B) to provide additional internal volume and thereby reduce the added length required for bulky storage and converter systems. Raising C_B improved technical feasibility for low-density fuels without significantly affecting overall emissions or lifecycle costs, Fig.6. The analysis is simplified to consider only geometric effects, as a comprehensive evaluation of hydrodynamic resistance would require additional vessel data and advanced methods, such as computational fluid dynamics (CFD). Within these limitations, the results still indicate that modest hull-form adaptations may expand the feasible design space for zero-carbon configurations. Both iterations confirm the flexibility of the combined MORDM-EEA framework in guiding adaptive design strategies. While the analysis of blended fuels highlights how transitional energy pathways can improve economic robustness, the hull-iteration demonstrates how geometric adjustments can expand technical feasibility.

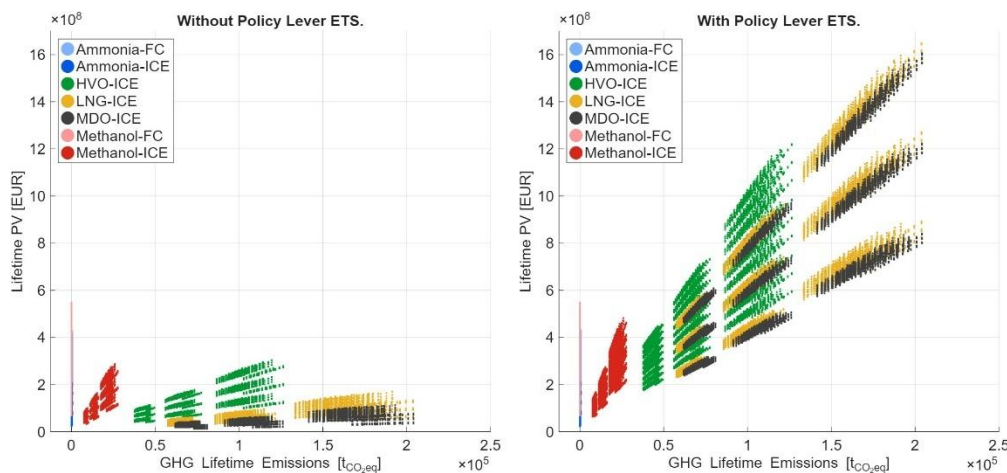


Fig.6: Lifecycle PV against GHG emissions for fuller hull, by fuel-converter combinations

6. Verification and Validation

To ensure the reliability of the modelling results, both verification and validation procedures were carried out, following the recommendations by *Law (2015)*.

6.1. Verification

Verification aims to confirm that the conceptual model described in Section 4 was correctly implemented in MATLAB and functioned according to its theoretical formulation. The model's individual modules – covering energy demand, tank sizing, hull geometry, emissions, and lifecycle costs – were developed and tested sequentially to enable visual inspection and early detection of inconsistencies. Systematic input variations, including extreme test cases, are conducted to examine whether the model responds logically to parameter changes. Selected calculations, such as tank volume determination and mission energy estimation, are manually verified to confirm internal consistency. Visual inspection of intermediate outputs (e.g., annual fuel cost trends and geometric constraints) ensures that key relationships behave as expected. Simplifying assumptions, such as constant power demand during research operations, are maintained to ensure traceability of results. Statistical consistency checks on the model output – including means, variances, and box-plot analyses – further

demonstrate the model's internal coherence. Although no external code audit is conducted, the modular structure, repeated hand-calculations, and visual testing confirm that the MATLAB implementation accurately represents the conceptual model and supports reproducible outcomes.

6.1. Validation

Validation assesses the credibility of model results in a real-world context. Given that few research vessels currently operate on alternative fuels, expert judgment and literature-based comparison are employed. The model reproduces key relationships reported in the literature, *DNV (2019,2022)*: methanol showing favourable technical feasibility and emission reductions, hydrogen being infeasible for long-range operations due to volumetric constraints, and ammonia gaining competitiveness in the future. Minor deviations, for instance, slightly higher lifecycle costs for LNG, can be explained by different boundary assumptions regarding price developments and installation costs.

Furthermore, the results' tendencies are consistent with other applications of robust decision-making frameworks in the maritime sector, *Teri'in et al. (2022)*, *Suy (2022)*, indicating that the overall relationships among technology, costs, and emission performance are captured correctly. The model therefore provides a valid representation of the long-term behaviour of research vessel configurations under uncertainty. The verification and validation process confirms that the developed MATLAB-based model is internally consistent and externally plausible. Within the exploratory scope of this study, the combined MORDM and EEA framework can therefore be considered a reliable and suitable basis for analysing the decarbonisation strategies of research vessels under deep uncertainty.

7. Conclusion

This study applies a combined MORDM and EEA framework to assess decarbonisation strategies for ocean-class and global-class research vessels under deep uncertainty. The analysis illustrates how technological, regulatory, economic, and operational uncertainties jointly influence the long-term feasibility and competitiveness of propulsion concepts. Methanol-based configurations consistently emerge as robust low-carbon pathways across all operational profiles, while ammonia offers potential for vessels with lower energy demand. The introduction of carbon pricing fundamentally reshapes economic outcomes, aligning cost and emission objectives and enabling low-carbon fuels to become competitive under regulated conditions. Iterative assessments show that transitional measures – such as blended fuels and hull adaptations – can enhance robustness and facilitate a gradual shift towards carbon-neutral operation. Overall, the integrated MORDM-EEA framework provides a systematic basis for navigating deep uncertainty and guiding design and policy strategies for future research vessels.

