



FUTURE PROOF EFFICIENT AND SUSTAINABLE DEPLOYMENT OF ZEWT

Deliverable ID: D4.1
Deliverable title: ZEWT Barrier analysis
Document version: 1.0
Partner responsible: ISSNOVA
Due date: 31/07/2026
Status: Final
Dissemination level PU - Public

This document is currently pending formal approval by CINEA and should not be considered as officially approved at this stage



**Funded by
the European Union**

This project has received funding from the European Union's Horizon Europe Programme under Grant Agreement 101192328

DELIVERABLE INFORMATION

AUTHORS

NAME	AFFILIATION
Daniele Palma Esposito	ISSNOVA
Maria Vittoria Gargiulo	ISSNOVA
Gabriella Duca	ISSNOVA
Ana Palanca Roig	VPF
Simone Panfiglio	NAVTEC

DELIVERABLE HISTORY

VERSION	DATE	MODIFICATION & REVISION	MANAGED BY
0.1	21/04/2026	Deliverable set-up	Daniele Palma Esposito (ISSNOVA)
0.2	04/05/2026	Methodological structure	Gabriella Duca (ISSNOVA)
0.3	25/05/2026	First Draft	Daniele Palma Esposito (ISSNOVA)
0.4	30/06/2026	Partner contributions	All
0.5	10/07/2026	Second Draft	Daniele Palma Esposito (ISSNOVA)
0.6	17/07/2026	Consolidated version of the document ready	Daniele Palma Esposito (ISSNOVA)
0.7	22/07/2026	Review and integration of feedback	Daniele Palma Esposito (ISSNOVA) Maria Vittoria Gargiulo (ISSNOVA) Gabriella Duca (ISSNOVA))
1.0	30/07/2026	Quality check for approval	Daniele Palma Esposito (ISSNOVA)

DELIVERABLE APPROVAL

ORGANISATION	NAME	ROLE	DATE
1 - ISSNOVA	Gabriella Duca	ISSNOVA appointed representative	30/07/2026
2 - ISL	Holger Kramer	ISL appointed representative	30/07/2026
3 - VPF	Rafael Company Peris	VPF appointed representative	30/07/2026
4 - FORMARE	Lidia Rossi	FORMARE appointed representative	30/07/2026
5 – AGSKK	Jana Kudlacek	AGSKK appointed representative	30/07/2026
6 – NAVTEC	Simone Panfiglio	NAVTEC appointed representative	30/07/2026
7 - RINA GE	Patrizio Di Francesco	RINA GE appointed representative	30/07/2026

ABSTRACT

This deliverable (D4.1) presents a structured analysis of the barriers potentially hindering the deployment of Zero-Emission Waterborne Transport (ZEWI) within the European maritime sector. The primary objective is to establish an evidence-based mapping of the systemic constraints affecting the transition, evaluated across two strategic timeframes: the 2030 evolutionary phase, focused on retrofitting, energy efficiency, and transitional fuels, and the 2050 transformative phase, centred on native zero-emission vessel architectures and carbon-neutral energy carriers.

To capture the operational and structural diversity of the maritime and inland fleets, the analysis is strictly grounded in five distinct vessel Use Cases: General Cargo Vessels, Tanker Ships, Passenger Ships, Inland Waterway Vessels, and Special Operation Vessels.

The assessment employs a holistic PESTLE framework—encompassing Political, Economic, Social, Technological, Legal, and Environmental dimensions—to deconstruct barriers beyond isolated engineering challenges, fully integrating market dynamics, regulatory fragmentation, workforce readiness, and infrastructure dependencies. Methodologically, this deliverable adopts a dual-strand approach, combining a rigorous literature-based evaluation with direct empirical validation gathered through extensive stakeholder consultations across the ZEWI ecosystem.

The consolidated findings demonstrate that economic constraints, specifically the persistent cost-competitiveness gap (CAPEX and OPEX) between conventional and zero-emission solutions, remain the most universally acknowledged barrier across all maritime segments.

The analysis reveals a critical shift in the nature of transition obstacles over time. While the 2030 horizon is predominantly constrained by retrofit feasibility, split incentives, and compliance friction related to emerging regional regulations (e.g., FuelEU Maritime and EU ETS), the 2050 horizon introduces profound systemic challenges.

These long-term barriers include the global governance of alternative fuel supply chains, the complex safety engineering required for hazardous energy carriers such as ammonia and hydrogen, and the cross-sectoral competition for renewable green electricity. Furthermore, stakeholder validation surfaced critical real-world nuances, including a communication deficit between regulatory bodies and shipowners, the operational gap in safety procedure implementation, and the emerging relevance of alternative pathways like nuclear propulsion for energy-intensive vessels.



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LIST OF ACRONYMS

AFIR	Alternative Fuels Infrastructure Regulation
AHTS	Anchor Handling Tug Supply
BESS	Battery Energy Storage Systems
CAPEX	Capital Expenditure
CCNR	Central Commission for the Navigation of the Rhine
CESNI	European Committee for Drawing Up Standards in the Field of Inland Navigation
CII	Carbon Intensity Indicator
DWT	Deadweight Tonnage
EEXI	Energy Efficiency Existing Ship Index
EIB	European Investment Bank
EMS	Energy Management System
EMSA	European Maritime Safety Agency
ES-TRIN	European Standard laying down Technical Requirements for Inland Navigation vessels
EU ETS	European Union Emissions Trading System
GHG	Greenhouse Gas
GT	Gross Tonnage
HVAC	Heating, Ventilation, and Air Conditioning
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
IGF	International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels
IMO	International Maritime Organization
ISPS	International Ship and Port Facility Security Code
IWT	Inland Waterway Transport
LCA	Life Cycle Assessment
LNG	Liquefied Natural Gas
LOA	Length Overall
LSFO	Low Sulphur Fuel Oil
MCA	Multi-Criteria Assessment
MGO	Marine Gas Oil
MR	Medium Range
MRV	Monitoring, Reporting, and Verification
NIS2	Network and Information Security (Directive)
OCCS	Onboard Carbon Capture and Storage
OPEX	Operational Expenditure
OPS	Onshore Power Supply
OSV	Offshore Support Vessel
PESTLE	Political, Economic, Social, Technological, Legal, Environmental
PMS	Power Management System
PSV	Platform Supply Vessel
R&D	Research and Development
Ro-Pax	Roll-on/Roll-off Passenger

SEEMP	Ship Energy Efficiency Management Plan
SFOC	Specific Fuel Oil Consumption
SME	Small and Medium-sized Enterprise
SMR	Small Modular Reactor
SPS	Special Purpose Ships (Code)
TEN-T	Trans-European Transport Network
TEU	Twenty-Foot Equivalent Unit
TRL	Technology Readiness Level
WAPS	Wind-Assisted Propulsion Systems
WHR	Waste Heat Recovery
WtT	Well-to-Tank
WtW	Well-to-Wake
ZEWT	Zero-Emission Waterborne Transport

1. INTRODUCTION

This deliverable, D4.1 – ZEWT Barrier Analysis, provides a structured and validated mapping of the barriers that could hinder the deployment of Zero-Emission Waterborne Transport (ZEWT). Its purpose is to establish a systematic, evidence-based understanding of these barriers, and of how they are expected to evolve between the near-term (2030) and long-term (2050) horizons, across five representative vessel Use Cases. This understanding is a precondition for the credible, actionable scenarios and recommendations that later stages of the project are intended to deliver: without it, subsequent activities — including scenario development, the Multi-Criteria Assessment of alternative pathways, and the formulation of policy and industry recommendations — would risk being built on incomplete or untested assumptions about what is actually preventing the ZEWT transition from advancing.

To this end, the deliverable combines two complementary strands of evidence: a structured, literature-based identification of barriers, and a validation and enrichment of this evidence through direct engagement with stakeholders across the ZEWT ecosystem. This dual approach ensures that the resulting barrier landscape is both theoretically robust and grounded in operational reality.

This deliverable pursues three main objectives:

- **Systematic identification and categorisation of barriers.** Drawing on an extensive review of scientific and technical literature, barriers to ZEWT deployment are identified and organised according to a structured PESTLE framework (Political, Economic, Social, Technological, Legal and Environmental), applied consistently across five representative vessel Use Cases (general cargo vessels, tankers, passenger ships, inland waterway vessels and special operation vessels) and across two analytical horizons, 2030 and 2050.
- **Validation and enrichment through stakeholder consultation.** The literature-based barrier set is tested against, and enriched by, first-hand evidence gathered through semi-structured interviews conducted with stakeholders and experts across the ZEWT ecosystem within the project's stakeholder engagement activities (Work Package 3), ensuring that the analysis reflects operational reality alongside scientific evidence.
- **Provision of a shared evidence base for subsequent project activities.** The consolidated barrier landscape presented in this deliverable is intended to underpin the development of TRUSTEE's foresight scenarios, to inform the project's Multi-Criteria Assessment of alternative ZEWT pathways, and to provide a defensible foundation for the policy and industry recommendations to be developed in later stages of the project.

This deliverable builds directly on the Use Case definitions developed earlier in the project and on the stakeholder engagement activities carried out under Work Package 3, and it constitutes a foundational input to the subsequent, forward-looking stages of TRUSTEE's work — in particular scenario development and the Multi-Criteria Assessment of ZEWT deployment pathways. As such, it occupies a pivotal position in the overall project workflow: it translates the general ambition of a future-proof, efficient and sustainable ZEWT transition

into a concrete, evidence-based account of what currently stands in its way, and of how this may change between now and 2050.

The structure of this deliverable is organised as follows. Chapter 2 (Methodology) presents the analytical framework underpinning the barrier analysis, including the systems-oriented and socio-technical perspective adopted, the PESTLE taxonomy, and the two-stage process combining literature-based identification with stakeholder validation. Chapters 3 to 7 each address one of the five vessel Use Cases in turn, presenting its defining technical and operational profile followed by the detailed, literature-based PESTLE assessment of its barriers across the 2030 and 2050 horizons. Chapter 8 (Stakeholder Perspectives on ZEWB Barriers) presents the findings of the stakeholder consultation, examining the extent to which they confirm, refine or extend the barriers identified in Chapters 3 to 7. Chapter 9 (Conclusions) synthesises the key findings from both strands of the analysis and sets out their implications for future work within the TRUSTEE project.

2. METHODOLOGY

The analytical framework adopted for the identification and assessment of barriers to the deployment of Zero-Emission Waterborne Transport (ZEWT) is grounded in a systems-oriented approach combined with a socio-technical perspective. Within this framework, barriers are not analysed in isolation; rather, they are conceptualised as interdependent elements embedded within the broader maritime system. The transition to ZEWT involves multiple interacting components—including vessel design, port infrastructure, energy supply systems, and logistics chains—whose mutual interactions significantly influence the emergence and reinforcement of barriers. Consequently, an isolated analysis of these elements would not provide a comprehensive understanding of systemic constraints.

For instance, the absence of standardised bunkering infrastructure not only generates operational limitations but also amplifies financial risks, thereby slowing technological development and large-scale adoption. To address this complexity, the methodology emphasises the identification and mapping of interdependencies across sectors, transforming qualitative insights into structured, evidence-based inputs. This approach underpins the subsequent Multi-Criteria Assessment (MCA), enabling a consistent evaluation of use cases across environmental, economic, and technical dimensions.

A central component of the analysis is the systematic identification of barriers through an extensive review of scientific and technical literature. This process enables the definition of a comprehensive set of challenges affecting the ZEWT transition, with particular attention to their relevance to the use cases developed within the project.

Rather than only providing a general overview, the analysis also explicitly links each barrier to the operational, technological, and infrastructural features of the selected vessel typologies.

To ensure strategic relevance and consistency with the project's scenario logic, the barrier framework is applied across two distinct analytical horizons:

1. **The 2030 Horizon (Evolutionary Perspective):** Focuses on the near-term optimisation of existing assets within current regulatory and technological constraints. Given the long operational lifespan of vessels, this phase emphasizes retrofit solutions, incremental efficiency improvements, and the deployment of transitional fuels. Key considerations include minimising operational disruptions and ensuring compliance with short-term regulatory targets (e.g., FuelEU Maritime, EU ETS).
2. **The 2050 Horizon (Transformative Perspective):** Centred on the full realisation of zero-emission maritime systems. This long-term view assumes the maturation of enabling technologies and shifted regulatory frameworks. At this stage, barriers reflect systemic challenges, such as international policy coordination, global market alignment, and the establishment of a fully decarbonised transport network.

From a methodological perspective, the barrier analysis follows a multi-step and iterative process. It begins with an initial assessment carried out by the experts of the TRUSTEE consortium, based on the results of the in-depth literature review.

This preliminary phase provided a structured identification and categorisation of barriers across different domains, utilising the PESTLE framework (Political, Economic, Social, Technological, Legal, and Environmental) to systematically capture the macro-environmental factors impeding ZEWI deployment. This taxonomy ensures a holistic evaluation of the ecosystem, extending the analysis beyond immediate engineering constraints to include supply chain limitations, human capital deficits, and regulatory friction.

The initial expert-based analysis was subsequently **validated, refined, and expanded through an extensive stakeholder involvement process conducted within Work Package 3**. This phase represents a critical element of the methodology, as it ensures that the analysis is not only theoretically robust but also grounded in real-world experience and practical knowledge.

In particular, WP3 activities involved the **active participation of a wide range of stakeholders representing different stakeholder groups across the maritime sector**. These included shipowners, port authorities, technology providers, policymakers, classification societies, and training organisations. Their involvement was ensured through a combination of structured consultations, targeted interviews, and interactive workshops.

These engagement activities served multiple purposes:

- **Validation of identified barriers**, confirming their relevance and priority from an operational and industrial perspective;
- **Identification of additional challenges** not fully captured in the literature, particularly those emerging from practical implementation and market conditions;
- **Refinement of barrier classification**, improving clarity and consistency across different domains;
- **Collection of qualitative insights** regarding feasibility, risks, and enabling conditions for ZEWI deployment.

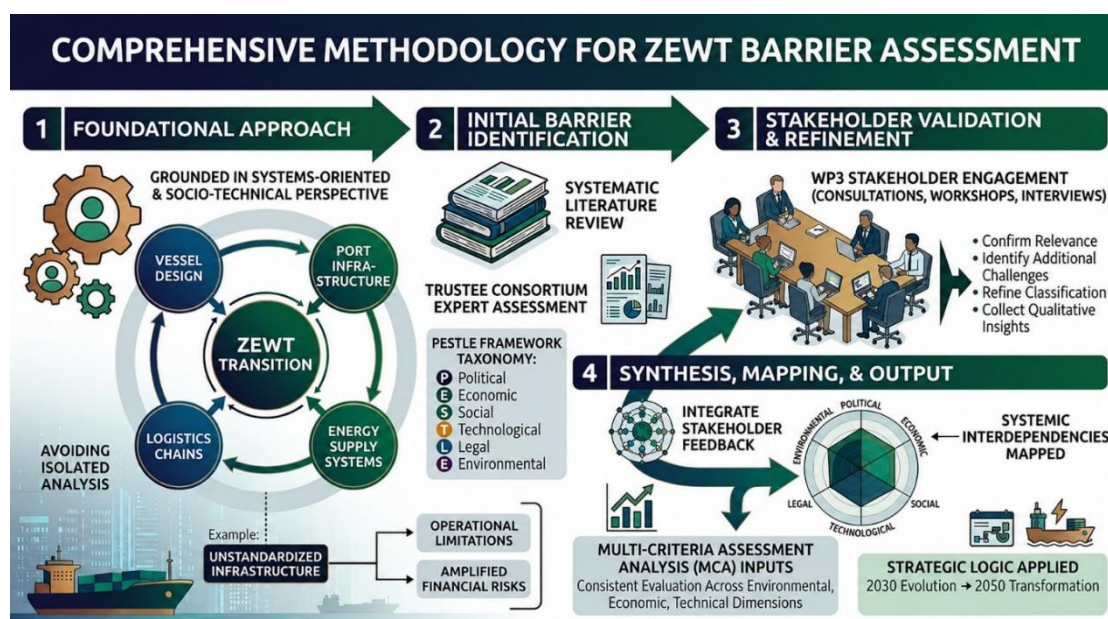


Figure 1 - Comprehensive methodology for ZEWI barrier assessment

The integration of stakeholder feedback significantly enhanced the robustness and credibility of the analysis, allowing the transformation of expert-based assumptions into **validated and shared knowledge across the ZEWT ecosystem**. Moreover, this participatory approach ensured that the final set of barriers reflects a balanced perspective, combining scientific evidence with industry-driven insights.

To ensure analytical consistency and comparability across various use cases, and to align with the macro-environmental taxonomy defined during the preliminary assessment phase, the identified barriers have been structured into **six principal pillars** corresponding to the PESTLE framework. Each pillar addresses a specific dimension of the transition toward Zero-Emission Waterborne Transport (ZEWT).

- **The Political Pillar**

This pillar examines impediments arising from governance and strategic planning at the macro level. A fundamental barrier is the misalignment between international and regional policies, coupled with a lack of cross-border coordination necessary for the establishment of "green shipping corridors". This fragmentation results in systemic delays in developing a standardised global supply chain for alternative fuels and the required port infrastructure. Methodologically, this fuels a "chicken-and-egg" dynamic, where insufficient infrastructure discourages vessel investment, while limited demand simultaneously stifles infrastructural expansion.

- **The Economic Pillar**

The economic pillar focuses on the financial viability and market feasibility of ZEWT technologies. It encompasses the high capital expenditures (CAPEX) required for advanced propulsion systems, specialised fuel storage, and enhanced safety measures, alongside significant uncertainties regarding operational costs (OPEX). The current price gap between conventional and zero-emission fuels remains a primary barrier, further exacerbated by structural market issues such as "split incentives" between shipowners and charterers. Furthermore, capital markets exhibit reluctance due to the risks of "stranded assets" and uncertain returns on investment for solutions with low TRL.

- **The Social Pillar**

This category addresses the human dimension and societal implications of the maritime transition. The adoption of ZEWT technologies necessitates a paradigm shift in skills and competencies, particularly concerning electrical systems, energy management, and the handling of toxic or highly flammable alternative fuels. There are severe shortages in the specialised maritime workforce and a lack of standardised training protocols, creating significant bottlenecks. Beyond education, this pillar considers public acceptance; potential resistance from port communities regarding the safety and environmental impact of novel infrastructure can critically influence project implementation.

- **The Technological Pillar**

The technological pillar evaluates the maturity, scalability, and integration challenges of emerging propulsion and energy systems. Significant attention is devoted to the intrinsic limitations of zero-emission fuels, specifically their low volumetric and gravimetric energy density. These constraints directly impact cargo payload capacity and operational range, increasing engineering complexity. Analysis also highlights

barriers such as immature fuel cell durability and the severe spatial constraints associated with retrofitting existing vessels compared to optimised newbuild designs.

- **The Legal Pillar**

This dimension analyses the evolving legislative framework, compliance burdens, and regulatory gaps. Ambiguities in compliance verification and the fragmented enforcement of key regulations, such as FuelEU Maritime and the EU ETS, generate operational uncertainty and heightened administrative costs. A critical constraint remains the absence of harmonised international safety codes and unified standards for the bunkering and onboard utilisation of alternative fuels, which creates an uneven playing field across different jurisdictions. In addition, mandatory regulation such as NIS2 Directive (EU 2022/2555) that uphold cybersecurity across the EU and the International Ship and Port Facility Security Code (ISPS Code) that enhances the security of ships and port facilities should be considered. Introducing technological changes will involve reassessments to comply with both of them. All the use case vessels and their associated port facilities require approved security plans.

- **The Environmental Pillar**

The environmental pillar extends beyond the vessel to assess the broader ecosystemic implications of ZEWT deployment. A key barrier is the current inadequacy of comprehensive Well-to-Wake (WtW) lifecycle accounting, which introduces the risk of shifting emissions upstream (Well-to-Tank) rather than achieving absolute zero-emission targets. Furthermore, the transition depends on massive increases in renewable energy production and grid capacity. This introduces systemic constraints, including land-use conflicts for renewable generation at ports and intensified competition for clean energy resources with other industrial sectors.

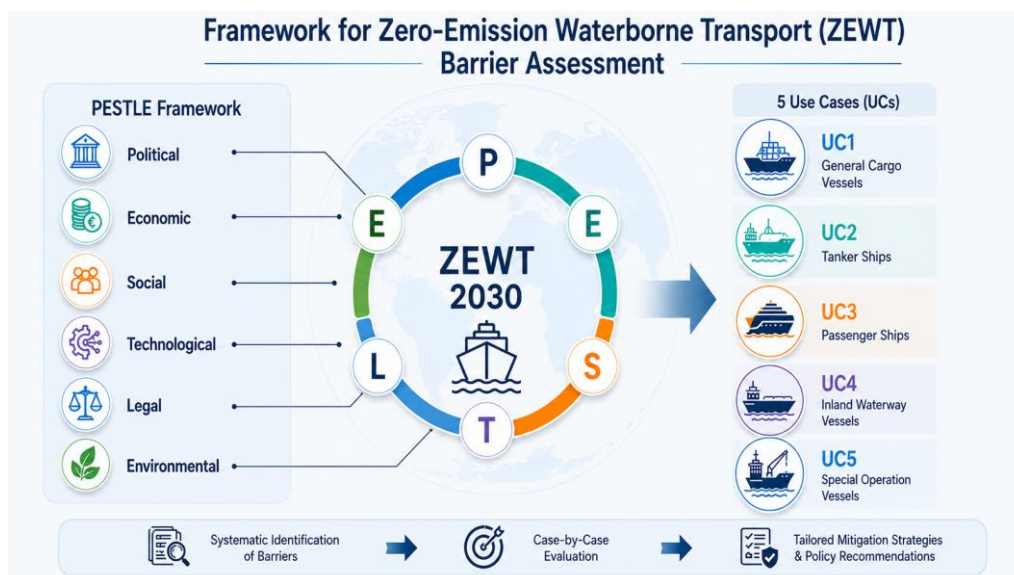


Figure 2 - Framework for Zero-Emission Waterborne Transport (ZEWT) Barrier Assessment

The barrier analysis in this deliverable is anchored to a set of reference Use Cases that serve as the foundational backbone for the assessment. The comprehensive identification, selection, and technical characterisation of these use cases were meticulously carried out within Work Package 2 and are extensively detailed in Deliverable D2.1 – Initial ZEWT Use Cases. Rather than evaluating the maritime sector as a monolithic entity, D2.1 established five distinct vessel typologies designed to capture the structural diversity, operational complexities, and specific technological challenges of the European fleet: General Cargo Vessels, Tanker Ships, Passenger Ships, Inland Waterway Vessels, and Special Operation Vessels.

Defining and anchoring the analysis to these specific use cases is of paramount importance for the objectives of this deliverable. The transition to Zero-Emission Waterborne Transport (ZEWT) is highly contextual; it is dictated by the unique energy profiles, mission envelopes, and infrastructural dependencies of each vessel category. Consequently, the barriers impeding this transition (whether technological, economic, regulatory, or infrastructural) manifest differently across the sector. For instance, a systemic bottleneck affecting a passenger ship characterised by massive continuous hotel loads will differ fundamentally from the spatial constraints of an inland waterway vessel, or the highly transient power demands of a special operations tug.

By grounding our assessment in these empirically derived, realistic scenarios across both the 2030 evolutionary horizon and the 2050 transformative horizon, we ensure that the evaluation of systemic barriers remains targeted and operationally relevant. Chapters 3 through 7 are structured accordingly, each dedicated to one of the five selected use cases and articulating, in sequence, its defining technical and operational characteristics and the corresponding barrier landscape across the 2030 and 2050 horizons.

Because certain horizontal barriers and overarching market dynamics affect multiple vessel segments simultaneously, and to ensure that each chapter remains fully self-contained and can be read independently by segment-specific stakeholders without the need for cross-referencing, these common observations are intentionally repeated within the analysis of each applicable use case.

3. USE CASE 1 – GENERAL CARGO VESSELS BARRIERS ANALYSIS

3.1. *Use Case 1: General Cargo Vessels Overview*

The reference vessel considered for this use case represents a statistically derived, anonymised configuration reflecting the dominant characteristics of the global dry cargo fleet. Specifically, it models a mid-size cargo ship operating within the medium-to-large segment, characterised by a deadweight tonnage (DWT) of 70,000 to 80,000 tonnes, an overall length of 210–230 metres, a beam of 30–36 metres, and a design draft of 12.5–14.5 metres. The vessel features a full-form displacement hull (block coefficient > 0.80) optimised for cargo capacity and efficiency rather than speed, typically operating at a service speed of 13–15 knots with a cargo arrangement of 5 to 7 holds.

The operational scenario involves recurrent regional and interregional trade routes with voyage legs of 1,000–3,000 nautical miles. The vessel's energy profile is heavily propulsion-dominated due to extended steady-state navigation phases, accounting for 85–90% of total energy consumption estimated at 200–260 MWh/day. This profile makes it highly conducive to efficiency-oriented interventions governed by IMO (CII, EEXI, SEEMP) and EU (FuelEU Maritime) regulatory frameworks. While auxiliary-dominated port stays with power demands of 0.5–2 MW present distinct opportunities for local emission management, particularly for reducing the impact on coastal populated areas.

The decarbonisation strategy for this vessel class reveals a fundamental evolution between the 2030 and 2050 timeframes, shifting from a pragmatic transition phase to a natively zero-emission paradigm. In the 2030 scenario, the technological approach is primarily retrofit-oriented. The primary propulsion architecture relies on conventional low-speed, two-stroke internal combustion engines (10–13 MW), with a baseline specific fuel oil consumption (SFOC) of 165–175 g/kWh, utilising drop-in alternative fuels, such as biofuels or LNG, to achieve immediate emissions reductions without necessitating major structural overhauls. During this phase, energy efficiency is enhanced through modular integrations: hydrodynamic optimisations, advanced low-friction coatings, air lubrication systems and Wind-Assisted Propulsion Systems (WAPS) are adopted as auxiliary contributors. Furthermore, hybridisation is limited to shaft-generators and small-scale battery storage aimed strictly at peak shaving and auxiliary load optimisation rather than sustained propulsion.

Conversely, the 2050 scenario is characterised by comprehensive, system-level integration and native carbon-neutral design. Unconstrained by legacy infrastructure, vessels are architected from the design phase around zero-emission energy carriers—primarily ammonia, with methanol considered alongside integrated carbon management solutions. Hull and machinery layouts are fundamentally redesigned to accommodate the increased volumetric demands of alternative fuel storage, stringent safety zoning, and advanced automation. Technologies that were considered modular add-ons in 2030, such as WAPS and air lubrication, become intrinsic baseline design features dynamically synergised with the vessel's aerodynamics and hydrodynamics. Ultimately, the operational focus shifts from rudimentary fuel consumption reduction to integrated, real-time carbon and energy management, managed by digital-twin systems and supported by a mature, standardised global supply network for carbon-neutral fuels.

The following table summarizes the structural, technological, and operational transition of the General Cargo Vessel use case across the two target timeframes.

Table 1 - Use Case 1: General Cargo Vessels

Feature / System	2030 Scenario (Transition & Retrofit)	2050 Scenario (Native Zero-Emission)
Design Philosophy	Retrofit-oriented; constrained by legacy structural and fuel system layouts.	Native carbon-neutral design; <i>ab initio</i> layout optimisation for new fuels and safety zoning.
Primary Fuel Strategy	Drop-in biofuels, LNG, and dual-fuel applications.	Carbon-neutral energy carriers (primarily ammonia, neutrally sourced methanol).
Efficiency Integration	Modular enhancements (coatings, propeller upgrades) applied to existing hull forms.	Embedded integration; hull forms natively designed in synergy with aerodynamic/hydrodynamic devices.
Wind-Assisted Propulsion (WAPS)	Treated as an auxiliary retrofit or modular addition, limited by existing deck space.	Intrinsic design feature; propulsion is dimensioned accounting for continuous auxiliary wind thrust.
Electrical Architecture	Shaft-generators and limited batteries used for peak shaving and auxiliary loads.	Highly integrated power systems with advanced automation and digital twin-based energy routing.
Operational Paradigm	Focused on fuel consumption optimisation to comply with transitional regulations (CII, EEXI).	Focused on integrated, real-time carbon and energy management linked with smart port infrastructure.

