



FUTURE PROOF EFFICIENT AND SUSTAINABLE DEPLOYMENT OF ZEWT

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ABSTRACT

Deliverable D2.1 – *Initial ZEWT Use Cases* provides a high-impact, system-level definition of Zero-Emission Waterborne Transport (ZEWT) operational scenarios, establishing a robust analytical backbone for the TRUSTEE project. Developed within Work Package 2, the deliverable identifies and formalises ten representative use cases—five for 2030 and five for 2050—designed to capture the full complexity, scalability challenges, and transformation pathways of the European maritime sector towards climate neutrality.

The core ambition of this work is not merely to describe future configurations, but to operationalise the ZEWT transition through realistic, evidence-based scenarios that bridge technological potential, regulatory constraints, and market adoption dynamics. In this context, “promising” use cases are defined as those capable of achieving tangible deployment within the sector, rather than theoretical optimums detached from industrial feasibility. This ensures a direct contribution to EU decarbonisation objectives under the Green Deal, Fit for 55, and ZEWT partnership frameworks. [1]

The deliverable adopts a rigorous, system-oriented and scenario-driven methodology, enabling consistency, comparability, and cross-sectoral relevance. Each use case is structured along three tightly coupled dimensions—reference vessel configuration, operational scenario, and integrated ZEWT technology portfolio—allowing for a holistic assessment of energy demand, technological integration, and operational feasibility. This harmonised framework ensures direct usability of the results for subsequent life cycle assessment (LCA), techno-economic analysis, and workforce impact evaluation.

A defining element of the approach is the explicit dual-horizon modelling, which distinguishes between two fundamentally different transition regimes. The 2030 horizon reflects an **evolutionary decarbonisation phase**, constrained by existing fleet inertia, infrastructure limitations, and regulatory enforcement (FuelEU Maritime, EU ETS). [2] [3] Accordingly, the analysis prioritises retrofit-compatible solutions, including energy efficiency technologies, hybridisation strategies, and transitional fuels such as biofuels, LNG, and e-methanol. In contrast, the 2050 horizon represents a **systemic and transformative transition**, assuming full infrastructure maturity and regulatory alignment with climate neutrality targets. This enables the exploration of disruptive solutions such as hydrogen and ammonia-based propulsion, fuel cell systems, and high levels of digital integration and automation.

To ensure representativeness and strategic relevance, the study identifies five core vessel typologies that collectively account for the majority of European maritime activity and emissions: **General Cargo Vessels, Tanker Ships, Passenger Ships, Inland Waterway Vessels, and Special Operation Vessels**. These five use case families capture the full operational diversity of the sector, from deep-sea transport and energy-intensive logistics to short-sea passenger mobility, inland navigation, and port-based operations. Their selection is driven by a multi-criteria approach, encompassing fleet representativeness, environmental impact, operational variability, infrastructure dependency, and technological challenge, including hard-to-abate segments.

The deliverable further establishes a rigorous set of assumptions and boundary conditions to ensure analytical robustness. Environmental performance is assessed using a Well-to-Wake (WtW) approach, enabling a consistent comparison of alternative fuels and energy systems across their full lifecycle. Infrastructure availability is explicitly integrated as a dynamic constraint, distinguishing between near-term deployment limitations and long-term scalability conditions. Representative vessel configurations are derived from real-world fleet data (including MRV and EMSA datasets), ensuring both technical realism and scalability of results. [4] [5]

A key innovation of this work lies in the explicit recognition of digitalisation as a cross-cutting enabler of the ZEWT transition. In the 2030 horizon, digital tools act as efficiency multipliers through energy monitoring, predictive maintenance, and voyage optimisation. By 2050, digitalisation evolves into a structural component of maritime operations, enabling real-time optimisation, digital twins, and varying degrees of vessel autonomy, thus unlocking system-level efficiency gains and facilitating the integration of complex energy architectures.

The resulting use cases constitute a high-fidelity, scalable, and policy-relevant framework that directly supports the downstream analytical activities of the TRUSTEE project, including environmental impact assessment, economic modelling, and stakeholder-driven validation. More broadly, Deliverable D2.1 provides a critical bridge between foresight scenarios and

implementation pathways, offering a concrete, evidence-based roadmap for the progressive deployment of zero-emission technologies across the European waterborne transport system.



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TABLE OF CONTENTS

List of Tables.....	8
List of Figures	8
List of acronyms	9
1. Introduction	11
2. Methodological Framework for Use Case Definition	12
2.1. Overall Approach and Design Principles	12
2.2. Time Horizons and Scenario Logic (2030 vs 2050)	12
2.3. Criteria for Use Case Selection and Representativeness	14
2.4. Assumptions, Constraints, and Boundary Conditions.....	15
2.5. Selection of reference vessel types.....	17
General Cargo Vessels	19
Tanker Ships	19
Passenger Ships.....	20
Inland Waterways Vessels	20
Special Operation Vessels	21
2.6. Digital Domain - Cross-cutting Role in the 2030 and 2050 Scenarios.....	21
3. Use Cases for the 2030 Time Horizon	22
3.1. Use Case 2030–UC1: General Cargo Vessels.....	29
Section 1 – General Ship’s features.....	29
Section 2 – Technology under investigation	30
Section 3 – Operational scenario	31
3.2. Use Case 2030–UC2: Tanker	33
Section 1 – General Ship’s features.....	33
Section 2 – Technology under investigation	35
Section 3 – Operational scenario	36
3.3. Use Case 2030–UC3: Passenger ships.....	38
Section 1 – General Ship’s features.....	38
Section 2 – Technology under investigation	39
Section 3 – Operational scenario	40
3.4. Use Case 2030–UC4: Inland Waterway.....	42
Section 1 – Reference vessel characteristics.....	42
Section 2 – Technology under investigation	43
Section 3 – Operational scenario	44

3.5.	Use Case 2030–UC5: Special Operation Vessels	45
	Section 1 – Reference vessel characteristics	45
	Section 2 – Technology under investigation	46
	Section 3 – Operational scenario	48
4.	Use Cases for the 2050 Time Horizon	50
4.1.	Use Case 2050–UC1: General Cargo Vessels.....	57
	Main differences compared to the 2030 scenario	57
4.2.	Use Case 2050–UC2: Tanker Ships	57
	Main differences compared to the 2030 scenario	57
4.3.	Use Case 2050–UC3: Passenger Ships	59
	Main differences compared to the 2030 scenario	59
4.4.	Use Case 2050–UC4: Inland Waterway Vessels	60
	Main differences compared to the 2030 scenario	60
4.5.	Use Case 2050–UC5: Special Operations Vessels	61
	Main differences compared to the 2030 scenario	61
5.	Recommendations for Refinement and Validation	62
	References.....	63
	ANNEX I - 2030 Time Horizon Use Cases Framework	65
	Use Case 2030–UC1: General Cargo Vessels.....	65
	Table 1 – General Ship’s features	65
	Table 2 – Technology under investigation	66
	Table 3 – Operational scenario	67
	Use Case 2030–UC2: Tanker Ships	68
	Table 1 – General Ship’s features	68
	Table 2 – Technology under investigation	69
	Table 3 – Operational scenario	70
	Use Case 2030–UC3: Passenger Ships	71
	Table 1 – General Ship’s features	71
	Table 2 – Technology under investigation	72
	Table 3 – Operational scenario	73
	Use Case 2030–UC4: Inland Waterway Vessels	74
	Table 1 – Reference vessel characteristics	74
	Table 2 – Technology under investigation	75
	Table 3 – Operational scenario	76

Use Case 2030–UC5: Special Operation Vessels	77
Table 1 – Reference vessel characteristics	77
Table 2 – Technology under investigation	78
Table 3 – Operational scenario	79

LIST OF TABLES

TABLE 1 - SCENARIO 2030 - TECHNOLOGIES FRAMEWORK	24
TABLE 2 - 2050 TECHNOLOGICAL FRAMEWORK.....	51

LIST OF FIGURES

FIGURE 1 - USE CASE DEVELOPMENT	12
FIGURE 2 -DRIVERS FOR THE SELECTION OF THE USE CASES	15
FIGURE 3 - CARGO UC - MAIN FEATURES	32
FIGURE 4 – TANKER UC - MAIN FEATURES	36
FIGURE 5 – PASSENGER SHIP UC - MAIN FEATURES.....	40
FIGURE 6 – INLAND WATERWAYS VESSEL UC - MAIN FEATURES.....	44
FIGURE 7 – SPECIAL OPERATION VESSEL UC - MAIN FEATURES.....	48

LIST OF ACRONYMS

AFIR	Alternative Fuels Infrastructure Regulation
AIS	Automatic Identification System
ALS	Air Lubrication System
AHTS	Anchor Handling Tug Supply Vessel
CAPEX	Capital Expenditure
CII	Carbon Intensity Indicator
CO ₂	Carbon Dioxide
DP	Dynamic Positioning
EMS	Energy Management System
EMSA	European Maritime Safety Agency
ETS	Emissions Trading System
EU	European Union
EEXI	Energy Efficiency Existing Ship Index
FAME	Fatty Acid Methyl Esters
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
HVAC	Heating, Ventilation and Air Conditioning
HVO	Hydrotreated Vegetable Oil
ICE	Internal Combustion Engine
IMO	International Maritime Organization
IWT	Inland Waterway Transport
LCA	Life Cycle Assessment
LNG	Liquefied Natural Gas
LOA	Length Overall
MCR	Maximum Continuous Rating
MGO	Marine Gas Oil
MRV	Monitoring, Reporting and Verification
NO _x	Nitrogen Oxides
OPS	Onshore Power Supply (Cold Ironing)
OSV	Offshore Support Vessel
PSV	Platform Supply Vessel

SEEMP	Ship Energy Efficiency Management Plan
SFOC	Specific Fuel Oil Consumption
SOx	Sulphur Oxides
SOLAS	Safety of Life at Sea Convention
TEN-T	Trans-European Transport Network
TRL	Technology Readiness Level
TtW	Tank-to-Wake
WtT	Well-to-Tank
WtW	Well-to-Wake
WAPS	Wind-Assisted Propulsion Systems
WHR	Waste Heat Recovery
WH-to-X	Waste Heat to Energy/Products Conversion
ZEWT	Zero-Emission Waterborne Transport

1. INTRODUCTION

Deliverable D2.1 – Initial ZEWT Use Cases is developed within Work Package 2 of the TRUSTEE project and addresses Task T2.1, which focuses on the identification and definition of realistic and credible Zero-Emission Waterborne Transport (ZEWT) use cases for the European waterborne transport sector. The overarching objective of the deliverable is to define a structured and representative set of ten use cases (five for the 2030 time horizon and five for the 2050 time horizon) capable of capturing the diversity, complexity, and evolution of the ZEWT ecosystem.

Specifically, the aim is to identify the most promising initial use cases. In this context, “promising” refers not necessarily to those with the highest theoretical potential or the greatest environmental impact, but rather to the scenarios most likely to achieve market adoption within the maritime sector during the considered timeframe.

The use cases will therefore be determined by the combination of vessel types, selected according to the criteria identified in 2.3, and the most suitable technology based on the vessel type and the considered time horizon.

To provide a comprehensive overview, the characteristics of each Use Case have been constructed by identifying the specific technologies under investigation alongside the attributes of the selected vessels. This characterisation further includes the definition of the operational scenario and environment, detailing travel and routing conditions as well as the necessary prerequisites and assumptions.

The use cases provide a common framework to explore how different vessel categories, operational profiles, and transport services may progressively integrate ZEWT solutions under varying technological, regulatory, and infrastructural conditions. As such, they constitute a foundational input for subsequent WP2 activities, including environmental assessment (Task 2.2), technical integration analysis (Task 2.3), workforce implications (Task 2.4), and economic evaluation (Task 2.5).

Furthermore, the defined use cases support cross-work-package coherence by building upon the foresight scenarios and technology mapping developed in WP1 and by feeding the stakeholder-oriented foresight and barrier analysis activities foreseen in WP3 and WP4. The deliverable therefore plays a pivotal role in linking strategic scenario development with quantitative and qualitative assessment activities across the project.

2. METHODOLOGICAL FRAMEWORK FOR USE CASE DEFINITION

2.1. Overall Approach and Design Principles

The definition of ZEWT use cases follows a structured, system-oriented, and scenario-based methodological framework. [6] [7]

The approach is designed to ensure internal consistency across use cases while preserving sufficient flexibility to account for the heterogeneity of vessel types, transport services, and operational environments within the European waterborne transport landscape.

Each use case is described using a harmonised analytical process covering three main dimensions:

1. vessel and technical characteristics,
2. operational scenario and mission profile,
3. ZEWT technologies and energy carriers.

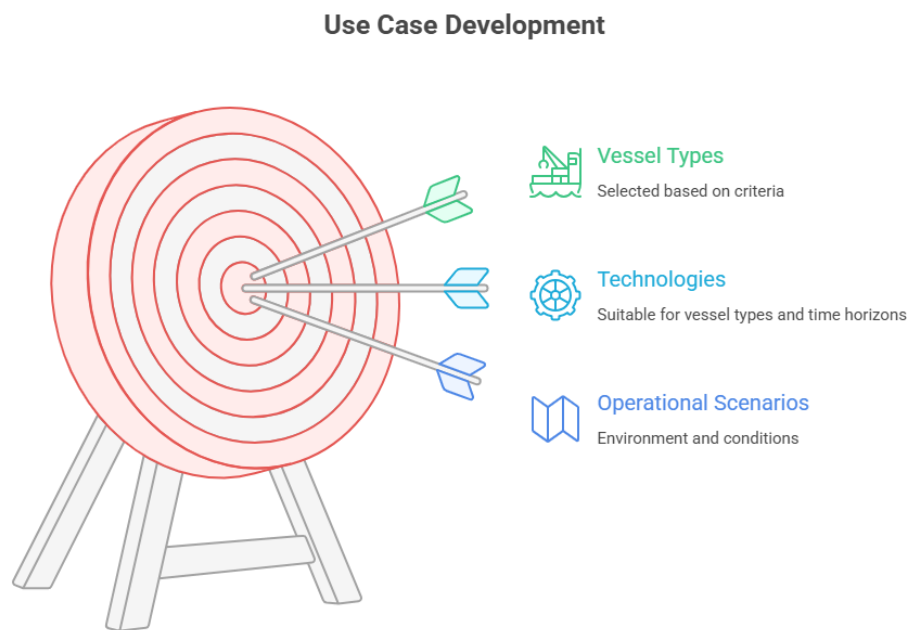


Figure 1 - Use Case Development

This common structure enables comparability across use cases and facilitates their subsequent use as input for life cycle, techno-economic, and workforce analyses.