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References

- BORA, N.; SINGH, A.K.; PAL, P.; SAHOO, U.K.; SETH, D.; RATHORE, D.; BHADRA, S.; SEVDA, S.; VENKATRAMANAN, V.; PRASAD, S.; SINGH, A.; KATAKI, R.; SARANGI, P.K. (2024), *Green ammonia production: Process technologies and challenges*, Fuel 369, 131808
- CENTER FOR SUSTAINABLE SYSTEMS (2024), *Hydrogen Factsheet*, Univ. of Michigan. Pub.No. CSS23-07
- CHAI, W.S.; BAO, Y.; JIN, P.; TANG, G. & ZHOU, L. (2021), *A review on ammonia, ammonia-hydrogen and ammonia-methane fuels*, Renewable and Sustainable Energy Reviews 147, 111254

- CHICA, M.; HERMANN, R.R.; LIN, N. (2023), *Adopting different wind-assisted ship propulsion technologies as fleet retrofit: An agent-based modeling approach*, Technological Forecasting and Social Change 192, 122559
- DE KWANT, J.; HEKKENBERG, R.; SOUFLIS-RIGAS, A.; KANA, A.A. (2023), *Design and performance analysis of iron fueled container ships*, Int. Shipb. Progress. 70/1
- DNV (2019), *Assessment of Selected Alternative Fuels and Technologies*, DNV, Hovik
- DNV (2022), *Alternative Fuels for Containerships - LNG, Methanol Extended, Ammonia*, DNV, Hovik
- DNV (2023), *Methanol as fuel heads for the mainstream in shipping*, DNV, Hovik
- DNV (2025a), *IMO MEPC 83: New GHG requirements approved*, DNV, Hovik
- DNV (2025b), *Rising LNG demand: Overcoming bunkering challenges*, DNV, Hovik
- EU (2023a), *Directive (EU) 2023/959 of the European Parliament and of the Council of 10 May 2023 amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union and Decision (EU) 2015/1814 concerning the establishment and operation of a market stability reserve for the Union greenhouse gas emission trading system*, <https://eur-lex.europa.eu/>
- EU (2023b), *Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC*, <https://eur-lex.europa.eu/>
- FUN-SANG CEPEDA, M.A.; PEREIRA, N.N.; KAHN, S.; CAPRACE, J.-D. (2019), *A review of the use of LNG versus HFO in maritime industry*, Marine Systems & Ocean Technology 14, pp.75–84
- GASPAR, H.M.; BRETT, P.O.; ERIKSTAD, S.O.; ROSS, A.M. (2015), *Quantifying value robustness of OSV designs taking into consideration medium to long term stakeholders' expectations*, pp.247–259, 12th Int. Marine Design Conf., Tokyo
- IMO (1997), *MARPOL Annex VI: Prevention of Air Pollution from Ships*, Int. Mar. Org., London
- IRENA (2024), *Shaping sustainable international hydrogen value chains*, Tech. Rep., Int. Renewable Energy Agency, Abu Dhabi
- KAYA, C. (2024), *Sodium Borohydride (NaBH₄) as a Maritime Transportation Fuel*, Hydrogen 5, pp.540–558
- KLEIN WOOD, H.; STAPERSMA, D. (2019), *Design of Propulsion and Electric Power Generation Systems*, Institute of Marine Engineering, Science & Technology, London
- LAURSEN, R.; BARCAROLO, D.; PATEL, H.; DOWLING, M.; PENFOLD, M.; FABER, J.; KIRÁLY, J.; VAN DRE VEEN, R.; PANG, E.; VAN GRINSVEN, A. (2023), *Update on potential of Biofuels in Shipping*, Tech. Rep., European Maritime Safety Agency
- LAW, A.M. (2015), *Simulation Modeling and Analysis*, McGraw-Hill
- MAN (2019), *Batteries on board ocean-going vessels*, Tech. Rep., MAN Energy Solutions, Copenhagen
- MAN (n.d.)a, *Hydrogen in Shipping*, Tech. Rep., MAN Energy Solutions, Augsburg

MAN (n.d.)b, *LPG*, Tech. Rep., MAN Energy Solutions, Augsburg

MARCHAU, V.A.W.J.; WALKER, W.E.; BLOEMEN, P.J.T.M. & POPPER, S.W. (eds.) (2019). *Decision Making under Deep Uncertainty - From Theory to Practice*. Springer. Cham, Switzerland.

MONDEJAR, M.E; ANDREASEN, J.G.; PIERBON, L.; LARSEN, U.; THERN, M.; HAGLIND, F. (2018), *A review of the use of organic Rankine cycle power systems for maritime applications*, *Renewable and Sustainable Energy Reviews* 91, pp.126–151

MYLONOPOULOS, F.; DURGAPRASAD, S.; CORADDU, A.; POLINDER, H. (2024), *Lifetime design, operation, and cost analysis for the energy system of a retrofitted cargo vessel with fuel cells and batteries*, *Int. J. Hydrogen Energy* 91, pp.1262–1273

NIEUWJAAR, P.; MAZAURIC, V. (2019), *Next Generation European Research Vessels: Current Status and Foreseeable Evolution*, Position paper 25, European Marine Board, Ostend

SCHNEEKLUTH, H. (1988), *Hydromechanik zum Schiffsentwurf: Vorlesungen*, Koehler

SUY, X.G. (2022), *Technical and economical feasibility of zero-emission walk to work vessels*, MSc thesis, Delft University of Technology

TERÜN, K.; KANA, A.A.; DEKKER, R. (2022), *Assessing alternative fuel types for ultra large container vessels in face of uncertainty*, 21st COMPIT Conf., Pontignano

WIROOKS, C.S. (2025), *Future-Proof Research Vessels Analysis of Decarbonisation Strategies under Market Uncertainty*, MSc thesis, Delft University of Technology