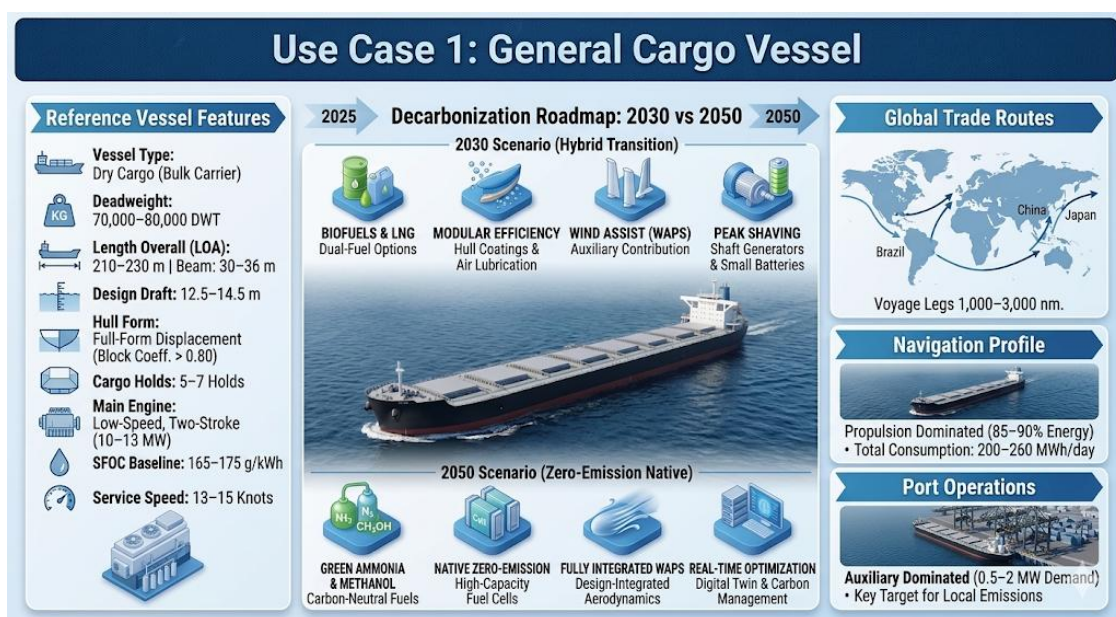


Figure 3 - Use Case 1: General Cargo Vessels

3.2. Use Case 1 Barriers for 2030 Horizon

This section examines the barrier analysis for **Use Case 1 (UC1): General Cargo Vessels** within the 2030 horizon. General cargo vessels constitute a highly versatile and fragmented segment of the maritime industry, presenting distinct decarbonisation challenges due to their operational flexibility, complex trading patterns, and varied port-call requirements.

Applying the PESTLE framework, this analysis evaluates the political, economic, social, technological, legal, and environmental factors hindering the integration of Zero-Emission Waterborne Transport (ZEWT) technologies. Special focus is placed on the multi-dimensional market and regulatory challenges unique to this fleet.

As a baseline for the following qualitative assessment, the following table provides an overview of the use case defining characteristics for 2030.

Table 2 - Use Case 1: General Cargo Vessels 2030 Horizon

Category	Use Case 1 – General Cargo Vessel (2030 Horizon)
Operational Profile	Regional and interregional cargo transport
Typical Voyage Range	1,000–3,000 nautical miles
Service Speed	13–15 knots
Vessel Size	70,000–80,000 DWT
Energy Demand Profile	Propulsion-dominated operations
Total Energy Consumption	Approximately 200–260 MWh/day
Design Philosophy	Retrofit-oriented approach constrained by legacy layouts and existing machinery spaces
Primary Fuel Strategy	Drop-in biofuels, LNG, and dual-fuel configurations
Propulsion System	Conventional low-speed two-stroke ICE (10–13 MW)
Electrical Architecture	Shaft generators and limited battery systems for peak shaving and auxiliary optimisation
Efficiency Measures	Advanced hull coatings, propeller optimisation, air lubrication systems
Wind-Assisted Propulsion	Modular WAPS integration constrained by existing deck configuration
Operational Objective	Fuel consumption reduction and compliance with transitional regulations

Political barriers

A key political barrier for general cargo vessels by 2030 is the **misalignment between global and regional decarbonisation frameworks**. The IMO has adopted initial GHG reduction

targets and technical and operational measures (EEXI, CII), while the EU is implementing more stringent instruments such as EU ETS and FuelEU Maritime for voyages involving EU ports. This creates a complex compliance environment for ships that alternate between intra-EU, international and third-country routes, as is often the case for general cargo operators. [1]

The lack of fully coordinated **green shipping corridor policies** across jurisdictions further complicates planning for investments in alternative fuels and supporting infrastructure. ZEW T documents underline that, although green corridors are considered a key lever for early ZEW T deployment, their detailed governance and cross-border coordination are still emerging. For general cargo vessels, which frequently serve opportunistic or tramp-like trades, the political focus on a limited number of high-volume corridors may translate into unequal access to early ZEW T opportunities. [2] [3]

Moreover, there is a **risk of policy uncertainty** regarding long-term trajectories beyond 2030, particularly concerning the stringency and evolution of carbon pricing schemes and fuel GHG-intensity requirements. This uncertainty can discourage shipowners from committing to ambitious retrofit packages or fuel conversions before 2030, as they cannot be sure whether current measures will be sufficient to meet future regulatory benchmarks. [4] [5]

Economic barriers

A central economic barrier is the **high capital expenditure (CAPEX) required for energy-efficiency upgrades and fuel-flexible retrofits**. Studies show that measures such as installing wind-assisted propulsion, advanced waste-heat recovery or dual-fuel engines can significantly reduce emissions, but they involve cost levels that many owners perceive as risky under current chartering and freight market conditions. The combination of low freight rates and uncertain payback periods delays large-scale uptake of innovative solutions. [6]

Another economic barrier is the **split-incentive problem** between shipowners and charterers. In tramp and bulk trades, fuel costs are often paid fully or partly by charterers, while retrofit investments are made by shipowners. This weakens the direct economic signal for owners to invest in technologies that primarily reduce fuel consumption, unless charter contracts explicitly reward improved energy performance. As highlighted in systems-oriented analyses of maritime decarbonisation, such contractual misalignments reduce the effectiveness of price-based and regulatory incentives. [5]

Fuel costs represent the single largest expense in the maritime sector, potentially accounting for over 50% of the daily operating costs of a fast or merchant vessel. Therefore, when analysing the barriers to the transition toward Zero-Emission Waterborne Transport (ZEW T) (especially looking ahead to the 2030 and 2050 strategic horizons) the primary economic obstacle lies in the cost gap between conventional petroleum-derived fuels and green alternatives. Without strong policy support or the implementation of carbon pricing mechanisms, which studies estimate must range between \$300 and \$800 per ton of CO₂ equivalent, renewable options currently struggle to achieve economic competitiveness on a global scale.

Specifically examining operating expenses (OPEX), which in the shipping sector are largely dominated by daily fuel procurement costs, liquefied natural gas (LNG) and biofuels exhibit

sharply contrasting profiles. Currently, LNG offers the most advantageous performance in terms of cost-effectiveness, driven by a highly competitive baseline price. Depending on regional market dynamics, the price of fossil-based LNG can range from 16% to 66% of the price of Marine Gas Oil (MGO). Long-term average price projections (2025–2050) also confirm this advantage, estimating LNG at approximately 425 USD/t, a figure lower than the 455 USD/t forecast for Low Sulphur Fuel Oil (LSFO). However, it must be noted that operators face highly variable bunkering logistics, which can incur additional supply costs ranging from 50 to 630 USD per ton.

Conversely, biofuels face much more rigid economic barriers due to exceptionally high production and procurement costs. The OPEX for this category is fundamentally driven by the price of raw materials, such as biomass or waste oils, which can account for 25% to 90% of the total production cost. Unlike LNG, biofuel market prices far exceed those of traditional fuels: estimates indicate an average price of 1,750 USD/t for Hydrotreated Vegetable Oil (HVO) and 1,416 USD/t for Bio-LNG. While it is true that diesel-like biofuels allow for a reduction in initial capital expenditures (CAPEX), as they can be used as "drop-in" solutions without requiring complex engine retrofits, the exorbitant cost of the fuel itself ultimately translates into a massive net increase in the overall operating costs for every single voyage. [7] [8] [9]

Social barriers

From a social perspective, the transition towards ZEWT for general cargo vessels is constrained by **skills shortages and training gaps**. The ZEWT partnership documents emphasise that crew members and technical staff will need new competences to safely handle alternative fuels, advanced power systems and digital optimisation tools. However, training curricula and certification schemes are still adjusting, and there is limited standardised guidance on the practical handling of novel fuels such as methanol and ammonia on board cargo vessels. [1] [10] [11]

In addition, the broader maritime workforce is undergoing demographic changes, with concerns about recruitment and retention in seafaring professions. The need for higher digital and technical skills, without corresponding improvements in working conditions and career attractiveness, may exacerbate labour shortages, thereby limiting the sector's capacity to implement and operate new ZEWT technologies effectively by 2030. [12]

Technological barriers

The **low volumetric energy density and storage requirements of alternative fuels** represent a critical obstacle. Compared with conventional fuel oil, LNG and biofuels require larger tank volumes and more complex containment and safety systems, which can reduce cargo capacity or require major structural modifications. For general cargo carriers where cargo flexibility and hold space are central to competitiveness, such trade-offs are particularly significant. [13]

Moreover, the integration of digital optimisation tools and advanced energy-management systems within the maritime sector remains at a relatively nascent stage, particularly in the context of general cargo fleets. Although technologies such as route and speed optimisation,

weather routing, predictive analytics and digital twins are widely acknowledged in the scientific and industrial literature as strategic enablers for enhancing energy efficiency and facilitating the transition towards Zero-Emission Waterborne Transport (ZEWI), their operational deployment is still far from being fully consolidated. Indeed, the practical implementation of these solutions continues to represent a major research and innovation challenge, as evidenced by the growing number of ongoing European and international research projects dedicated to maritime digitalisation and smart energy management.

Current barriers are associated not only with the limited quality, availability and interoperability of operational data, but also with the prevalence of heterogeneous legacy systems, fragmented onboard digital infrastructures and the shortage of specialised technical expertise required for the effective integration and maintenance of such technologies. Furthermore, uncertainties related to standardisation, cybersecurity, regulatory compliance (NIS2 Directive (EU 2022/2555)) and cost-effectiveness continue to hinder large-scale adoption across the sector. [14]

Legal barriers

Legally, general cargo vessels face **fragmented and evolving compliance requirements**. The EU's introduction of FuelEU Maritime and the extension of the ETS to shipping add layers of regional obligations on top of IMO regulations, including monitoring, reporting and verification regimes that differ in scope and methodology. For a bulk carrier of 5 000 GT and above operating on LNG and biofuels and calling at EU ports, the recent extension of the EU Emissions Trading System (EU ETS) to maritime transport and the entry into force of the FuelEU Maritime Regulation create additional climate-related obligations on top of IMO rules. The EU ETS now covers CO₂ emissions from voyages between and to/from EU ports, while FuelEU Maritime sets progressively stricter well-to-wake greenhouse-gas intensity limits for the energy used on board and applies penalties and possible operational measures in case of non-compliance. Under this framework, FuelEU Maritime explicitly accounts for emissions of carbon dioxide, methane and nitrous oxide, and recent guidance highlights that methane emissions from the use of LNG, including methane slip from engines, are a point of concern and are reflected in predefined slip factors by engine type.

This means that the effective climate advantage of LNG-fuelled bulk carriers increasingly depends on the methane performance of their engines and on the possibility to progressively shift towards lower-carbon variants such as bio-LNG to comply with tightening GHG-intensity requirements. At the same time, only biofuels and other renewable fuels that meet EU sustainability and greenhouse-gas saving criteria can benefit from favourable default emission factors under FuelEU Maritime, while non-eligible biofuels are treated as fossil fuels, which makes robust sustainability verification and documentation a practical legal requirement for bulk carriers planning to use advanced biofuels alongside LNG by 2030. [15]

Furthermore, the **enforcement of carbon intensity measures and regional climate policies** remains uneven across jurisdictions. While regional initiatives aimed at the international maritime industry encourage a shift toward greener practices, they simultaneously risk inducing carbon leakage. This phenomenon occurs when shipping activities are diverted to unregulated regions, effectively relocating greenhouse gas emissions beyond the

jurisdictional boundaries of these environmental policies. Studies on maritime decarbonisation highlight that inconsistent enforcement of rules can create an uneven playing field, where compliant operators may face higher costs without equivalent competitive benefits. For general cargo vessels competing in global markets, this legal unevenness reduces the incentive to be early movers in ZEWT adoption. [5]

Environmental barriers

From an environmental perspective, a major barrier in 2030 is the **risk that measures focus on operational emissions without fully accounting for Well-to-Wake (WtW) impacts**. The IMO has started to develop a framework for life-cycle GHG intensity of marine fuels, but its implementation is still evolving. Several studies warn that some transitional fuels may reduce tank-to-wake emissions while offering limited WtW benefits or even shifting emissions upstream, particularly when renewable electricity or sustainable feedstocks are scarce. [16] [17]

A further environmental barrier concerns the **large-scale use of biofuels** as a decarbonisation option for shipping. International assessments stress that the climate benefits of marine biofuels depend critically on the sustainability of their feedstocks and on avoiding direct and indirect land-use change, which can occur when agricultural land or high-carbon ecosystems are converted to grow energy crops. Studies on biofuels for marine and other transport sectors warn that increased demand risks competing with food production and other uses of arable land, and that land-use change can significantly erode or even reverse the Well-to-Wake GHG savings if not properly controlled. Recent reports also highlight that sustainable biofuel feedstocks are limited and already in demand from aviation and road transport, so scaling biofuels for shipping without robust safeguards on land use and biodiversity may shift environmental pressures upstream rather than delivering net climate benefits by 2030. [18]

3.3. Use Case 1 Barriers for 2050 Horizon

This section examines the barriers affecting the deployment of Zero-Emission Waterborne Transport (ZEWT) solutions for **Use Case 1 (UC1): General Cargo Vessels** within the 2050 horizon. In line with the methodological architecture introduced in Section 2, the assessment applies the PESTLE framework to identify the political, economic, social, technological, legal, and environmental barriers that may hinder the full transition of the general cargo segment toward zero-emission operation by mid-century. [1] [19] [20]

As outlined in the Use Case 1 Overview presented above, the 2050 scenario for general cargo vessels is no longer based on incremental retrofit logic, but on a **transformative paradigm** in which vessels are conceived *ab initio* around carbon-neutral energy carriers, digitalized energy-management systems, and integrated design solutions combining propulsion efficiency, safety zoning, and compatibility with mature alternative-fuel supply chains. [21] Accordingly, the barriers discussed below are not limited to the feasibility of isolated technologies, but concern the broader systemic conditions required to ensure that

general cargo shipping can operate as part of a fully decarbonised maritime ecosystem by 2050.

As a baseline for the following qualitative assessment, the following table provides an overview of the use case defining characteristics for 2050.

Table 3 - Use Case 1: General Cargo Vessels 2050 Horizon

Category	Use Case 1 – General Cargo Vessel (2050 Horizon)
Operational Profile	Regional and interregional cargo transport, including medium-to-large dry bulk and general cargo trades
Typical Voyage Range	1,000–3,000 nautical miles
Service Speed	13--15 knots
Vessel Size	70,000--80,000 DWT
Energy Demand Profile	Predominantly propulsion-dominated, with auxiliary port loads remaining relevant for local emissions management
Design Philosophy	Native zero-emission design optimised around alternative-fuel storage, safety zoning, and integrated energy management
Primary Fuel Strategy	Carbon-neutral energy carriers, primarily ammonia, with methanol as an additional relevant pathway
Efficiency Measures	Integrated hull optimisation, air lubrication, wind-assisted propulsion, digital twin-based control, and real-time energy routing
Operational Objective	Full decarbonisation aligned with ZEWT and net-zero maritime pathways

Political barriers

A first political barrier concerns the **alignment between global and regional decarbonisation regimes** in a mature net-zero context. By 2050, the general cargo segment will likely operate under a denser and more ambitious regulatory environment than in the 2030 horizon, yet the coexistence of IMO-wide measures and regional instruments may continue to create asymmetries in compliance obligations, fuel eligibility criteria, and carbon-accounting methodologies. For vessels trading across heterogeneous regulatory spaces, persistent discrepancies between international and regional rules could generate uncertainty over long-term investment decisions and route-level competitiveness, thereby undermining the predictability needed for large-scale ZEWT deployment. [22] [23]

A second political barrier relates to the **governance of global zero-emission fuel supply chains**. Scenario work and strategic research agendas consistently underline that maritime decarbonisation depends on coordinated progress across vessels, ports, fuel production systems, and logistics chains rather than on standalone technological advances. In the 2050 horizon, this systemic logic becomes even more critical, because general cargo vessels

designed around ammonia- or methanol-based propulsion depend on internationally coordinated fuel certification, sustainability criteria, and cross-border infrastructure planning. Without stable governance frameworks for green fuels and mature coordination mechanisms for green shipping corridors, there remains a risk of fragmentation, uneven infrastructure rollout, and strategic dependence on a limited number of fuel-exporting hubs.

A third political barrier concerns the **integration of shipping decarbonisation into wider industrial and energy policies**. The 2050 ZEWI transition for general cargo cannot be considered in isolation from renewable power expansion, hydrogen production, industrial carbon management, and port development strategies. If maritime policy evolves faster than the energy or industrial sectors that must supply climate-neutral fuels, zero-emission vessel deployment may outpace the availability of scalable and affordable fuel pathways, creating structural bottlenecks even under otherwise supportive maritime regulation.

Economic barriers

By 2050, the central economic barrier for general cargo vessels is expected to shift from the cost of retrofit packages toward the **cost, availability, and resilience of zero-emission fuel and infrastructure systems**. Forecast and pathway studies indicate that the uptake of zero-emission fuels in shipping depends on synchronised progress in production capacity, distribution networks, bunkering infrastructure, and onboard conversion technologies, all of which imply high capital intensity and uncertain returns. Native zero-emission vessels require substantial capital not only for propulsion technologies, but also for redesigned tank arrangements, additional safety systems, digital control architectures, and port-interface compatibility. Even in a mature market, such investments may remain challenging for operators exposed to volatile freight markets and fragmented contractual structures.

A second economic barrier is the **fuel-price premium and supply-chain exposure associated with green ammonia and green methanol**. Comparative evaluations of alternative marine fuels show that the lifecycle performance and competitiveness of these fuels depend heavily on renewable electricity supply, conversion pathways, transport chains, and regional production conditions. In particular, while e-ammonia can provide strong decarbonisation potential, its delivered cost remains closely linked to the availability of low-carbon electricity and hydrogen production capacity. For the general cargo segment, which often operates under narrow margins and heterogeneous chartering conditions, profitability by 2050 will therefore depend not only on vessel efficiency but also on secure access to competitively priced fuels, long-term offtake structures, and geographically reliable bunkering networks. [24]

A third economic barrier concerns **payload penalties and space-allocation trade-offs**. General cargo vessels designed for ammonia or methanol must accommodate larger fuel volumes and stricter safety zoning than conventional ships, which can influence the balance between fuel storage, cargo space, operational flexibility, and commercial viability. For a segment whose business model is highly sensitive to transported volume and route economics, these design trade-offs remain a structural economic constraint rather than a merely transitional one. [7] [8] [9]

Finally, the **risk of technology lock-in and stranded assets** remains significant. The long operational lifetime of merchant vessels means that fuel choices made in the 2040s may still shape fleet competitiveness well beyond 2050. If shipowners commit too early to one pathway that later proves sub-optimal under revised regulation, sustainability criteria, or fuel-cost assumptions, they may face additional conversion costs or impaired asset value.

Social barriers

In the 2050 horizon, social barriers for general cargo shipping are less likely to revolve around the basic acceptance of decarbonisation itself and more around the **availability of a sufficiently skilled workforce** able to operate complex zero-emission ships safely and efficiently. Strategic research agendas for ZEWI repeatedly stress that the transition requires new competences in fuel handling, electrical systems, digital operations, safety management, and integrated energy optimisation. [25] This issue becomes even more acute in a mature 2050 scenario, in which crews and shore-side personnel must combine competencies in fuel safety, digital energy management, automation, emergency response, and lifecycle compliance monitoring. [26]

A second social barrier is linked to the **specific risks associated with ammonia handling**, including its acute toxicity for crew, port workers, and nearby communities in the event of leaks or accidental release. Current ammonia-shipping safety projects explicitly identify the need for dedicated hazard identification procedures, revised storage concepts, and adapted safety rules precisely because ammonia introduces risks that are qualitatively different from those associated with conventional marine fuels. [27] [28] As a result, even where ammonia is accepted as a strategic zero-carbon marine fuel, its deployment at scale may face resistance unless training, emergency preparedness, detection systems, evacuation procedures, and public communication are robust and standardised across ports and fleets.

A third social barrier concerns the **competition for technical and digital talent** across multiple decarbonising sectors. Shipping will have to compete with renewable energy, hydrogen, advanced manufacturing, and digital industries for workers possessing similar competences. If maritime careers do not offer adequate working conditions, training pathways, and professional recognition, the general cargo segment may face persistent shortages of personnel capable of safely managing ZEWI systems at scale. [29]

Finally, the demographic and recruitment challenges already identified for 2030 — an ageing workforce and competition for talent with other decarbonising sectors — do not disappear by 2050 and may in fact be compounded by the cumulative effect of 20 additional years of workforce attrition; explicit continuity with the 2030-era demographic barrier should therefore be acknowledged rather than superseded by the narrower framing of talent competition alone.

Technological barriers

By 2050, many ZEWI technologies relevant to general cargo vessels are expected to have progressed substantially; however, the main technological barriers will likely persist at the level of **system integration, reliability, and operational robustness**. General cargo decarbonisation depends not on one isolated breakthrough, but on the coordinated

integration of alternative fuels, redesigned hull arrangements, digital-twin systems, wind-assisted propulsion, and advanced automation. While the maturity of individual components may improve, integrating them into reliable whole-ship architectures across diverse trade patterns remains a non-trivial challenge.

A further barrier concerns the extent to which **Wind-Assisted Propulsion Systems (WAPS)**, constrained in 2030 by existing deck configurations and cargo-handling equipment, can be fully integrated into native 2050 designs. While ab initio design in principle removes the retrofit-era spatial constraints, WAPS still competes for deck space and structural allocation with alternative-fuel storage, cargo-handling systems and safety zoning; whether this trade-off is resolved by design or continues to limit WAPS uptake at scale remains an open question that the 2050 assessment should address explicitly, rather than assuming the 2030-era constraint has been superseded.

A particularly relevant technological barrier concerns the **use of ammonia as a marine fuel**. Comparative fuel assessments show that ammonia remains attractive from a carbon perspective, but its practical deployment is associated with challenges linked to engine efficiency, pilot-fuel requirements, possible N₂O emissions, and the lifecycle implications of different production pathways. In parallel, ammonia-storage and ship-integration projects underline the importance of safe containment, ventilation, leak detection, hazardous-area management, and classification-rule adaptation. For general cargo vessels, where cargo capacity and machinery integration must be carefully balanced, these requirements can complicate system architecture and increase both technical and operational risk. [30] [31]

Another technological barrier relates to **fuel-system interoperability and digital resilience**. By 2050, general cargo vessels are likely to rely on sophisticated digital energy-management systems and real-time decision-support platforms for route optimisation, energy routing, maintenance planning, and compliance verification. Such digital dependence improves efficiency but also creates vulnerabilities associated with cyber-risk, software failure, data-quality issues, and poor interoperability between onboard and port-side systems. If not properly governed, digitalisation may therefore become a barrier in itself rather than a pure enabler of ZEWT deployment.

Legal barriers

At the legal level, a first barrier concerns the harmonisation of international safety regulations, technical standards, and operational procedures governing alternative marine fuels, particularly ammonia. Current regulatory frameworks, including the IGF Code, are still evolving to address the specific hazards associated with toxic and low-flashpoint fuels. The IMO decarbonisation agenda has recognised the need for the progressive development of internationally harmonised safety regulations, while industry-led research and classification societies continue to identify unresolved issues concerning fuel storage, bunkering operations, onboard risk management, crew protection, emergency response, and classification requirements. Looking towards 2050, these challenges are expected to evolve rather than disappear, requiring globally consistent and enforceable regulatory frameworks capable of ensuring the safe handling and operation of toxic alternative fuels throughout the maritime value chain. [32] [33]

A second legal barrier concerns the definition, certification, and verification of genuine zero-emission performance. The IMO Life Cycle Assessment (LCA) Guidelines establish that the climate performance of marine fuels should be assessed on a Well-to-Wake basis, accounting for emissions associated with feedstock production, energy supply, fuel conversion, transportation, bunkering, onboard use, and carbon release. As lifecycle-based regulation becomes increasingly central to international maritime decarbonisation, legal uncertainty may emerge regarding system boundaries, lifecycle GHG intensity thresholds, treatment of upstream emissions, carbon accounting methodologies, and certification schemes for renewable and low-carbon fuels such as ammonia and methanol. In the absence of internationally harmonised verification procedures, ship operators may face uncertainty concerning regulatory compliance, contractual obligations, and environmental claims. [16]

Environmental barriers

From an environmental perspective, a major barrier for general cargo vessels in 2050 is ensuring that the transition to alternative fuels delivers **genuine lifecycle greenhouse gas (GHG) emission reductions**, rather than simply shifting emissions from onboard operations to upstream fuel production. The IMO Life Cycle Assessment (LCA) Guidelines and numerous comparative fuel studies emphasise that apparent Tank-to-Wake emission reductions may be offset by high upstream emissions if fuel production relies on carbon-intensive electricity, fossil-derived hydrogen, or unsustainable feedstocks. This issue is particularly relevant for ammonia and methanol, whose overall climate performance depends largely on the carbon intensity of hydrogen production, electricity generation, carbon sourcing, transportation, and fuel supply chains.

A second environmental barrier concerns the broader ecological and human health implications associated with ammonia deployment. Although ammonia has the potential to support near-zero or zero-carbon propulsion pathways when produced from renewable sources, its acute toxicity and corrosive properties require dedicated risk assessment, monitoring, and mitigation measures throughout storage, bunkering, transportation, and onboard operations. Consequently, the environmental assessment of ammonia-fuelled general cargo vessels should not be limited to climate-change indicators alone but should also consider accidental release scenarios, atmospheric emissions, impacts on water quality, ecological toxicity, and the effectiveness of emergency response systems in ports and coastal areas.

A third environmental barrier relates to the availability of clean energy resources and the upstream trade-offs associated with large-scale production of synthetic fuels. Long-term decarbonisation scenarios consistently indicate that the widespread deployment of e-ammonia, e-methanol, and other electrofuels will require substantial expansion of renewable electricity generation, low-carbon hydrogen production, carbon capture or sustainable carbon sources for methanol synthesis, and supporting industrial infrastructure. If these resources remain limited, unevenly distributed, or subject to competition from other hard-to-abate sectors, the scalability and environmental benefits of alternative marine fuels may be constrained.

4. USE CASE 2 – TANKER SHIPS BARRIERS ANALYSIS

4.1. Use Case 2: Tanker Ships Overview

The reference vessel considered within this use case represents a statistically derived, anonymised configuration of the medium-range tanker fleet. This typology reflects the most recurrent characteristics of product and chemical tankers, which together constitute the largest share of tanker vessels operating in European and global maritime transport. Structurally, the vessel is defined within the Medium Range (MR) class, designed to operate at a service speed of 13–15 knots, characterised by a deadweight tonnage (DWT) of 40,000 to 50,000 tonnes, a length overall (LOA) of 180–200 metres, a beam of 30–32 metres, and a design draft between 10 and 12 metres. The hull form features a high block coefficient optimised for cargo volume, while the internal arrangement consists of multiple segregated, double-hull tanks designed for the safe transport of refined petroleum products, chemicals, and other bulk liquids.

A defining characteristic of the tanker use case is its highly complex, dual-energy profile. Unlike dry cargo vessels, tankers present substantial auxiliary energy demands driven by cargo handling and conditioning. Operations such as cargo pumping, thermal heating to maintain product viscosity, and the generation of inert gas for safe tank atmospheres require significant power. Consequently, while propulsion remains the dominant energy consumer during the vessel's 800–2,500 nautical mile voyage legs (accounting for 70–80% of total energy with a total daily energy consumption that ranges from 170 to 250 MWh/day), port operations are frequent (every 5–10 days) and exceptionally energy-intensive. During 18- to 60-hour port stays, cargo pumps and heating systems can drive total power demand to 2–6 MW, resulting in an energy consumption of 40 to 150 MWh per call.

The decarbonisation trajectory for MR tankers reveals a critical evolution from a retrofit-oriented approach in the 2030 timeframe to a natively integrated, zero-emission paradigm by 2050.

In the **2030 scenario**, the technological strategy prioritises pragmatic, safety-driven solutions compatible with existing vessel layouts. Primary propulsion relies on conventional low-speed, two-stroke diesel engines (8–10 MW) utilising drop-in alternative fuels, such as biofuels or LNG, to mitigate emissions in the short-to-medium term. Energy efficiency is improved through modular enhancements—such as advanced low-friction coatings, air lubrication systems, and propeller upgrades. Crucially, decarbonisation efforts heavily target cargo-related systems. Waste Heat Recovery (WHR) plays a pivotal role, capturing thermal energy from the propulsion plant to supply cargo heating, thereby reducing auxiliary fuel consumption. Hybridisation (shaft generators and batteries) is deployed strictly for peak shaving during intensive cargo operations. Wind-Assisted Propulsion Systems (WAPS) are considered but remain highly constrained by the presence of deck-mounted piping systems, hazardous safety zones, and cargo handling equipment.