2.2. Time Horizons and Scenario Logic (2030 vs 2050)

As established in the preceding sections, the use cases utilised in this study have been rigorously designed to present credible operational scenarios across two distinct temporal horizons: the medium-to-short term, represented by the year 2030, and the long term, culminating in the 2050 horizon. However, it is pertinent to reference the analysis conducted in Deliverable 1.1 (D1.1) [6], which highlights the inherent stochasticity of future energy

landscapes. As demonstrated by the three distinct scenarios developed in D1.1, the geopolitical, economic, and technological conditions likely to materialize are subject to significant variability. Nevertheless, the analytical distinction between the 2030 and 2050 timeframes remains a foundational pillar of this deliverable's logic, as these dates reflect two qualitatively different phases of the maritime energy transition.

For this reason, the conditions of the balanced scenario that have been considered in the study of the Use Cases are described here:

The 2030 Horizon represents a phase of immediate transition and regulatory adaptation. The scenarios projected for this period are heavily constrained by the compliance requirements of the European Union's "Fit for 55" package, with particular emphasis on the FuelEU Maritime regulation and the progressive inclusion of the maritime sector within the EU Emissions Trading System (ETS). [1] [2] [8] A critical factor defining this horizon is the inertial nature of the global fleet turnover; given the standard twenty-five to thirty-year commercial lifespan of merchant vessels, the active fleet in 2030 will consist predominantly of assets that are already in service today.

Consequently, the use cases developed for the 2030 horizon place a strong strategic emphasis on retrofitting solutions rather than new builds. The technological focus is directed toward energy efficiency measures, such as the integration of Wind Assisted Propulsion Systems (WAPS), and the adoption of drop-in fuels, including sustainable biofuels and e-methanol, utilised within dual-fuel engine configurations. The underlying logic of the 2030 scenarios is therefore "evolutionary" in nature. It prioritises the maximisation of efficiency in existing assets and the integration of hybrid systems to satisfy increasingly stringent Carbon Intensity Indicator (CII) ratings, ensuring regulatory compliance without necessitating a total replacement of the current infrastructure. [9]

Conversely, **the 2050 Horizon** is conceptualised in alignment with the overarching objectives of the European Green Deal, specifically the attainment of total climate neutrality. [1] These use cases are predicated on the assumption of a matured zero-emission infrastructure and a supply chain capable of supporting widespread decarbonisation. Unlike the retrofit-heavy approach of 2030, the 2050 scenarios focus on "greenfield" projects, new build vessels explicitly designed to accommodate disruptive technologies.

In this long-term view, the strategic logic shifts from evolutionary adaptation to a "revolutionary" overhaul of maritime operations. This involves the deployment of radical naval architectures, such as hull forms optimised for pure ammonia propulsion or liquid hydrogen fuel cells, alongside high levels of vessel autonomy designed to offset the operational complexities and safety challenges associated with these novel fuels. These scenarios are intended to explore the upper boundaries of technical feasibility, operating under the assumption that current barriers regarding fuel availability, bunkering infrastructure, and cost parity will have been effectively surmounted through sustained policy intervention and technological maturation.

2.3. *Criteria for Use Case Selection and Representativeness*

To ensure the ten selected use cases provide a comprehensive map of the ZEWT ecosystem, the TRUSTEE project applied a structured set of selection criteria, as outlined in the preliminary WP2 analysis. The approach builds upon the activities carried out in WP1, in particular the fleet characterisation developed in Deliverable D1.1, which provides the statistical and technical basis for the identification and aggregation of representative vessel categories. [6]

In this context, the Use Cases do not represent purely conceptual or illustrative configurations, but rather synthetic archetypes derived from real vessel populations through a structured aggregation process. The transition from the detailed taxonomy of the D1.1 dataset to a limited number of representative Use Cases follows a functional logic, grouping vessels based on similarities in operational profile, energy demand characteristics, and decarbonisation constraints. This ensures that the selected Use Cases reflect both the structure of the existing fleet and the key technological challenges associated with the ZEWT transition.

1. **EU Fleet Representation:** The selected vessel types must represent a significant percentage of the European fleet in terms of numbers and gross tonnage. This necessitates the inclusion of general cargo vessels, which form the backbone of short sea shipping, and tugs, which are ubiquitous in all ports.
2. **Environmental Impact:** Priority is given to sectors with the highest aggregate emissions (CO₂, NO_x, SO_x). [10] Deep-sea container shipping and cruise vessels are critical inclusions due to their high fuel consumption and public visibility.
3. **Inland Structure Support:** Use cases are selected to test the readiness of inland infrastructure. This includes examining the capacity of ports to supply high-voltage shore power (OPS) and the logistics of distributing hydrogen or ammonia to bunkering hubs.
4. **Financing and Business Models:** The selection covers diverse ownership structures, from the fragmented, family-owned businesses typical of the Inland Waterway Transport (IWT) sector to the consolidated, capital-intensive nature of the cruise industry, to analyse varying financial barriers.
5. **Personnel Upskilling:** The transition requires a workforce skilled in handling hazardous fuels (ammonia/hydrogen) and high-voltage systems. Use cases were chosen to highlight these training gaps.
6. **Technological Challenge:** The set includes "hard-to-abate" sectors where energy density is the limiting factor (e.g., high-speed ferries, deep-sea shipping) alongside sectors where electrification is more immediately feasible (e.g., harbour tugs).



Figure 2 -Drivers for the selection of the use cases

2.4. Assumptions, Constraints, and Boundary Conditions

In order to carry out a rigorous and meaningful definition of the use cases to be analysed, it is first necessary to establish a clear set of assumptions, constraints, and boundary conditions. These elements provide the conceptual and methodological framework within which the subsequent analyses will be conducted, ensuring internal consistency and transparency of the modelling process.

First and foremost, it is essential to clarify the boundaries adopted in the Life Cycle Assessment (LCA). [11] The environmental impact of the technologies investigated is evaluated according to a Well-to-Wake (WtW) perspective, which represents a holistic boundary encompassing the entire fuel life cycle. [12] [13] This includes the Well-to-Tank (WtT) stage, covering emissions resulting from fuel production, processing, and transportation, and the Tank-to-Wake (TtW) stage, which accounts for emissions generated during the onboard combustion or energy conversion processes. Such a comprehensive approach is of critical importance when comparing alternative fuel options, such as hydrogen and biofuels.

For instance, hydrogen may exhibit zero TtW emissions, yet still present significant WtT impacts if produced using fossil-based energy sources. Conversely, biofuels may offer moderate WtT emissions but result in measurable TtW outputs depending on combustion efficiency and onboard systems. Hence, adopting the WtW boundary ensures a fair and systemic assessment of the overall environmental performance across different technological pathways.

A further uncertainty concerns the characteristics of the vessels under analysis. Since the specific design parameters of future ships remain partly indeterminate, this study relies on a

representative operational profile derived from previous project deliverables (namely D1.1, D1.2, and particularly the appendix of D1.2). These documents were informed by data sourced from the fleet database developed by ISL which has been used to delineate an operational configuration representative of the current and projected European maritime landscape. Consequently, ship dimensions, cruising speeds, load factors, and other nautical attributes are here modelled as standardised profiles reflecting typical vessel behaviour within the relevant market segments, thus enabling a credible and comparable analytical foundation.

From a regulatory standpoint, a significant limitation emerges from the prevailing and foreseeable legislative framework. The study therefore assumes the full legal operability of all technologies described in D1.2, under the presumption that their current or near-future deployment complies with applicable maritime and environmental regulations. Regarding emission-related restrictions, for the 2030 time horizon, it is assumed that the FuelEU Maritime Regulation, specifically the greenhouse gas (GHG) intensity limits [2], and the Alternative Fuels Infrastructure Regulation (AFIR) will be fully enforced across the European maritime sector. [14]

Looking further ahead to 2050, the analysis assumes the existence of a regulatory framework that effectively prohibits the use of fossil fuels unless coupled with carbon capture or equivalent mitigation technologies. These assumptions provide a consistent framework for evaluating the transition pathways under credible policy scenarios aligned with the European Green Deal objectives.

Furthermore, a critical consideration must be given to the role of supporting infrastructure, as even the most disruptive and promising technological innovations remain ineffective in the absence of enabling physical and logistical ecosystems. Hence, when describing the prospective scenarios for 2030 and 2050, the definition of use cases explicitly integrates infrastructure availability as a boundary condition. Specifically, 2030 use cases are constrained by infrastructure projects currently funded or already under construction, such as those encompassed within the Trans-European Transport Network (TEN-T) corridors. By contrast, 2050 use cases assume a widespread and mature deployment of green fuel bunkering facilities at major European maritime hubs, reflecting an advanced stage of decarbonised infrastructure development. This assumption acknowledges the temporal evolution of infrastructure readiness as a decisive enabler of large-scale adoption of zero- and low-emission maritime technologies.

Finally, the definition of the use cases necessitates a broader evaluation regarding the scalability of the investigated technologies across the maritime market. This introduces a critical dimension concerning the systemic consequences of large-scale deployment. Indeed, the mass adoption of novel propulsion or energy systems carries complex implications (encompassing economic, social, and environmental externalities) that extend beyond the immediate operational boundary. Addressing this scalability challenge is essential to ensure that the transition pathways remain robust and that the potential ripple effects on the wider maritime community and society at large are adequately understood and mitigated.

2.5. Selection of reference vessel types

Building upon the theoretical framework and analysis established in the preceding sections, this chapter moves towards the practical application of the research parameters. To ensure a rigorous selection process, it is imperative to synthesise the qualitative data discussed thus far with the specific findings derived from the project's foundational deliverables.

Specifically, this selection process is deeply rooted in the strategic outcomes of D1.1, which established the ZEWT (Zero Emission Waterborne Transport) foresight scenarios. These scenarios provide the necessary forward-looking context regarding market trends, regulatory shifts, and operational demands. Furthermore, the selection is constrained and guided by the technical realities outlined in D1.2, which conducted a comprehensive ZEWT technology readiness review. By cross-referencing the future operational requirements identified in D1.1 with the current and near-future technological maturity assessed in D1.2, we establish a robust logic for determining which vessels are most relevant for detailed study.

The selection of reference vessel types for each Use Case is based on the combined use of two complementary data sources developed and analysed within the TRUSTEE project: the global fleet dataset established in Deliverable D1.1 and the European operational dataset derived from the EMSA MRV database. [4] Together, these datasets provide both structural and operational perspectives of the maritime fleet, enabling a robust and consistent definition of representative vessel configurations.

The D1.1 dataset, [6] comprising approximately 90,000 vessels, provides a comprehensive characterisation of the global and European fleet in terms of vessel type, deadweight tonnage (DWT), installed engine power, and design speed. [15] This dataset is used to define the structural distribution of vessel categories and to identify the dominant segments in terms of fleet composition and technical characteristics.

In parallel, the EMSA MRV database provides operational data for EU-related shipping activities, including fuel consumption, emissions, transport work, and operational profiles. This dataset enables the identification of the segments that are most relevant in terms of actual energy use and emissions within the European context, thereby complementing the structural perspective of D1.1 with real-world operational evidence.

The integration of these two datasets enables a structured flow-down process from fleet-level statistics to Use Case-level definitions. In particular:

- the D1.1 dataset is used to define the **representative vessel envelope**, identifying typical ranges of DWT, installed power, and speed for each vessel category;
- the EMSA MRV dataset is used to **weight and validate these selections**, highlighting which segments are most relevant in terms of energy demand, emissions intensity, and operational patterns within EU waters.

This combined approach ensures that the selected reference vessels are not only statistically representative of the fleet structure, but also aligned with the actual operational relevance of different segments.

A representative example of this methodology can be observed in the definition of UC1 (General Cargo / Dry Bulk proxy). The D1.1 dataset shows that the bulk carrier fleet includes approximately 13,800 vessels, with a strong concentration in the 35,000–100,000 DWT

range. Within this range, a large share of vessels falls between 35,000–59,999 DWT (approximately 3,400 units) and 60,000–99,999 DWT (approximately 4,800 units), indicating that the Handymax–Panamax segment captures the majority of fleet configurations.

This structural evidence is complemented by the EMSA MRV dataset, which confirms that vessels within this size range account for a significant share of fuel consumption and emissions in EU-related operations, due to their extensive use in both short-sea and regional trade routes. As a result, the reference vessel for UC1 is defined within a range of approximately 50,000–80,000 DWT, with associated propulsion power in the order of 11–15 MW and service speeds of 13–15 knots, reflecting both fleet distribution and operational relevance.

The same integrated approach is applied across all Use Cases.

In defining the vessel typologies used throughout this analysis, reference is made to the main international regulatory and classification frameworks governing maritime transport, including the SOLAS Convention, the AIS ship type codes defined in ITU-R Recommendation M.1371, and the ship categories adopted in environmental monitoring and reporting systems such as the EU MRV framework and EMSA reports. As the scope of this research requires grouping multiple operational vessel types into broader analytical categories, the terminology adopted for the use cases does not always correspond exactly to a single regulatory definition. Instead, where aggregation is necessary, the denomination chosen corresponds as closely as possible to the official terminology used in these regulatory and monitoring frameworks. Whenever feasible, priority is given to the naming conventions adopted in environmental monitoring reports (e.g., EMSA and EU MRV datasets) in order to maintain lexical consistency with the categories commonly used in maritime emissions analyses.

Furthermore, each use case is represented through the definition of a reference vessel, selected from real-world ship characteristics but appropriately anonymized. This approach allows the study to perform detailed technical and operational assessments on a specific vessel configuration, while ensuring that the results remain applicable to a broader range of vessels belonging to the same aggregated category. The analysis therefore combines the depth of a case-study approach with the flexibility required to consider alternative technological solutions that may be applicable across a wider spectrum of ships within each typology.

Consequently, the primary objective of the following section is to identify and delineate the vessel typologies that have been chosen to serve as the most accurate representatives of the contemporary and future European maritime market. Rather than focusing on a single ship class, the research necessitates a broader approach to capture the heterogeneity of the sector. Therefore, five distinct vessel typologies have been selected. These specific classes have been chosen not only for their market relevance but because they embody markedly different service profiles and operational cycles, thereby ensuring that the subsequent analysis captures a comprehensive spectrum of the European waterborne transport industry.