Conversely, the **2050 scenario** represents a fundamental architectural shift. Tanker vessels are natively designed around carbon-neutral energy carriers, primarily ammonia, with neutrally sourced methanol serving as a viable alternative. This transition profoundly impacts vessel design: tank arrangements are reconfigured to accommodate the larger volumetric requirements of alternative fuels, balancing cargo capacity with rigorous

hazardous area management and advanced containment safety regulations. Furthermore, the 2030 dichotomy between propulsion and auxiliary systems is eliminated. By 2050, vessels feature a unified energy architecture where alternative fuels supply both propulsion and cargo-handling demands through highly optimised distribution networks. Efficiency technologies (such as air lubrication and hull optimisation) transition from modular retrofits to embedded baseline design features. Finally, advanced digital twins and energy management platforms become intrinsic, enabling the real-time optimisation of energy flows across both navigation and complex port operations, supported by a mature, standardised global bunkering infrastructure.

The following table synthesizes the primary structural, technological, and operational differences driving the decarbonisation of the Tanker Vessel use case across the two target timeframes.

Table 4 - Use Case 2: Tanker Ships

Feature / System	2030 Scenario (Transition & Retrofit)	2050 Scenario (Native Zero-Emission)
Design Philosophy	Retrofit-oriented; constrained by existing hull designs, deck piping, and safety layouts.	Native carbon-neutral design; <i>ab initio</i> layout optimisation balancing fuel volume, cargo capacity, and strict safety zoning.
Primary Fuel Strategy	Conventional marine fuels supplemented by drop-in biofuels and LNG.	Carbon-neutral energy carriers (primarily ammonia and integrated methanol solutions).
Energy Architecture	Segregated systems: propulsion relies on the main engine, while heavy cargo loads rely on auxiliary generators.	Unified architecture: a highly integrated system where alternative fuels optimally supply both propulsion and cargo demands.
Cargo Energy Optimisation	Waste Heat Recovery (WHR) used to offset auxiliary fuel for cargo heating; battery peak-shaving for pumps.	Full integration of zero-emission auxiliary power; digitally optimised thermal and electrical routing for cargo handling.
Digitalisation & Operations	Focus on regulatory compliance (CII, EEXI) and managing peak loads during 18-60 hour port stays.	Digital twin-based platforms for real-time optimisation of propulsion, complex cargo operations, and predictive safety monitoring.

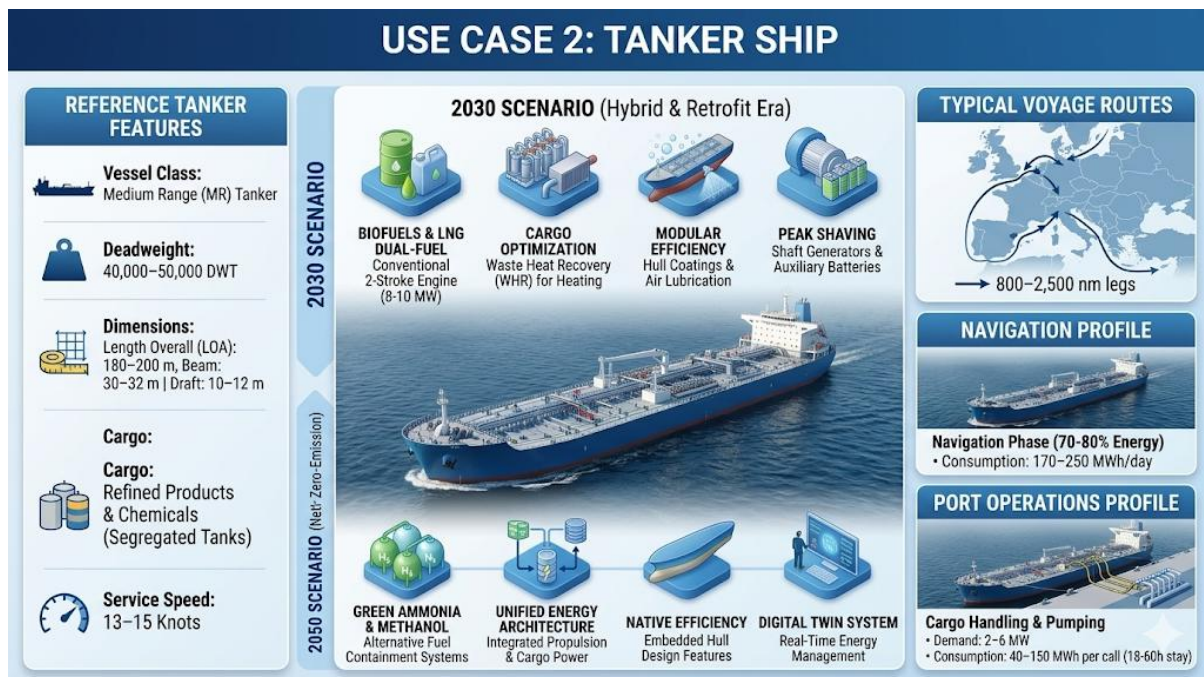


Figure 4 - Use Case 2: Tanker Ships

4.2. Use Case 2 Barriers for 2030 Horizon

This section examines the barrier analysis for **Use Case 2 (UC2): Tanker Ships** within the 2030 horizon. The tanker segment presents unique decarbonisation challenges due to its capital-intensive assets, global trading routes, and stringent safety standards for hazardous cargo. Applying the PESTLE framework, this analysis evaluates the political, economic, social, technological, legal, and environmental factors hindering the adoption of Zero-Emission Waterborne Transport (ZEWT) technologies. Special focus is placed on international regulatory alignment and infrastructure availability at major energy hubs.

As a baseline for the following qualitative assessment, the following table provides an overview of the use case defining characteristics for 2030.

Table 5 - Use Case 2: Tanker Ships

Category	Use Case 2 – Tanker Ship (2030 Horizon)
Operational Profile	Transport of refined petroleum products, chemicals, and other bulk liquids.
Typical Voyage Range	800–2,500 nautical miles.
Service Speed	13–15 knots.
Vessel Size	40,000–50,000 DWT (Medium Range class).

Category	Use Case 2 – Tanker Ship (2030 Horizon)
Energy Demand Profile	Complex dual-energy profile with substantial auxiliary energy demands driven by cargo handling, pumping, and thermal heating.
Total Energy Consumption	170–250 MWh/day during navigation; 40–150 MWh per call during energy-intensive port operations.
Design Philosophy	Retrofit-oriented; constrained by existing hull designs, deck piping, and safety layouts.
Primary Fuel Strategy	Conventional marine fuels supplemented by drop-in biofuels and LNG.
Propulsion System	Conventional low-speed, two-stroke diesel engines (8–10 MW).
Electrical Architecture	Shaft generators and batteries strictly for peak shaving during intensive cargo operations, coupled with Waste Heat Recovery (WHR) for cargo heating.
Efficiency Measures	Modular enhancements such as advanced low-friction coatings, air lubrication systems, and propeller upgrades.
Wind-Assisted Propulsion	Highly constrained by the presence of deck-mounted piping systems, hazardous safety zones, and cargo handling equipment.
Operational Objective	Focus on regulatory compliance (CII, EEXI) and managing peak loads during 18–60 hour port stays.

Political barriers

A first political barrier is the interaction between global IMO measures and regional schemes such as the EU ETS and FuelEU Maritime, which create a layered compliance environment for tankers trading across jurisdictions. For MR tankers operating on mixed EU and non-EU routes, the applicable carbon-cost and fuel-intensity obligations can vary depending on voyage pattern, making future fuel strategy more difficult to standardise across the fleet.

A second political barrier is the absence of a single stable global signal on the role of transitional fuels by 2030. While LNG and biofuels are both used in current decarbonisation discussions, the long-term policy direction increasingly depends on lifecycle GHG treatment, methane accounting, and sustainability criteria rather than on simple tank-to-wake performance alone.

In addition, many green shipping corridor initiatives announced so far have focused more clearly on container, ferry, or short-sea trades, while tanker routes remain more diffuse and opportunistic. As a result, MR tanker operators have less clarity on where and when corridor-based LNG or advanced biofuel supply hubs are likely to emerge, which weakens the political signal for early fuel-switching in the tanker segment.

Economic barriers

The MR tanker market is capital-intensive and cyclical, which amplifies the economic risks of fuel-related investment decisions. Retrofitting ships for LNG can require substantial changes to tanks, piping, fuel-handling systems, engine arrangements, and safety systems, while large-scale use of biofuels depends on reliable access to compliant fuels at commercially acceptable prices.

These investment decisions are further complicated by the persistence of split incentives in tanker markets. Under common time charter and voyage charter arrangements, the shipowner bears the capital cost of efficiency upgrades or fuel-switching, while the charterer often pays for the fuel and captures most of the direct savings, reducing the owner's immediate financial incentive to invest unless charter contracts explicitly reward lower fuel consumption or lower GHG intensity. This problem is particularly relevant in tanker shipping, where charter-based business models are widespread and where operational savings do not automatically translate into recoverable returns for owners investing in decarbonisation measures.

A further economic barrier is the uncertain long-term value of fuel-specific investments. LNG remains commercially relevant in the near term, but its lifecycle performance depends increasingly on methane-slip control and possible transition to bio-LNG, while biofuels face cost and supply competition from aviation, road transport, and industry. For tanker owners, this means that both compliance economics and fuel availability remain exposed to policy and market developments through 2030.

Because most tanker assets have long economic lifetimes, owners are also wary of committing to fuel-specific retrofits that could become misaligned with future climate policies or fuel-availability scenarios. Academic and industry analyses emphasise that investing in technologies that have not yet reached full maturity increases the risk of early obsolescence and stranded assets, reinforcing a cautious investment posture among many shipowners.

Fuel costs represent the single largest expense in the maritime sector, potentially accounting for over 50% of the daily operating costs of a fast or merchant vessel. Therefore, when analysing the barriers to the transition toward Zero-Emission Waterborne Transport (ZEWT) (especially looking ahead to the 2030 and 2050 strategic horizons) the primary economic obstacle lies in the cost gap between conventional petroleum-derived fuels and green alternatives. Without strong policy support or the implementation of carbon pricing mechanisms, which studies estimate must range between \$300 and \$800 per ton of CO₂ equivalent, renewable options currently struggle to achieve economic competitiveness on a global scale.

Specifically examining operating expenses (OPEX), which in the shipping sector are largely dominated by daily fuel procurement costs, liquefied natural gas (LNG) and biofuels exhibit sharply contrasting profiles. Currently, LNG offers the most advantageous performance in terms of cost-effectiveness, driven by a highly competitive baseline price. Depending on regional market dynamics, the price of fossil-based LNG can range from 16% to 66% of the price of Marine Gas Oil (MGO). Long-term average price projections (2025–2050) also confirm this advantage, estimating LNG at approximately 425 USD/t, a figure lower than the 455 USD/t forecast for Low Sulphur Fuel Oil (LSFO). However, it must be noted that

operators face highly variable bunkering logistics, which can incur additional supply costs ranging from 50 to 630 USD per ton.

Conversely, biofuels face much more rigid economic barriers due to exceptionally high production and procurement costs. The OPEX for this category is fundamentally driven by the price of raw materials, such as biomass or waste oils, which can account for 25% to 90% of the total production cost. Unlike LNG, biofuel market prices far exceed those of traditional fuels: estimates indicate an average price of 1,750 USD/t for Hydrotreated Vegetable Oil (HVO) and 1,416 USD/t for Bio-LNG. While it is true that diesel-like biofuels allow for a reduction in initial capital expenditures (CAPEX), as they can be used as "drop-in" solutions without requiring complex engine retrofits, the exorbitant cost of the fuel itself ultimately translates into a massive net increase in the overall operating costs for every single voyage. [7] [8] [9]

Social barriers

Social barriers for MR tankers relate mainly to workforce readiness and operational acceptance of new fuel-management practices. Even when the fuels in question are limited to LNG and biofuels, implementation still requires updated onboard procedures, additional fuel-quality awareness, and stronger coordination between ship and shore personnel.

The ZEWI partnership documents emphasise that crew members and technical staff will need new competences to safely handle alternative fuels, advanced power systems and digital optimisation tools. However, training curricula and certification schemes are still adjusting, and there is limited standardised guidance on the practical handling of novel fuels on board. [10] [1] In this sense, the social barrier is not only acceptance of the fuels themselves, but also the sector's ability to embed new compliance and fuel-handling routines into normal tanker operations by 2030.

In addition, the broader maritime workforce is undergoing demographic changes, with concerns about recruitment and retention in seafaring professions. The need for higher digital and technical skills, without corresponding improvements in working conditions and career attractiveness, may exacerbate labour shortages, thereby limiting the sector's capacity to implement and operate new ZEWI technologies effectively by 2030. [12]

Technological barriers

Technological barriers in this use case are less about experimental propulsion concepts and more about the practical integration of LNG systems, certified biofuel use, and digital efficiency tools into existing ships. For LNG, onboard integration requires space, segregation, and safety arrangements that are often challenging on existing hulls designed around conventional fuel oil.

For biofuels, the main technological issue is not a wholly new propulsion architecture but compatibility, traceability, and reliable performance across blends, engines, and supply chains.

The **low volumetric energy density and storage requirements of alternative fuels** represent a critical obstacle. Compared with conventional fuel oil, LNG and biofuels require larger tank

volumes and more complex containment and safety systems, which can reduce cargo capacity or require major structural modifications. [13]

Moreover, the integration of digital optimisation tools and advanced energy-management systems within the maritime sector remains at a relatively nascent stage, particularly in the context of tanker fleets. Although technologies such as route and speed optimisation, weather routing, predictive analytics and digital twins are widely acknowledged in the scientific and industrial literature as strategic enablers for enhancing energy efficiency and facilitating the transition towards Zero-Emission Waterborne Transport (ZEWT), their operational deployment is still far from being fully consolidated. Indeed, the practical implementation of these solutions continues to represent a major research and innovation challenge, as evidenced by the growing number of ongoing European and international research projects dedicated to maritime digitalisation and smart energy management.

Current barriers are associated not only with the limited quality, availability and interoperability of operational data, but also with the prevalence of heterogeneous legacy systems, fragmented onboard digital infrastructures and the shortage of specialised technical expertise required for the effective integration and maintenance of such technologies. Furthermore, uncertainties related to standardisation, cybersecurity (NIS2 Directive (EU 2022/2555), regulatory compliance and cost-effectiveness continue to hinder large-scale adoption across the sector. [14]

Wind-Assisted Propulsion Systems (WAPS) could be a valuable option for reducing emission and consumption, but they can be highly constrained by the presence of deck-mounted piping systems, hazardous safety zones, and cargo handling equipment.

Legal barriers

Legally, MR tankers face **fragmented and evolving compliance requirements**. The EU's introduction of FuelEU Maritime and the extension of the ETS to shipping add layers of regional obligations on top of IMO regulations, including monitoring, reporting and verification regimes that differ in scope and methodology. For a ship operating on LNG and biofuels and calling at EU ports, the recent extension of the EU Emissions Trading System (EU ETS) to maritime transport and the entry into force of the FuelEU Maritime Regulation create additional climate-related obligations on top of IMO rules. The EU ETS now covers CO₂ emissions from voyages between and to/from EU ports, while FuelEU Maritime sets progressively stricter well-to-wake greenhouse-gas intensity limits for the energy used on board and applies penalties and possible operational measures in case of non-compliance. Under this framework, FuelEU Maritime explicitly accounts for emissions of carbon dioxide, methane and nitrous oxide, and recent guidance highlights that methane emissions from the use of LNG, including methane slip from engines, are a point of concern and are reflected in predefined slip factors by engine type.

This means that the effective climate advantage of LNG-fuelled tankers increasingly depends on the methane performance of their engines and on the possibility to progressively shift towards lower-carbon variants such as bio-LNG to comply with tightening GHG-intensity requirements. At the same time, only biofuels and other renewable fuels that meet EU sustainability and greenhouse-gas saving criteria can benefit from favourable default

emission factors under FuelEU Maritime, while non-eligible biofuels are treated as fossil fuels, which makes robust sustainability verification and documentation a practical legal requirement for tankers planning to use advanced biofuels alongside LNG by 2030. [15]

Furthermore, the **enforcement of carbon-intensity measures and regional climate policies** remains uneven across jurisdictions. While regional initiatives aimed at the international maritime industry encourage a shift toward greener practices, they simultaneously risk inducing carbon leakage. This phenomenon occurs when shipping activities are diverted to unregulated regions, effectively relocating greenhouse gas emissions beyond the jurisdictional boundaries of these environmental policies. Studies on maritime decarbonisation highlight that inconsistent enforcement of rules can create an uneven playing field, where compliant operators may face higher costs without equivalent competitive benefits. For tanker vessels competing in global markets, this legal unevenness reduces the incentive to be early movers in ZEW adoption. [5]

Environmental barriers

From an environmental perspective, a major barrier in 2030 is the **risk that measures focus on operational emissions without fully accounting for Well-to-Wake (WtW) impacts**. The IMO has started to develop a framework for life-cycle GHG intensity of marine fuels, but its implementation is still evolving. Several studies warn that some transitional fuels may reduce tank-to-wake emissions while offering limited WtW benefits or even shifting emissions upstream, particularly when renewable electricity or sustainable feedstocks are scarce. [16] [17]

A further environmental barrier concerns the **large-scale use of biofuels** as a decarbonisation option for shipping. International assessments stress that the climate benefits of marine biofuels depend critically on the sustainability of their feedstocks and on avoiding direct and indirect land-use change, which can occur when agricultural land or high-carbon ecosystems are converted to grow energy crops. Studies on biofuels for marine and other transport sectors warn that increased demand risks competing with food production and other uses of arable land, and that land-use change can significantly erode or even reverse the Well-to-Wake GHG savings if not properly controlled. Recent reports also highlight that sustainable biofuel feedstocks are limited and already in demand from aviation and road transport, so scaling biofuels for shipping without robust safeguards on land use and biodiversity may shift environmental pressures upstream rather than delivering net climate benefits by 2030. [18]

4.3. Use Case 2 Barriers for 2050 Horizon

This section examines the barrier analysis for **Use Case 2 (UC2): Tanker Ships** within the 2050 horizon. The reference segment remains the 40,000–50,000 DWT Medium Range (MR) tanker fleet defined for this use case, characterised by a dual-energy profile in which propulsion is complemented by substantial auxiliary demand for cargo pumping, heating and containment, and by typical voyage legs of 800–2,500 nautical miles. Applying the same PESTLE framework used for the 2030 assessment, this analysis evaluates the political,

economic, social, technological, legal and environmental factors expected to shape ZEWT integration at this horizon, with barriers framed around the specific implications of tankers' dual role as both energy consumers and, increasingly, carriers of low-carbon energy cargoes, rather than generic maritime decarbonisation challenges.

By 2050, international tanker shipping is expected to operate under a net-zero or near-zero GHG regime, in line with the IMO's revised GHG Strategy and its emerging global fuel-GHG intensity framework. Unlike the 2030 horizon, which is built around retrofitting existing MR hulls with LNG or biofuel-compatible systems within constrained deck and piping layouts, the 2050 scenario assumes newbuild vessels designed natively around high-energy-density, near-zero-GHG fuels — principally green ammonia and e-hydrogen derivatives, with e-methanol considered as a partial-compliance option depending on its production pathway. A distinguishing feature of this use case is the deep coupling between ship fuel systems and transported cargo: as global energy systems shift toward low-carbon commodities, MR tankers may increasingly carry as cargo the same hydrogen-based energy carriers they consume for propulsion, which adds design and safety considerations not present in propulsion-only use cases such as general cargo.

As a baseline for the following qualitative assessment, the following table provides an overview of the use case defining characteristics for 2050.

Table 6 - Use Case 2: Tanker Ships (2050 Horizon)

Category	Use Case 2 – Tanker Ships (2050 Horizon)
Operational Profile	Transport of refined petroleum products and chemicals, with a growing share of low-carbon energy commodities (green hydrogen derivatives and ammonia) as cargo
Typical Voyage Range	800–2,500 nautical miles
Service Speed	13–15 knots
Vessel Size	40,000–50,000 DWT (Medium Range class)
Energy Demand Profile	Dual-energy profile combining propulsion with substantial auxiliary demand for cargo pumping, heating and, where cargo includes hydrogen-based carriers, containment management
Total Energy Consumption	Comparable in structure to the 2030 baseline, moderated by natively integrated efficiency measures, with auxiliary demand shaped increasingly by low-carbon cargo handling rather than only conventional product heating
Design Philosophy	Newbuild, purpose-designed approach integrating dual-role fuel/cargo safety zoning, containment and automation from the concept stage rather than retrofitted
Primary Fuel Strategy	Green ammonia and e-hydrogen derivatives as primary propulsion fuels; e-methanol considered as a partial-compliance option depending on production pathway

Category	Use Case 2 – Tanker Ships (2050 Horizon)
Propulsion System	Next-generation ammonia- and hydrogen-capable propulsion (combustion or fuel cell), purpose-built to meet combined fuel- and cargo-safety requirements
Electrical Architecture	Digitally integrated electrical and automation architecture supporting real-time energy management, coupled with Waste Heat Recovery (WHR) for cargo heating
Efficiency Measures	Hull-form and machinery-layout optimisation integrated at the design stage; air lubrication as a standard feature
Wind-Assisted Propulsion	Still constrained by deck piping, hazardous safety zones and cargo-handling equipment, though less severely than in 2030 owing to design-stage integration
Operational Objective	Integrated, real-time carbon and energy management across a combined fuel-and-cargo value chain, supported by digital-twin systems and a maturing global ammonia/hydrogen bunkering and cargo-handling network

Political barriers

The 2030 assessment identified a layered compliance environment across IMO, EU ETS and FuelEU Maritime, an unresolved policy signal on transitional fuels, and limited tanker-specific green-corridor initiatives as the principal political barriers for UC2. By 2050 these evolve from near-term compliance friction into structural uncertainty over the global governance of the fuels and cargoes this fleet depends on.

A first barrier is the **stability of the global GHG-pricing and fuel-intensity framework itself**. The IMO's draft Net-Zero Framework, provisionally agreed in April 2025, was expected to introduce a global fuel-GHG intensity standard and associated carbon-pricing mechanism, but its formal adoption was deferred by IMO member states in October 2025 and is now scheduled for a further vote in October 2026. [34] For a globally trading MR tanker fleet, this unresolved timeline compounds the 2030-era uncertainty over regional-versus-global stringency: owners must plan newbuild and fuel-supply investments without a settled global reference framework, while the EU's ETS and FuelEU Maritime instruments continue to apply regardless. [35]

A second, closely related barrier is the **governance of global hydrogen and ammonia value chains** in which tankers play a pivotal carrying role. Cross-border sustainability criteria, safety standards and market-design rules for hydrogen and ammonia trade are still emerging, extending the 2030-era barrier of diffuse, tanker-specific green-corridor coverage into a broader governance gap over the fuel-and-cargo value chain this use case is built around. [36]

A third barrier is the **potential misalignment between global energy-transition pathways and tanker-sector decarbonisation**. Achieving net-zero shipping by 2050 depends on a managed decline in fossil-fuel demand and parallel scaling of low-carbon fuel supply; if global policy slows fossil-fuel phase-out or fails to deliver low-carbon fuel volumes at scale,

the tanker fleet may remain structurally tied to transitional cargoes and fuels, complicating its own transition. [37]

Economic barriers

In 2030, the central economic barriers for UC2 were the CAPEX of LNG-compatible retrofits, the split-incentive problem between owners and charterers, and the cyclical, price-sensitive nature of tanker freight markets. By 2050, with newbuild ammonia/hydrogen-fuelled vessels replacing retrofit strategies, the economic barrier shifts to the **cost and availability of near-zero-GHG fuels at the scale this dual-energy fleet requires**, layered onto pre-existing market cyclicity.

Life-cycle fuel-intensity assessments indicate that conventional fuels and LNG will not meet 2050-horizon fuel-intensity standards, while e-hydrogen and e-ammonia can achieve full compliance only at substantially higher cost, reflecting the price of renewable electricity and fuel-synthesis processes. [38] Because MR tankers already carry a heavier auxiliary energy load than pure propulsion-dominated segments, this cost premium compounds across both propulsion and cargo-handling energy demand, making the economic viability of the transition highly dependent on freight contracts that pass through the higher cost of compliant fuels. [31]

A second economic barrier is the **risk of stranded or under-utilised assets** as cargo patterns evolve. As global oil demand declines under stringent climate scenarios, demand for crude and some product-tanker capacity is expected to fall even as demand for transporting hydrogen and ammonia grows; tankers designed around fossil cargoes may find fewer profitable employment options, while new tonnage optimised for hydrogen-based fuels requires substantial upfront investment with uncertain utilisation, extending the 2030-era caution around fuel-specific retrofits into a broader risk of misjudging the fleet's future cargo mix.

A third barrier is that tanker markets remain **cyclical and highly price-sensitive**, with revenue depending on short-term freight-rate volatility rather than long, stable contracts. This pattern sits awkwardly with the capital-intensive, long-horizon investments zero-emission fuel systems require, and may necessitate new financial instruments or de-risking mechanisms to make 2050-compatible newbuilds bankable.

Social barriers

The 2030 social barrier for UC2 centred on workforce readiness for handling LNG and biofuels alongside conventional hazardous cargoes. By 2050, with ammonia and hydrogen established as both fuel and, increasingly, cargo, the barrier shifts to **sustaining a safety culture and skills base for a fleet where fuel and cargo hazards overlap**.

A key barrier is the **combination of hazardous cargoes and advanced zero-emission fuel systems**: crews and shore personnel must be competent in both managing potentially dangerous cargoes and handling ammonia, hydrogen or methanol as fuel, a dual responsibility that extends the 2030-era training gap into a more demanding, continuously updated competence requirement. [39] [40]

A second barrier is **occupational health and toxicity risk**, particularly for ammonia and certain hydrogen-based carriers; because tankers already face heightened public scrutiny following historical oil-spill incidents, any high-profile accident involving a zero-emission fuel could undermine public and political support for specific fuel pathways more acutely than for other use cases. [41]

A further related barrier is the sector's need to meet **evolving expectations from investors and cargo owners** for transparent, independently verified life-cycle emissions accounting; operators unable to demonstrate this risk reduced access to capital or premium cargoes.

Finally, the last barrier is the **availability of a sufficiently skilled workforce** able to operate complex zero-emission ships safely and efficiently. Strategic research agendas for ZEWI repeatedly stress that the transition requires new competences in fuel handling, electrical systems, digital operations, safety management, and integrated energy optimisation. [25] This issue becomes even more acute in a mature 2050 scenario, in which crews and shore-side personnel must combine competencies in fuel safety, digital energy management, automation, emergency response, and lifecycle compliance monitoring. [26]

Technological barriers

In 2030, technological barriers for UC2 centred on integrating LNG systems and certified biofuel use into existing hulls constrained by deck piping and safety zoning. By 2050, because vessels are designed natively around ammonia/hydrogen propulsion, the barrier shifts from retrofit integration to the **robust, safe and efficient engineering of dual fuel-and-cargo systems into large tanker designs**.

A first barrier is **combustion, emission control and storage** for ammonia and hydrogen propulsion at tanker scale: mature solutions are still required for managing unburned ammonia and N₂O slip, and for cryogenic or pressurised storage, extending the 2030-era barrier of LNG containment into a more demanding safety-engineering challenge where both fuel and cargo may be hazardous. [42]

A second barrier is the **naval-architectural integration of safe containment, ventilation, detection and emergency-response systems** without compromising cargo capacity, stability or survivability. A related and still-debated option is **onboard carbon capture and storage (OCCS)** as a transitional pathway; it significantly increases system complexity, energy consumption and space requirements, which is particularly challenging for tankers that may already incorporate complex cargo and alternative-fuel infrastructure.

Finally, tankers will rely on **advanced digital systems for route optimisation, energy management and predictive maintenance**; ensuring cyber-resilience and functional safety when these systems are integrated with fuel-handling and cargo-management functions remains an ongoing barrier distinct from the 2030-era challenge of simply deploying digital tools.

Legal barriers

The 2030 legal barrier for UC2 was fragmented and evolving compliance across IMO, EU ETS and FuelEU Maritime requirements. By 2050, with transitional fuels largely phased out, the

legal barrier shifts to the **dual regulatory treatment of fuel and cargo** and to the precise definition of net-zero compliance.

A first barrier is that, because ammonia or methanol may serve simultaneously as cargo and propulsion energy, safety, design and operational rules must satisfy both cargo-transport and fuel-use requirements at once; multiple IMO instruments governing LNG, methanol, ammonia, hydrogen and biofuels are still evolving toward this dual treatment. [43] [44]

A second barrier is the **precise definition and verification of compliance** under whatever global fuel-intensity framework is ultimately adopted, alongside the EU's FuelEU Maritime trajectory, which already tightens from a 2% GHG-intensity reduction in 2025 to 80% by 2050 relative to the 2020 fleet average. [45] Interpreting these rules across complex tanker trades — with blended fuels, varying cargoes and multi-leg voyages — risks disputes unless robust verification and auditing systems are in place, extending the 2030-era barrier of uneven enforcement into a more technically demanding compliance environment. [46]

Environmental barriers

In 2030, the environmental barrier for this use case was the risk that operational-emissions measures would not capture well-to-wake impacts, particularly for biofuels. By 2050, with ammonia and hydrogen established as the primary fuels for this fleet, the barrier shifts to **ensuring genuine climate benefit while managing the new environmental risk profiles these fuels introduce**.

A first barrier is that expanded use of ammonia and hydrogen as marine fuels introduces **new environmental risk profiles**: very low CO₂ emissions are offset by risks such as ammonia toxicity to marine life, nitrogen-cycle impacts, and indirect emissions from upstream production if not carefully managed. Because UC2 vessels both transport and consume these substances, environmental safeguards are needed across the full lifecycle, from production and bunkering to potential spill scenarios — a materially larger scope than for propulsion-only use cases. [47]

Finally, the tanker sector remains embedded in the **broader decarbonisation of global energy supply**: even if UC2 vessels reach net-zero operational emissions, continued large-scale transport of fossil fuels would be inconsistent with global net-zero scenarios.

Coordinating fleet decarbonisation with the managed decline of fossil-fuel extraction and the ramp-up of low-carbon commodity transport is essential to avoid environmental lock-in and stranded climate liabilities by 2050.

5. USE CASE 3 – PASSENGER SHIPS BARRIERS ANALYSIS

5.1. Use Case 3: Passenger Ships Overview

The reference vessel considered within this use case represents a statistically derived, anonymised configuration of the medium-size passenger ship segment, specifically targeting Ro-Pax ferries and small-to-medium cruise ships operating in European and regional contexts. From a dimensional perspective, the vessel features a length overall (LOA) of 180 to 220 metres, a beam of 26 to 30 metres, and a design draft of 6.5 to 8 metres. Designed to accommodate between 800 and 1,800 passengers—as well as rolling cargo in Ro-Pax configurations, the multi-deck arrangement is structurally complex, dominated by large superstructures, vehicle decks, and extensive accommodation spaces.

A defining feature of the passenger ship use case is its uniquely balanced, dual-energy profile. Unlike dry cargo or tanker vessels, where propulsion overwhelmingly dominates the energy balance, passenger vessels require continuous, massive power for "hotel loads." These include Heating, Ventilation, and Air Conditioning (HVAC), lighting, catering systems, and freshwater production essential for passenger comfort. Consequently, hotel loads account for an exceptional 40–50% of the total onboard energy demand (approximately 150–300 MWh/day during navigation), remaining active across all operational phases. Primary propulsion typically relies on a diesel-electric architecture with an installed power of 15 to 30 MW, enabling service speeds of 18 to 22 knots while providing the redundancy and flexibility needed to balance propulsion (250–500 MWh/day) and hotel services.

The mission envelope for these vessels is highly repetitive and dictated by strict schedule constraints. Operating on short-sea and regional routes, individual voyage legs typically range from 100 to 600 nautical miles (4 to 24 hours of navigation). High-frequency operations result in frequent port calls—often multiple times a day—with turnaround times of 1 to 6 hours. During navigation, cruising energy demand ranges from 400 to 700 MWh/day (combining propulsion and hotel loads). Crucially, during port operations, while propulsion is minimised, hotel loads remain fully active, creating a port power demand of 3 to 10 MW. Given their proximity to densely populated tourist destinations, these port phases are a primary target for stringent environmental optimisation.

The decarbonisation trajectory for passenger ships illustrates a profound shift from a hybrid, operational-based transition in 2030 to a structurally integrated, zero-emission architecture by 2050.

In the **2030 scenario**, the technological strategy is hybridisation-driven and retrofit-compatible. Primary propulsion transitions incrementally through the use of drop-in biofuels and LNG within existing diesel-electric frameworks. The most prominent technological integration is the extensive use of Battery Energy Storage Systems (BESS). Rather than serving as the sole propulsion source, batteries enable partial electrification for peak shaving, highly responsive manoeuvring, and zero-emission port operations. Efficiency improvements focus heavily on operational measures: low-friction hull coatings, optimised HVAC systems, and Waste Heat Recovery (WHR) applied selectively to offset boiler fuel consumption. Notably, Wind-Assisted Propulsion Systems (WAPS) are considered highly restricted and generally unfeasible due to deck space limitations, large passenger superstructures, and aesthetic requirements.

By the **2050 scenario**, the paradigm shifts completely to fully integrated zero-emission energy architectures. Passenger ships are predominantly newbuild platforms conceived intrinsically around climate-neutral energy carriers. The 2030 reliance on auxiliary batteries evolves into an electric-dominant architecture powered by hydrogen-based systems—specifically high-capacity fuel cells acting as continuous base-load providers with minimal noise and vibration. Furthermore, hotel load reduction transforms from an operational enhancement to a fundamental design driver. HVAC systems are fully electrified and synergised with advanced heat pumps, thermal storage, and structurally embedded waste heat recovery networks. Port operations transition to a zero-emission baseline, supported by globally standardised, interoperable shore power. Ultimately, the 2050 vessel is no longer an adapted conventional ship, but rather a holistically redesigned, zero-emission floating hospitality platform governed by digital twin systems that continuously optimise energy flows and passenger services.

The following table summarizes the structural, technological, and operational transition of the Passenger Ship use case across the two target timeframes.

Table 7 - Use Case 3: Passenger Ships

Feature / System	2030 Scenario (Hybrid & Transition)	2050 Scenario (Native Zero-Emission)
Design Philosophy	Retrofit and hybrid-oriented; optimised around existing diesel-electric architectures.	Native zero-emission design; holistically architected as a fully integrated floating hospitality platform.
Primary Energy Strategy	Drop-in biofuels, LNG, and the extensive integration of Battery Energy Storage Systems (BESS).	Climate-neutral carriers and hydrogen-based systems serving as continuous base-load power.
Power Architecture	Internal combustion engines driving electrical generators; batteries utilised for peak shaving and port operations.	Electric-dominant architectures; propulsion and hotel loads supplied via a common, high-capacity electrical backbone.
Hotel Load Management	Operational efficiency enhancements (LEDs, HVAC tuning) and selective Waste Heat Recovery (WHR).	Demand reduction as a core design driver; fully electrified HVAC, thermal storage, and structurally embedded WHR networks.
Port Operations	Target for local emission reduction using onboard batteries and early-stage shore power integration.	Strictly zero-emission baseline; fully standardised and seamlessly interoperable shore power capabilities.

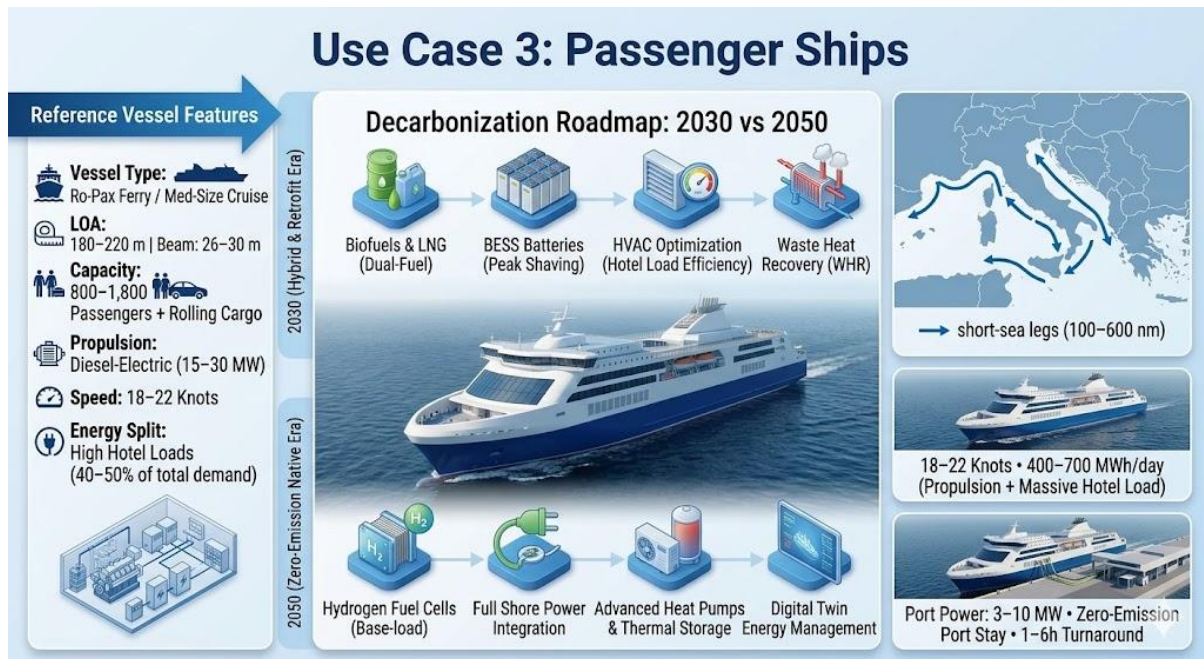


Figure 5 - Use Case 3: Passenger Ships

5.2. Use Case 3 Barriers for 2030 Horizon

This section examines the barrier analysis for Use Case 3 (UC3): Passenger Ships within the 2030 horizon. The passenger ship segment presents highly specific decarbonisation challenges due to its direct interaction with the public, strict comfort and noise standards, predictable yet rigid schedule constraints, and significant hotel power loads.

As a baseline for the following qualitative assessment, the following table provides an overview of the use case defining characteristics for 2030.

Table 8 - Use Case 3: Passenger Ships

Category	Use Case 3 – Passenger Ships (2030 Horizon)
Operational Profile	Medium-size Ro-Pax and cruise vessels on short-sea regional routes.
Typical Voyage Range	100–600 nautical miles per leg, 4–24 hours of navigation.
Service Speed	Service speed in the range of 18–22 knots.
Vessel Size	180–220 m LOA, 26–30 m beam, 6.5–8 m draft, 800–1,800 passengers.
Energy Demand Profile	Dual profile with continuous hotel loads accounting for 40–50% of energy.
Total Energy Consumption	Around 400–700 MWh/day combining propulsion and hotel loads.
Port Power Demand	Port stays of 1–6 hours with hotel loads of about 3–10 MW.

Category	Use Case 3 – Passenger Ships (2030 Horizon)
Design Philosophy	Retrofit- and hybrid-oriented design based on existing diesel-electric layouts.
Primary Fuel Strategy	Conventional marine fuels with gradual uptake of biofuels and LNG.
Propulsion System	Diesel-electric propulsion with approximately 15–30 MW installed power.
Power/Electrical Architecture	Central electrical backbone with BESS for peak shaving and port operations.
Hotel Load Management	Efficiency measures on HVAC, lighting and selective WHR.
Port Operations Objective	Reduce local emissions and noise at berth through the combined use of onboard batteries and early-stage shore power connections.
Operational Objective	Maintain strict timetable reliability and high comfort standards while reducing GHG and pollutant emissions through hybridisation, operational optimisation and incremental use of low-carbon fuels.

Political barriers

A first political barrier is the interaction between global IMO measures and regional schemes such as the EU ETS and FuelEU Maritime, which create a layered compliance environment for ships trading across jurisdictions. A second political barrier is the absence of a single stable global signal on the role of transitional fuels by 2030. While LNG and biofuels are both used in current decarbonisation discussions, the long-term policy direction increasingly depends on lifecycle GHG treatment, methane accounting, and sustainability criteria rather than on simple tank-to-wake performance alone.

In addition, a major political barrier for passenger ships in the 2030 horizon is the fragmented interaction between EU-level regulation, national transport policies and local port governance. The regulatory direction is becoming clearer through FuelEU Maritime, including the requirement for relevant passenger ships to achieve zero emissions at berth through connection to onshore power supply or equivalent solutions in covered ports from 2030, but the practical implementation of this obligation depends on national investment choices, port planning and grid readiness, which remain uneven across Europe. This creates an inconsistent enabling environment for passenger operators serving multi-port routes, particularly where one port advances rapidly with shore-side electrification while another remains delayed by administrative, financial or infrastructure constraints. [48] [49]

The matter is further complicated if it is also considered the insufficient coordination between maritime decarbonisation and urban energy planning. Passenger terminals are frequently located near dense urban areas, meaning that OPS deployment depends not only on port equipment but also on substations, grid reinforcement and coordinated infrastructure planning across municipal and regional authorities.

Economic barriers

Passenger ships face substantial economic barriers because the most relevant ZEWT options in the 2030 horizon require high upfront investment at both vessel and port level.

Retrofitting ships for LNG can require substantial changes to tanks, piping, fuel-handling systems, engine arrangements, and safety systems, while large-scale use of biofuels depends on reliable access to compliant fuels at commercially acceptable prices.

A further economic barrier is the uncertain long-term value of fuel-specific investments. LNG remains commercially relevant in the near term, but its lifecycle performance depends increasingly on methane-slip control and possible transition to bio-LNG, while biofuels face cost and supply competition from aviation, road transport, and industry. For shipowners, this means that both compliance economics and fuel availability remain exposed to policy and market developments through 2030.

Also OPS-ready ships, battery-hybrid ferries and upgraded electrical architectures entail significant capital expenditure for onboard conversion equipment, connection systems, batteries, shore-side substations and, in some cases, modifications to internal layouts and service systems.

For Ro-Pax ferries, the business case depends strongly on route geometry, charging time and power availability in port. Even where technical electrification is possible, economic viability may remain weak unless port charging systems, electricity pricing and vessel schedules are adapted to create a workable operational model. [50]

For small and medium cruise vessels, the economic challenge is reinforced by the scale of onboard hotel demand. OPS can substantially reduce emissions at berth and improve local environmental performance, but it does not resolve the full voyage energy demand and still requires large investment in port infrastructure and onboard compatibility.

A further economic barrier is the interdependence between ship and port investment. [48] Passenger operators may be reluctant to invest in OPS-ready or battery-hybrid ships unless there is confidence that relevant ports along the route will provide compatible infrastructure at reasonable cost, while ports may delay investment if the fleet transition remains uncertain. As far as the cost of the service is concerned, the port must obviously guarantee an energy price lower than that borne by the ship through the use of auxiliary generators so as to make the use of the shore connection attractive, but it must still be high enough to cover the costs incurred by the port. This approach becomes particularly challenging in situations where the cost of fuel is subject to high volatility. [51]

Fuel costs represent the single largest expense in the maritime sector, potentially accounting for over 50% of the daily operating costs of a fast or merchant vessel. Therefore, when analysing the barriers to the transition toward Zero-Emission Waterborne Transport (ZEWT) (especially looking ahead to the 2030 and 2050 strategic horizons) the primary economic obstacle lies in the cost gap between conventional petroleum-derived fuels and green alternatives. Without strong policy support or the implementation of carbon pricing mechanisms, which studies estimate must range between \$300 and \$800 per ton of CO₂ equivalent, renewable options currently struggle to achieve economic competitiveness on a global scale.

Specifically examining operating expenses (OPEX), which in the shipping sector are largely dominated by daily fuel procurement costs, liquefied natural gas (LNG) and biofuels exhibit sharply contrasting profiles. Currently, LNG offers the most advantageous performance in terms of cost-effectiveness, driven by a highly competitive baseline price. Depending on regional market dynamics, the price of fossil-based LNG can range from 16% to 66% of the price of Marine Gas Oil (MGO). Long-term average price projections (2025–2050) also confirm this advantage, estimating LNG at approximately 425 USD/t, a figure lower than the 455 USD/t forecast for Low Sulphur Fuel Oil (LSFO). However, it must be noted that operators face highly variable bunkering logistics, which can incur additional supply costs ranging from 50 to 630 USD per ton.

Conversely, biofuels face much more rigid economic barriers due to exceptionally high production and procurement costs. The OPEX for this category is fundamentally driven by the price of raw materials, such as biomass or waste oils, which can account for 25% to 90% of the total production cost. Unlike LNG, biofuel market prices far exceed those of traditional fuels: estimates indicate an average price of 1,750 USD/t for Hydrotreated Vegetable Oil (HVO) and 1,416 USD/t for Bio-LNG. While it is true that diesel-like biofuels allow for a reduction in initial capital expenditures (CAPEX), as they can be used as "drop-in" solutions without requiring complex engine retrofits, the exorbitant cost of the fuel itself ultimately translates into a massive net increase in the overall operating costs for every single voyage. [7] [8] [9]

Social barriers

Passenger shipping is especially exposed to social barriers because it combines high public visibility with direct responsibility for passenger safety and service continuity. Passenger vessels operate in cities, islands and tourism destinations where emissions, noise and port externalities are highly visible, so there is strong societal pressure to reduce local impacts rapidly. [52] At the same time, stringent safety standards, the need for operational reliability, and passenger comfort require operators to adopt a prudent approach, integrating new technologies only once they have demonstrated proven technical and operational maturity.

A key social barrier is the skills and training gap associated with the growing electrification, the management of more complex onboard electrical systems, and operational acceptance of new fuel-management practices. Even when the fuels in question are limited to LNG and biofuels, implementation still requires updated onboard procedures, additional fuel-quality awareness, and stronger coordination between ship and shore personnel.

The ZEWT partnership documents emphasise that crew members and technical staff will need new competences to safely handle alternative fuels, advanced power systems and digital optimisation tools. However, training curricula and certification schemes are still adjusting, and there is limited standardised guidance on the practical handling of novel fuels such as methanol and ammonia on board cargo vessels. [1] [10] [11]

In this sense, the social barrier is not only acceptance of the fuels themselves, but also the sector's ability to embed new compliance and fuel-handling routines into normal ship operations by 2030.

In addition, the broader maritime workforce is undergoing demographic changes, with concerns about recruitment and retention in seafaring professions. The need for higher digital and technical skills, without corresponding improvements in working conditions and career attractiveness, may exacerbate labour shortages, thereby limiting the sector's capacity to implement and operate new ZEWT technologies effectively by 2030. [12]

Technological barriers

Low volumetric energy density of alternative fuels constitutes a primary barrier. LNG requires significantly larger tank volumes and complex containment systems compared to conventional marine fuel oil. For passenger vessels with large superstructures, multiple decks, and extensive accommodation spaces, integrating bulky fuel storage creates severe spatial constraints. The volumetric penalty necessitates expensive structural modifications and can reduce cargo capacity. [53]

BESS integration presents technical and safety complexities. Passenger ships require battery systems managing both peak propulsion demands during manoeuvring and sustained hotel loads for HVAC, lighting, and catering systems. Fire and explosion hazards associated with lithium-ion batteries represent critical safety concerns, requiring upgraded automatic fire detection systems and provisions for emergency response. BESS units also have limitations on tilting angles during loading and operation, and vessel classification society approvals may be required. The European Maritime Safety Agency notes the absence of comprehensive international regulatory instruments governing battery safety in ships. [54]

Limited maturity of digital energy-management systems hinders operational optimisation. Although digital twins, predictive analytics, and route optimisation are recognised as strategic enablers, their deployment remains nascent. Barriers include limited data quality, interoperability issues, and fragmented onboard digital infrastructures. Passenger ships operate multiple independent control systems for propulsion, hotel services, and safety equipment, creating integration challenges. Shortages of specialised technical expertise and uncertainties regarding standardisation, cybersecurity protocols (NIS2 Directive (EU 2022/2555)), and cost-effectiveness delay widespread adoption.

OPS infrastructure compatibility and standardisation represent a barrier for the 2030 timeframe. FuelEU Maritime mandates that passenger ships above specified tonnage must connect to OPS when calling at EU ports from 2030. However, technical standards for voltage, frequency, and connection procedures vary across European ports. Retrofitting existing vessels requires modifications to electrical distribution systems, including transformers, switchgear, and connection interfaces compatible with multiple port configurations encountered along a vessel's route. [55] [56]

Legal barriers

Passenger vessels face increasingly complex compliance obligations under FuelEU Maritime and related port-level requirements, which affect how energy rules are implemented at the ship-port interface. FuelEU Maritime provides a clearer regulatory framework by introducing greenhouse-gas intensity limits and a zero-emission-at-berth requirement for relevant passenger ships from 2030, but implementation still depends on how ports, operators and

verifiers apply the rules in practice. Differences in OPS availability, detailed technical standards and local implementation timelines across ports can complicate investment planning for ships serving multiple ports.

The technical and operational rules for key ZEWT solutions (especially OPS connections and port electrification) are still being developed and implemented at different speeds across EU ports, which can result in non-fully harmonised requirements for operators. While the policy direction is clear, the detailed implementation of connection standards, port procedures, certification pathways and allocation of operational responsibilities can still vary across ports, Member States and competent authorities. This creates additional administrative burden and legal complexity for operators that need compatible compliance conditions across an entire route rather than in a single terminal.

Passenger ships are also highly exposed to port-specific regulatory conditions. Environmental rules, local connection requirements and infrastructure obligations may differ from port to port, particularly in urban passenger terminals where air-quality and noise concerns are politically sensitive. This variability can complicate route planning and reduce the predictability of ZEWT investment decisions, even where the underlying technologies are already available.

Furthermore, dual exposure to SPS Code and NIS2 Directive requires security reassessments when technological changes are introduced.

Lastly, the **enforcement of carbon-intensity measures and regional climate policies** remains uneven across jurisdictions serving passenger routes that extend beyond the EU/EEA. Ferries and cruise itineraries calling at non-EU ports risk uneven application of EU ETS and FuelEU Maritime obligations relative to competitors operating purely domestic or non-EU routes, creating a carbon-leakage risk analogous to that identified for cargo and tanker shipping, whereby compliant operators bear costs not matched by equivalent obligations on competing routes.

Environmental barriers

Passenger ships face **fragmented and evolving compliance requirements**. The EU ETS now covers CO₂ emissions from voyages between and to/from EU ports, while FuelEU Maritime sets progressively stricter well-to-wake greenhouse-gas intensity limits for the energy used on board and applies penalties and possible operational measures in case of non-compliance. Under this framework, FuelEU Maritime explicitly accounts for emissions of carbon dioxide, methane and nitrous oxide, and recent guidance highlights that methane emissions from the use of LNG, including methane slip from engines, are a point of concern and are reflected in predefined slip factors by engine type.

This means that the effective climate advantage of LNG-fuelled ships increasingly depends on the methane performance of their engines and on the possibility to progressively shift towards lower-carbon variants such as bio-LNG to comply with tightening GHG-intensity requirements. At the same time, only biofuels and other renewable fuels that meet EU sustainability and greenhouse-gas saving criteria can benefit from favourable default emission factors under FuelEU Maritime, while non-eligible biofuels are treated as fossil

fuels, which makes robust sustainability verification and documentation a practical legal requirement for ship planning to use advanced biofuels alongside LNG by 2030. [15]

From an environmental perspective, a major barrier in 2030 is the **risk that measures focus on operational emissions without fully accounting for Well-to-Wake (WtW) impacts**. The IMO has started to develop a framework for life-cycle GHG intensity of marine fuels, but its implementation is still evolving. Several studies warn that some transitional fuels may reduce tank-to-wake emissions while offering limited WtW benefits or even shifting emissions upstream, particularly when renewable electricity or sustainable feedstocks are scarce. [16] [17]

A further environmental barrier concerns the **large-scale use of biofuels** as a decarbonisation option for shipping. International assessments stress that the climate benefits of marine biofuels depend critically on the sustainability of their feedstocks and on avoiding direct and indirect land-use change, which can occur when agricultural land or high-carbon ecosystems are converted to grow energy crops. Studies on biofuels for marine and other transport sectors warn that increased demand risks competing with food production and other uses of arable land, and that land-use change can significantly erode or even reverse the Well-to-Wake GHG savings if not properly controlled. Recent reports also highlight that sustainable biofuel feedstocks are limited and already in demand from aviation and road transport, so scaling biofuels for shipping without robust safeguards on land use and biodiversity may shift environmental pressures upstream rather than delivering net climate benefits by 2030. [18]

5.3. Use Case 3 Barriers for 2050 Horizon

This section examines the barrier analysis for **Use Case 3 (UC3): Passenger Ships** within the 2050 horizon. The reference segment remains the medium-size Ro-Pax and cruise fleet defined for this use case, operating on short-sea regional routes of 100–600 nautical miles with a dual energy profile in which continuous hotel loads account for roughly 40–50% of total demand. Applying the same PESTLE framework used for the 2030 assessment, this analysis evaluates the political, economic, social, technological, legal and environmental factors expected to shape ZEWI integration at this horizon, with barriers framed around the distinct trajectories of ferries and cruise ships rather than generic maritime decarbonisation challenges.

By 2050, the passenger segment is expected to operate under net-zero or near-zero GHG constraints, aligned with the IMO's GHG strategy and with cruise and ferry industry commitments to pursue net-zero emissions by mid-century. Unlike the 2030 horizon, which is built around retrofitting existing diesel-electric hulls with early-stage OPS connections and gradual biofuel/LNG uptake, the 2050 scenario assumes purpose-built vessels architected around distinct zero-emission concepts for each vessel type: short-sea ferries as battery-electric or battery-dominant hybrids, with hydrogen serving longer routes where direct electrification is not feasible; and cruise ships combining advanced low- and zero-GHG fuels (e-methanol, ammonia, hydrogen-based fuels) with extensive shore-power use and deep efficiency gains in both propulsion and hotel loads. Engines capable of running on sustainable marine fuels, fuel cells and large battery systems are expected to become

standard elements of newbuild passenger ship design, with ferries increasingly integrated into decarbonised regional and island energy systems.

As a baseline for the following qualitative assessment, the following table provides an overview of the use case defining characteristics for 2050.

Table 9 - Use Case 3: Passenger Ships (2050 Horizon)

Category	Use Case 3 – Passenger Ships (2050 Horizon)
Operational Profile	Medium-size Ro-Pax and cruise vessels on short-sea regional routes, with ferries and cruise ships following distinct zero-emission trajectories
Typical Voyage Range	100–600 nautical miles per leg, 4–24 hours of navigation
Service Speed	18–22 knots
Vessel Size	180–220 m LOA, 26–30 m beam, 6.5–8 m draft, 800–1,800 passengers
Energy Demand Profile	Dual profile with continuous hotel loads still accounting for approximately 40–50% of energy, now met by battery, fuel-cell and e-fuel systems rather than fossil auxiliary generation
Total Energy Consumption	Comparable in scale to the 2030 baseline, moderated by deep efficiency gains in both propulsion and hotel loads
Port Power Demand	Zero-emission berth operation as standard, through onshore power supply or equivalent solutions at all covered ports, rather than early-stage or partial connection
Design Philosophy	Newbuild, purpose-built zero-emission architecture: battery-electric or battery-dominant hybrid for ferries; multi-fuel fuel-cell/engine hybrid for cruise, integrated from the concept stage
Primary Fuel Strategy	Ferries: battery-electric or battery-dominant hybrid, with hydrogen for longer routes; Cruise: e-methanol, ammonia and hydrogen-based fuels combined with extensive shore power
Propulsion System	Diesel-electric backbone replaced or complemented by battery, fuel-cell and e-fuel-capable engines, in a comparable 15–30 MW installed-power range
Power/Electrical Architecture	Fully integrated battery/fuel-cell/e-fuel electrical backbone with large-scale BESS for propulsion, hotel loads and port operations
Hotel Load Management	Integrated, high-efficiency hotel-energy management (HVAC, lighting, waste-heat recovery) as a baseline design feature rather than a selective retrofit
Port Operations Objective	Full zero-emission berth operation via OPS or equivalent zero-emission technology at all relevant ports
Operational Objective	Net-zero performance across both propulsion and hotel loads, maintaining schedule reliability and comfort standards through integrated, real-time energy management

Political barriers

The 2030 assessment identified a layered IMO/EU compliance environment, fragmented interaction between EU, national and local port governance, and insufficient coordination between maritime and urban energy planning as the principal political barriers for UC3. By 2050 these evolve from implementation-stage friction into structural coordination requirements across three distinct policy domains: shipping, energy and urban/tourism governance.

A first barrier is the **long-term coordination of maritime, energy and urban policies**. Full realisation of net-zero passenger concepts depends on parallel decarbonisation of electricity and hydrogen systems in the ports and regions this fleet serves; incomplete alignment between shipping policy, power-system planning and city-level climate strategy could leave vessels designed for zero-emission operation without adequate clean energy access, extending the 2030-era barrier of uneven OPS and grid readiness into a broader systemic dependency. [35] [57]

A second barrier is the **robust and consistent implementation of the global net-zero framework** across flag and port states. If life-cycle GHG standards, monitoring and enforcement differ significantly between jurisdictions, passenger operators serving multi-port, multi-jurisdiction routes may face heterogeneous compliance conditions that weaken incentives to invest in best-available zero-emission technology.