The objective is not merely to select the most common ships, but to curate a representative sample that allows for the rigorous testing of zero-emission technologies across varied service profiles. The selected typologies are detailed below.

General Cargo Vessels

The first category selected is the General Cargo vessel, representing a core segment of the commercial shipping sector and serving as a reference case for dry cargo transport within the broader maritime fleet. Within the overall framework of the study, this category captures a large share of conventional cargo transport activities while maintaining technological comparability across multiple dry cargo segments, including bulk carriers and medium-size container vessels. To ensure statistical relevance and representativeness, the reference vessel is defined based on the dominant dimensional envelope and tonnage classes identified in the fleet analysis, with particular emphasis on medium-to-large cargo vessels rather than extreme ship sizes such as Ultra Large Container Vessels (ULCVs). This approach allows the analysis to reflect the most recurrent operational and technical configurations within the global fleet, while remaining applicable to a broad spectrum of cargo ships engaged in both regional and long-haul trade.

Importantly, the selected typology is not limited to a purely standard cargo configuration. Instead, it encompasses operational variability typical of dry cargo vessels, including multipurpose cargo arrangements and auxiliary onboard systems associated with cargo handling and conditioning. These features are deliberately considered because they introduce additional auxiliary energy demands, enabling the analysis to capture realistic operational conditions and evaluate the integration of emerging energy technologies under variable onboard load profiles.

Within this context, the General Cargo vessel represents an effective platform for assessing the applicability of several decarbonisation solutions across a broad class of cargo ships. In particular, the configuration allows for the evaluation of Waste Heat Recovery systems, air lubrication technologies, and Wind-Assisted Propulsion Systems (WAPS). The deck layout, propulsion characteristics, and operational profiles typically associated with this aggregated category make it especially suitable for analysing the integration of these technologies and their potential impact on overall vessel energy performance.

By adopting this representative vessel envelope, the study ensures that the findings remain applicable not only to general cargo ships but also to a wider family of dry cargo vessels operating within both the European and global maritime transport system, thereby complementing the technological perspectives explored in the other use cases.

Tanker Ships

The second category considered in the analysis is the Tanker vessel, representing a key segment of maritime transport dedicated to the carriage of liquid cargoes in bulk, including crude oil, refined petroleum products, chemicals, and other liquid commodities. Within the broader framework of the study the tanker category captures a technologically distinct segment of the fleet characterised by highly standardized hull designs, stringent safety requirements, and operational profiles driven by large-volume energy transport.

To ensure representativeness within the European maritime context, the reference tanker selected for the analysis reflects the typical dimensional and operational characteristics of medium-sized product and chemical tankers operating in European and regional trade

routes, rather than focusing on the largest crude carriers such as VLCCs or ULCCs. This approach allows the study to address a vessel category that is both widely present in European waters and relevant to the transport of refined fuels and chemical products between major industrial hubs and ports.

The tanker typology is characterised by segregated cargo tanks, extensive pumping and cargo-handling systems, and strict safety and environmental protection requirements, which significantly influence the onboard energy balance. In addition to propulsion demand, these vessels typically exhibit considerable auxiliary energy consumption associated with cargo heating systems, inert gas systems, pumping operations, and tank management. The inclusion of these operational loads is essential for evaluating the feasibility and performance of emerging decarbonisation technologies under realistic operating conditions.

From a technological perspective, tanker vessels offer a particularly relevant platform for assessing the integration of energy efficiency solutions and alternative propulsion concepts, including advanced waste heat recovery systems, air lubrication technologies, and optimised hull and propulsion configurations. At the same time, the structural layout and safety constraints associated with hazardous cargo transport impose additional limitations on the adoption of certain technologies, making this vessel category especially useful for analysing the practical boundaries of decarbonisation strategies in the maritime sector.

By selecting a representative tanker configuration within this dimensional and operational envelope, the study ensures that the resulting analyses remain applicable to a broad portion of the tanker fleet operating in European waters, while also capturing the specific technical constraints and opportunities associated with liquid cargo transport.

Passenger Ships

The third typology addresses the passenger transport sector through the Cruise Ship category. This selection is driven by the sector's immense market relevance and its unique "hotel load" energy profile, where the power required for passenger comfort often rivals propulsion demands.

However, a deliberate boundary has been set regarding vessel size. The study advises against the inclusion of "extra-large" or mega-class cruise ships. Instead, the focus is placed on large passenger ships at the lower-to-medium end of the tonnage spectrum. This strategic decision ensures that the resulting data remains applicable to a broader segment of the market, including ferries and expedition cruise vessels, rather than being skewed by the niche engineering requirements of the world's largest floating resorts.

Inland Waterways Vessels

The fourth typology focuses on Inland Waterways Vessels. While these ships possess distinctive hull forms and propulsion constraints due to shallow water operations, they are strictly necessary to cover a vital, specific segment of the European market. As the EU pushes for a modal shift from road to river transport, understanding the decarbonisation potential of IWWs is essential. Their inclusion ensures the research captures the unique regulatory and geographical nuances of intra-continental European logistics.

Special Operation Vessels

Special Operation Vessels represents a heterogeneous group of ships designed to support specialized maritime activities rather than conventional cargo or passenger transport. Within the overall framework of the analysis this category captures vessels operating in port, coastal, and offshore environments where operational flexibility, manoeuvrability, and mission-specific equipment play a central role.

This category encompasses a range of vessel types typically involved in maritime service and offshore support activities, including **tugs, offshore support vessels (OSVs), platform supply vessels (PSVs), anchor handling tug supply vessels (AHTS), and other specialized operational units**. Up to a certain extent this category can represent also the fishing sector, especially when considering large fishing vessel for oceanic or deep sea fishing activities. These ships are characterised by highly variable operational profiles, often combining extended periods of low-power operation with short bursts of very high power demand during towing, manoeuvring, or offshore support activities. As a result, their propulsion systems and onboard energy architectures differ substantially from those of conventional transport vessels.

Taken together, the vessel typologies identified in this study—namely **General Cargo Vessels, Tanker Ships, Passenger Ships, Inland Waterway Vessels, and Special Operation Vessels**—cover a substantial share of the European commercial maritime fleet and capture the operational diversity of the sector. Based on data from the **EU Monitoring, Reporting and Verification (MRV) system and EMSA environmental monitoring reports**, the main ship categories represented by the General Cargo and Tanker segments (including container ships, bulk carriers, general cargo vessels, oil tankers, and chemical tankers) account for the vast majority of emissions reported under the MRV framework. When combined with passenger vessels and other operational ships, these typologies collectively represent **approximately 85–95% of the vessel categories responsible for CO₂ emissions within the EU maritime monitoring system**.

2.6. Digital Domain - Cross-cutting Role in the 2030 and 2050 Scenarios

Although not specifically assessed in each use case in the following chapters, the digital domain will play a critical role across the naval sector, acting as a transversal enabler for both the 2030 and 2050 decarbonisation scenarios. [16] [17]

In the 2030 timeframe, digitalisation is primarily deployed as an augmentation layer to conventional ship operation, supporting energy monitoring, decision-support systems, predictive maintenance, and operational optimisation. These capabilities enable efficiency improvements through weather routing, energy management, assisted manoeuvring, and condition-based maintenance, while maintaining crew-centred control and limited automation confined to specific subsystems.

In the 2050 scenario, the digital domain evolves into a structural component of vessel design and operation, tightly integrated with propulsion systems, energy architectures, and shore-based infrastructure. High-fidelity sensing, artificial intelligence, and digital twin

technologies enable continuous, real-time optimisation of energy flows, routing, and safety functions at both vessel and fleet level. The degree of automation becomes use-case dependent: vessels operating in constrained and predictable environments—such as tugs, service vessels, and inland waterway cargo units—are expected to achieve fully unmanned or remotely supervised operation, supported by port-based control centres and harmonised regulatory frameworks. Conversely, passenger-carrying vessels, including cruise ships and high-speed craft, are expected to retain onboard crews, with automation primarily enabling assisted manoeuvring, collision avoidance, and energy optimisation rather than full autonomy. Across both scenarios, digitalisation underpins the safe, efficient, and scalable deployment of decarbonisation technologies, supporting the transition from efficiency-driven optimisation in 2030 to system-level, autonomy-enabled operation in 2050.

3. USE CASES FOR THE 2030 TIME HORIZON

The strategic selection of use cases suitable for the 2030 time horizon necessitates a rigorous examination of the immediate technological landscape. Given the proximity of this milestone, the analysis is fundamentally anchored in the assessment of the **near-term technological horizon**. Consequently, particular emphasis is placed on identifying solutions that either already demonstrate operational maturity in the current maritime market or exhibit a high probability of practical implementation within the coming decade.

This temporal constraint significantly shapes the scope of the investigation. The primary objective of the 2030 use cases is therefore to identify **technological solutions compatible with retrofit strategies**. Rather than focusing exclusively on disruptive concepts requiring entirely new vessel designs, the analysis prioritises solutions capable of improving the efficiency and environmental performance of the **existing global fleet**. Given that the operational lifetime of commercial vessels typically exceeds 20–25 years, the 2030 timeframe offers limited opportunity for large-scale fleet renewal. As a result, decarbonisation strategies must largely rely on technologies that can be integrated into vessels currently in service.

Within this framework, the selection of the specific use cases for the 2030 horizon has been tailored to address the operational characteristics and technological constraints associated with each of the vessel typologies identified in Section 2.5.

- **UC1 – General Cargo Vessels:** For conventional dry cargo transport, the analysis focuses on **drop-in fuels such as biofuels and LNG**, combined with operational and hydrodynamic efficiency solutions including **Wind Assisted Propulsion Systems (WAPS)**, **air lubrication systems**, and **waste heat recovery technologies**. These solutions allow improvements in fuel consumption and emissions performance without requiring a complete overhaul of the propulsion architecture.
- **UC2 – Tanker Ships:** Tanker vessels present additional operational constraints due to safety requirements and hazardous cargo handling systems. For this category, the use case investigates **fuel substitution strategies (biofuels and LNG)** combined with **energy efficiency technologies**, including optimised propulsion systems and waste heat recovery. Particular attention is given to solutions compatible with the structural and safety requirements governing liquid bulk transport.

- **UC3 – Passenger Ships:** Passenger vessels exhibit a unique energy profile characterised by significant auxiliary loads associated with hotel services and passenger comfort. In this case, the analysis prioritises **hybrid propulsion architectures**, combining conventional engines operating on transitional fuels with **battery systems capable of supporting zero-emission operations during port stays and manoeuvring phases**.
- **UC4 – Inland Waterway Vessels (IWT):** Due to shorter operating distances and frequent proximity to port infrastructure, inland vessels represent one of the most promising segments for **full electrification**. This use case explores the feasibility of battery-electric propulsion systems supported by shore-based charging infrastructure, in line with increasingly stringent air quality and emissions regulations affecting inland waterways.
- **UC5 – Special Operation Vessels:** This category includes tugs, offshore support vessels, and other service ships operating in port and nearshore environments. Their operational profile—characterised by prolonged low-power operation combined with short bursts of high thrust—makes them particularly suitable for **hybrid-electric propulsion systems**, including battery integration and advanced energy management strategies aimed at reducing idle emissions and improving energy efficiency.

The following tables provide a detailed overview of the **most probable and less probable technological configurations** for each of these five use cases, outlining the rationale behind their selection within the technological and operational constraints of the 2030 horizon.

Table 1 - Scenario 2030 - Technologies framework

UC1: General Cargo -2030 Technology Uptake scenario			
Energy & Propulsion Solutions	Optimisation strategies	Rationale	Strengths and Weaknesses
Most probable: • Drop-in biofuels (FAME, HVO) • LNG (selective / case-dependent) • Wind Assisted Propulsion Systems (route-dependent) • Air Lubrication Systems (ALS) (selective) • Waste Heat Recovery (WHR)	Most probable: • Weather routing and voyage optimisation • Speed optimisation / virtual slow steaming • Hull & propeller retrofit (coatings, ESDs, propeller upgrades) • Engine load optimisation and power management • Digital energy monitoring, trim & performance analytics • Predictive maintenance and fouling management	Rationale for the most probable technologies: • Retrofit-driven approach: solutions are compatible with existing vessels and limited downtime. • Energy demand reduction first: efficiency measures reduce fuel consumption independently of fuel type. • Fuel flexibility: biofuels enable immediate emissions reduction without major modifications. • Selective adoption: WAPS, ALS and WHR are applied where operational and economic conditions are favourable. • Digitalisation as enabler: operational optimisation provides low-CAPEX, scalable improvements across the fleet.	Strengths: • High scalability across existing fleet • Limited CAPEX compared to new propulsion systems • Immediate impact on fuel consumption and emissions • Technology modularity (solutions can be combined incrementally) Weaknesses: • Fragmented gains (requires combination of multiple solutions) • Variable effectiveness depending on route and vessel profile • Biofuel availability and sustainability constraints • LNG lock-in risk and infrastructure dependency • Retrofit constraints (space, downtime, integration complexity)
Less probable: • Ammonia (combustion or fuel cells) • Hydrogen (FC or ICE) • Full electric propulsion • Methanol (large-scale retrofit application)	Less probable: • Radical vessel redesign for zero-carbon fuels • Fully optimised zero-emission routing dependent on dedicated infrastructure • Large-scale onboard energy storage for propulsion	Rationale for the less probable technologies: • Require newbuild-oriented designs rather than retrofit solutions. • Depend on immature or insufficient bunkering infrastructure at scale. • Volumetric and gravimetric constraints incompatible with deep-sea cargo operations. • High CAPEX and operational uncertainty limit large-scale deployment by 2030.	Weaknesses: • Low technological and commercial readiness for deep-sea cargo • Significant impact on cargo capacity and vessel layout • High investment costs and operational risks • Regulatory and safety frameworks still evolving