Economic barriers

In 2030, the central economic barriers for UC3 were the CAPEX of OPS-ready and battery-hybrid conversions and the interdependence between ship and port investment. By 2050, with purpose-built zero-emission newbuilds replacing retrofit strategies, the economic barrier shifts to the **high capital intensity of fully zero-emission designs and the cost of the fuels and infrastructure they require**, particularly for cruise ships with sustained hotel loads.

For ferries on short routes, electrification with local renewables can often achieve a favourable total cost of ownership, extending the 2030-era case for battery-hybrid conversion to full electrification; but longer ferry and cruise routes depend on e-methanol or hydrogen-based fuels whose future price and availability remain uncertain, meaning the economic case now hinges on route geometry and fuel-supply maturity rather than retrofit cost alone. [58]

A second economic barrier is specific to cruise: **demand-side and business-model risk**. Net-zero operations raise operating costs through fuel premiums and capital charges, while passenger price sensitivity and tourism-market competition limit the extent to which these costs can be passed on; achieving sector-wide net-zero commitments also depends on fuel-supply and infrastructure investment beyond any single operator's control, creating collective-action problems and first-mover disadvantages that extend the 2030-era ship/port interdependence into a sector-wide coordination challenge. [7] [8] [9]

A third barrier, specific to ferries, is that economic feasibility continues to depend strongly on **route geometry, utilisation and integration with local energy systems**: electric concepts remain most cost-effective on short routes with surplus renewable supply, while hydrogen-

based concepts require higher onshore investment but lower onboard cost on longer lines, so not all regions may be able to finance the infrastructure a given route requires.

Social barriers

The 2030 social barrier for UC3 centred on crew and technical-staff training for early alternative-fuel and hybrid systems. By 2050, with passengers and communities directly exposed to hydrogen, ammonia and e-methanol systems on board and at berth, the barrier shifts to **building public confidence in unfamiliar fuel technologies operating in direct proximity to passengers**.

A key barrier is that hydrogen and other alternative fuels introduce unfamiliar risk profiles — fire, explosion and high-pressure systems — that must be robustly designed for and clearly communicated to maintain confidence; this is a materially higher bar for passenger vessels than for cargo-only use cases, given direct passenger and crew exposure.

A second, cruise-specific barrier is **reputational pressure related to climate and environmental impacts**: public discourse increasingly questions the compatibility of mass cruising with climate neutrality, and claims of “net-zero voyages” or “green cruises” face growing scrutiny. Reliance on offsets or fuels with contested life-cycle performance risks undermining social legitimacy in some destinations, potentially triggering stricter local restrictions.

A further barrier, common to both sub-segments, is the **workforce requirement for highly skilled technical crew** able to operate sophisticated fuel-cell and hotel-energy systems while maintaining passenger safety and comfort — a more demanding, continuously updated version of the 2030-era training gap. [25] [26]

Technological barriers

In 2030, technological barriers for passenger ships are centred on integrating early hybrid-electric systems, selective hotel-load efficiency measures and early-stage OPS into existing hulls. By 2050, with purpose-built battery/fuel-cell/e-fuel architectures as the baseline, the barrier shifts to **reliably integrating these systems at the scale and duty-cycle each sub-segment requires**.

A first barrier is **combustion, emission control and storage** for ammonia and hydrogen propulsion: mature solutions are still required for managing unburned ammonia and N₂O slip, and for cryogenic or pressurised storage, extending the 2030-era barrier of LNG containment into a more demanding safety-engineering challenge where both fuel and cargo may be hazardous. [42]

For ferries, the key barriers are achieving sufficient energy density for longer routes, fast and reliable charging or hydrogen bunkering, and integrating propulsion and hotel loads without compromising schedule reliability; feasibility has been demonstrated for fuel-cell/battery catamaran architectures, but dynamic performance under varying load and appropriately sized energy storage remain open engineering questions.

For cruise ships, the barrier is amplified by **very high and continuous hotel energy demand**: hybrid combinations of low-carbon fuels, batteries, fuel cells and shore power can

significantly cut emissions, but full voyage-scale zero-emission operation remains demanding because of storage-volume constraints and the sheer scale of energy required, extending the 2030-era barrier of selective hotel-load efficiency into a full-voyage energy-architecture challenge. [38]

Finally, as in other use cases, both ferries and cruise ships depend on **pervasive digital optimisation, automation and integrated control systems**; achieving reliable, cyber-secure operation of complex energy and passenger-service systems, potentially with higher levels of autonomy, requires software, data standards and cybersecurity solutions that are still evolving.

Although OPS and shore-power connection become the operational baseline by 2050, the 2030-era barrier of **non-harmonised OPS technical standards** (voltage, frequency, connection procedures) across ports is not automatically resolved by the maturation of alternative-fuel propulsion discussed above; unless connection standards are fully harmonised across European ports in the interim, passenger vessels serving multi-port routes may continue to face compatibility constraints at berth even once shipboard technology has matured.

Legal barriers

The 2030 legal barrier for passenger ships was fragmented compliance across IMO, EU ETS and FuelEU Maritime, compounded by uneven national implementation of OPS obligations. By 2050, with alternative fuels and OPS established as the baseline, the legal barrier shifts to **safety regulation for novel fuels in a passenger context and to the precise definition of net-zero compliance**.

A first barrier is that passenger ships face stricter safety and survivability requirements than cargo vessels, making approval of innovative fuel arrangements and machinery spaces more complex; although the IMO and classification societies are progressively expanding fuel-specific codes, full incorporation of hydrogen, ammonia and other novel fuels into passenger-ship safety frameworks remains an ongoing process. [59]

A second barrier is the **application of life-cycle GHG criteria and net-zero definitions** to passenger ships using blended, bio- and synthetic fuels: demonstrating compliant well-to-wake emissions without over-reliance on offsets, and with transparent verification across multi-jurisdiction voyages, extends the 2030-era barrier of layered IMO/EU compliance into a more technically demanding verification challenge.

Environmental barriers

In 2030, the environmental barrier for passenger ships was the risk that operational-emissions measures would not capture well-to-wake impacts. By 2050, with alternative fuels established across both sub-segments, the barrier shifts to **demonstrating genuine climate and local environmental benefit rather than measurement scope alone**.

A first barrier is that expanded use of ammonia and hydrogen as marine fuels introduces **new environmental risk profiles**: very low CO₂ emissions are offset by risks such as

ammonia toxicity to marine life, nitrogen-cycle impacts, and indirect emissions from upstream production if not carefully managed. [47]

A second barrier is that passenger vessels retain significant **local environmental footprints** even with zero-carbon fuels: underwater noise, local air pollutants from auxiliary systems, waste management and port-side energy-infrastructure impacts remain relevant, and for cruise ships the concentration of emissions and waste streams in sensitive coastal and tourism areas can generate ecosystem and community impacts beyond climate considerations.

Finally, the environmental effectiveness of zero-emission passenger shipping depends on **upstream energy-system decarbonisation**: hydrogen and electricity deliver full climate benefit only when produced from renewable or near-zero-carbon sources, and large-scale e-fuel deployment requires additional renewable capacity.

6. USE CASE 4 – INLAND WATERWAY VESSELS BARRIERS ANALYSIS

6.1. *Use Case 4: Inland Waterway Vessels Overview*

The reference vessel considered within this use case represents the core segment of European inland waterway cargo logistics, operating primarily along major river corridors such as the Rhine, Danube, and interconnected TEN-T networks. Rather than focusing on small leisure craft, this configuration models vessels engaged in bulk cargo, container transport, and general inland freight. Unlike maritime shipping, the dimensional and structural envelope of inland vessels is strictly dictated by fixed navigational infrastructure and hydrological variability. Principal dimensions are constrained by lock systems, bridge air-draft clearances, and seasonal water depths, resulting in a highly standardised European fleet. The typical length overall (LOA) ranges from 80 to 135 metres, with a beam of 9 to 17 metres and a maximum design draft strictly limited to 2.5 to 3.5 metres. Within these immutable constraints, the vessel achieves a cargo capacity of 1,500 to 4,000 tonnes, or approximately 100 to 300 TEU for container-capable configurations.

The operational profile of inland vessels is characterised by highly predictable, repetitive, and corridor-based navigation. Operations are structured around fixed routes and scheduled departures, often divided into daily or multi-day cycles covering 20 to 300 kilometers per day. Navigation occurs in sheltered waters at modest, stable speeds of 8 to 13 knots (15–24 km/h), as energy efficiency and safe passage take precedence over high transit speed. However, lock transits, speed-restricted zones, and varying river currents introduce frequent stop-and-go cycles. These variable load profiles, combined with regular port calls and minimal hotel loads, create an operational environment exceptionally well-suited for targeted electrification.

The decarbonisation trajectory for inland waterway vessels leverages the sector's unique proximity to urban and industrial infrastructure, progressing from hybrid retrofits in the 2030 timeframe to purpose-built, zero-emission platforms by 2050.

In the 2030 scenario, the technological strategy is highly pragmatic, focusing on the large-scale electrification of short-to-medium routes and hybrid solutions for longer corridors. Primary propulsion (typically 500 kW to 2.5 MW) relies on conventional diesel-mechanical configurations modified to incorporate commercially mature alternative fuels. Drop-in biofuels and Liquefied Natural Gas (LNG) serve as critical transitional fuels, mitigating local pollutants and greenhouse gas emissions without requiring profound structural modifications. For shorter routes, battery-electric systems are heavily adopted, enabling zero-emission navigation in environmentally sensitive urban areas and during manoeuvring. Because inland vessels frequently dock at river ports and logistics hubs, the 2030 strategy relies on the rapid rollout of shore-side charging infrastructure, minimising the need for massive onboard energy reserves. Advanced digital power management systems coordinate these hybrid elements, dynamically adjusting to river currents and lock delays.

By the 2050 scenario, the inland vessel undergoes a fundamental internal transformation. Crucially, the external dimensional constraints remain identical to the 2030 baseline due to the permanent nature of river locks and bridges. Therefore, the evolution is entirely focused on internal arrangement, mass distribution, and system integration. Vessels transition from

hybrid retrofits to purpose-designed hulls natively optimised for full-electric or hydrogen-electric propulsion.

Electric motors directly coupled to propellers or azimuthing units replace traditional internal combustion engines, shifting the machinery layout to distributed, modular electrical spaces. For vessels requiring extended endurance, hydrogen storage systems (pressurised or liquid) and massive battery banks are integrated directly into the hull. This introduces severe volumetric and mass constraints, necessitating the reallocation of internal space previously utilised for cargo or ballast. To preserve compliance with strict inland stability and trim criteria, 2050 designs require highly refined weight management, optimised scantlings, and lightweight structural solutions to offset the added mass of modern energy storage systems. The following table summarizes the structural, technological, and operational transition of the Inland Waterway Vessel use case across the two target timeframes.

Table 10 - Use Case 4: Inland Waterway Vessels

Feature / System	2030 Scenario (Transitional & Hybrid)	2050 Scenario (Native Zero-Emission)
External Dimensions	Constrained by locks, bridges, and draft (80–135m LOA, 2.5–3.5m draft).	Identical constraints; external geometry remains strictly bounded by river infrastructure.
Internal Architecture	Conventional diesel-mechanical layouts with modular battery retrofits.	Purpose-built hulls; internal space radically reallocated to accommodate bulky hydrogen tanks and heavy batteries.
Primary Fuel Strategy	LNG, drop-in biofuels, and hybrid battery-electric integrations.	Fully electric systems supported by high-capacity batteries and/or hydrogen fuel cells.
Propulsion System	Internal combustion engines driving conventional propellers through gearboxes.	Fully electric drive systems (direct-coupled motors or azimuthing units) with distributed electrical spaces.
Infrastructure Reliance	High reliance on emerging shore-based charging at urban/industrial nodes to minimise onboard battery size.	Seamless integration with mature, globally standardised shore charging and hydrogen bunkering networks along TEN-T corridors.



Figure 6 - Use Case 4: Inland Waterway Vessels

6.2. Use Case 4 Barriers for 2030 Horizon

This section examines the barrier analysis for **Use Case 4 (UC4): Inland Waterway Vessels** within the 2030 horizon. The inland waterway sector presents unique decarbonisation challenges due to strict vessel dimension constraints, varying river water levels, long asset lifespans, and operational proximity to urban environments.

Applying the PESTLE framework, this analysis evaluates the political, economic, social, technological, legal, and environmental factors hindering the adoption of Zero-Emission Waterborne Transport (ZEWT) technologies.

As a baseline for the following qualitative assessment, the following table provides an overview of the use case defining characteristics for 2030.

Table 11 - Use Case 4: Inland Waterway Vessels

Category	Use Case 4: Inland Waterway Vessels (2030 Horizon)
Operational Profile	Inland cargo vessels operating on rivers and canals along fixed corridors.
Typical Voyage Range	Short to medium legs with frequent port calls and repeated round trips.
Service Speed	Typical service speed in the range of 8–15 knots, limited by waterway conditions.
Vessel Size	Small to medium vessels constrained by fairway depth, locks and bridge clearances.

Category	Use Case 4: Inland Waterway Vessels (2030 Horizon)
Energy Demand Profile	Energy demand mainly driven by low-speed propulsion and frequent manoeuvring.
Total Energy Consumption	Daily energy demand moderate, linked to short routes and variable flow conditions.
Port Power Demand	Frequent berthing with low propulsion demand but relevant auxiliary and cargo-handling loads.
Design Philosophy	Retrofit-oriented design with strong constraints from shallow draft and limited deck volume.
Primary Fuel Strategy	Conventional diesel fuels with gradual uptake of biofuels and hybrid propulsion options.
Propulsion System	Conventional diesel or diesel-electric systems optimised for shallow-water operation.
Power/Electrical Architecture	Hybrid architectures with batteries supporting manoeuvring and low-emission operation in ports.
Auxiliary Load Management	Targeted efficiency on auxiliary systems during navigation and at berth.
Port Operations Objective	Reduce local emissions and noise in urban and peri-urban inland ports.
Operational Objective	Ensure reliable inland transport while decreasing GHG and pollutant emissions along waterways.

Political barriers

For the 2030 horizon, a first political barrier relevant to the inland waterway vessel of Use Case 4 arises from the fragmented governance of the European inland waterway transport system. Sector reports highlight that inland waterways in the EU are regulated through a combination of EU legislation, river commission rules and national policies, which leads to heterogeneous implementation of climate and energy measures along main corridors. [60] The lack of cross-border coordination in implementing alternative fuel strategies prevents the development of standardised "green shipping corridors". While political declarations set targets for reducing emissions, they fail to provide the standardised, binding regional mechanisms needed to coordinate public and private infrastructure spending by 2030. [61]

A second political barrier concerns the conditions for developing green energy infrastructure for inland navigation. European inland waterway platforms and initiatives on green energy underline that, for shore-side electricity and alternative fuels, political decisions are needed to prioritise core inland ports and to follow a corridor-based approach, since infrastructure deployment is currently not homogeneous along the network.

Furthermore, research highlights a disconnect between the political role assigned to inland shipping in EU transport strategies and the actual financial support it receives. Although policy programmes promote the modal shift from road to waterborne transport as a key tool for greening urban and corridor logistics, there is a mismatch between these ambitions and the scope of financial and programmatic support provided by the EU, which disproportionately favours rail and intermodal systems. This policy imbalance reduces the

competitiveness of the IWT sector, making it more difficult for operators to absorb the risks associated with the early deployment of 2030 zero-emission technologies. [62]

Economic barriers

The IWT fleet in Europe is characterised by a **large number of small and ageing vessels operated by small and medium-sized enterprises (SMEs)**. This ownership structure creates an economic barrier to ZEWT deployment, because many operators lack the capital and risk-bearing capacity needed for major retrofits or new zero-emission vessels. The European IWT Platform has therefore emphasised fleet modernisation and retrofitting as one of three key levers (alongside fuel and commercialisation) to accelerate the transition to zero-emission inland shipping. [63]

Another economic barrier arises from the **limited and route-specific business case for alternative powertrains and fuels by 2030**. Technical analyses show that LNG engines, electric vessels and hybrid systems can offer meaningful emission reductions, but they face constraints such as fuel availability, battery energy density, fuel-cell durability and cost. Solutions such as HVO have so far not been transparent in their costs which creates uncertainty for potential users. For many inland routes, especially those with low freight rates and uncertain future demand, the payback period of ZEWT investments can be too long or uncertain to justify upfront costs. Canals in the inland waterway network are expensive to maintain and build in the first instance, and adequate water supplies can also be an issue to maintain, particularly during the summer months. In some instances, this is a crucial issue as the use of a number of canals depends on a suitable supply of surface water. The recent low water levels on Germany's River Rhine attest such an issue, with barges moving at just 20-30% of capacity due to draught limitations. [64]

Moreover, the **development of supporting infrastructure** (such as charging stations and clean-energy hubs in inland ports) requires significant investment that may not be economically viable in all locations. The AFIR framework seeks to ensure minimum availability of alternative fuel infrastructure by 2030, but for IWT the coverage and timing remain less concrete than for major seaports, which can deter both operators and investors from committing to ZEWT technologies in the near term. [62]

A further economic barrier is the **risk of stranded assets from premature technology or fuel-specific investment**. Given the long operational lifetimes typical of inland vessels, operators investing now in LNG- or hybrid-specific retrofits face the risk that these choices become misaligned with future EU or CCNR regulatory requirements before the vessel's economic life is exhausted, echoing the stranded-asset risk already identified for general cargo and tanker shipping.

Fuel costs represent the single largest expense in the maritime sector, potentially accounting for over 50% of the daily operating costs of a fast or merchant vessel. Therefore, when analysing the barriers to the transition toward Zero-Emission Waterborne Transport (ZEWT) (especially looking ahead to the 2030 and 2050 strategic horizons) the primary economic obstacle lies in the cost gap between conventional petroleum-derived fuels and green alternatives. Without strong policy support or the implementation of carbon pricing mechanisms, which studies estimate must range between \$300 and \$800 per ton of CO₂

equivalent, renewable options currently struggle to achieve economic competitiveness on a global scale.

Specifically examining operating expenses (OPEX), which in the shipping sector are largely dominated by daily fuel procurement costs, liquefied natural gas (LNG) and biofuels exhibit sharply contrasting profiles. Currently, LNG offers the most advantageous performance in terms of cost-effectiveness, driven by a highly competitive baseline price. Depending on regional market dynamics, the price of fossil-based LNG can range from 16% to 66% of the price of Marine Gas Oil (MGO). Long-term average price projections (2025–2050) also confirm this advantage, estimating LNG at approximately 425 USD/t, a figure lower than the 455 USD/t forecast for Low Sulphur Fuel Oil (LSFO). However, it must be noted that operators face highly variable bunkering logistics, which can incur additional supply costs ranging from 50 to 630 USD per ton.

Conversely, biofuels face much more rigid economic barriers due to exceptionally high production and procurement costs. The OPEX for this category is fundamentally driven by the price of raw materials, such as biomass or waste oils, which can account for 25% to 90% of the total production cost. Unlike LNG, biofuel market prices far exceed those of traditional fuels: estimates indicate an average price of 1,750 USD/t for Hydrotreated Vegetable Oil (HVO) and 1,416 USD/t for Bio-LNG. While it is true that diesel-like biofuels allow for a reduction in initial capital expenditures (CAPEX), as they can be used as "drop-in" solutions without requiring complex engine retrofits, the exorbitant cost of the fuel itself ultimately translates into a massive net increase in the overall operating costs for every single voyage. [7] [8] [9]

Social barriers

The human dimension of the maritime transition presents social barriers, characterised by workforce demographics, recruitment challenges, and a specialised skills shortage. The European inland navigation workforce is an ageing labour pool, which introduces resistance to the rapid adoption of automated digital systems, electronic fuel-routing software, and hybrid energy management platforms. [61]

Furthermore, the introduction of 2030 technologies (such as pressurised and flammable LNG containment units, high-voltage battery-hybrid systems, and megawatt-scale shore connections) requires specialised technical competencies that differ from conventional diesel-mechanical operations.

A critical barrier is the lack of standardised training protocols, certified qualification standards, and refresher classes to support this transition. While international bodies like CESNI are working to update competence standards for zero-emission and automated propulsion systems, the formal integration of these standards into national licensing frameworks is slow. This delay creates a qualified labour shortage, leaving vessel operators unable to deploy retrofitted vessels because they cannot find crew members who are legally certified to handle alternative fuels or operate high-power onboard electrical systems. [10] [1]

Technological barriers

The physical and hydrological boundaries of European inland waterways impose strict engineering limitations on the integration of 2030 technologies. Unlike maritime Use Cases, the geometry of inland vessels is limited by river lock sizes, bridge clearances, and seasonal water depths. [60] Within these dimensions, alternative fuel systems and batteries introduce severe volumetric and gravimetric (weight) penalties.

Because lithium-ion battery packs and LNG containment systems have lower volumetric and gravimetric energy densities than conventional marine gas oil, they require larger internal volumes and add significant structural mass to the ship. For a retrofitted cargo vessel, accommodating these systems requires reallocating internal volume previously used for cargo or ballast, which reduces the cargo payload capacity and compromises the vessel's economic competitiveness. [65] [66]

These physical weight penalties are exacerbated by climate-induced hydrological variability. Climate change is causing more frequent and severe seasonal droughts, leading to low water levels along major arteries like the Rhine and Danube. During these low-water events, vessels must operate at extremely reduced drafts, forcing them to carry only a fraction of their standard cargo weight to avoid grounding. [67]

The added deadweight of heavy hybrid battery retrofits or dual-fuel LNG tanks acts as a physical penalty, directly compounding the cargo capacity loss during dry seasons and threatening operational viability.

At the port-grid interface, electrical capacity constraints represent a major barrier to electrification. Delivering high-power shore connections to support battery-electric vessel operations requires massive energy throughput.

However, many local utilities and municipal grids serving inland ports lack the sub-station capacity and network infrastructure to deliver this power to berths. The rising penetration of variable renewable energy in national grids also introduces power quality losses and system instability, compromising the safety and reliability of megawatt-scale port charging systems. [68]

Furthermore, retrofitting legacy vessels involves complex electrical engineering and automation challenges. Operators must integrate shore connection panels, voltage transformers, frequency converters, and modified main switchboards.

These components must be coordinated by digital PMS to prevent blackouts, harmonic distortion, and synchronisation faults during power transfer, representing a highly complex, non-standardised engineering task. [69] For vessels utilising LNG, the technology-specific barrier of methane slip from internal combustion engines also remains unresolved, as unburned methane emissions can offset the greenhouse gas reduction benefits of switching to gas.

Furthermore, as digital Power Management Systems become integral to safe shore-power transfer and hybrid-energy coordination, uncertainties related to cybersecurity, standardisation and regulatory compliance — including the NIS2 Directive (EU 2022/2555) — apply to inland vessels in the same way as to seagoing fleets, yet remain largely unaddressed in current inland-sector digitalisation planning.

Legal barriers

The legal and regulatory framework governing European inland shipping is highly fragmented, creating compliance burdens and legal uncertainties. The legislation for decarbonisation regarding inland waterways is not harmonised but involves several actors. Furthermore, in the case of ships of limited tonnage such as those operating in these waters, FuelEU Maritime and EU ETS size thresholds exclude vessels under 5000 GT, there is no harmonised, EU-wide legal framework mandating decarbonisation for the IWT fleet. [70] [60] This regulatory vacuum forces vessel owners to navigate a disjointed legal landscape of varying national taxation laws, regional voluntary emission labels, and local municipal port rules.

Furthermore, the implementation of AFIR targets for shore-side electricity, which mandates at least one connection facility in all TEN-T core inland ports by 2025 and comprehensive ports by 2030, lacks legally unified technical and operational standards.

The absence of harmonised international rules for connection interfaces, safety procedures, and the legal allocation of liability between port authorities, utility providers, and vessel operators creates administrative friction, slowing down the commercial approval of retrofitted installations.

Additionally, the development of physical infrastructure, such as installing port-side charging substations, alternative bunkering terminals, or performing fairway dredging to mitigate low-water draft restrictions, is hindered by complex, multi-layered environmental protection laws. [71]

Project developers must comply with national and EU-level environmental legislation, including biodiversity, habitat, and water protection directives. The lengthy permitting and environmental impact assessment procedures required to satisfy these overlapping regulations often delay critical infrastructure investments by years, preventing the establishment of a cohesive network of clean energy hubs along TEN-T corridors by 2030.

Furthermore, **enforcement of climate and carbon-pricing measures remains uneven along cross-border river corridors**, particularly where EU and non-EU riparian states (e.g. along the Danube) apply different levels of regulatory stringency. This creates a risk of traffic diversion toward less-regulated stretches of the network, echoing the carbon-leakage dynamic already identified for seagoing cargo and tanker shipping, and undermines the level playing field the EU's decarbonisation framework seeks to establish for the IWT sector.

Environmental barriers

The environmental viability of the 2030 transitional technologies is limited by upstream lifecycle emissions and ecological risks. The 2030 transition roadmap relies heavily on a Tank-to-Wake approach, which focuses on localised, tailpipe emission reductions at the vessel level while ignoring emissions produced upstream.

Under a comprehensive Well-to-Wake (WtW) lifecycle accounting framework, the environmental benefits of battery-hybrid systems are diminished if the electricity supplied at port berths is drawn from national grids with high fossil-fuel shares, shifting emissions from the river corridor to upstream power generation facilities. [16] [17]

For vessels utilising drop-in biofuels like HVO, the environmental benefits depend on feedstock sustainability and lifecycle greenhouse gas accounting.

The large-scale use of biofuels in shipping is constrained by limited sustainable feedstock availability and intense competition from other transport sectors, such as aviation and road transport. This supply scarcity risks driving direct and indirect land-use change, converting carbon-rich ecosystems or agricultural land to grow energy crops. If not controlled by robust, cross-border certification schemes, this can negate or reverse the lifecycle greenhouse gas savings of the biofuel, making the transition environmentally counterproductive.

Finally, the combustion of biofuels or transitional fuels like LNG and e-diesel, while reducing CO₂, continues to emit high levels of localised air pollutants, including nitrogen oxides (NO_x), carbon monoxide (CO), and particulate matter (PM).

Because inland vessels operate in close proximity to major urban populations, these ongoing tailpipe emissions conflict with local municipal "zero pollution" and air-quality targets, representing an environmental barrier to their long-term social and legal acceptance in urban river corridors. [18]

6.3. *Use Case 4 Barriers for 2050 Horizon*

This section examines the barrier analysis for **Use Case 4 (UC4): Inland Waterway Vessels** within the 2050 horizon. The reference segment remains the small-to-medium inland cargo fleet defined for this use case, operating on rivers and canals along fixed corridors with short-to-medium legs, frequent port calls and energy demand dominated by low-speed propulsion and manoeuvring. Applying the same PESTLE framework used for the 2030 assessment, this analysis evaluates the political, economic, social, technological, legal and environmental factors expected to shape ZEWT integration at this horizon, with barriers framed around the fragmented, SME-dominated structure of this sector and its exposure to hydrological variability, rather than generic maritime decarbonisation challenges.

By 2050, European inland waterway transport is expected to operate as a zero- or near-zero-emission mode, in line with the EU Green Deal objective of climate neutrality and the CCNR roadmap to largely eliminate GHG and pollutant emissions from inland navigation by mid-century. Unlike the 2030 horizon, which is built around retrofitting existing hulls with hybrid-electric systems under strong shallow-draft and deck-volume constraints, the 2050 scenario envisions a dual transformation: a modernised fleet of standardised, purpose-built zero-emission vessels — battery-electric, hydrogen, ammonia or other alternatives depending on route and vessel type — and a smart, climate-resilient waterway and port infrastructure equipped with clean-energy hubs. Zero-emission barges and push-tows are expected increasingly to operate with modular energy containers, shore-side charging and fuel-supply systems, while automation and digital twins support optimisation under variable hydrological conditions distinctive to this use case.

As a baseline for the following qualitative assessment, the following table provides an overview of the use case defining characteristics for 2050.

Table 12 - Use Case 4: Inland Waterway Vessels (2050 Horizon)

Category	Use Case 4 – Inland Waterway Vessels (2050 Horizon)
Operational Profile	Inland cargo vessels (barges and push-tows) operating on rivers and canals along fixed corridors, increasingly integrated with modular energy containers and clean-energy hubs at inland ports
Typical Voyage Range	Short to medium legs with frequent port calls and repeated round trips
Service Speed	8–15 knots, limited by waterway conditions
Vessel Size	Small to medium vessels constrained by fairway depth, locks and bridge clearances
Energy Demand Profile	Still dominated by low-speed propulsion and frequent manoeuvring, now met by battery-electric, hydrogen or ammonia systems depending on route and vessel type
Total Energy Consumption	Moderate, comparable in structure to the 2030 baseline, but increasingly sensitive to climate-driven hydrological variability affecting energy demand per tonne-kilometre
Port Power Demand	Standardised zero-emission charging or bunkering at berth via clean-energy hubs, rather than the targeted efficiency measures of 2030
Design Philosophy	Newbuild, standardised and scalable zero-emission vessel families designed from the concept stage for shallow draft, modular energy containers and automation
Primary Fuel Strategy	Battery-electric propulsion for shorter, regional routes; hydrogen or ammonia for longer-range or higher-power segments, depending on route and vessel type
Propulsion System	Full-electric or hydrogen/ammonia fuel-cell and engine systems, optimised for shallow-water operation and variable hydrological conditions
Power/Electrical Architecture	Fully electric or hybrid backbone with modular battery-container swapping and shore-side charging, replacing the 2030 hybrid-retrofit architecture
Auxiliary Load Management	Integrated, near-fully electrified auxiliary systems, with minimal residual fossil auxiliary demand
Port Operations Objective	Zero local emissions and noise in urban and peri-urban inland ports as standard practice
Operational Objective	Reliable, climate-resilient inland transport with zero or near-zero GHG and pollutant emissions, integrating adaptation to variable water levels into vessel and network design

Political barriers

The 2030 assessment identified fragmented governance across EU institutions, river commissions and national authorities, uneven green-infrastructure prioritisation, and a mismatch between IWT's policy role and its actual financial support as the principal political barriers for UC4. By 2050 these evolve from near-term coordination gaps into structural requirements for sustained, multi-decade political commitment.

A first barrier is the **need to maintain coherent, long-term commitment to both modal shift and zero-emission fleet objectives** across multiple EU programming periods; achieving full IWT carbon neutrality by 2050 requires sustained political support and coordination with national and regional policies on land use, energy and environmental protection well beyond any single funding cycle.

A second, closely related barrier is that the **fragmented governance** already identified in 2030 — spanning EU institutions, international river commissions, national authorities, regions and municipalities — may, by 2050, impede the creation of consistent corridor-based ZEWT strategies, producing disparities in the availability of zero-emission solutions along different river basins. [60] [61]

A third, use-case-specific barrier is the need to **balance decarbonisation with river restoration and biodiversity policy**: the EU Biodiversity Strategy promotes barrier removal and ecological restoration of rivers, while IWT policy seeks improved navigability for freight transport. Without integrated political frameworks, environmental and transport objectives risk conflicting, delaying investment in climate-neutral IWT corridors. [72]

Economic barriers

In 2030, the central economic barrier for inland shipping was the limited capital and risk-bearing capacity of the SME-dominated fleet, alongside route-specific business cases for alternative powertrains and uneven infrastructure investment. By 2050, with fleet renewal expected to be largely complete, the economic barrier shifts to **financing the final, capital-intensive replacement of a fragmented SME fleet** under continued competition from road and rail. [73]

Economic analyses of inland power systems show that battery-electric, hydrogen and ammonia options each carry distinct cost and feasibility profiles: electric vessels offer high decarbonisation potential but require expensive batteries and charging infrastructure, while hydrogen and ammonia enable zero-carbon operation but depend on cost-intensive fuel production and bunkering networks. For the many small operators typical of this use case, the business case still depends on predictable support schemes and stable freight volumes, extending the 2030-era uncertainty around route-specific paybacks into a longer-horizon financing challenge. [74] [75] [7]

A second economic barrier is the **need to synchronise investment in fleet and infrastructure** at full European scale. Pilot programmes have shown that electrification can be viable when paired with parallel deployment of energy containers and charging points, but scaling this model across the network by 2050 requires large, coordinated investment with long payback periods, which may be difficult to mobilise on routes with moderate or fluctuating freight

demand — extending the 2030-era barrier of uneven infrastructure coverage into a fully synchronised, network-wide investment challenge.

A third economic barrier is the growing exposure of investment decisions to climate-related hydrological uncertainty: reduced and more variable water levels, driven by shifting precipitation and glacial-melt patterns, threaten the reliable navigability of key European river corridors during low-water periods, directly affecting vessel loading capacity, service reliability and route economics. Because zero-emission newbuilds and shore-side charging or bunkering infrastructure represent long-lived, capital-intensive assets tied to specific waterway sections, this uncertainty complicates investment appraisal and may deter financiers and operators from committing to routes whose long-term navigability cannot be confidently guaranteed, adding a further layer of risk on top of the already challenging financing landscape for the sector's SME-dominated fleet.

Social barriers

The 2030 social barrier for inland shipping was centred on workforce readiness for early hybrid and digital systems. By 2050, with electric, hydrogen and ammonia propulsion and higher levels of automation established as the baseline, the barrier shifts to **sustaining a re-skilled workforce and public visibility for a sector that remains structurally less prominent than road transport**.

A key barrier is the **workforce transition**: the sector already faces ageing demographics, recruitment difficulties and a skills profile oriented toward conventional diesel technology; transitioning to electric, hydrogen or ammonia-powered vessels and more automated operations demands extensive re-skilling and attractive working conditions to retain and attract personnel, extending the 2030-era training gap into a sustained, sector-wide re-skilling requirement. [76]

A second barrier is that inland waterways continue to suffer from **low public visibility compared with road transport**, which may limit societal and political support for large ZEWT investments; without effective communication of IWT's contribution to decarbonisation and congestion reduction, local communities may not prioritise zero-emission inland corridors even where they deliver clear environmental benefits. [65] A further barrier concerns local acceptance of new **energy and charging infrastructure** along rivers and in inland ports: while such infrastructure reduces emissions and noise, concerns about safety, visual impact and land use can slow permitting, particularly in densely populated or environmentally sensitive areas. [77]

Technological barriers

A first barrier is that, although ammonia and advanced electric systems are promising long-term options, they still require further development to address combustion stability, NOx control, battery energy density and fuel-cell longevity; the optimal technology mix continues to depend strongly on route length, vessel size and local energy resources, extending the 2030-era barrier of route-specific feasibility into a still-unresolved propulsion-maturity question. [42]

A second barrier is that automation and zero-emission propulsion affect **vessel design and performance**: adopting electric propulsion and higher automation changes general arrangement, cargo capacity, safety and structural design, and not all vessel classes are equally suited to fully zero-emission concepts, making standardised, scalable vessel families for diverse European waterways a continuing design challenge.

A third, use-case-specific barrier is that **climate-induced hydrological variability** means water levels, currents and navigability fluctuate more strongly, directly influencing energy consumption and route planning; In some instances, climate change does not merely alter hydrological conditions but can threaten the very existence of inland waterways, forcing a complete re-routing of the voyage with obvious economic repercussions.

A further barrier, already identified for 2030 and not necessarily resolved by 2050, is the **capacity of local and regional electricity grids serving inland ports**. As battery-electric propulsion becomes the standard rather than the exception by 2050, aggregate power demand at inland berths increases substantially; unless sub-station capacity and grid reinforcement keep pace with fleet-wide electrification, the 2030-era barrier of insufficient local grid capacity may persist or intensify, rather than being automatically resolved by vessel-side technology maturation.

Legal barriers

The 2030 legal barrier for UC4 was the complex, evolving regulatory framework covering vessel standards, environmental requirements and state aid. By 2050, with EU and CCNR objectives largely translated into binding rules, the legal barrier shifts to **the completeness and cross-border consistency of technical and safety frameworks for zero-emission vessels**.

A first barrier is that technical regulations such as ES-TRIN, originally developed for conventional propulsion, are being updated to accommodate alternative fuels, batteries and automation; until these frameworks fully integrate zero-emission technologies and provide clear, stable rules for design approval and cross-border recognition, legal uncertainty may still inhibit investment in innovative vessel types, extending the 2030-era regulatory-adaptation barrier into a completeness question by 2050. [78]

A second barrier is that cross-border IWT corridors must navigate **different national implementations of EU directives and river-commission rules**, which can produce discrepancies in enforcement, permitting and support schemes across countries; incomplete legal harmonisation may still expose operators to administrative burdens and inconsistent conditions along multi-state routes, extending the 2030-era governance fragmentation into the legal domain.

Environmental barriers

In 2030, the environmental barrier for UC4 was ensuring that measures captured genuine lifecycle benefit as the sector modernised. By 2050, with the fleet largely decarbonised, the barrier shifts to **ensuring that IWT's growth as a freight mode does not compromise climate and ecological objectives**.

A first barrier is the **interaction between navigation infrastructure and river ecosystems**: river-restoration initiatives aimed at improving biodiversity and removing barriers can conflict with the need to maintain or upgrade navigation channels, so achieving both climate-neutral IWT and healthy river ecosystems requires integrated environmental planning and potentially new infrastructure concepts that minimise ecological disturbance.

Finally, **hydrological impacts of climate change** — more frequent low-water or high-water events — pose environmental and operational risks distinctive to this use case: fluctuating water levels can reduce cargo loads, increase emissions per tonne-kilometre and necessitate detours or increased dredging, with associated environmental impacts. Zero-emission IWT in 2050 must therefore be climate-resilient, integrating adaptation measures into vessel design, operations and infrastructure planning to preserve both environmental performance and transport reliability.

7. USE CASE 5 – SPECIAL OPERATION VESSELS BARRIERS ANALYSIS

7.1. *Use Case 5: Special Operation Vessels Overview*

The reference vessel considered within this use case represents a statistically derived configuration of special operation vessels active in European maritime contexts, encompassing offshore support vessels (OSVs), platform supply vessels (PSVs), anchor handling tug supply vessels (AHTS), and harbour service units. To maintain analytical robustness, the vessel is defined within the most recurrent dimensional envelope for European service craft: a length overall (LOA) of 55 to 70 metres, a beam of 12 to 15 metres, and a draft of 4.0 to 5.0 metres. Installed propulsion power ranges from 3.0 to 4.5 MW, typically delivered by two medium-speed diesel engines in a twin-screw or azimuth thruster arrangement to ensure high bollard pull and precise dynamic response. Designed for mission-driven tasks rather than transit efficiency, service speeds are limited to 11 to 13 knots. Notably, the technical considerations developed for this use case also serve as a partial proxy for large European fishing vessels, which exhibit similar operational patterns, intermittent high-load phases, and comparable auxiliary demands, representing an estimated 5 MtCO₂ of annual emissions.

The operational profile of special operation vessels is fundamentally distinct from conventional cargo or passenger ships, characterised by a highly transient load profile and task-driven missions within a limited geographical radius of 50 to 150 nautical miles from a base port. The daily duty cycle is defined by a severe mismatch between installed capacity and average power demand. Approximately 40–60% of operational time is spent in low-load or standby conditions (e.g., at quay or awaiting assignment) requiring less than 20–30% of installed power. Transit phases account for 20–30% of the cycle at moderate loads, while critical peak operational phases—such as towing, dynamic positioning, or offshore intervention—make up the remaining 10–20%, demanding near 100% of installed capacity. This fluctuating energy demand, compounded by mission-specific auxiliary loads from heavy deck machinery, frequently forces conventional engines to operate outside their optimal efficiency range, creating a strong imperative for advanced energy management.

Consequently, the 2030 decarbonisation strategy for this vessel class is distinctly power-centric, prioritising hybridisation and load optimisation over the complete substitution of conventional fuels. Primary propulsion remains reliant on internal combustion engines running on drop-in biofuels, coupled with advanced Battery Energy Storage Systems (BESS). Rather than providing sustained propulsion, these batteries are sized for high-power discharge (kW) to enable peak shaving, load leveling, and zero-emission operation during extended standby phases. This hybrid-electric architecture allows the internal combustion engines to operate smoothly at peak efficiency, absorbing transient shocks during sudden towing or manoeuvring events. Advanced Power and Energy Management Systems (PMS/EMS) are strictly required to coordinate these complex energy flows dynamically. Furthermore, deck machinery is fully electrified to minimise peak loads on the main engines, while highly efficient controllable pitch propellers and azimuth thrusters maximise thrust vectoring. In this timeframe, disruptive alternative fuels like LNG or hydrogen are considered unfeasible due to severe onboard storage constraints and incompatibility with rapid load fluctuations.

By the 2050 scenario, the special operation vessel undergoes a comprehensive architectural evolution to achieve native zero-emission capabilities. While the external dimensions required for port maneuverability and escort operations remain unchanged from the 2030 baseline, the internal geometry is radically redesigned. The hybrid mechanical systems of 2030 are replaced by fully electric-dominant configurations, driven by electric motors supplied by massive battery banks and integrated hydrogen fuel cell systems. This fundamental shift requires the reallocation of below-deck volumes to accommodate bulky hydrogen storage tanks and distributed electrical spaces, increasing overall displacement. Because preserving bollard pull and dynamic stability is paramount, weight sensitivity becomes the defining design constraint of the 2050 vessel. Naval architects must employ lightweight structural materials, compact energy storage solutions, and highly refined centre-of-gravity positioning to offset the mass of zero-emission systems, ensuring the vessel retains its critical manoeuvring performance and compliance with stringent harbour regulations.

The following table summarizes the structural, technological, and operational transition of the Special Operation Vessel use case across the two target timeframes.

Table 13 - Use Case 5: Special Operation Vessels

Feature / System	2030 Scenario (Hybrid & Power-Centric)	2050 Scenario (Native Zero-Emission)
External Dimensions	55–70m LOA, 12–15m beam; optimised for robust manoeuvring and deck strength.	Dimensions remain unchanged to ensure operability in confined ports and coastal zones.
Internal Architecture	Conventional engine rooms supplemented by modular battery energy storage spaces.	Distributed machinery spaces; volume radically reallocated to house hydrogen tanks and large battery banks.
Propulsion Strategy	Medium-speed internal combustion engines paired with hybrid-electric systems (BESS).	Electric-dominant architectures utilising electric motors driven by batteries and hydrogen fuel cells.
Energy Management	Batteries used strictly for peak shaving, spinning reserve, and zero-emission standby.	Batteries and fuel cells provide the entirety of the power demand across all transient load phases.
Alternative Fuels	Drop-in biofuels (LNG and hydrogen considered unfeasible due to space/transient load limits).	Completely reliant on climate-neutral energy carriers (primarily hydrogen and clean electricity).

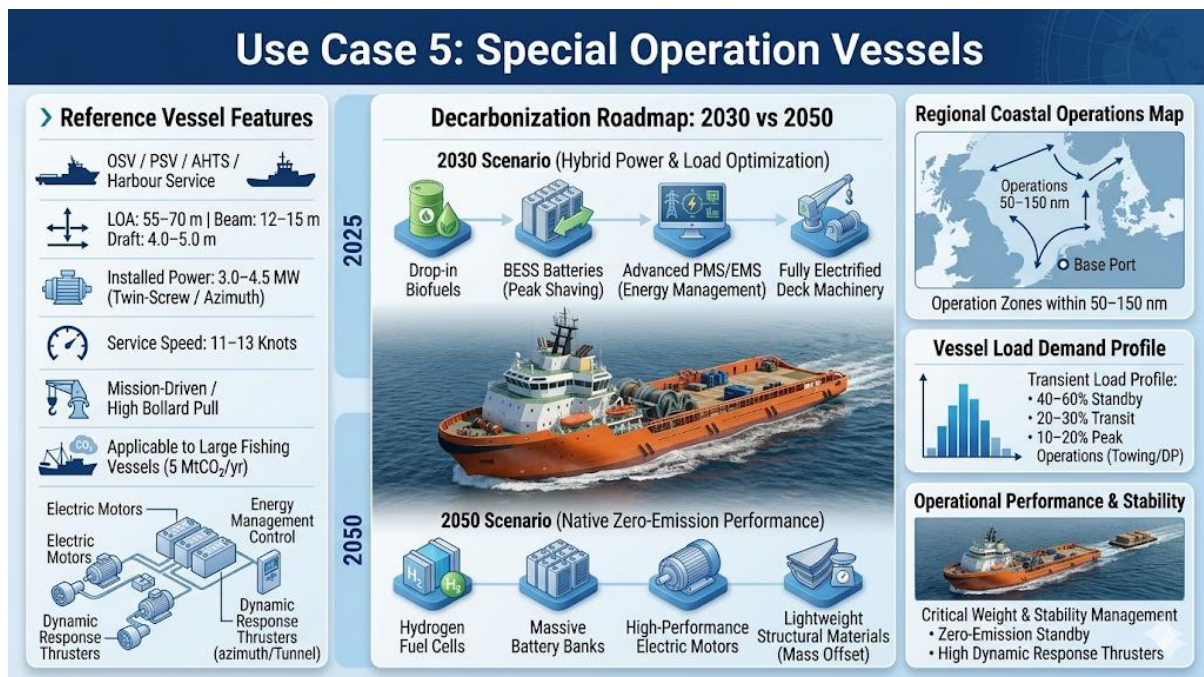


Figure 7 - Use Case 5: Special Operation Vessels

7.2. Use Case 5 Barriers for 2030 Horizon

This section examines the barrier analysis for **Use Case 5 (UC5): Special Operation Vessels** within the 2030 horizon. This highly heterogeneous segment presents unique decarbonisation challenges due to extremely variable operational profiles, high power-demand peaks, and critical safety requirements related to dynamic positioning and redundancy. Applying the PESTLE framework, this analysis evaluates the political, economic, social, technological, legal, and environmental factors hindering the adoption of Zero-Emission Waterborne Transport (ZEWT) technologies.

As a baseline for the following qualitative assessment, the following table provides an overview of the use case defining characteristics for 2030.

Table 14 - Use Case 5: Special Operation Vessels

Category	Use Case 5: Special Operation Vessels (2030 Horizon)
Operational Profile	Specialised vessels providing harbour, coastal and offshore support services.
Typical Mission Profile	Short but highly dynamic operations with frequent power transients and standby phases.
Service Area	Mainly coastal and port areas, sometimes nearshore offshore fields and infrastructure.
Vessel Size	Small to medium units with high installed power relative to length and displacement.

Category	Use Case 5: Special Operation Vessels (2030 Horizon)
Energy Demand Profile	Energy demand dominated by transient propulsion and high bollard-pull or thrust requirements.
Total Energy Consumption	Daily consumption highly variable, driven by task intensity and operational duty cycle.
Port Power Demand	Frequent returns to port with significant demand during standby, hotel and auxiliary operations.
Design Philosophy	Robust, maneuverability-focused designs with strong constraints from mission-specific equipment.
Primary Fuel Strategy	Conventional marine fuels with growing use of biofuels and pilot hybrid solutions.
Propulsion System	High-maneuverability propulsion (e.g. azimuth thrusters) designed for low-speed, high-thrust work.
Power/Electrical Architecture	Hybrid architectures combining engines, electric drives and batteries for peak shaving.
Auxiliary Load Management	Efficiency measures targeting winches, cranes, pumps and mission-related auxiliaries.
Port Operations Objective	Reduce emissions and noise in ports and coastal areas during standby and low-load operation.
Operational Objective	Maintain high operational readiness and maneuverability while lowering GHG and pollutant emissions.

Political barriers

A major political barrier is that **special operations vessels are not always prioritised to the same degree as deep-sea commercial fleets** in maritime decarbonisation strategies. National and international policy documents often focus first on larger vessel classes or on those with clearer compliance exposure to IMO and EU measures, while smaller or operationally specialised vessels may be addressed later or through more targeted subsector policies. This can delay the creation of strong, segment-specific ZEWI signals.

A second political barrier concerns the **dependency of these vessels on local or sectoral policy ecosystems**. Tug decarbonisation depends heavily on port authorities, concession structures and local infrastructure decisions, while OSV decarbonisation is shaped by offshore energy policy, especially in oil and gas and offshore wind contexts. Where these governance frameworks do not explicitly include low- and zero-emission service vessels in their investment and procurement priorities, the transition is likely to remain fragmented.

There is also a **coordination challenge between maritime and energy policies**. Electrified tugs and hybrid OSV require shore-side power, charging systems or access to alternative fuels that are not automatically delivered by general shipping policy alone. Without integrated planning between port, grid and maritime authorities, the policy ambition for ZEWI in this segment may exceed the practical capacity to implement it by 2030.

Economic barriers

The financial viability of the 2030 transition roadmap for special operation vessels is severely constrained by high upfront capital expenditure (CAPEX). Integrating advanced marine BESS, power electronics, and modified electrical architectures within the restricted hull forms of existing service craft is highly complex and cost-prohibitive. The market cost of a fully electric or hybrid newbuild vessel is approximately double that of a conventional diesel equivalent, a cost premium that is exceptionally difficult to amortise under current market conditions. This financial barrier is particularly acute because the local towage, offshore service, and fishing sectors are dominated by small and medium-sized enterprises (SMEs) that lack the deep capital reserves and risk-bearing capacity of large international container lines.

Fuel costs represent the single largest expense in the maritime sector, potentially accounting for over 50% of the daily operating costs of a fast or merchant vessel. Therefore, when analysing the barriers to the transition toward Zero-Emission Waterborne Transport (ZEWI) (especially looking ahead to the 2030 and 2050 strategic horizons) the primary economic obstacle lies in the cost gap between conventional petroleum-derived fuels and green alternatives. Without strong policy support or the implementation of carbon pricing mechanisms, which studies estimate must range between \$300 and \$800 per ton of CO₂ equivalent, renewable options currently struggle to achieve economic competitiveness on a global scale.

Specifically examining operating expenses (OPEX), which in the shipping sector are largely dominated by daily fuel procurement costs, liquefied natural gas (LNG) and biofuels exhibit sharply contrasting profiles. Currently, LNG offers the most advantageous performance in terms of cost-effectiveness, driven by a highly competitive baseline price. Depending on regional market dynamics, the price of fossil-based LNG can range from 16% to 66% of the price of Marine Gas Oil (MGO). Long-term average price projections (2025–2050) also confirm this advantage, estimating LNG at approximately 425 USD/t, a figure lower than the 455 USD/t forecast for Low Sulphur Fuel Oil (LSFO). However, it must be noted that operators face highly variable bunkering logistics, which can incur additional supply costs ranging from 50 to 630 USD per ton.

Conversely, biofuels face much more rigid economic barriers due to exceptionally high production and procurement costs. The OPEX for this category is fundamentally driven by the price of raw materials, such as biomass or waste oils, which can account for 25% to 90% of the total production cost. Unlike LNG, biofuel market prices far exceed those of traditional fuels: estimates indicate an average price of 1,750 USD/t for Hydrotreated Vegetable Oil (HVO) and 1,416 USD/t for Bio-LNG. While it is true that diesel-like biofuels allow for a reduction in initial capital expenditures (CAPEX), as they can be used as "drop-in" solutions without requiring complex engine retrofits, the exorbitant cost of the fuel itself ultimately translates into a massive net increase in the overall operating costs for every single voyage.

Another barrier is represented by the possibility of **stranded investment**: operators committing capital to a specific hybrid or fuel pathway ahead of clearer segment-specific regulation (see Legal barriers below) risk that their choice becomes commercially or technically obsolete before the investment is recovered, a risk already flagged for general

cargo and tanker shipping and equally applicable to this capital-intensive, long-lived segment.

Social barriers

The human and organisational dimensions of the maritime transition present significant social barriers to deploying 2030 technologies on special operation vessels. The integration of complex hybrid-electric drivetrains, high-voltage battery networks, and advanced digital PMS/EMS requires a profound shift in seafarer and technical staff competencies. However, the sector is constrained by severe skills shortages and training gaps across key disciplines, including electrical, electronic, and software engineering. Current maritime education and training curricula are adjusting too slowly, resulting in a critical lack of standardised guidance and certified instruction on the storage, handling, and operation of high-voltage battery systems and alternative fuel blends on board specialised craft.

This training deficit creates a dual challenge for shipboard operations: seafarers must manage escalating systemic occupational risks, such as high-voltage electrical hazards and thermal runaway events, without a mature safety culture or standardised emergency response procedures in place. The inability to easily develop and execute appropriate safety cases for hybrid and alternative-fuelled vessels represents a major bottleneck. Consequently, vessel operators face a qualified labour shortage, leaving them unable to deploy technically ready hybrid fleets because they cannot find crew members who are legally certified to operate these novel systems.

Furthermore, these challenges are exacerbated by the demographic profile and cultural characteristics of the workforce. The crew and management structures of local towage, service, and coastal fleets are often characterised by an ageing labour pool with deeply entrenched operational traditions. This demographic trend introduces substantial resistance to the rapid adoption of automated power-routing software, digital monitoring systems, and unfamiliar onboard procedures. This cultural friction, combined with broader industry concerns regarding recruitment, retention, and the lack of career path development, severely limits the capacity of specialised vessel operators to absorb and sustain the human transition required for 2030 technologies. [12]

Although these vessels play a critical role due to their high frequency of operation near port areas, thereby generating significant emissions that directly affect both the municipality and the port infrastructure, they are nevertheless regarded as marginal. As a result, they are consistently overlooked and do not receive the requisite consideration from the public sphere. [79] [80] [81]

Technological barriers

The core technological barrier for special operations vessels is the **difficulty of matching ZEWT technologies to highly variable, power-intensive operational profiles**. Harbour tugs need high bollard pull and rapid response, while OSV may require dynamic positioning, extended offshore endurance and complex auxiliary loads. These operating conditions make the direct transfer of ZEWT solutions from ferries technically inappropriate in many cases.

For tugs, battery-electric concepts are technically promising, but their viability depends on **battery capacity, charging time and duty-cycle alignment**. Early electric tug projects show that zero-emission harbour duties are possible under suitable charging conditions, including fast charging or overnight connection. However, widespread replication by 2030 is limited by the need to ensure that battery systems can cover real operational peaks without compromising towing capability or turnaround time.

For OSV, the main technological pathway to 2030 is **hybridisation rather than full ZEWT**. Industry and research sources indicate that battery integration, energy-storage systems and hybrid propulsion can significantly reduce emissions, but that full zero-emission operation remains constrained by fuel availability, energy density and the complexity of offshore mission requirements. This means that alternative fuels and high-capacity storage systems are likely to remain at partial deployment stage in 2030 rather than being standard across the fleet.

A further technological barrier concerns the cybersecurity and functional safety of digital Power and Energy Management Systems (PMS/EMS) increasingly used to coordinate hybrid propulsion, battery management and mission-critical auxiliary loads on tugs and OSV. Given the safety-critical nature of these vessels' operations (towing, dynamic positioning, emergency response), a cyber incident or software failure affecting propulsion coordination could have more immediate safety consequences than on cargo vessels, making compliance with the NIS2 Directive (EU 2022/2555) and robust cyber-resilience design a distinct barrier for this use case.

Legal barriers

A key legal barrier is the **limited maturity of segment-specific regulatory frameworks** for low- and zero-emission service vessels. Under the European Union's "Fit for 55" package, from January 1, 2025, the amended EU MRV Maritime Regulation extends its scope to offshore ships of 400 gross tonnage (GT) and above, legally requiring operators to establish precise greenhouse gas emissions monitoring and reporting plans. However, the EU ETS only includes large offshore vessels exceeding 5,000 GT starting January 1, 2027, leaving vessels between 400 and 5,000 GT under ongoing review.

Crucially, offshore support vessels are currently excluded from the FuelEU Maritime Regulation. This regulatory misalignment creates a fragmented legal compliance landscape where operators must invest in administrative data collection and reporting without the clear legal and economic structures of FuelEU or ETS for their specific vessel class.

This regulatory asymmetry is further complicated by the complete absence of mandatory international safety codes specifically governing battery installations and alternative fuel bunkering on board specialised vessels. At the international level, maritime administrations and class societies must rely on non-mandatory guidelines, such as the advisory safety guidance published by the European Maritime Safety Agency (EMSA) in 2023, and fragmented, country-specific requirements. [54]

A further legal barrier is the risk of uneven enforcement of carbon-pricing and emissions measures across jurisdictions in which OSV and harbour tugs operate, particularly for OSV servicing offshore assets that may fall under different flag-state or coastal-state regimes.

Where regulatory stringency differs significantly between operating areas, this can create a carbon-leakage-type incentive to relocate service contracts toward less-regulated jurisdictions, mirroring the barrier already identified for general cargo and tanker shipping.

Environmental barriers

Environmentally, special operations vessels are important because they often operate in **sensitive port and offshore environments**, where emissions contribute directly to local air pollution and to the carbon footprint of wider logistics and energy systems. Harbour tugs may be few in number but are highly visible and operate close to population centres, while OSV form a critical part of offshore supply chains with substantial cumulative emissions.

Another environmental issue is the **life-cycle and energy-supply dimension** of ZEWI technologies. Batteries and low-carbon fuels only yield deep environmental benefits if electricity and fuel production are sufficiently low-carbon, and several studies on transport electrification more generally emphasise that upstream energy systems remain decisive for total climate benefit. Under a comprehensive Well-to-Wake (WtW) lifecycle accounting framework, the environmental benefits of battery-hybrid systems are diminished if the electricity supplied at port berths is drawn from national grids with high fossil-fuel shares, shifting emissions from the the port and coastal environmentst to upstream power generation facilities. [16] [17]

For vessels utilising drop-in biofuels like HVO, the environmental benefits depend on feedstock sustainability and lifecycle greenhouse gas accounting.