UC2: Tanker -2030 Technology Uptake scenario			
Energy & Propulsion Solutions	Optimisation strategies	Rationale	Strengths and Weaknesses
Most probable: - Drop-in biofuels (FAME, HVO) - LNG (selective / route-dependent) - Methanol (limited, case-dependent) - Waste Heat Recovery (WHR) (incl. cargo heating integration) - Air Lubrication Systems (ALS) (selective)	Most probable: - Speed and voyage optimisation (CII-driven) - Engine load and propulsion optimisation (derating, EPL) - Hull & propeller efficiency (coatings, ESDs) - Thermal energy management (WHR → cargo heating, fuel heating) - Cargo handling optimisation (pumping efficiency, scheduling) - Digital monitoring & energy performance analytics	Rationale for the most probable technologies: - Retrofit compatibility: solutions can be applied to existing tanker fleet with limited structural impact. - High auxiliary demand: tankers have significant thermal and pumping loads, enabling effective WHR integration. - Steady operational profile: long steady-state navigation favours efficiency technologies. - Fuel flexibility: biofuels provide immediate emissions reduction without major system redesign. - Selective adoption: LNG and methanol depend on vessel type, route, and tank arrangement constraints.	Strengths: - High applicability across tanker sub-segments (oil, chemical, product) - Strong synergy between propulsion and auxiliary systems (WHR → cargo systems) - Immediate emissions reduction potential - Mature and commercially available technologies Weaknesses: - Retrofit complexity due to safety constraints (hazardous cargo, ATEX zones) - Space limitations for alternative fuel tanks - LNG/methanol integration may affect cargo capacity - Biofuel availability and sustainability concerns - Variable performance gains depending on operational profile
Less probable: - Ammonia (combustion or fuel cells) - Hydrogen (FC or ICE) - Full electric propulsion - Large-scale battery hybridisation	Less probable: - Full electrification of cargo and propulsion systems - Large onboard energy storage for propulsion support - Radical vessel redesign for zero-carbon fuels - Dedicated zero-emission logistics chains requiring new infrastructure	Rationale for the less probable technologies: - Require newbuild-oriented designs rather than retrofit solutions. - Safety constraints are more severe due to hazardous cargo (flammability, toxicity). - Volumetric penalties incompatible with cargo tank arrangements. - Limited infrastructure availability at scale by 2030. - High CAPEX and operational risk for fleet-wide deployment.	Weaknesses: - Significant impact on vessel layout and cargo capacity - High investment cost and technological uncertainty - Safety and regulatory frameworks not fully mature - Limited scalability within existing tanker fleet

UC3: Passenger ship -2030 Technology Uptake scenario			
Energy & Propulsion Solutions	Optimisation strategies	Rationale	Strengths and Weaknesses
Most probable: - Hybrid systems with battery integration (auxiliary support, peak shaving, limited zero-emission operations) - Drop-in biofuels (primary pathway) - LNG / bio-LNG (selective, infrastructure-dependent) - Onshore Power Supply (OPS) - Waste Heat Recovery (WHR) for hotel loads	Most probable: - Hotel load optimisation (HVAC, smart load management, heat integration) - Advanced Energy Management Systems (EMS) - Peak shaving & spinning reserve replacement - Integration of WHR into hotel services (heating, desalination, HVAC) - Itinerary optimisation and speed optimisation - Shore power integration during port stays - Digital monitoring of hotel and propulsion energy demand	Rationale for the most probable technologies: - High auxiliary demand: passenger ships have dominant hotel loads, making hybridisation and WHR highly effective. - Retrofit feasibility: batteries and EMS can be integrated without major redesign of propulsion systems. - Port emissions priority: OPS and battery-supported operations reduce emissions in highly regulated and populated areas. - Fuel flexibility: biofuels enable immediate decarbonisation without major system changes, while LNG remains a transitional option. - Operational optimisation: energy demand management is a primary lever due to the variability of hotel loads.	Strengths: - Significant reduction of emissions in port and coastal areas - High impact on total energy consumption through hotel load optimisation - Mature and commercially available technologies - Strong alignment with regulatory pressure in passenger hubs - Positive public perception and visibility of green solutions Weaknesses: - Limited impact on deep-sea propulsion emissions - High CAPEX for hybrid integration and system complexity - Space and weight constraints for battery systems - Dependence on OPS availability across ports - Operational complexity in energy management
Less probable: - Ammonia (combustion or fuel cells) - Hydrogen Fuel Cells (primary propulsion) - Full electric propulsion (beyond short-range vessels)	Less probable: - Radical redesign for zero-carbon fuel storage - Full zero-emission propulsion for large passenger ships - Large-scale fuel cell-based primary power systems - Fully electrified hotel and propulsion systems	Rationale for the less probable technologies: - Safety constraints: hydrogen and ammonia introduce significant risks for high passenger density vessels. - Space limitations: storage of alternative fuels (especially H₂) impacts passenger capacity and layout. - Energy density limitations: batteries are not suitable for large vessels with long routes. - Infrastructure gap: large-scale bunkering and regulatory frameworks not fully mature by 2030. - Retrofit incompatibility: most solutions require newbuild-oriented designs.	Weaknesses: - Significant impact on vessel layout and revenue space - High investment cost and technological uncertainty - Safety and certification challenges - Limited scalability for existing fleet by 2030

UC4: Inland waterways -2030 Technology Uptake scenario			
Energy & Propulsion Solutions	Optimisation strategies	Rationale	Strengths and Weaknesses
Most probable: • Full electric propulsion (short-range / fixed routes) • Battery-hybrid systems (primary scalable solution) • OPS / shore-based charging infrastructure • Drop-in biofuels (for hybrid backup systems)	Most probable: • Energy management & predictive routing (based on fixed corridors) • Speed and power optimisation vs river current and water depth • Hull & propeller optimisation (low-speed / shallow-water regime) • Charging optimisation and grid integration • Operational optimisation (lock transits, waiting time, stop-and-go cycles) • Digital fleet and route energy planning	Rationale for the most probable technologies: • Strong modal fit: short distances, predictable routes, and frequent port access favour electrification. • Infrastructure proximity: continuous interaction with shore enables charging-based solutions. • High operational regularity: repetitive duty cycles allow optimisation and right-sizing of batteries. • Hybrid flexibility: battery-hybrid systems mitigate range limitations and infrastructure gaps. • Regulatory push: strict inland emission standards favour zero-emission solutions.	Strengths: • Zero direct emissions (TtW) in full electric mode • Very high energy efficiency compared to combustion systems • Low noise and vibration (benefits for crew and urban environments) • Strong compatibility with EU modal shift strategies • High optimisation potential due to predictable operations Weaknesses: • Dependence on charging infrastructure availability • Grid capacity and connection constraints • Range limitations for full electric configurations • CAPEX for battery systems and charging infrastructure • Operational sensitivity to seasonal water levels and currents
Less probable: • Hydrogen-based propulsion (fuel cells or ICE) (niche / pilot scale) • Ammonia-based propulsion • WAPS (Wind Assisted Propulsion Systems) • Pure LNG propulsion (non-hybrid)	Less probable: • Wind-based operational optimisation • Fuel-centric optimisation strategies without electrification • Radical vessel redesign for alternative fuels • Long-range endurance optimisation approaches	Rationale for the less probable technologies: • Electrification provides a more efficient and scalable solution in inland contexts. • Hydrogen solutions remain limited by infrastructure and cost at scale in 2030. • Ammonia is incompatible with safety requirements in densely populated inland environments. • WAPS has limited applicability due to low speeds, constrained waterways, and infrastructure interference (bridges, locks). • LNG does not align with long-term decarbonisation targets and offers limited advantage over electrification in this segment.	Weaknesses: • Low economic competitiveness compared to electrification • Infrastructure and safety barriers • Limited applicability within constrained inland environments • Poor alignment with operational profiles and regulatory drivers

5: Special Operation Vessels -2030 Technology Uptake scenario			
Energy & Propulsion Solutions	Optimisation strategies	Rationale	Strengths and Weaknesses
Most probable: - Battery-hybrid propulsion systems (primary solution) - Full electric propulsion (harbour / short-duty applications) - Drop-in biofuels (in hybrid configurations) - OPS / shore-based charging	Most probable: - Peak shaving and spinning reserve replacement - Engine stop–start optimisation - Power demand forecasting and load smoothing - Dynamic positioning (DP) and thrust optimisation - Smart charging and shore-side energy integration - Idle-time elimination through battery operation - Mission-based energy management (duty-cycle optimisation)	Rationale for the most probable technologies: - Duty-cycle match: vessels such as tugs and OSVs operate with long idle periods and short high-power peaks, ideally suited to hybridisation. - Instant power demand: batteries provide immediate torque and improve responsiveness for towing and manoeuvring operations. - Port-based operations: frequent proximity to shore infrastructure enables charging and OPS integration. - Retrofit feasibility: hybrid systems can be integrated without radical redesign of compact vessels. - Fuel flexibility: biofuels allow emissions reduction without impacting operational readiness.	Strengths: - Significant reduction of idle and low-load emissions - Immediate torque availability and improved operational control - High efficiency in variable load conditions - Strong compatibility with port decarbonisation strategies - Reduced noise and vibration in harbour environments Weaknesses: - High CAPEX for battery systems and integration - Space and weight constraints on small vessels - Dependence on charging infrastructure availability - Operational complexity in hybrid energy management
Less probable: - Hydrogen-based propulsion (fuel cells or ICE) (niche / pilot scale) - Ammonia-based propulsion - Full alternative-fuel propulsion without hybrid support	Less probable: - Fuel-centric optimisation relying solely on alternative fuels - Large-scale onboard fuel storage in compact vessels - Radical redesign for alternative fuel integration	Rationale for the less probable technologies: - Hydrogen solutions are limited by infrastructure availability and onboard storage constraints in compact vessels. - Ammonia presents challenges in dynamic response and safety for port operations. - Pure fuel-based solutions do not address the highly variable load profile typical of these vessels. - Hybridisation remains more effective in capturing operational efficiency gains.	Weaknesses: - Infrastructure and safety constraints - Limited applicability in compact vessel designs - High cost and technological uncertainty for 2030 deployment - Reduced operational flexibility compared to hybrid solutions

The ship features described in the following sections are based on the **technical configuration of an existing vessel**, selected as a representative platform for the corresponding ship typology. For confidentiality reasons, the specific vessel has been **appropriately anonymized**, while preserving the key dimensional, operational, and energy-related characteristics necessary for the analysis. The selected vessel therefore serves as a **reference platform**, reflecting realistic design parameters and operational conditions within the defined operational and regulatory context.

Starting from this baseline configuration, the analysis considers the typical operational envelope of similar vessels operating within the same market segment. In cases where specific operational aspects—such as **special cargo loads, auxiliary systems, or mission-related energy demands**—are relevant to the assessment of decarbonisation technologies, these elements are evaluated on the basis of the existing vessel platform. At the same time, the study extends beyond the exact operational configuration currently observed in navigation, developing **additional technical considerations and alternative system arrangements** that could realistically be implemented on vessels with comparable characteristics.

This approach ensures that the use case remains grounded in the **technical reality of an existing ship**, while maintaining sufficient flexibility to explore technological integrations and operational scenarios that go beyond the vessel's current configuration. In this way, the reference vessel acts both as a realistic engineering baseline and as a platform for assessing the broader applicability of decarbonisation solutions within the relevant ship category.

3.1. Use Case 2030–UC1: General Cargo Vessels

Section 1 – General Ship's features

The reference vessel considered within this use case represents a statistically derived, anonymised ship configuration reflecting the dominant characteristics of the dry cargo fleet, as identified in Deliverable D1.1. Rather than referring to a specific existing vessel, the selected configuration corresponds to a representative mid-size cargo ship within the most recurrent dimensional and operational envelope observed across bulk carriers, general cargo ships, and medium-size container vessels. This approach ensures both technical realism and scalability of the results across a large portion of the fleet.

From a dimensional perspective, the reference vessel is defined within the medium-to-large cargo segment, with a deadweight of approximately 70,000 to 80,000 tonnes. The main principal dimensions are assumed to be consistent with this class, with a length overall (LOA) in the range of 210–230 metres, a beam of approximately 30–36 metres, and a design draft between 12.5 and 14.5 metres. The hull form is characterised by a high block coefficient (typically above 0.80), reflecting a full-form displacement vessel optimised for cargo capacity and fuel efficiency rather than speed. The cargo arrangement consists of multiple holds (typically 5 to 7), enabling the transport of a wide range of dry commodities, including bulk materials, general cargo, and, in some configurations, containerised goods.

The propulsion system is based on a conventional single-shaft configuration, driven by a low-speed two-stroke diesel engine, which represents the dominant propulsion technology

within this segment of the fleet. The installed main engine power is typically in the range of 10 to 13 MW, enabling a service speed of approximately 13 to 15 knots under normal operating conditions. The propulsion architecture is complemented by auxiliary engines supporting onboard electrical loads, including cargo handling systems and hotel services, although the latter remain limited compared to passenger vessels. The specific fuel oil consumption (SFOC) is assumed to be in the range of 165–175 g/kWh, consistent with vessels built in the 2010–2015 timeframe.

The fuel system is based on conventional marine fuels (HFO/MGO), with no hybridisation or alternative fuel integration in the baseline configuration. Electrical architecture is typically arranged around diesel-driven generators supplying onboard systems, with limited redundancy and no advanced energy management systems in the reference case. Thermal energy is available through exhaust gas and cooling systems, offering potential for waste heat recovery applications.

From a materials and structural perspective, the vessel is constructed in conventional steel, with a hull design optimised for robustness and cargo capacity. Hydrodynamic characteristics are typical of displacement vessels operating at moderate Froude numbers, with resistance dominated by viscous and wave components. The deck layout provides sufficient available space for the integration of additional systems, such as Wind-Assisted Propulsion Systems (WAPS), while internal arrangements may allow partial retrofitting of auxiliary energy systems, depending on space and weight margins.

The operational flexibility of the vessel is reflected in its capability to handle variable cargo types and loading conditions, including ballast and laden voyages. Auxiliary loads may vary depending on cargo configuration, particularly in the presence of cargo handling equipment or conditioning systems. Overall, the selected reference vessel provides a technically consistent and representative baseline for evaluating decarbonisation technologies applicable to a broad spectrum of dry cargo ships within both European and global maritime transport contexts.

Section 2 – Technology under investigation

The technology portfolio investigated for UC1 is defined in coherence with the reference vessel envelope described in Section 1 and reflects a pragmatic, retrofit-oriented approach to the decarbonisation of medium-to-large dry cargo vessels. Rather than relying on a single disruptive solution, the technological strategy is based on the progressive integration of complementary measures that can be deployed primarily on existing vessels, while remaining compatible with newbuild configurations. This ensures broad applicability across the fleet and alignment with the short- to medium-term decarbonisation pathway.

Primary propulsion remains based on internal combustion engines, with the technological focus placed on fuel flexibility and progressive fuel transition. The use of drop-in biofuels and LNG is considered a key enabler for emissions reduction without requiring major modifications to propulsion systems or fuel storage arrangements. Where operational and infrastructural conditions allow, dual-fuel configurations are also considered as a means to enhance long-term flexibility while preserving operational reliability.