The large-scale use of biofuels in shipping is constrained by limited sustainable feedstock availability and intense competition from other transport sectors, such as aviation and road transport. This supply scarcity risks driving direct and indirect land-use change, converting carbon-rich ecosystems or agricultural land to grow energy crops. If not controlled by robust, cross-border certification schemes, this can negate or reverse the lifecycle greenhouse gas savings of the biofuel, making the transition environmentally counterproductive.

Finally, the combustion of biofuels or transitional fuels like LNG and e-diesel, while reducing CO₂, continues to emit high levels of localised air pollutants, including nitrogen oxides (NO_x), carbon monoxide (CO), and particulate matter (PM).

Because special operation vessels, particularly harbour tugs, operate in close proximity to major urban populations, these ongoing tailpipe emissions conflict with local municipal "zero pollution" and air-quality targets, representing an environmental barrier to their long-term social and legal acceptance in port cities and coastal hubs. [18]

7.3. Use Case 5 Barriers for 2050 Horizon

This section examines the barrier analysis for **Use Case 5 (UC5): Special Operation Vessels** within the 2050 horizon. The reference segment remains the highly heterogeneous fleet of harbour tugs and offshore support vessels (OSV) defined for this use case, combining high installed power, rapid load variation, low average sailing distance and mission-critical manoeuvring or offshore-service functions. Applying the same PESTLE framework used for the 2030 assessment, this analysis evaluates the political, economic, social, technological,

legal and environmental factors expected to shape ZEWI integration at this horizon, with barriers framed around the structurally different duty cycles of tugs and OSV rather than generic maritime decarbonisation challenges.

By 2050, special operations vessels are expected to form an integral part of net-zero port and offshore ecosystems, rather than being treated as a marginal auxiliary segment.

Unlike the 2030 horizon, which is built around hybrid architectures combining conventional engines, electric drives and batteries for peak shaving within pilot-scale deployments, the 2050 scenario assumes purpose-built zero-emission designs differentiated by mission: harbour tugs are expected to rely predominantly on battery-electric or battery-dominant hybrid architectures, supported by high-power shore charging and renewable port electricity, because their short and repetitive duty cycles are structurally suited to electrification. OSV, by contrast, are expected to follow more diversified pathways combining batteries with hydrogen-based fuels, ammonia, methanol or other zero-/near-zero-GHG fuels, depending on endurance requirements, dynamic-positioning loads and offshore energy-supply conditions. As a result, the 2050 challenge for this use case is not simply proving technical feasibility, but establishing safe, scalable and economically viable ZEWI architectures across highly heterogeneous vessel classes.

As a baseline for the following qualitative assessment, the following table provides an overview of the use case defining characteristics for 2050.

Table 15 - Use Case 5: Special Operation Vessels (2050 Horizon)

Category	Use Case 5 – Special Operation Vessels (2050 Horizon)
Operational Profile	Specialised vessels providing harbour, coastal and offshore support services, now treated as an integral part of net-zero port and offshore ecosystems rather than a marginal auxiliary segment
Typical Mission Profile	Short but highly dynamic operations with frequent power transients and standby phases for tugs; longer-endurance, dynamic-positioning-intensive missions for offshore support vessels (OSV)
Service Area	Mainly coastal and port areas for tugs; nearshore and offshore fields and infrastructure for OSV
Vessel Size	Small to medium units with high installed power relative to length and displacement
Energy Demand Profile	Transient propulsion and high bollard-pull demand for tugs, met by battery-electric systems; long-endurance and dynamic-positioning loads for OSV, met by hydrogen-, ammonia- or methanol-based hybrid systems
Total Energy Consumption	Highly variable, driven by task intensity and duty cycle, now met by zero- or near-zero-GHG energy sources across the duty cycle rather than by conventional fuel
Port Power Demand	High-power shore charging and renewable port electricity as standard for tugs; standardised bunkering infrastructure for OSV fuels

Category	Use Case 5 – Special Operation Vessels (2050 Horizon)
Design Philosophy	Newbuild, purpose-built zero-emission architectures differentiated by mission: battery-dominant for tugs, multi-fuel hybrid for OSV, rather than the pilot/retrofit approach of 2030
Primary Fuel Strategy	Tugs: battery-electric or battery-dominant hybrid; OSV: hydrogen-based fuels, ammonia, methanol or other zero-/near-zero-GHG fuels, depending on endurance and dynamic-positioning requirements
Propulsion System	High-maneuvrability propulsion (e.g. azimuth thrusters) powered by battery-electric drives for tugs, or multi-fuel hybrid systems for OSV
Power/Electrical Architecture	Fully electric backbone with high-power shore charging for tugs; hybrid multi-fuel electrical architecture with large-scale energy storage for OSV
Auxiliary Load Management	Winches, cranes, pumps and mission-related auxiliaries electrified and optimised at the design stage, rather than retrofitted for efficiency
Port Operations Objective	Zero emissions and noise in ports and coastal areas during standby and low-load operation, as standard practice
Operational Objective	Maintain high operational readiness and manoeuvrability at zero or near-zero GHG and pollutant emissions across highly heterogeneous vessel classes

Political barriers

The 2030 assessment identified lower policy prioritisation relative to deep-sea commercial fleets and dependency on local or sectoral policy ecosystems as the principal political barriers for UC5. By 2050 these evolve from a prioritisation gap into a structural requirement to embed this heterogeneous segment explicitly within wider net-zero strategies.

A first barrier is the **need to explicitly embed special operations vessels within net-zero port and offshore strategies**: general shipping decarbonisation frameworks continue to prioritise deep-sea commercial fleets, while tugs and OSV may be addressed only indirectly through port or offshore policy; by 2050, the persistence of fossil-fuelled service vessels would undermine claims of truly net-zero maritime clusters, extending the 2030-era prioritisation gap into a credibility risk for entire port ecosystems. [82] [83]

A second barrier is the **interaction between maritime decarbonisation and offshore energy policy**. OSV are closely linked to offshore oil and gas, offshore wind and subsea logistics, so their transition depends on the decarbonisation trajectories of these sectors as much as on shipping policy; if offshore industrial policy continues to support carbon-intensive activity without requiring zero-emission support logistics, OSV decarbonisation may lag behind the maritime sector's formal net-zero ambitions. [84]

A third barrier is a **port-energy governance challenge**: fully electric tugs and hybrid/fuel-based OSV fleets require port authorities and coastal energy planners to coordinate charging, bunkering and grid reinforcement; where this coordination remains weak, special operations vessels may still face slower ZEWT uptake than larger vessels benefiting from

stronger international policy attention, extending the 2030-era dependency on local policy ecosystems into a persistent coordination requirement. [85]

Economic barriers

In 2030, the central economic barrier for UC5 was the high CAPEX of hybrid retrofits relative to the specialised, often small-scale business models of tug and OSV operators. By 2050, with purpose-built zero-emission newbuilds replacing pilot-scale hybrids, the economic barrier shifts to **financing mission-differentiated zero-emission fleets under contract structures that do not automatically reward higher CAPEX**.

Tug operators typically work under concession or service contracts with ports, while OSV earnings depend on cyclical offshore markets and project-based chartering; neither structure automatically rewards the higher upfront cost of zero-emission propulsion, even where lifecycle emissions benefits are substantial, extending the 2030-era split-incentive barrier into a still-unresolved contractual misalignment. [86]

For harbour tugs, full electrification is technically attractive by 2050, but the **economic case still depends on charging infrastructure, electricity price, duty cycle and asset utilisation**; in ports with irregular tug deployment or limited grid capacity, the economics of zero-emission towage may remain challenging despite technical maturity, extending the 2030-era infrastructure-dependency barrier rather than resolving it.

For OSV, the economic barrier is more pronounced because long missions and high auxiliary loads limit the applicability of pure electrification: net-zero compliance requires ammonia, methanol, hydrogen or other costly fuels, often in hybrid configurations, together with safety and storage systems that raise CAPEX and operational complexity. These costs can only be justified if offshore charterers and energy clients are willing to internalise low-carbon logistics within project economics, which remains uncertain in many offshore sectors.

Social barriers

The 2030 social barrier for UC5 centred on skills shortages and lack of standardised training for early hybrid systems. By 2050, with battery-electric tugs and multi-fuel hybrid OSV established as the baseline, the barrier shifts to **retaining and continuously upskilling crews to the level of technical proficiency these mission-critical vessels require**.

A key barrier is that tugs and OSV perform critical missions — towage, escort, emergency response, anchor handling, offshore support — where propulsion failure or reduced responsiveness can have immediate safety consequences; even in 2050, widespread adoption of zero-emission systems depends on whether crews, port operators, charterers and regulators trust these systems to match or exceed the reliability of conventional diesel configurations.

A second barrier concerns the **skills transition for complex fuel and power systems**: zero-emission tugs and OSV involve batteries, power electronics, fuel cells or combustion systems for ammonia and methanol, together with new safety procedures for handling toxic, flammable or cryogenic fuels, extending the 2030-era training gap into a more demanding, continuously updated competence requirement specific to this segment. [87] [36] A further barrier is local social acceptance: while zero-emission service vessels reduce local air pollution and noise, associated infrastructure such as battery charging stations, hydrogen

bunkering or ammonia storage may be perceived as risky or intrusive in densely populated port areas, making public confidence in these systems a continuing condition for deployment.

Technological barriers

In 2030, technological barriers for UC5 centred on integrating early hybrid architectures into robust, manoeuvrability-focused hulls constrained by mission-specific equipment. By 2050, with mission-differentiated zero-emission designs as the baseline, the barrier shifts to **matching zero-emission energy systems to the segment's extreme and heterogeneous power profiles**.

Harbour tugs require very high short-duration power for towing and manoeuvring, while OSV require long endurance, dynamic positioning and operation in remote offshore environments; as a result, no single ZEWI solution dominates the entire segment, extending the 2030-era barrier of hybrid-architecture integration into a still-unresolved diversity of technical pathways.

For tugs, battery-electric systems remain particularly promising given bounded operations and access to shore charging, but technical challenges persist in sizing batteries for peak bollard-pull demand, preserving battery life under repeated high-power cycles, and ensuring rapid recharging without disrupting service schedules; for some classes, hybridisation may still be needed to guarantee resilience.

For OSV, the main barrier concerns the **integration of high-energy-density fuels with advanced hybrid systems**: ammonia is frequently identified as a leading long-term marine fuel for its zero-carbon combustion potential, methanol offers storage and handling advantages but lower zero-carbon certainty unless sustainably produced, and hydrogen may suit selected offshore applications where local production is available, though storage volume and system complexity remain limiting. These trade-offs make standardised, scalable OSV ZEWI architectures technologically demanding even in a mature 2050 setting, extending the 2030-era barrier of mission-specific equipment constraints into a fuel-selection and system-integration challenge. Taken together, UC5's 2050 technological barriers concern matching heterogeneous, mission-specific power profiles to an equally heterogeneous set of zero-emission energy carriers.

Legal barriers

The 2030 legal barrier for UC5 was the lack of segment-specific rules for early alternative-fuel and hybrid systems in high-maneuvring, safety-critical vessels. By 2050, with these technologies established as the baseline, the barrier shifts to **the completeness of harmonised, segment-specific legal frameworks**.

A first barrier is the **lack of fully harmonised, segment-specific rules for zero-emission service vessels**: although broad IMO and class frameworks for alternative fuels continue to advance, harbour tugs and OSV often require specialised treatment because of their proximity operations, high manoeuvring loads and safety-critical roles; if approval and compliance continue to depend heavily on case-by-case arrangements, legal uncertainty may persist even where the underlying technologies are mature. [88]

A second barrier concerns the **treatment of local port requirements and concession frameworks**: tug services are often governed by port-specific rules or licensing systems, while OSV operations depend on sector-specific offshore regulations and chartering standards; unless these frameworks explicitly include zero-emission requirements and transparent methods for rewarding lifecycle performance, the market may fail to support the necessary ZEWI investments, extending the 2030-era local-governance dependency into the legal domain.

A third barrier is legal clarity on the **safe use and environmental liability of ammonia, methanol, hydrogen and large battery systems** in ports and offshore zones: the IMO's net-zero trajectory and related lifecycle accounting increase pressure to adopt compliant fuels, but legal uncertainty over accident liability, environmental damage and fuel certification could still slow uptake in this sensitive segment.

Environmental barriers

In 2030, the environmental barrier for UC5 was that residual fossil-fuelled operation in sensitive port and coastal environments carried disproportionate local impacts. By 2050, with net-zero port and offshore ecosystems as the expectation, the barrier shifts to **ensuring genuine lifecycle benefit rather than merely eliminating combustion emissions**.

A first barrier is that special operations vessels continue to operate in **highly sensitive port, coastal and offshore environments**, where emissions, noise and spill risks have disproportionate local impacts; by 2050, ports and offshore clusters are expected to present themselves as net-zero ecosystems, so continued reliance on residual fossil-fuelled service vessels would become increasingly inconsistent with these wider environmental claims.

A further legal barrier concerns whether the **exclusion of offshore support vessels from FuelEU Maritime**, already identified as a 2030-era regulatory gap, has been resolved by 2050. If OSV remain outside the scope of FuelEU Maritime while other segments operate under a mature, harmonised compliance framework, this would leave a structural regulatory asymmetry unaddressed even in a mature 2050 setting; the analysis should state explicitly whether this exclusion is assumed to persist, be resolved, or be superseded by a broader net-zero port framework.

A third barrier is that the environmental benefit of ZEWI solutions depends on the **life-cycle performance of fuels and electricity supply**: ammonia, methanol and hydrogen support deep decarbonisation only when produced from renewable or very low-carbon pathways, otherwise shifting emissions upstream rather than eliminating them — a barrier particularly relevant for OSV, whose high energy demand could make them significant consumers of zero-emission fuels in offshore logistics chains.

Finally, some zero-emission pathways introduce **new environmental risk profiles**: ammonia toxicity, methanol spills, battery end-of-life impacts and the environmental footprint of new port energy infrastructure all require careful management. Special operations vessels in 2050 must therefore not only eliminate combustion emissions but also fit within a broader environmental governance framework addressing lifecycle sustainability and local ecological risk.

8. STAKEHOLDER PERSPECTIVES ON ZEWI BARRIERS

This chapter presents the findings emerging from the semi-structured stakeholder interviews conducted within the TRUSTEE consultation process, and examines the extent to which they confirm, refine, or extend the barriers to Zero-Emission Waterborne Transport (ZEWI) deployment identified through the literature-based PESTLE analysis. The purpose of this chapter is threefold: (i) to test the external validity of the previously identified barriers against first-hand stakeholder experience; (ii) to surface concerns, trade-offs and enabling conditions that emerged specifically from practitioner insight and were not, or not fully, captured by the literature review; and (iii) to characterise areas of convergence and divergence across different stakeholder profiles.

Consistent with the overall methodology of this deliverable, the stakeholder evidence is organised around the same PESTLE dimensions (Political, Economic, Social, Technological, Legal, Environmental) used, allowing a direct, section-by-section comparison between the literature-derived barrier set and the barriers, uncertainties, enabling conditions and recommendations that emerged from the interviews.

The evidence base for this chapter derives from semi-structured interviews conducted with stakeholders and experts engaged through the TRUSTEE stakeholder consultation process, spanning academic and research experts, an industry association, a ship design/shipbuilding company, an EU policymaking body, and a vessel operator. Interviews were conducted in English or Italian, following a common interview guide covering feasibility of the 2030/2050 targets, barriers and constraints, underestimated trade-offs, enabling conditions, technological pathways, operational and retrofit considerations, safety and security concerns, and priority recommendations. Each transcript was analysed through a structured thematic coding process, in which relevant passages were classified by macro-theme, sub-theme, time horizon (2030, 2050, both, or not specified) and type of contribution (barrier, uncertainty, enabling condition, recommendation, evidence/example, or general assessment). For the purposes of this chapter, the resulting codes have been cross-mapped onto the six PESTLE dimensions used, to allow direct comparison with the literature-based barrier analysis.

In line with the project's ethical and data protection requirements, all interview evidence is anonymised throughout this chapter. Findings are attributed only by broad stakeholder role (for example, "the industry association representative" or "the EU policy officer"); individual interviews are not separately identified or numbered, and no names, specific job titles that could enable identification, or organisation names are disclosed.

For each PESTLE dimension, the analysis is structured into three parts: (a) barriers and uncertainties that confirm findings already established in Chapters 3 to 7; (b) issues, trade-offs or enabling conditions that emerged from the interviews but were not explicitly captured, or were only partially captured, in the literature-based analysis; and (c) distinctions made by interviewees between the 2030 and 2050 horizons, where relevant. It should be noted that most interviewees addressed ZEWI deployment in general, cross-cutting terms rather than with reference to a specific Use Case (UC1–UC5); where an interviewee's evidence is specific to a vessel type or operating context, this is indicated explicitly.

8.1. *Political dimension*

Political barriers concern the alignment of international and regional governance, the stability and predictability of the regulatory environment, and geopolitical conditions affecting the transition.

Confirmation of previously identified barriers

The interviews strongly confirm the barrier, relating to the misalignment between international (IMO) and regional (EU) decarbonisation frameworks. Half of the interviewees raised this issue spontaneously and without prompting specifically about it. The EU policy officer described the postponement of the IMO net-zero framework agreement as having caused a number of financial decisions to be paused pending greater clarity and stressed that European decarbonisation alone cannot resolve global maritime emissions, since the largest share of emissions originates from long-distance international shipping. The industry association representative similarly warned that, should the IMO fail to adopt sufficiently ambitious measures, shipowners trading internationally could face diverging regional requirements across Europe, the Americas and Asia. The energy decarbonisation expert framed the same concern in structural terms, arguing that unilateral EU targets risk having limited real-world effect on a transnational sector such as shipping unless major trading partners adopt comparable commitments.

The interviews also confirm the importance, already flagged in the literature-based analysis, of regulatory predictability as a precondition for investment. A third of interviewees explicitly linked long vessel lifetimes (25–50 years) to the need for stable, trustworthy regulatory frameworks over multi-year horizons. The industry association representative cited the precedent of LNG-fuelled vessels, whose investment case was later undermined when LNG was reclassified as insufficiently “green”, as a concrete illustration of the risk that policy instability poses to long-term capital commitments; the ship design industry representative made a structurally identical argument with specific reference to EU ETS and FuelEU Maritime.

Issues emerging from stakeholder consultation

Beyond confirming existing findings, half of the interviewees raised a geopolitical dimension of the political barrier that adds a further layer to Chapters 3–7: the risk that uneven global climate commitment, or active disinvestment by some international actors, could undermine the conditions needed to reach the 2050 target. The environmental impact researcher cited, as a concrete illustration, an attempted defunding of an international ocean-sensor monitoring network, which was contained only after opposition from the international scientific community. The energy decarbonisation expert and the EU policy officer both referred, independently, to the risk associated with key maritime chokepoints (e.g. the Strait of Hormuz) for fuel and energy supply security, framing this as a rational long-term planning consideration for a sector in which vessels can remain in service for several decades.

A further, more specific issue raised by a third of interviewees is the existence of a regulatory divergence between the EU and neighbouring non-EU operating contexts. The industry

association representative observed that many small and medium vessels are still built outside the EU, meaning that part of the EU's own deployment targets will in practice be met by external competitors, often using EU-manufactured equipment. The vessel operator, active in a non-EU regulatory context, provided first-hand evidence of the practical consequence of this divergence: a substantial share of the fleet operating in that context consists of older vessels no longer compliant with EU regulation and displaced to jurisdictions with lower regulatory standards. This finding adds a concrete operational illustration to the cross-jurisdictional divergence already flagged in Chapters 3–7 — both through the Legal pillar's reference to an uneven playing field across jurisdictions arising from fragmented enforcement of key regulations, and through the Political pillar's discussion of the compliance complexity facing vessels that alternate between intra-EU, international and third-country routes — and points to a geographically differentiated feasibility of the 2030/2050 targets that may warrant further attention as additional interviews are completed.

Finally, a smaller share of interviewees raised a distinct political risk that offers a further angle on Chapters 3–7: the possibility that ambitious, costly decarbonisation policies could generate public debate and political polarisation, particularly where parts of the population perceive limited short-term personal benefit relative to the costs involved. This dynamic was described as already visible in several EU countries and identified as a risk to the political stability needed to sustain the transition over time.

2030 versus 2050 horizon

Most political barriers raised by interviewees were not explicitly attributed to one horizon over the other, reflecting their structural and cross-cutting nature. Where a horizon was specified, interviewees tended to associate international regulatory alignment (IMO/EU) and geopolitical risk more strongly with the 2050 horizon, on the grounds that the cumulative effect of misalignment or disinvestment becomes more consequential the further the target horizon extends.

Table 16 summarizes the recurrent Political-dimension issues identified across the interview sample.

Table 16 - Recurrent Political-dimension issues raised by interviewees

Recurrent issue	Share of interviewees
Misalignment between international (IMO) and regional (EU) decarbonisation frameworks	50%
Absence of long-term regulatory predictability discouraging investment	33%
Geopolitical risk (fuel-route chokepoints, uneven global climate commitment, disinvestment risk)	50%

Recurrent issue	Share of interviewees
Regulatory divergence between EU and neighbouring non-EU operating contexts	33%
Risk of political/social polarisation eroding sustained policy support	17%

8.2. Economic dimension

Economic barriers concern the cost-competitiveness of ZEWI solutions, access to finance, and the distribution of transition costs across the value chain.

Confirmation of previously identified barriers

The interviews provide the strongest and most consistent confirmation of any barrier examined in this chapter: the full set of interviewees raised cost, in one form or another, as a central barrier to ZEWI deployment. This directly corroborates the Economic pillar of Chapters 3–7, which identifies the CAPEX/OPEX gap between conventional and zero-emission solutions as a primary obstacle. Several interviewees provided evidence that sharpens the scale of this gap beyond what is captured in the literature-based analysis: the energy decarbonisation expert illustrated the cost differential using the aviation sector as a benchmark, noting that while aviation fuel margins allow some room for higher-cost sustainable fuels, the cost gap for alternative marine fuels is an order of magnitude — not a marginal difference — and is expected to become an increasingly binding constraint as deployment deadlines approach. The ship design industry representative confirmed, from direct commercial experience, that shipowners currently do not find zero-emission vessels cost-competitive to build or operate, despite genuine interest in emissions reduction within the limits of continued profitability.

The interviews also confirm the relevance of fuel price and availability uncertainty as a distinct economic barrier, raised by half of the interviewees. The EU policy officer identified uncertainty over which fuels will be available, where, and at what price as the single most important economic barrier, noting that vessel investment decisions commit owners for approximately 30 years, so unresolved fuel-supply uncertainty has a disproportionately large effect on investment behaviour. The industry association representative made a structurally similar point regarding the EU's FuelEU Maritime regulation, which was assessed as failing to resolve the fundamental question of fuel availability and cost, with fuel providers seen as insufficiently incentivised relative to shipowners and shipyards.

Issues emerging from stakeholder consultation

A third of interviewees raised a specific dimension of the financing barrier that adds further detail to Chapters 3–7: constrained access to commercial (as opposed to public) finance. The industry association representative reported that ship financing from European commercial banks has become almost non-existent since the 2007–2008 financial crisis, owing to risk-averse legislation, and contrasted this with more favourable financing conditions reportedly offered to shipowners in China, suggesting greater use of European Investment Bank

guarantees as a way to unlock commercial investment. The EU policy officer corroborated this concern from the EU institutional side, acknowledging limited visibility into private-sector financing difficulties and suggesting greater use of public procurement to build a pipeline of bankable projects.

A further, more specific concern — raised explicitly by one interviewee and echoed in part by another, through the lens of shipowner resistance — is the risk that smaller shipowners and SMEs will bear a disproportionate share of the transition cost and will face greater difficulty establishing the trust-based relationships needed to access new, specialised supply chains, favouring larger and earlier-moving firms. This builds directly on the Economic pillar's existing recognition that fleets composed largely of small, SME-operated vessels face constrained capital and risk-bearing capacity for retrofit investment, extending it into a broader equity concern about how transition costs are distributed by firm size.

2030 versus 2050 horizon

Interviewees generally treated the cost barrier as relevant across both horizons, though several noted that fuel price and availability uncertainty is expected to become more binding as the 2050 deadline approaches and as a larger share of the fleet is required to transition. No interviewee suggested that the economic barrier would be resolved by 2030 without dedicated intervention.

Table 17 summarises the recurrent Economic-dimension issues identified across the interview sample.

Table 17 - Recurrent Economic-dimension issues raised by interviewees

Recurrent issue	Share of interviewees
Cost / cost-competitiveness gap between zero-emission and conventional solutions	100%
Uncertainty over future fuel availability and price	50%
Constrained access to commercial/bank financing	33%
Disproportionate cost burden on smaller shipowners / SMEs	17% expl.; 33% broad

8.3. Social dimension

Social barriers concern workforce skills and training, occupational safety, public and worker acceptance of new technologies, and the equitable distribution of the costs and benefits of the transition.

Confirmation of previously identified barriers

The interviews confirm the relevance of the skills and training barrier already identified in Chapters 3–7. Half of the interviewees explicitly identified the need for structured investment in training, upskilling and reskilling as a precondition for the safe and effective deployment of ZEWT technologies; an additional interviewee raised a related, broader point about the need for improved general scientific literacy from school level, bringing the share of interviewees raising some form of education or training need to 67%. The industry association representative linked this directly to the fact that zero-emission technologies and fuels require different competences from both seafarers and shore-based integration personnel; the vessel operator provided first-hand operational evidence, noting that crew retraining will be required and that vessel downtime for retrofit work compounds the operational cost of the transition.

The interviews also confirm the relevance of public and worker acceptance as a barrier, already flagged in the Social pillar of Chapters 3–7, while adding fuel-specific detail. The EU policy officer noted that the acceptance of new, flammable or explosive fuels such as ammonia is a distinct concern for both workers handling the fuel and residents of port cities, and stressed that this requires adequate knowledge-sharing and testing to build trust before large-scale deployment.

Issues emerging from stakeholder consultation

Half of the interviewees raised, independently, a concern about the equitable distribution of the costs and benefits of the transition that adds further texture to Chapters 3–7. The environmental impact researcher argued for a genuinely “360-degree” engagement of all stakeholder categories, including those less directly engaged with environmental or scientific issues, on the grounds that this wider group ultimately determines whether change becomes real; the EU policy officer noted that smaller shipowners, including the many SMEs active in EU ship ownership, are likely to bear a disproportionate share of the transition cost and to face greater difficulty establishing trust-based relationships with new, specialised supply chains; the vessel operator echoed this concern from an operational perspective, anticipating resistance from shipowners in contexts where the rationale for costly technical changes is not well understood or communicated.

Closely related to this, a specific and recurrent issue raised by a third of interviewees — and touched upon less directly by others — is a communication and understanding gap between shipowners, regulatory bodies and, in some cases, crew. The vessel operator described this as the central obstacle to smooth deployment in their operating context, noting that shipowners are often not themselves from the shipbuilding industry and, without a clear explanation of the rationale for costly technical requirements, tend to resist them by default, and recommended bringing shipowners and regulatory bodies together as the single highest-priority enabling action. This framing extends, to the shipowner-regulator relationship, the trust dimension the Social pillar already associates with confidence among crews, port operators, charterers and regulators in the reliability of new systems, and is highlighted here as a further angle worth incorporating alongside the existing skills-gap framing.

Finally, it should be noted that the political-social polarisation risk discussed in Section 8.1 under the Political dimension also has a clear social dimension, insofar as it concerns the distributional perception of costs and benefits among the wider population rather than within the maritime sector alone; it is cross-referenced here to avoid duplicating the analysis.

2030 versus 2050 horizon

Interviewees did not generally differentiate social barriers by horizon, treating training, acceptance and equity concerns as preconditions that need to be addressed early — well ahead of the 2030 horizon — in order to avoid compounding resistance or skills shortages as deployment accelerates towards 2050.

Table 18 summarises the recurrent Social-dimension issues identified across the interview sample.

Table 18 - Recurrent Social-dimension issues raised by interviewees

Recurrent issue	Share of interviewees
Need for structured training / upskilling / reskilling of the workforce	50%; 67% incl. broader education point
Public/worker acceptance of new, flammable or explosive fuels (e.g. ammonia)	17% explicit
Equitable distribution of transition costs and benefits across stakeholder groups	50%
Communication/understanding gap between shipowners, regulators and crew	33%

8.4. Technological dimension

Technological barriers concern the maturity, integration, and operational suitability of propulsion systems, fuels, and enabling infrastructure.