Alongside fuel-related measures, energy efficiency improvements represent a central element of the technology set. These include hydrodynamic optimisation of the hull and appendages, advanced low-friction coatings, propeller and rudder efficiency enhancements, and the adoption of energy-saving devices such as air lubrication systems. Such measures directly reduce baseline energy demand and provide immediate benefits across all operating conditions, independently of the fuel pathway adopted.

Hybridisation and electrical optimisation are investigated as enabling technologies aimed at improving overall system efficiency rather than replacing conventional propulsion. The integration of shaft-generator systems and limited battery energy storage is considered primarily for auxiliary load optimisation, peak shaving, and manoeuvring support. In this context, battery systems are sized to improve engine operating conditions and reduce inefficiencies, rather than to provide sustained propulsion capability. Advanced power and energy management systems play a key role in coordinating propulsion and auxiliary loads to minimise fuel consumption across the operational profile.

In addition to these measures, the UC includes the assessment of Wind-Assisted Propulsion Systems (WAPS) as a complementary technology for reducing propulsion energy demand. For medium-to-large cargo vessels, solutions such as rotor sails, rigid sails, or suction-based devices are considered where deck layout, stability margins, and cargo operations allow. WAPS is treated as an auxiliary propulsion contributor, capable of reducing main engine load under favourable wind conditions rather than as a primary means of propulsion. Its integration is evaluated with particular attention to structural implications, interaction with cargo operations, port compatibility, and route-dependent wind availability. When combined with digital voyage optimisation and performance monitoring tools, WAPS can significantly enhance overall energy efficiency without constraining fuel choice or operational flexibility.

Section 3 – Operational scenario

The operational scenario defined for UC1 reflects the typical duty cycle of medium-to-large dry cargo vessels operating on recurrent regional and interregional trade routes, while maintaining relevance for ships calling at European ports. The scenario is calibrated on the operational patterns of mid-size bulk carriers, which represent a dominant share of the fleet and exhibit stable, energy-intensive navigation profiles suitable for efficiency-oriented interventions.

The mission envelope is defined to capture the most representative trading patterns for this vessel class, with individual voyage legs typically ranging between **1,000 and 3,000 nautical miles**, corresponding to navigation periods of approximately **3 to 10 days** depending on routing and operating conditions. Port calls occur on a regular basis, typically every **1 to 2 weeks**, with port stays ranging from **12 to 48 hours**, depending on cargo handling operations and terminal efficiency. This configuration reflects a balanced operational profile between regional and medium-haul shipping, ensuring consistency with both international operations and EU regulatory frameworks such as MRV and FuelEU Maritime.

During navigation, the vessel operates at a service speed of approximately **13–15 knots**, resulting in a propulsion-dominated energy demand profile characterised by long periods of quasi-steady engine operation. For the reference vessel, the main engine operates in the

range of **70–85% of Maximum Continuous Rating (MCR)**, corresponding to an effective propulsion power demand of approximately **8–10 MW**. Over a typical 24-hour navigation period, this results in a propulsion energy consumption in the order of **190–240 MWh/day**.

Auxiliary systems during navigation—including electrical generation for onboard services, cargo support systems, and navigation equipment—contribute an additional **5–10% of total energy demand**, corresponding to approximately **10–20 MWh/day**. The combined daily energy consumption during cruising conditions can therefore be estimated in the range of **200–260 MWh/day**, with propulsion accounting for the vast majority of the energy balance.

Manoeuvring phases associated with port approach, berthing, and departure introduce short-duration peak power demands driven by propulsion transients, thrusters, and auxiliary systems. During these phases, total instantaneous power demand may exceed typical cruising levels, although the duration remains limited (typically a few hours per port call), making their overall energy contribution relatively small but relevant for peak-load management and system flexibility.

During port stays, the main propulsion system is typically shut down, and onboard energy demand is supplied by auxiliary generators. Power demand in port is significantly lower than during navigation, typically in the range of **0.5 to 2 MW**, depending on cargo operations and onboard systems. Over a typical port stay, this corresponds to an energy consumption of approximately **10–50 MWh per call**. Despite the lower absolute energy demand, these phases are particularly relevant due to their occurrence in proximity to populated areas and their contribution to local emissions.

Overall, the operational profile of UC1 can be described as a combination of long-duration steady-state navigation (accounting for approximately **85–90% of total energy consumption**), short transient manoeuvring phases with elevated power demand, and auxiliary-dominated port operations. This structure makes the vessel particularly suitable for the integration of energy-efficiency technologies, waste heat recovery, and wind-assisted propulsion, all of which benefit from stable propulsion loads and extended cruising conditions.

In addition to mission-dependent characteristics, the operational scenario is bounded by international regulatory frameworks. The reference vessel operates under the IMO Carbon Intensity Indicator (CII) [9], which evaluates annual operational efficiency and drives optimisation strategies across the full duty cycle. Compliance with the Energy Efficiency Existing Ship Index (EEXI) establishes a technical efficiency baseline, influencing propulsion characteristics and retrofit measures. These requirements are embedded within the Ship Energy Efficiency Management Plan (SEEMP), which ensures continuous monitoring, reporting, and improvement of vessel energy performance across both operational and annual time scales. [18]

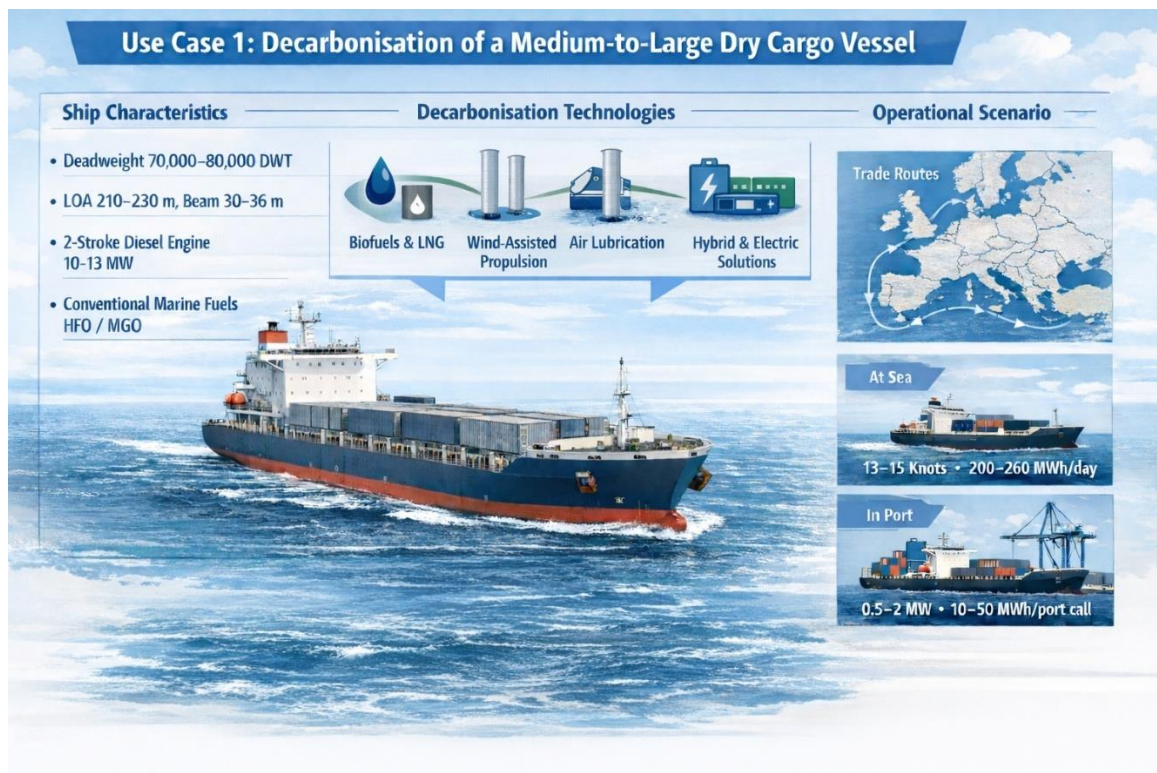


Figure 3 - Cargo UC - Main Features

3.2. Use Case 2030–UC2: Tanker

Section 1 – General Ship’s features

The reference vessel considered within UC2 represents a statistically derived and anonymised configuration of the tanker fleet, based on the analysis of the datasets provided in Deliverable D1.1. The selected 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. Rather than focusing on extreme ship sizes such as Very Large Crude Carriers (VLCCs), the reference vessel is defined within the medium-size tanker segment, ensuring representativeness across a wide portion of the fleet and alignment with typical operational and regulatory conditions.

While the reference vessel is defined based on the most statistically representative segment of liquid cargo tankers (product and chemical tankers), the UC2 scope also considers gas carriers and LNG carriers as part of the broader tanker family included in the dataset. These vessel types exhibit significantly different technical characteristics—particularly in terms of cargo containment systems, fuel usage, and energy management (e.g. boil-off gas utilisation)—and are therefore treated as complementary sub-cases within the analysis rather than as the primary reference configuration.

From a dimensional perspective, the reference vessel is defined within the Medium Range (MR) tanker class, with a deadweight in the range of approximately **40,000 to 50,000 tonnes**. The principal dimensions are assumed to be consistent with this segment, with a length

overall (LOA) of approximately **180–200 metres**, a beam of **30–32 metres**, and a design draft typically between **10 and 12 metres**. The hull form is characterised by a relatively high block coefficient, reflecting a full-form displacement vessel optimised for cargo volume and transport efficiency. The internal arrangement consists of multiple segregated cargo tanks, enabling the safe transport of liquid cargoes such as refined petroleum products, chemicals, and other bulk liquids, with strict requirements in terms of containment, segregation, and safety systems.

The propulsion system is based on a conventional single-shaft configuration, driven predominantly by a low-speed two-stroke diesel engine, which represents the most widespread propulsion technology in medium-to-large tanker segments. Installed main engine power is typically in the range of **8 to 10 MW**, enabling a service speed of approximately **13 to 15 knots** under normal operating conditions. In certain sub-segments, particularly chemical tankers, medium-speed four-stroke engines may also be present; however, the two-stroke configuration is considered representative for the reference vessel. The propulsion layout includes a fixed pitch propeller and conventional rudder system, without hybridisation in the baseline configuration.

From an energy system perspective, tanker vessels are characterised by a more complex onboard energy balance compared to dry cargo ships. In addition to propulsion demand, significant auxiliary loads are associated with cargo handling and conditioning systems. These include cargo pumps for loading and unloading operations, heating systems required to maintain cargo viscosity and temperature (particularly for heavy products), and inert gas systems necessary to ensure safe tank atmospheres. As a result, auxiliary energy demand can represent a substantial share of total energy consumption, especially during port operations and cargo handling phases.

The fuel system is based on conventional marine fuels (HFO and MGO), with no alternative fuel integration in the baseline configuration. Electrical power is generated through auxiliary diesel generators supplying both ship service loads and cargo-related systems. Thermal energy is available from exhaust gases and engine cooling systems, providing potential for waste heat recovery applications, particularly in relation to cargo heating requirements.

Structurally, the vessel is constructed in conventional steel, with a hull and tank arrangement designed to comply with strict safety and environmental protection standards, including double-hull configurations and segregation of cargo spaces. These design constraints influence both the available space and the feasibility of retrofitting additional systems. While deck space is generally more constrained compared to dry cargo vessels due to piping systems and safety requirements, certain areas may still allow the integration of additional technologies depending on layout and operational constraints.

The reference vessel therefore provides a technically consistent and representative baseline for analysing decarbonisation strategies in the tanker sector, capturing both the propulsion-driven and cargo-driven energy demands that characterise this class of ships. This dual energy profile is a defining feature of the use case and plays a central role in the assessment of applicable technologies in the following sections.

Section 2 – Technology under investigation

The technology portfolio investigated for UC2 is defined in coherence with the reference vessel described in Section 1 and reflects a pragmatic, safety-driven and retrofit-oriented approach to the decarbonisation of medium-range tanker vessels. Given the specific operational constraints associated with liquid cargo transport—particularly safety requirements, tank segregation, and the presence of hazardous or temperature-sensitive cargoes—the technological strategy prioritises solutions that are compatible with existing vessel layouts and regulatory frameworks, while ensuring reliability and operational continuity.

Primary propulsion remains based on internal combustion engines, with the technological focus placed on fuel flexibility and progressive transition toward lower-carbon fuels that are already available at commercial scale. In this context, **drop-in biofuels** and **LNG** are considered the most viable options for reducing emissions in the short to medium term, as they can be integrated with limited modifications to existing propulsion systems and fuel storage arrangements. Where feasible, dual-fuel configurations are also considered, although their adoption in tanker vessels is constrained by safety regulations, space limitations, and the need to preserve cargo capacity and segregation.

Energy efficiency measures represent a central pillar of the technology set, particularly given the energy-intensive nature of tanker operations. These include hull and appendage optimisation, advanced low-friction coatings, propeller and rudder improvements, and the adoption of energy-saving devices such as **air lubrication systems**. These solutions directly reduce propulsion energy demand and are fully compatible with both existing vessels and newbuilds, offering immediate and scalable benefits across the fleet.

In addition to propulsion-related efficiency, particular attention is given to the optimisation of **cargo-related energy systems**, which represent a distinguishing feature of tanker vessels. Technologies under investigation include the optimisation of cargo pumping systems, improved thermal insulation of cargo tanks, and enhanced control of cargo heating processes. In this context, **waste heat recovery (WHR)** plays a particularly relevant role, as it can be used not only to improve overall engine efficiency but also to supply thermal energy for cargo heating, thereby reducing the need for auxiliary fuel consumption. This integration between propulsion and cargo systems represents a key decarbonisation lever specific to the tanker sector.

Hybridisation and electrical optimisation are considered as enabling technologies, primarily aimed at improving system efficiency rather than replacing conventional propulsion. The integration of shaft generators and limited battery energy storage is investigated for auxiliary load management, peak shaving during cargo operations, and optimisation of generator loading conditions. Battery systems are therefore sized for operational flexibility and efficiency improvements rather than for propulsion purposes. Advanced energy management systems are essential to coordinate propulsion, cargo systems, and auxiliary loads, ensuring optimal energy distribution across different operational phases.

The applicability of **Wind-Assisted Propulsion Systems (WAPS)** is also assessed within UC2, although with more constraints compared to dry cargo vessels. The presence of deck-mounted piping systems, safety zones, and cargo handling equipment limits the available

installation space and introduces additional safety considerations. Nevertheless, selected solutions such as compact rotor sails may be considered in specific configurations where compatibility with tanker safety regulations, stability margins, and operational procedures can be ensured. In this context, WAPS is treated as a supplementary energy-saving technology, capable of reducing propulsion demand under favourable wind conditions without interfering with cargo operations.

Section 3 – Operational scenario

The operational scenario defined for UC2 reflects the typical duty cycle of medium-range tanker vessels engaged in the transport of liquid cargoes along regional and interregional trade routes, with frequent interaction with European ports. Unlike dry cargo vessels, tanker operations are strongly influenced by cargo handling requirements, safety procedures, and terminal constraints, resulting in a more articulated operational profile where both propulsion and cargo-related energy demands play a significant role.

The mission envelope is defined to represent the most recurrent trading patterns for product and chemical tankers, with individual voyage legs typically ranging between **800 and 2,500 nautical miles**, corresponding to navigation periods of approximately **2 to 7 days**. Port calls occur more frequently than in bulk shipping, generally every **5 to 10 days**, reflecting shorter trading cycles and higher logistical turnover. Port stays are typically longer and more energy-intensive, ranging from **18 to 60 hours**, due to loading, unloading, tank cleaning, and safety procedures associated with liquid cargo handling.

During navigation, the vessel operates at a service speed of approximately **13 to 15 knots**, with the main engine typically running at **65–85% of Maximum Continuous Rating (MCR)**. This corresponds to an effective propulsion power demand in the range of **6 to 9 MW**, depending on loading condition and weather. The resulting propulsion energy consumption is estimated at approximately **150–210 MWh/day**, representing the primary energy component during cruising conditions.

Auxiliary loads during navigation are higher than in dry cargo vessels due to continuous operation of onboard systems related to cargo conditioning, tank monitoring, and safety (e.g. inert gas systems, ventilation, control systems). These loads typically account for **10–20% of total energy demand**, corresponding to approximately **20–40 MWh/day**, leading to a total daily energy consumption during navigation in the range of **170–250 MWh/day**.

Manoeuvring phases, including port approach and departure, introduce short-duration peaks in power demand due to the combined use of propulsion, thrusters, and auxiliary systems. While these phases are limited in duration, they are relevant for assessing peak-load management and the potential benefits of hybridisation and energy storage systems.

Port operations represent a critical component of the tanker operational profile and are significantly more energy-intensive than for dry cargo vessels. During loading and unloading, cargo pumps operate continuously, often requiring power levels in the range of **1 to 5 MW**, depending on cargo type and system configuration. In addition, **cargo heating systems** may be required to maintain product temperature and viscosity, particularly for heavy or temperature-sensitive cargoes, further increasing energy demand. As a result, total power

demand during port stays can reach **2 to 6 MW**, with total energy consumption per port call typically ranging from **40 to 150 MWh**, depending on the duration and nature of operations.

Overall, the energy distribution of UC2 differs significantly from that of dry cargo vessels. While propulsion remains the dominant energy consumer, accounting for approximately **70–80% of total energy consumption**, cargo-related systems and auxiliary loads represent a substantial share, particularly during port operations. This dual energy profile—combining propulsion demand with significant cargo-handling and thermal loads—is a defining characteristic of tanker vessels and a key factor in the selection and assessment of decarbonisation technologies.

In addition to mission-dependent characteristics, the operational scenario is framed by international regulatory requirements. The reference vessel is assumed to operate under the IMO Carbon Intensity Indicator (CII), which evaluates annual operational efficiency and drives optimisation strategies across both navigation and cargo-handling phases. Compliance with the Energy Efficiency Existing Ship Index (EEXI) defines a technical efficiency baseline influencing propulsion performance and retrofit measures. These requirements are implemented through the Ship Energy Efficiency Management Plan (SEEMP), which establishes a continuous process of monitoring, reporting, and optimisation of vessel energy performance across the full operational cycle.



Figure 4 – Tanker UC - Main Features

3.3. Use Case 2030–UC3: Passenger ships

Section 1 – General Ship's features

The reference vessel considered within UC3 represents a statistically derived and anonymised configuration of the passenger ship segment, based on the analysis of the datasets provided in Deliverable D1.1. The selected typology reflects the most recurrent characteristics of medium-size passenger vessels operating in European and regional contexts, with particular emphasis on Ro-Pax ferries and small-to-medium cruise ships. Rather than focusing on extreme vessel sizes such as large cruise liners, the reference configuration is defined within a dimensional and operational envelope that ensures representativeness across a broad portion of the fleet while maintaining technical consistency with retrofit-oriented decarbonisation strategies.

From a dimensional perspective, the reference vessel is defined within a length overall (LOA) range of approximately 180 to 220 metres, with a beam of 26 to 30 metres and a design draft typically between 6.5 and 8 metres. The vessel is designed to accommodate both passengers and, in the case of Ro-Pax configurations, rolling cargo or vehicles, resulting in a multi-deck arrangement combining accommodation spaces, vehicle decks, and service areas. Passenger capacity is typically in the range of 800 to 1,800 persons, depending on the specific configuration and service profile.

The propulsion system is generally based on a diesel-electric architecture, which represents a common solution within this segment due to its flexibility, redundancy, and ability to support variable load profiles. Installed propulsion power typically falls within the range of 15 to 30 MW, enabling service speeds of approximately 18 to 22 knots, depending on route requirements and vessel design. This configuration allows for efficient distribution of power between propulsion and onboard services, which is a critical feature given the significant energy demand associated with passenger-related systems.

A defining characteristic of passenger vessels is the presence of substantial hotel loads, which include heating, ventilation, and air conditioning (HVAC), lighting, catering systems, freshwater production, and other onboard services required to ensure passenger comfort. Unlike cargo vessels, these loads represent a significant and continuous share of total energy consumption, often accounting for up to 40–50% of the overall onboard energy demand. This results in a more balanced energy profile between propulsion and auxiliary systems, with implications for both system design and decarbonisation strategies.

The fuel system in the baseline configuration is based on conventional marine fuels (MGO or low-sulphur fuels), although some vessels within this category may already incorporate LNG or dual-fuel solutions. Electrical power is generated through multiple auxiliary engines integrated within the diesel-electric system, enabling flexible load management and redundancy. Thermal energy is available from engine exhaust and cooling systems, offering potential for integration with onboard heating and HVAC systems.

From a structural and layout perspective, passenger vessels present a high degree of complexity due to the integration of accommodation spaces, safety systems, and cargo areas (in the case of Ro-Pax vessels). This complexity influences the availability of space and weight margins for retrofitting additional systems. While deck space may be partially available, it is often constrained by superstructures and passenger-related equipment, which

can limit the integration of certain technologies such as large-scale wind-assisted propulsion systems.

Section 2 – Technology under investigation

The technology portfolio investigated for UC3 is defined in coherence with the reference vessel described in Section 1 and reflects a hybridisation-driven and operationally flexible approach to the decarbonisation of passenger ships. Given the dual energy profile of this vessel category—characterised by a significant balance between propulsion demand and hotel loads—the technological strategy prioritises solutions capable of addressing both components simultaneously, while ensuring compatibility with existing vessel layouts and service requirements.

Primary propulsion remains based on internal combustion engines within a diesel-electric architecture, with the technological focus placed on fuel flexibility and progressive transition toward lower-carbon fuels that are commercially available within the considered timeframe. In this context, **drop-in biofuels** and **LNG** represent the most viable solutions, allowing emissions reduction without requiring fundamental modifications to propulsion systems. Dual-fuel configurations are particularly relevant in this segment due to the widespread adoption of diesel-electric systems, which inherently facilitate integration of multiple energy sources and operational redundancy.

A central element of the UC3 technology set is the integration of **battery energy storage systems**, which play a significantly more prominent role compared to cargo vessels. Batteries are considered for multiple operational functions, including **zero-emission port operations**, manoeuvring, and peak shaving during both navigation and hotel load fluctuations. While full-electric propulsion remains unfeasible for medium-size passenger vessels due to energy density limitations, battery systems enable partial electrification of operations and contribute to improved overall system efficiency and reduced emissions in port areas.

Energy efficiency measures are applied across both propulsion and hotel systems. On the propulsion side, these include hull optimisation, low-friction coatings, and propeller efficiency improvements, which reduce baseline energy demand during navigation. On the hotel side, significant efficiency gains can be achieved through optimisation of HVAC systems, energy-efficient lighting, heat recovery from ventilation systems, and improved insulation. Given the continuous nature of hotel loads, these measures represent a major opportunity for reducing total onboard energy consumption.

Thermal energy management is also a key aspect of the technology portfolio. Waste heat recovery systems are assessed for their ability to supply thermal energy to onboard services such as heating, hot water production, and HVAC systems, thereby reducing the need for additional fuel consumption in auxiliary boilers. The integration of thermal and electrical systems is particularly relevant in passenger vessels, where energy demand is distributed across multiple subsystems with different load profiles.

Hybridisation is further enhanced through advanced **power and energy management systems**, which coordinate the operation of engines, batteries, and auxiliary systems. These systems enable dynamic load balancing, optimisation of engine operating points, and

efficient allocation of energy between propulsion and hotel loads, particularly under variable operational conditions such as port stays, manoeuvring, and fluctuating passenger demand.

The applicability of **Wind-Assisted Propulsion Systems (WAPS)** is considered limited within this use case. The presence of large superstructures, passenger safety requirements, and aesthetic considerations significantly constrain the installation of wind-assisted devices. While certain niche applications may be feasible, WAPS is not considered a primary or widely deployable solution within the passenger ship segment.

Section 3 – Operational scenario

The operational scenario defined for UC3 reflects the typical duty cycle of medium-size passenger vessels operating in European waters, with particular reference to Ro-Pax ferries and small-to-medium cruise ships engaged in short-sea and regional routes. Unlike cargo vessels, passenger ships operate under strict schedule constraints and service regularity, with operational profiles strongly influenced by fixed timetables, passenger demand, and port turnaround requirements. This results in a highly repetitive and predictable mission profile, with limited flexibility in speed and routing compared to other vessel categories.

The mission envelope is characterised by relatively short to medium routes, with individual voyage legs typically ranging between **100 and 600 nautical miles**, corresponding to **4 to 24 hours of navigation**, depending on the service type. High-frequency operations are common, with vessels performing **daily or multiple daily rotations** on fixed routes, particularly in ferry services. Port calls are therefore very frequent, often occurring several times per day, with **port stays typically ranging from 1 to 6 hours**, depending on loading operations and passenger turnaround.

During navigation, the vessel operates at relatively high and stable service speeds, typically in the range of **18 to 22 knots**, with propulsion systems running at approximately **60–85% of Maximum Continuous Rating (MCR)**. The propulsion power demand during cruising is generally in the range of **10 to 25 MW**, depending on vessel size, loading condition, and route characteristics. This results in a propulsion energy demand of approximately **250–500 MWh/day**, representing a major share of total energy consumption but not the dominant one.

A defining feature of UC3 is the significant contribution of **hotel loads**, which remain active throughout all operational phases, including navigation, manoeuvring, and port stays. These loads include HVAC systems, lighting, catering, accommodation services, and auxiliary systems, and typically account for **40–50% of total onboard energy demand**. During navigation, hotel energy consumption is typically in the range of **150–300 MWh/day**, leading to a total energy demand during cruising of approximately **400–700 MWh/day**.

During manoeuvring phases, which occur frequently due to the high number of port calls, the vessel experiences transient peaks in power demand associated with propulsion adjustments, thruster operation, and auxiliary systems. These phases are relatively short but operationally critical, requiring high responsiveness and power availability, which makes them particularly suitable for hybridisation and battery-assisted operation.

Port operations represent a recurring and operationally significant phase for passenger vessels. During port stays, propulsion systems are typically shut down or operating at minimum load, while hotel loads remain fully active. The total onboard power demand during port stays typically ranges between **3 and 10 MW**, depending on passenger occupancy and service level. Given the proximity to populated areas, these phases are particularly relevant from an environmental perspective and represent a key target for zero-emission operation through battery systems or shore-side electrical supply. Total energy consumption per port stay typically ranges between **5 and 50 MWh**, depending on duration and onboard demand.

The overall energy distribution for UC3 is therefore more balanced than in cargo vessels, with **propulsion accounting for approximately 50–60% of total energy consumption and hotel loads accounting for 40–50%**. This balanced profile, combined with frequent port operations and high load variability, defines a unique operational context that strongly favours hybridisation and advanced energy management solutions.

In addition to mission-dependent characteristics, the operational scenario is framed by international regulatory requirements. The reference vessel operates under the IMO Carbon Intensity Indicator (CII), which evaluates annual operational efficiency and incentivises optimisation across both propulsion and auxiliary systems. Compliance with the Energy Efficiency Existing Ship Index (EEXI) establishes a technical baseline for propulsion efficiency, while the Ship Energy Efficiency Management Plan (SEEMP) ensures continuous monitoring and improvement of energy performance across all operational phases, including both navigation and hotel load management.



Figure 5 – Passenger ship UC - Main Features

3.4. Use Case 2030–UC4: Inland Waterway

Section 1 – Reference vessel characteristics

The reference vessel considered in UC4 represents **European inland waterway cargo vessels**, operating primarily along major river corridors such as the Rhine, Danube, and interconnected TEN-T inland networks. The use case focuses on vessels engaged in bulk cargo, container transport, and general inland freight, reflecting the core segment of European river logistics rather than small leisure craft or niche tourism vessels.

The reference vessel is defined within the most common European inland cargo class envelope. Typical principal dimensions fall within a **length of approximately 80 to 135 metres**, a beam between **9 and 17 metres**, and a maximum design draft typically limited to **2.5 to 3.5 metres**, depending on river conditions. These dimensional constraints are governed by lock systems, bridge clearances, and seasonal water levels, which strongly influence vessel design and operational flexibility.

Cargo capacity is typically in the range of **1,500 to 4,000 tonnes**, depending on hull configuration and water depth. Container-capable inland vessels in this size range may transport approximately **100 to 300 TEU**, depending on stacking height and route restrictions. Unlike maritime vessels, inland ships are strictly constrained by navigational infrastructure and hydrological variability, resulting in relatively standardised design envelopes across much of the European fleet.

Propulsion systems are typically based on **diesel-mechanical configurations**, often with one or two main engines driving conventional propellers through reduction gearboxes. Installed propulsion power generally falls within the range of **500 kW to 2.5 MW**, depending on vessel size and operational requirements. Service speeds are modest, typically between **8 and 13 knots (15–24 km/h)**, as energy efficiency and safe navigation in constrained waterways take precedence over high transit speed.