Confirmation of previously identified barriers

The interviews confirm, and add operational detail to, the retrofit-related barriers already discussed extensively in Chapters 3–7. Half of the interviewees addressed retrofit feasibility directly. Two of them converged independently on the same refinement of the existing analysis: retrofit economic viability depends primarily on vessel age rather than vessel type, since structural elements such as the engine room are typically purpose-built around a specific propulsion system, making older vessels (one interviewee cited vessels over 25 years old, another cited vessels over 50 years old) largely uneconomical to retrofit and more likely to require replacement. The ship design industry representative added a complementary,

segment-level nuance, noting that retrofit is more likely to deliver efficiency gains and partial emissions reductions than full decarbonisation, and that the choice between retrofitting and newbuilding will vary case by case.

The interviews also confirm the technology-specific safety concerns associated with ammonia and hydrogen already noted in Chapters 3–7, with two thirds of interviewees raising this point independently. Interviewees consistently singled out ammonia as comparatively more safety-critical owing to its toxicity (and, per the energy decarbonisation expert, its markedly higher nitrogen oxide emissions relative to conventional fuels), while battery-electric propulsion was associated with fire risk considered broadly comparable to that of electric vehicles.

Issues emerging from stakeholder consultation

A striking and consistent pattern across two thirds of interviewees is the explicit expectation that no single technological pathway will dominate; instead, several pathways (electrification, ammonia, methanol, hydrogen, wind-assisted propulsion, and increasingly nuclear propulsion) are expected to develop and be deployed in parallel, with the preferred solution depending on vessel segment, trade pattern and shipowner preference. The industry association representative linked this directly to a deliberate technology-neutral advocacy position; the vessel operator, by contrast, expressed this as a source of genuine uncertainty, citing the current lack of large-scale commercial deployment behind any specific solution as a reason for caution. This finding nuances, rather than contradicts, the current analysis in Chapters 3–7, which tends to discuss technology pathways in a more solution-specific manner; it suggests that the barrier analysis may benefit from an explicit acknowledgement of multi-pathway uncertainty as a barrier in its own right, distinct from the maturity of any individual technology.

The single most notable emerging theme in the sample is nuclear propulsion, raised independently by two thirds of interviewees as an increasingly discussed — if still very early-stage — pathway for larger, more energy-intensive vessels, opening a new angle to consider alongside the technology pathways already covered in Chapters 3–7. The EU policy officer situated this most precisely, noting that nuclear propulsion for shipping remains at a very low technology readiness level, citing ongoing efforts in China and South Korea to integrate small modular reactors into vessels, and noting that a prior EMSA study and a follow-up EU-funded coordination and support action are assessing technical feasibility, while the regulatory, legislative and public-acceptance dimensions of small modular reactor adoption remain largely unaddressed. The ship design industry representative confirmed that nuclear solutions depend on substantial capital investment and further technology development, but noted that deployment could in principle proceed faster than traditional land-based nuclear projects. Given that this theme was raised spontaneously (i.e. not directly prompted by the interview guide) by a majority of interviewees to date, it is flagged as a priority candidate for explicit inclusion in a future revision of the Technological pillar.

Finally, half of interviewees provided converging operational evidence for the “chicken-and-egg” dynamic between infrastructure and vessel-side technology already noted under the Political pillar of Chapters 3–7, here from a specifically technological angle: the EU policy

officer observed that port infrastructure development lags behind vessel-side technology partly because ports are awaiting clarity on which fuels and energy systems the fleet will ultimately adopt before committing to investment; the ship design industry representative confirmed that infrastructure for electrification (batteries, offshore charging, grid capacity) is currently insufficient to support growing customer demand; and the vessel operator provided a concrete, non-EU illustration, describing bunkering infrastructure on their operating waterway as currently underdeveloped, which they identified as a reason the 2050, rather than the 2030, horizon appears more realistic.

2030 versus 2050 horizon

Interviewees consistently associated electrification with the 2030 horizon and smaller/shorter-range vessel segments, and associated ammonia, hydrogen and — more tentatively — nuclear propulsion with the 2050 horizon and larger, longer-distance, more energy-intensive segments. This pattern was explicit for the ship design industry representative and the EU policy officer, and consistent with the general assessments offered by the industry association representative and the vessel operator.

Table 19 summarises the recurrent Technological-dimension issues identified across the interview sample.

Table 19 - Recurrent Technological-dimension issues raised by interviewees

Recurrent issue	Share of interviewees
Retrofit economic viability determined primarily by vessel age rather than vessel type	50%
Ammonia and hydrogen flagged as comparatively more safety-critical fuel pathways	67%
Expectation that multiple technology pathways will develop in parallel, with no single dominant solution	67%
Nuclear propulsion raised as an emerging pathway not currently covered in the barrier analysis	67%
Port/bunkering infrastructure lagging behind vessel-side technology (“chicken-and-egg” dynamic)	50%

8.5. Legal dimension

Legal barriers concern certification and classification requirements, digitalisation, and the regulatory treatment of safety, security and cybersecurity.

Confirmation of previously identified barriers

The interviews confirm the certification-related barrier already discussed in Chapters 3–7 in relation to classification society approvals. A third of interviewees raised the cost and complexity of testing and certifying new solutions as a distinct barrier. The EU policy officer explained that real-world testing is comparatively expensive in the maritime sector because vessels are largely bespoke and cannot easily be discarded or mass-produced as pilot units can in the automotive sector, which creates a structural disadvantage for maritime technology validation relative to other transport sectors; work is reportedly ongoing to develop lower-burden testbeds. The industry association representative added that safety analysis needs to extend beyond the product itself to the handling, maintenance and repair processes around it, citing the precedent of the first LNG-fuelled vessels, for which shipyards had to develop entirely new maintenance procedures and manuals.

The interviews also confirm the relevance of cybersecurity as a legal and regulatory concern, already noted in Chapters 3–7 with reference to the NIS2 Directive. Half of the interviewees raised cybersecurity independently. The ship design industry representative reported that cybersecurity is an area of growing investment for ship designers, citing known attempts to compromise ship and related infrastructure systems; the vessel operator, while noting that digitalisation in their own operating context remains relatively modest, acknowledged that increased automation inherently introduces cybersecurity risk and expressed confidence that lessons from more digitally mature sectors (e.g. aviation) can be adapted.

Issues emerging from stakeholder consultation

A specific and, at this stage, single-source concern raised by the industry association representative (17%) is that current regulation, although formally presented as technology-neutral, may not be fully so in practice: near-zero-emission solutions such as high-pressure fuel cells are, according to this account, disadvantaged relative to “full zero” solutions even where their overall life-cycle performance is comparable or better. This adds a practice-level nuance to the Legal pillar’s existing discussion of compliance ambiguity and regulatory burden.

A related and broader emerging theme, raised specifically by the same interviewee (17%) but touching on issues referenced more generally by other interviewees under cybersecurity, concerns data governance: who processes and owns operational data generated by sensors and ship-to-shore communication systems, what the data are used for, and where they are stored. A specific geopolitical dimension of this question was also noted, observing that vessels built outside the EU may carry onboard systems and sensors whose data-access arrangements are not fully transparent to the operator. This data-governance dimension complements the cybersecurity considerations already flagged in the Legal pillar, including its reference to the NIS2 Directive, by extending them to the specific question of who owns and controls vessel-generated operational data.

Finally, a third of interviewees illustrated, from different operating contexts, a gap between the existence of safety regulation and its practical observance. The vessel operator cited a recent incident at a port, attributed to a failure in the safety-regulation chain, as evidence that the primary vulnerability lies less in the adequacy of safety rules themselves than in the

practical awareness and preparedness of owners and crew; the industry association representative made a structurally similar point in relation to the introduction of new maintenance procedures for LNG-fuelled vessels. This framing — an implementation and awareness gap rather than a regulatory-text gap — nuances the existing Legal pillar, which currently focuses primarily on the adequacy and digitalization of the regulatory text itself.

2030 versus 2050 horizon

Certification and testing barriers were not explicitly attributed to one horizon over the other. Cybersecurity was the only Legal-dimension issue for which an interviewee suggested an implicit temporal trend, noting that its relevance is expected to grow as automation and digitalisation of vessels increases over time, positioning it as an issue of increasing rather than diminishing importance towards 2050.

Table 20 summarises the recurrent Legal-dimension issues identified across the interview sample.

Table 20 - Recurrent Legal-dimension issues raised by interviewees

Recurrent issue	Share of interviewees
Cost and complexity of testing/certifying new solutions (bespoke vessels, classification society approval)	33%
Cybersecurity of digital/automated ship systems	50%
Regulation not fully technology-neutral in practice (near-zero vs full-zero treatment)	17%
Data governance (ownership, processing, storage) of vessel-generated operational data	17%
Gap between existence of safety regulation and its practical observance/awareness	33%

8.6. Environmental dimension

Environmental barriers concern the scope and rigour of life-cycle environmental assessment, the management of environmental trade-offs associated with alternative fuels and energy sources, and the resilience of the transition to environmental and climatic variability.

Confirmation of previously identified barriers

The interviews confirm the central importance of comprehensive, well-to-wake life-cycle assessment already established in Chapters 3–7, while providing practitioner evidence of a gap between this principle and current assessment practice. A third of interviewees reported that, in practice, environmental assessments in industry are frequently limited to carbon footprint or CO₂ alone, with comparatively little awareness that CO₂ functions primarily as a proxy indicator and that other climate-forcing substances can have a materially larger

impact. The environmental impact researcher noted that a fully well-to-wake perspective would additionally require attention to water footprint (direct and indirect), water quality, toxicity-related impacts, eutrophication and acidification — categories that are not systematically incorporated into current practice.

The interviews also confirm the environmental risk profile of ammonia already flagged in Chapters 3–7, while shifting emphasis from marine toxicity towards direct human-health impact. A third of interviewees raised concerns regarding nitrogen oxide (NO_x) and N₂O emissions from ammonia combustion. The energy decarbonisation expert stressed that these emissions represent a direct human-health hazard distinct from, and additional to, ammonia's climate or marine-ecosystem impact; the EU policy officer noted that the actual climate impact of the associated N₂O emissions is still not fully understood and requires further research before large-scale deployment.

Finally, the interviews confirm the land-use and feedstock-related environmental trade-offs already discussed in Chapters 3–7 in relation to biofuels, while adding a specific socio-economic dimension. The energy decarbonisation expert (17%) raised the classic food-versus-fuel competition risk associated with biomass-based fuel production, questioning whether marginal CO₂ reductions justify potential upward pressure on food prices or added burden on livestock farming — a framing that complements, without duplicating, the ecosystem- and land-conversion framing already present in the existing analysis.

Issues emerging from stakeholder consultation

A cross-sectoral trade-off already flagged at a general level in Chapters 3–7 — which notes intensified competition for clean energy resources with other industrial sectors — is developed further by the ship design industry representative (17% explicit; a related point on renewable diversification was also made by another interviewee, broadening this to 33%): the volume of clean energy required to produce e-fuels for shipping may have been underestimated relative to the pace of new renewable energy deployment, and shipping competes for the same green electricity as land-based industry decarbonisation, which — owing to energy losses in fuel production — is likely to deliver a greater emissions reduction per unit of green electricity than shipping does. This adds a specific cross-sectoral prioritisation angle to the renewable energy allocation question already noted in the Environmental pillar.

A second theme, raised independently by a third of interviewees, offers a further angle not yet explicitly covered in Chapters 3–7: the resilience of the transition to climate variability and extreme weather itself. The environmental impact researcher noted that vessel routes may need to change within the same day in response to adverse weather or current conditions, requiring continuous technological adaptability rather than a one-off design solution. The energy decarbonisation expert provided a concrete illustration from the energy supply side, citing an unusually hot, dry summer that reduced river flow and hydropower output, to argue that renewable energy output itself — and not only fossil supply — is vulnerable to climate variability, with direct implications for the reliability of the clean electricity supply that ZEW T fuel pathways depend upon.

2030 versus 2050 horizon

Interviewees generally treated environmental assessment-scope and trade-off issues as relevant across both horizons. The cross-sectoral renewable-energy competition raised by the ship design industry representative was framed as an increasingly binding constraint towards 2050, as both shipping and land-based sectors scale up demand for green electricity simultaneously.

Table 21 summarises the recurrent Environmental-dimension issues identified across the interview sample.

Table 21 - Recurrent Environmental-dimension issues raised by interviewees

Recurrent issue	Share of interviewees
Environmental assessment in practice narrower than the well-to-wake principle it is meant to follow (CO ₂ /carbon-footprint focus)	33%
NO _x / N ₂ O emissions from ammonia combustion — human-health impact and unresolved climate impact	33%
Food-versus-fuel and livestock-feed competition risk from biomass-based fuel production	17%
Cross-sectoral competition for green electricity between shipping e-fuels and land-based decarbonisation	17% explicit; 33% broad
Vulnerability of the transition to climate variability and extreme weather (operational and renewable-supply side)	33%

8.7. Cross-cutting synthesis

Table 22 consolidates the barriers, uncertainties, enabling conditions and recommendations identified across all six PESTLE dimensions in Sections 8.1–8.6, together with the associated time horizon and the share of interviewees raising each issue.

Table 22 - Consolidated stakeholder-derived barriers, uncertainties, enabling conditions and recommendations

Dimension	Barrier / uncertainty	Enabling condition / recommendation	Horizon
Political	Lack of alignment between IMO and EU regulatory frameworks	Sustain EU regulatory ambition while actively pursuing international (IMO-level) alignment	Both
Political	Absence of long-term regulatory predictability discourages investment	Provide stable, long-horizon (10–15+ year) regulatory roadmaps	Both

Dimension	Barrier / uncertainty	Enabling condition / recommendation	Horizon
		with minimal retroactive reclassification risk	
Political	Geopolitical risk (fuel-route chokepoints, uneven global climate commitment, disinvestment risk)	Diversify fuel sourcing and strengthen strategic/energy autonomy	2050
Political	Regulatory divergence between EU and non-EU operating contexts	Extend technical support and awareness-raising to neighbouring non-EU jurisdictions	Both
Political	Risk of political/social polarisation eroding sustained policy support	Combine positive climate-action narrative with clear regulatory obligation and market incentives	Not specified
Economic	Cost / cost-competitiveness gap between zero-emission and conventional solutions	Continued public research funding; incentive design 96prioritising commercially competitive pathways	Both
Economic	Uncertainty over future fuel availability and price	Resolve fuel-supply uncertainty as a precondition for accelerating retrofit and supply-chain adaptation	Both (more acute by 2050)
Economic	Constrained access to commercial/bank financing	Greater use of EIB-type guarantees; public procurement to build bankable project pipelines	Not specified
Economic	Disproportionate cost burden on smaller shipowners / SMEs	Targeted support mechanisms and financing conditions for smaller operators	Not specified
Social	Workforce skills and training gap for new fuels/technologies	Dedicated training, upskilling and certification schemes ahead of deployment scale-up	Precondition, pre-2030
Social	Public/worker acceptance of new, hazardous fuels (e.g. ammonia)	Knowledge-sharing, testing and safety-by-	Not specified

Dimension	Barrier / uncertainty	Enabling condition / recommendation	Horizon
		design with structured end-user involvement	
Social	Inequitable distribution of transition costs and benefits	Broad, “360-degree” engagement of all stakeholder categories, including less-engaged actors	Not specified
Social	Communication/understanding gap between shipowners, regulators and crew	Structured dialogue platforms bridging technical rationale and cost implications	Not specified
Technological	Retrofit economic viability strongly age- rather than type-dependent	Differentiate retrofit vs newbuild policy support by fleet age profile	2050
Technological	Ammonia and hydrogen flagged as comparatively safety-critical pathways	Further R&D on combustion/safety performance; dedicated crew training	Both
Technological	No single dominant technology pathway; multi-pathway uncertainty	Maintain technology-neutral funding and regulation; prioritise real-world testing over further desk research	Both
Technological	Nuclear propulsion emerging as a pathway not yet reflected in the barrier analysis	Explicit inclusion of nuclear propulsion (incl. SMR) in future scenario and barrier-analysis updates	2050
Technological	Port/bunkering infrastructure lagging behind vessel-side technology	Sequence infrastructure investment with clearer fleet-level fuel decisions (“chicken-and-egg” resolution)	Both
Legal	Cost and complexity of testing/certifying new solutions	Lower-burden testbeds; shared classification-society protocols	Not specified
Legal	Cybersecurity of digital/automated ship systems	Extend NIS2-aligned requirements with explicit data-governance provisions	Increasing towards 2050
Legal	Regulation perceived as not fully technology-neutral in practice	Review regulatory treatment of near-zero	Not specified

Dimension	Barrier / uncertainty	Enabling condition / recommendation	Horizon
		vs full-zero solutions on a full life-cycle basis	
Legal	Gap between existence of safety regulation and its practical observance	Strengthen enforcement and awareness mechanisms alongside regulatory text	Not specified
Environmental	Environmental assessment in practice narrower than the well-to-wake principle (CO ₂ -only focus)	Mandate multi-indicator environmental assessment (beyond CO ₂) in ZEW project appraisal	Not specified
Environmental	Nox/N ₂ O emissions from ammonia combustion – human-health impact and unresolved climate effect	Further research on N ₂ O climate impact and Nox mitigation ahead of large-scale ammonia deployment	Not specified
Environmental	Food-versus-fuel and land-use competition risk from biomass-based fuels	Robust feedstock sustainability safeguards (reinforcing provisions already identified in Chapters 3–7)	Not specified
Environmental	Cross-sectoral competition for green electricity between shipping e-fuels and land-based decarbonisation	Cross-sectoral renewable energy allocation planning	2050 (increasingly binding)
Environmental	Vulnerability of the transition to climate variability and extreme weather	Integrate climate-adaptation considerations into ZEW infrastructure and operational planning	Not specified

8.8. Discussion: convergence and complementarity with the literature-based barrier analysis

Taken together, the interview evidence gathered to date shows a high degree of convergence with the barriers identified through the literature-based PESTLE analysis in Chapters 3–7, alongside a smaller number of issues that extend, nuance, or offer a further angle on the existing analysis.

Convergence is strongest in the Economic dimension, where the full set of interviewees to date raised the cost-competitiveness gap in some form, providing the most robust confirmation of any barrier examined in this chapter. Convergence is also substantial in the Technological dimension (retrofit feasibility, ammonia/hydrogen safety) and in the Legal

dimension (certification cost, cybersecurity), where stakeholder accounts largely corroborate, and add operational texture to, findings already present in Chapters 3–7.

The interviews add most distinct value in three respects. First, in the Political dimension, they add a concrete operational illustration to the cross-jurisdictional divergence already flagged in Chapters 3–7 — through the Legal pillar's reference to an uneven playing field across jurisdictions and the Political pillar's discussion of vessels operating across intra-EU, international and third-country routes — by documenting a geographically differentiated feasibility of the 2030/2050 targets between EU and non-EU operating contexts.

Second, in the Social dimension, they extend the trust dimension already noted in the Social pillar — concerning confidence among crews, port operators, charterers and regulators in the reliability of new systems — into an explicit communication deficit between shipowners, regulators and crew, alongside the skills gap already identified. Third, and most notably, in the Technological dimension, two thirds of interviewees raised nuclear propulsion spontaneously as an emerging pathway for larger, energy-intensive vessels — a theme that opens a genuinely new angle alongside the pathways already covered in the Technological pillar (electrification, ammonia, methanol, hydrogen, wind-assisted propulsion), and which stood out as the most consistently recurring new technological theme in the stakeholders consultation. Given the consistency with which this theme emerged unprompted across interviewees with markedly different professional backgrounds, it is recommended as a priority candidate for explicit treatment in future revisions of the Technological pillar and, potentially, in the 2050 foresight scenarios.

A smaller number of issues rest, at this stage, on a single interview (e.g. the technology-neutrality-in-practice concern and the data-governance question raised under the Legal dimension, or the food-versus-fuel competition point raised under the Environmental dimension).

The stakeholder interviews analysed in this preliminary phase provide a broadly convergent, and in several respects reinforcing, complement to the literature-based barrier analysis presented in Chapters 3–7. The Economic dimension emerges as the most unanimous point of concern across the sample, confirming the centrality of the cost-competitiveness gap to ZEWT deployment feasibility at both the 2030 and 2050 horizons. At the same time, the interviews contribute genuinely new evidence in specific areas — most notably the emerging relevance of nuclear propulsion, the practical gap between well-to-wake principles and environmental assessment practice, and the communication deficit between shipowners and regulatory bodies — that add to, and enrich, the picture already established through the literature review.

9. CONCLUSIONS

Across the five Use Cases, a number of barriers recur consistently regardless of vessel type, reflecting genuinely systemic constraints on the ZEWT transition rather than segment-specific difficulties. The persistent cost gap between conventional and zero-emission solutions, the “chicken-and-egg” dynamic between infrastructure availability and vessel-side investment, the insufficiency of well-to-wake lifecycle accounting in current practice, and the fragmented alignment between international and regional regulatory frameworks all emerge as cross-cutting constraints affecting general cargo, tanker, passenger, inland waterway and special operation vessels alike, consistent with the systems-oriented perspective set out in the Methodology.

At the same time, the Use Case-level analysis shows that the practical expression of these barriers is far from uniform. Tankers and special operation vessels are disproportionately exposed to the emerging environmental and safety risk profiles of ammonia, methanol and large battery systems given their operating contexts; inland waterway vessels face a distinct combination of ageing fleets, fragmented local regulation and constrained retrofit economics; and passenger vessels are more directly exposed to social-acceptance and port-community considerations given their proximity to the public. This differentiation reinforces the case for the Use Case-based structure adopted throughout this deliverable.

The distinction between the 2030 and 2050 horizons is equally consistent across Use Cases. The 2030 horizon is dominated by evolutionary barriers: the economics of retrofit versus newbuild, the availability of transitional fuels, and compliance with near-term regulatory instruments such as FuelEU Maritime and the EU ETS. The 2050 horizon, by contrast, is dominated by transformative, systemic barriers: international policy coordination, the maturation and mainstreaming of currently low-technology-readiness pathways, and the establishment of a fully decarbonised, well-to-wake-consistent transport network. This temporal pattern held consistently across the literature-based analysis and was independently corroborated through the stakeholder consultation.

The stakeholder consultation presented in Chapter 8 played a central methodological role in this deliverable, transforming the initial expert-based barrier set into validated and shared knowledge across the ZEWT ecosystem, in line with the participatory approach set out in the Methodology. Overall, the consultation shows a high degree of convergence with the literature-based analysis: the cost-competitiveness gap, in particular, was raised by the entirety of the interview sample to date, making it the single most consistently confirmed barrier across the whole deliverable. Strong convergence was also observed on retrofit feasibility, ammonia/hydrogen safety, and certification and cybersecurity-related constraints.

Beyond confirmation, the consultation extended the existing analysis in three notable respects: it documented a geographically differentiated feasibility of the 2030/2050 targets between EU and non-EU operating contexts; it reframed part of the workforce and acceptance barrier as an explicit communication and trust deficit between shipowners, regulators and crew, rather than a skills gap alone; and it surfaced nuclear propulsion as the most consistently recurring emerging technological theme not yet reflected in the barrier analysis, raised spontaneously by stakeholders with markedly different professional

backgrounds. These contributions illustrate the value of the two-stage methodology adopted in this deliverable, and are recommended as priority candidates for incorporation into subsequent revisions of the barrier analysis and into the project's foresight scenarios.

9.1. Implications and recommendations

The combined evidence from the literature-based barrier analysis and the stakeholder consultation points to a set of priority actions capable of addressing the most consistently observed barriers across Use Cases, PESTLE dimensions and time horizons. Table 23 summarises these priority areas.

Table 23 - Priority areas for action emerging from the combined barrier analysis and stakeholder consultation

Priority area	Recommended action	Primary horizon
Regulatory alignment	Sustain EU regulatory ambition while actively pursuing alignment with an international (IMO-level) net-zero framework, to avoid fragmented regional requirements.	Both, more consequential by 2050
Regulatory predictability	Provide long-horizon, stable regulatory roadmaps for fuels and technologies, minimising the risk of retroactive reclassification undermining long-term investment cases.	Both
Financing	Expand blended and guarantee-based financing instruments (e.g. EIB-type guarantees) and use public procurement to build bankable project pipelines, particularly for smaller operators.	2030 onward
Workforce	Invest in structured training, upskilling and certification schemes ahead of deployment scale-up, covering both seafarers and shore-based integration personnel.	Pre-2030
Stakeholder coordination	Establish structured dialogue platforms bringing together shipowners, regulators, crew and port authorities to build shared understanding of technical rationale and cost implications.	Both
Technology scope	Broaden the technology-neutral scope of funding and regulation to explicitly consider emerging pathways such as nuclear propulsion for larger, energy-intensive vessels.	2050
Environmental assessment	Move environmental assessment practice beyond a CO ₂ -only focus towards genuine multi-indicator, well-to-wake evaluation in ZEWI project appraisal.	Both
Infrastructure sequencing	Sequence port and bunkering infrastructure investment with clearer fleet-level fuel decisions,	Both

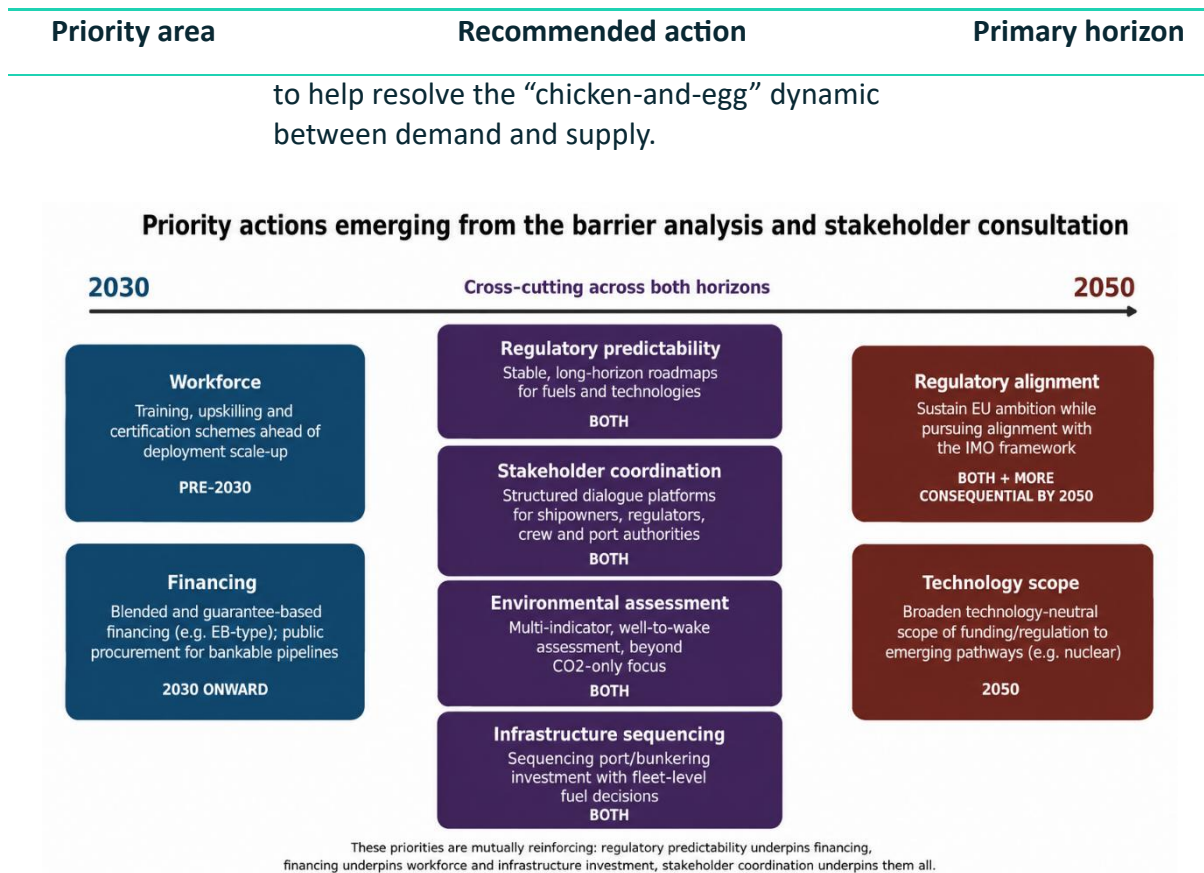


Figure 8 - Summary of priority actions by time horizon, emerging from the barrier analysis and stakeholder consultation

These priority areas are not sequential but mutually reinforcing: regulatory predictability underpins financing decisions, financing underpins workforce and infrastructure investment, and stakeholder coordination underpins the shared understanding needed to sustain political and social support for the transition over the two-and-a-half decades separating the 2030 and 2050 horizons.

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Institut für
Seeverkehrswirtschaft
und Logistik



FUNDACIÓN
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Agentur für Sicherheitsforschung,
Kriminologie und Kriminalpolitik



Funded by
the European Union

TRUSTEE is a Horizon Europe Project supported by the European Union under grant agreement no. 101192328. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

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