A defining feature of inland vessels is their **predictable and repetitive operational profile**, often characterised by fixed routes, scheduled departures, and high operational regularity. Navigation takes place in sheltered waters with limited wave exposure, resulting in lower resistance variability compared to open-sea operations. Hotel loads are minimal relative to propulsion demand, consisting mainly of navigation systems, basic accommodation, and cargo-handling support.

The hull structure is constructed from conventional steel, optimised for shallow-draft operation and low hydrodynamic resistance at modest speeds. Stability and manoeuvrability are strongly influenced by river current, bridge clearance, and lock operations rather than by open-sea seakeeping considerations.

Space and weight margins vary significantly depending on vessel age and cargo configuration, but inland vessels often provide comparatively favourable conditions for retrofitting due to their lower installed power and constrained mission range. Additionally, the proximity to urban and industrial areas along river corridors creates practical opportunities for shore-based charging infrastructure or alternative fuel supply chains.

Section 2 – Technology under investigation

The technology portfolio investigated for UC4 is centred on the **large-scale electrification of inland waterway vessels**, complemented by hybrid solutions based on **commercially mature alternative fuels** that are already deployable or demonstrably scalable within the 2030 timeframe. The selection of technologies explicitly excludes solutions that remain at pilot or pre-commercial stage, in order to ensure industrial relevance and realistic deployment potential.

The primary technology under investigation is **battery-electric and hybrid-electric propulsion**. Fully electric configurations are considered technically and operationally feasible for a significant share of inland vessels operating on short and medium routes, where predictable schedules and frequent port calls allow regular access to shore-based charging infrastructure. Battery systems are therefore assessed both as the main energy source for propulsion and as part of hybrid architectures, enabling zero-emission navigation in urban areas, during manoeuvring, and in environmentally sensitive river sections.

For routes requiring greater operational flexibility or extended endurance, the UC investigates **hybrid propulsion systems combining batteries with internal combustion engines fuelled by LNG or drop-in biofuels**. LNG is considered as the most established alternative fuel currently available for inland navigation, with existing vessel designs, certified engines, and emerging bunkering infrastructure already in operation on selected European river corridors. Its role within UC4 is explicitly transitional, enabling reductions in local air pollutants and partial greenhouse gas mitigation when combined with electrification and operational optimisation.

In addition to LNG, the use of **drop-in biofuels** compatible with existing diesel or dual-fuel engines is considered as a near-term and low-barrier solution. These fuels allow immediate emissions reduction without requiring major changes to vessel layout, fuel storage systems, or operational procedures, making them particularly attractive for retrofitting existing inland vessels within the 2030 timeframe.

Energy management and digital control systems represent a key enabling technology across all investigated configurations. Advanced power management systems are assessed for their ability to coordinate batteries, propulsion units, and auxiliary systems, optimising energy use under varying river current conditions, water levels, lock transits, and speed restrictions. Given the high repeatability of inland missions, predictive energy management based on route characteristics and operational scheduling is considered a major performance and efficiency lever.

From an infrastructure perspective, UC4 explicitly accounts for the interaction between vessel technologies and **shore-side electrical infrastructure**, including charging systems at ports, terminals, and inland logistics nodes. Infrastructure availability is treated as an integral part of the technology assessment, as it directly influences battery sizing, operational strategies, and the feasibility of fully electric operation.

Section 3 – Operational scenario

The operational scenario defined for UC4 reflects the characteristic mission profiles of inland waterway vessels operating along Europe's main river corridors and interconnected canal networks. Unlike maritime shipping, inland navigation is constrained by fixed infrastructure, hydrological conditions, and regulated traffic flows, resulting in **highly predictable, repetitive, and corridor-based operations**. These features play a central role in shaping both energy demand and the suitability of specific decarbonisation technologies.

From a mission-range perspective, inland vessels typically operate on **fixed routes between predefined terminals**, often covering daily or multi-day cycles rather than distinct voyage legs. Individual operating stretches commonly range from **20 to 300 kilometres per day**, depending on the corridor and operational schedule, with vessels frequently returning to the same ports or terminals at regular intervals. Longer-distance operations along major corridors such as the Rhine or Danube are structured as a sequence of short navigation segments interspersed with lock passages, waiting times, and port calls, rather than continuous uninterrupted sailing.

Navigation takes place at relatively low and stable speeds, generally between **8 and 13 knots**, with propulsion power adjusted continuously to account for river current, water depth, and traffic conditions. Load profiles are therefore smoother than those observed in port service vessels but more variable than in open-sea cargo shipping, particularly in shallow-water conditions or during periods of high or low flow. Lock transits and speed-restricted zones introduce frequent stop-and-go cycles, contributing to an operational profile well suited to electrified and hybrid propulsion systems.

Port and terminal operations are frequent and form an integral part of the operational cycle. Inland vessels regularly engage in loading and unloading at river ports, industrial terminals, and urban logistics nodes, with port stays ranging from a few hours to a full day depending on cargo type and handling equipment. During these phases, propulsion demand is minimal, and onboard energy consumption is dominated by auxiliary systems and cargo-handling support, creating favourable conditions for zero-emission operation supported by batteries and shore-side electrical supply.

A defining characteristic of the UC4 operational scenario is the **strong coupling between vessel operation and shore-based infrastructure**. Regular access to ports, terminals, and logistical hubs enables predictable charging opportunities and energy replenishment cycles, reducing the need for large onboard energy reserves. At the same time, seasonal variability in water levels and river currents introduces operational constraints that require flexibility in power management and propulsion control, reinforcing the importance of adaptive energy management systems.



Figure 6 – Inland waterways vessel UC - Main Features

3.5. Use Case 2030–UC5: Special Operation Vessels

Section 1 – Reference vessel characteristics

The reference vessel considered within UC5 represents a statistically derived and anonymised configuration of special operation vessels operating in European maritime contexts. This category encompasses a heterogeneous group of ships designed to support specialised maritime activities rather than conventional cargo or passenger transport, including offshore support vessels (OSVs), platform supply vessels (PSVs), anchor handling tug supply vessels (AHTS), harbour service units, and other operational craft employed in port, coastal, and offshore environments. Within the framework of the study, this use case captures vessels characterised by mission-driven operations, high manoeuvrability requirements, and strongly variable load profiles.

To ensure representativeness while maintaining a consistent and analytically robust reference, the vessel is defined within a **narrowed dimensional envelope representative of the most recurrent European service vessel segment**. The principal dimensions are therefore constrained to a length overall (LOA) of approximately **55 to 70 metres**, a beam between **12 and 15 metres**, and a draft in the range of **4.0 to 5.0 metres**. This dimensional selection reflects the most common size class operating in European ports and nearshore offshore activities, avoiding both small harbour-only units and large offshore construction vessels.

Installed propulsion power is correspondingly defined within a reduced range of approximately **3.0 to 4.5 MW**, typically delivered by **two medium-speed diesel engines** arranged in a twin-screw or azimuth thruster configuration. This setup ensures sufficient

bollard pull, redundancy, and dynamic response capabilities required for towing, positioning, and offshore support operations, while remaining representative of a large portion of the active fleet.

Service speed is limited to approximately **11 to 13 knots**, consistent with the operational focus on manoeuvrability and thrust control rather than transit efficiency. Propulsion systems are optimised for responsiveness and load variability, often incorporating controllable pitch propellers or azimuthing propulsion units to enable precise thrust vectoring.

A defining characteristic of this vessel category is its **highly transient load profile**, characterised by prolonged low-load operation (idle, standby, or transit at reduced power) combined with short-duration peaks approaching maximum installed power during towing, dynamic positioning, or offshore intervention activities. This operational behaviour leads to frequent operation of engines outside their optimal efficiency range and represents a key driver for the assessment of hybridisation and advanced energy management solutions.

Auxiliary loads are primarily mission-driven rather than hotel-related and include deck machinery, winches, cranes, pumps, and navigation systems. While moderate in average terms, these loads can exhibit significant short-term variability depending on the operational task, contributing to an overall energy profile that is both irregular and peak-intensive.

From a structural and design perspective, the hull is typically constructed in conventional steel and optimised for robustness, deck strength, and operational stability rather than hydrodynamic efficiency. Space and weight margins are limited but sufficient to allow targeted retrofitting interventions, particularly in relation to hybrid systems and compact energy storage solutions.

Up to a certain extent, this use case may also provide a **partial proxy for large fishing vessels**, particularly where similar operational patterns are observed, including mission-based operations, intermittent high-load phases, and significant auxiliary demand associated with onboard equipment. While the fishing fleet remains outside the EU MRV framework, available European estimates indicate that it contributes on the order of **~5 MtCO₂ annually**, confirming that it represents a non-negligible emission source within the broader maritime sector. For this reason, the technical considerations developed within UC5 may be extended, with appropriate limitations, to analogous vessel types operating under comparable conditions.

Section 2 – Technology under investigation

The technology portfolio investigated for UC5 is defined in coherence with the reference vessel described in Section 1 and reflects the specific operational constraints of special operation vessels, characterised by highly dynamic load profiles, frequent low-load operation, and short-duration peak power demand. In this context, the technological approach is centred on **hybridisation and power system optimisation**, rather than on the direct substitution of conventional propulsion systems with fully alternative solutions.

Primary propulsion remains based on **medium-speed internal combustion engines**, with the technological focus placed on improving operational efficiency across a wide load range.

Given the strong variability in power demand, engines are often required to operate under suboptimal conditions, making this category particularly suitable for solutions that enable load smoothing and efficiency optimisation. In this framework, the use of **drop-in biofuels** is considered a viable pathway to achieve immediate emissions reduction without requiring significant modifications to existing engine configurations or fuel systems.

The core technological element of UC5 is the integration of **hybrid-electric architectures**, combining conventional propulsion with **battery energy storage systems (BESS)**. Batteries are not intended to provide sustained propulsion over long durations, but rather to support peak shaving, spinning reserve, and zero-emission operation during low-load phases. This includes standby conditions, low-speed transit, and port operations, where battery systems can significantly reduce fuel consumption and emissions while improving engine operating profiles.

Hybrid systems also enable **load levelling**, allowing internal combustion engines to operate closer to their optimal efficiency range by absorbing transient peaks through the battery system. This is particularly relevant during towing operations, dynamic positioning, or other mission-critical activities requiring rapid power fluctuations. The sizing of battery systems is therefore driven by power requirements (kW) rather than by energy capacity (kWh), reflecting the need to manage short-duration high-power events.

Advanced **power and energy management systems (PMS/EMS)** represent a key enabling technology within UC5. These systems are responsible for coordinating engines, batteries, propulsion units, and auxiliary loads in real time, optimising power distribution and minimising fuel consumption across highly variable operating conditions. Given the repeatability of certain operational patterns (e.g. harbour assistance cycles or offshore standby), predictive control strategies can further enhance system performance.

From a propulsion standpoint, the use of **high-efficiency azimuth thrusters and controllable pitch propellers** is considered integral to the overall system performance, as these technologies enable precise thrust control and improved energy utilisation during manoeuvring and towing operations. While these are not new technologies per se, their integration within hybrid architectures significantly enhances overall vessel efficiency.

Electrification of auxiliary systems and deck machinery is also considered, particularly for winches, cranes, and pumps, which can be integrated into the hybrid power system and benefit from battery support during intermittent operation. This contributes to reducing peak loads on the main engines and improving overall energy management.

Alternative fuels such as LNG are considered of **secondary relevance** within this use case, primarily due to storage constraints, operational complexity, and limited compatibility with highly dynamic load profiles. Similarly, more disruptive solutions such as hydrogen or ammonia are not considered within the 2030 timeframe, as they require significant redesign of onboard systems and supporting infrastructure, which is not aligned with the retrofit-oriented approach adopted for this scenario.

Overall, the technology set investigated for UC5 reflects a **power-centric decarbonisation strategy**, where emissions reduction is achieved through the optimisation of energy flows, hybridisation, and operational efficiency improvements, rather than through a complete shift to alternative fuels. This approach is consistent with the technical and operational

realities of special operation vessels and ensures high applicability across the existing European fleet.

Section 3 – Operational scenario

The operational scenario defined for UC5 reflects the characteristic mission profiles of special operation vessels operating in European ports, coastal areas, and nearshore offshore environments. Unlike conventional transport vessels, these ships do not follow fixed point-to-point routes but operate within **task-driven and event-based missions**, where energy demand is dictated by operational requirements such as towing, positioning, or support activities rather than by transit distance alone.

The reference vessel typically operates within a **limited geographical radius**, generally not exceeding **50 to 150 nautical miles from the base port**, with frequent returns to harbour or operational hubs. Daily operations are structured around multiple short missions rather than continuous navigation, with a combination of standby periods, transit phases, and high-intensity operational tasks.

Transit phases occur at moderate speeds in the range of **10 to 13 knots**, with relatively low propulsion load compared to installed power. However, these phases represent only a portion of the overall duty cycle. A significant share of operational time is spent in **standby or low-load conditions**, often at quay, on station, or awaiting assignment, where propulsion demand is minimal but auxiliary systems remain active.

The most critical aspect of the operational profile is the occurrence of **short-duration, high-power events**, during which the vessel operates close to its maximum installed power. These include towing operations, dynamic positioning, offshore assistance, or harbour manoeuvring under constrained conditions. Such events typically last from a few minutes up to one hour and are characterised by rapid load fluctuations and high power peaks, placing significant stress on propulsion and energy systems.

The resulting energy profile can be broadly described as follows:

- **Low-load / standby operation:** approximately **40–60%** of operational time, with power demand typically below **20–30%** of installed capacity
- **Transit operation:** approximately **20–30%** of operational time, with power demand in the range of **30–60%** of installed capacity
- **Peak operational phases:** approximately **10–20%** of operational time, with power demand approaching **80–100%** of installed capacity

Auxiliary energy demand is primarily linked to mission-specific equipment rather than hotel loads and can become significant during operational phases. Systems such as winches, cranes, pumps, and dynamic positioning systems contribute to short-term peaks in electrical load, often coinciding with propulsion demand and reinforcing the highly variable nature of the onboard energy profile.

Port interaction is frequent and structurally embedded in the operational cycle. Vessels regularly return to port for standby, crew change, or task reassignment, resulting in **multiple daily port interface events**. During these phases, propulsion systems are typically inactive,

and onboard energy demand is limited to auxiliary systems, creating favourable conditions for low-emission or zero-emission operation through hybrid or shore-powered solutions.

A defining feature of the UC5 operational scenario is therefore the **mismatch between installed power and average power demand**, driven by the need to guarantee high instantaneous thrust while operating most of the time at low load. This characteristic strongly penalises conventional propulsion efficiency and represents the primary driver for hybridisation and advanced energy management strategies.

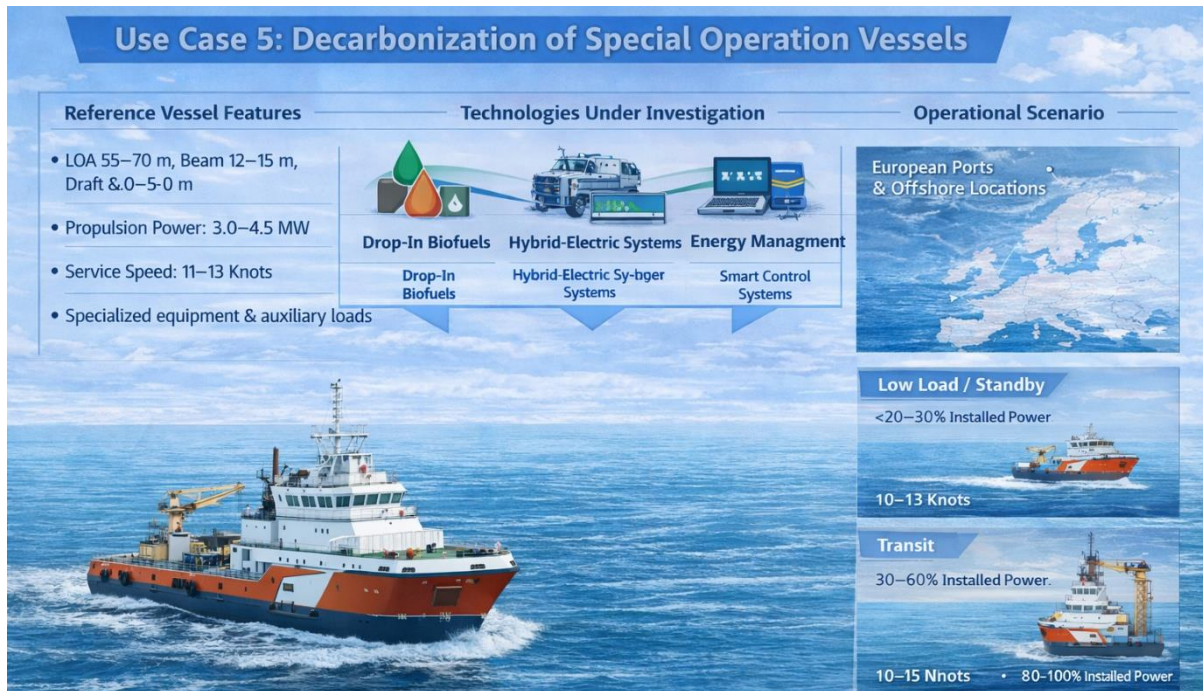


Figure 7 – Special operation vessel UC - Main Features

4. USE CASES FOR THE 2050 TIME HORIZON

In contrast to the evolutionary approach adopted for the 2030 horizon, the definition of use cases for the 2050 timeframe is developed in alignment with the long-term objectives of the European Green Deal, targeting full climate neutrality across the maritime sector. [19]

Within this context, the strategic perspective shifts from the optimisation of existing assets to the deployment of **next-generation vessels specifically designed to accommodate zero-emission technologies**, while still ensuring operational feasibility and system-level efficiency.

These scenarios assume the progressive maturation of alternative fuel supply chains, port infrastructure, and onboard technologies. [20] [21] However, rather than representing purely theoretical configurations, the use cases are defined by considering **technological scalability, system integration, and operational compatibility** across the different vessel typologies. As a result, the analysis does not rely on single-solution pathways but explores **combinations of propulsion technologies and optimisation strategies** capable of achieving near-zero or zero-emission performance at fleet level.

Accordingly, the selection of use cases for this horizon reflects the most plausible long-term configurations for each vessel category, integrating both **primary energy carriers** and **efficiency-enhancing technologies**:

- **UC1 – General Cargo:** Deep-sea vessels are expected to adopt **ammonia-based propulsion systems** as a primary pathway, potentially complemented by methanol in specific configurations where lifecycle emissions are mitigated through carbon-neutral production or integrated carbon management solutions. [22] These vessels are designed with fuel-specific architectures and are systematically coupled with **Wind Assisted Propulsion Systems (WAPS)** and advanced voyage optimisation tools to reduce overall energy demand.
- **UC2 – Passenger Ships:** The passenger sector is expected to converge towards **hydrogen-based power systems**, primarily fuel cells, enabling zero-emission operation in both navigation and port conditions. [23] System integration is driven not only by environmental performance but also by operational requirements related to comfort, noise reduction, and hotel load management, with hybrid architectures and energy storage supporting peak shaving and operational flexibility.
- **UC3 – Tugs & Service Vessels:** This segment is characterised by a transition towards **fully electrified and hydrogen-supported power systems**, where batteries provide instantaneous power response and hydrogen-based solutions ensure energy availability for sustained high-load operations. The system architecture is optimised around highly dynamic load profiles, with hybridisation and advanced energy management playing a central role.
- **UC4 – Inland Waterways (IWT):** Inland vessels are expected to adopt **full electric and hydrogen-based propulsion systems**, leveraging the proximity to shore infrastructure and the predictability of operations. The integration of these technologies is strongly linked to corridor-based energy supply systems and aims to eliminate both atmospheric emissions and environmental impact on inland ecosystems.
- **UC5 – Special Operation Vessels:** For service and offshore vessels, the 2050 scenario is based on **hybrid architectures combining electrification and hydrogen-based**

energy systems, optimised for highly transient operational profiles. The focus is on power management, load flexibility, and zero-emission operation in port and nearshore environments, rather than on long-range endurance.

Overall, the 2050 use cases are defined not only by the adoption of alternative fuels, but by a broader transformation of vessel design, integrating **energy-efficient hull forms, hybrid power systems, digital optimisation tools, and advanced operational strategies**. The following tables present the “Most Probable” and “Less Probable” technological pathways for each use case, outlining the expected evolution towards a fully decarbonised European maritime sector.

Table 2 - 2050 Technological framework

UC1: General Cargo -2050 Technology Uptake scenario			
Energy & Propulsion Solutions	Optimisation strategies	Rationale	Strengths and Weaknesses
Most probable: • Ammonia (primary carbon-free fuel) • E-methanol / CCU-methanol (carbon-neutral depending on pathway) • Wind Assisted Propulsion Systems (fully integrated by design) • Advanced Waste Heat Recovery (WHR) and energy cascade systems	Most probable: • Weather routing and predictive voyage optimisation • Speed optimisation integrated with carbon cost and energy minimisation • Hull air lubrication systems (integrated) • Advanced hull–propulsor co-design (low-resistance hull forms, optimised propellers) • Digital twin–based energy and performance management • Integrated energy system optimisation (propulsion + auxiliaries)	Rationale for the most probable technologies: • System-level optimisation: vessels are designed from the outset around alternative fuels and integrated efficiency solutions. • Energy density vs volume trade-off: ammonia and methanol provide viable solutions for long-range operations, despite storage penalties. • Carbon neutrality pathways: ammonia enables zero-carbon operation, while e-/CCU-methanol depends on upstream carbon sourcing. • Efficiency-first design: WAPS, ALS and WHR are embedded in the design phase to reduce total energy demand. • Digital integration: real-time optimisation enables continuous minimisation of energy consumption and emissions.	Strengths: • Potential for near-zero or zero lifecycle emissions (depending on fuel pathway) • Viable for long-range, deep-sea operations • Integrated efficiency significantly reduces fuel consumption • Flexibility across fuel pathways (ammonia vs methanol) Weaknesses: • Ammonia toxicity and safety management complexity • Increased fuel storage volume impacting cargo capacity • Dependence on global fuel supply chains (green fuels) • High CAPEX for newbuild vessels and infrastructure
Less probable / niche: • Full battery-electric propulsion (deep-sea) • Hydrogen-based propulsion for long-range cargo (FC or ICE) • Fossil-based fuels (including LNG) • Conventional biofuels as primary propulsion fuel • Nuclear propulsion (SMR-based, niche adoption)	Less probable / niche: • Full battery-electric propulsion for long-range operations • Hydrogen-based propulsion systems for transoceanic routes • Fuel strategies without integrated efficiency design • Conventional optimisation without digital/system integration	Rationale for the less probable technologies: • Batteries: insufficient energy density for deep-sea cargo operations. • Hydrogen: low volumetric energy density leads to excessive storage requirements. • Fossil fuels: incompatible with climate neutrality targets and regulatory frameworks. • Conventional biofuels: limited scalability and sustainability constraints at global level. • Nuclear: technically viable for long-range zero-emission propulsion, but constrained by regulatory frameworks, port access limitations, public acceptance, and high CAPEX.	Weaknesses: • Limited scalability for global cargo operations • Significant regulatory and societal barriers (especially for nuclear) • High investment costs and long development timelines • Infrastructure and governance requirements for nuclear fuel cycle • Operational and liability complexities

UC2: Tanker -2050 Technology Uptake scenario			
Energy & Propulsion Solutions	Optimisation strategies	Rationale	Strengths and Weaknesses
Most probable: - Ammonia (primary carbon-free fuel, with safety integration) - E-methanol / CCU-methanol (selective, depending on cargo type and route) - Advanced Waste Heat Recovery (WHR) integrated with cargo systems - Air Lubrication Systems (ALS) (integrated by design)	Most probable: - Integrated thermal energy management (WHR → cargo heating, tank conditioning) - Speed optimisation driven by carbon intensity and fuel cost - Hull–propulsor co-design for low-resistance operation - Advanced cargo handling optimisation (pumping, heating cycles) - Digital twin–based monitoring and predictive optimisation - Integrated energy system optimisation (propulsion + cargo systems)	Rationale for the most probable technologies: - System integration: tanker design allows strong coupling between propulsion and cargo energy systems. - Thermal demand advantage: high onboard heat demand makes WHR particularly effective compared to other vessel types. - Fuel selection constraints: ammonia and methanol provide viable decarbonisation pathways compatible with long-range transport, with ammonia offering zero-carbon potential. - Safety-driven design: newbuild vessels incorporate segregated fuel systems and advanced risk mitigation technologies. - Efficiency by design: hydrodynamic and system-level optimisation reduce total energy demand.	Strengths: - High efficiency through integration of propulsion and cargo systems - Significant potential for lifecycle emission reduction - Strong compatibility with long-haul operations - WHR provides additional value compared to other vessel types Weaknesses: - Safety complexity (toxic and hazardous fuels combined with hazardous cargo) - Increased system complexity and CAPEX - Space constraints due to fuel storage and segregation requirements - Dependence on global fuel availability and logistics
Less probable / niche: - Hydrogen-based propulsion (FC or ICE) - Full battery-electric propulsion - Fossil-based fuels (including LNG) - Conventional biofuels as primary propulsion fuel - Nuclear propulsion (highly constrained / niche)	Less probable / niche: - Full electrification of propulsion and cargo systems - Hydrogen-based long-range propulsion systems - Fuel strategies without integrated thermal optimisation - Conventional optimisation without system integration	Rationale for the less probable technologies: - Hydrogen: volumetric constraints and storage challenges are amplified by the need to preserve cargo capacity. - Batteries: unsuitable for long-range tanker operations due to energy density limitations. - Fossil fuels: incompatible with net-zero targets and regulatory frameworks. - Biofuels: limited scalability and competition with other sectors. - Nuclear: technically feasible but constrained by regulatory, safety, and port acceptance issues, particularly critical for vessels carrying hazardous cargo.	Weaknesses: - Limited scalability and high uncertainty - Significant design and safety challenges - Regulatory and societal barriers - Infrastructure and supply chain constraints

UC3: Passenger ship -2050 Technology Uptake scenario			
Energy & Propulsion Solutions	Optimisation strategies	Rationale	Strengths and Weaknesses
Most probable: - Hydrogen Fuel Cells (PEM / SOFC) (primary zero-emission solution) - E-methanol / CCU-methanol (backup or hybrid fuel pathway) - Advanced battery systems (large-scale hybridisation for hotel loads and port operations) - Onshore Power Supply (OPS) fully integrated - Advanced Waste Heat Recovery (WHR) for hotel services	Most probable: - Advanced hotel load optimisation (HVAC, thermal integration, smart cabins) - Integrated energy management (propulsion + hotel loads) - Peak shaving and spinning reserve replacement - Digital twin-based optimisation of energy demand and routing - Itinerary optimisation based on energy availability and carbon constraints - Full integration with port energy systems (OPS + charging + H₂ supply)	Rationale for the most probable technologies: - Zero-emission requirement in sensitive areas: passenger vessels operate in ports and coastal zones with strict environmental regulations. - Hotel load dominance: energy demand is driven as much by onboard services as by propulsion, favouring fuel cell systems with stable and efficient output. - Passenger comfort: hydrogen fuel cells provide low-noise and low-vibration operation. - System integration: vessels are designed around integrated energy systems combining fuel cells, batteries, and thermal recovery. - Infrastructure maturity: large ports are expected to support hydrogen bunkering and OPS by 2050.	Strengths: - Zero emissions at point of use (NO_x, SO_x, PM eliminated) - Silent and vibration-free operation (high passenger value) - High efficiency in part-load operation (hotel loads) - Strong alignment with environmental regulations and public perception Weaknesses: - High storage volume for hydrogen impacting passenger space - Complex safety and risk management systems - High CAPEX for fuel cells and cryogenic storage - Dependence on hydrogen supply infrastructure
Less probable / niche: - Ammonia-based propulsion - Full electric propulsion (large vessels) - Hydrogen internal combustion engines (H₂ ICE)	Less probable / niche: - Full electrification of propulsion and hotel loads - Fuel-centric strategies without hybrid integration - Radical redesigns prioritising fuel storage over passenger space	Rationale for the less probable technologies: - Ammonia: toxicity risks are difficult to reconcile with high passenger density. - Batteries: insufficient energy density for large vessels and long itineraries. - H₂ ICE: lower efficiency compared to fuel cells and higher emissions (NO_x).	Weaknesses: - Significant safety and certification challenges - High impact on vessel layout and revenue-generating space - Limited scalability across the global fleet - Infrastructure and public acceptance constraints

UC4: Inland waterways -2050 Technology Uptake scenario			
Energy & Propulsion Solutions	Optimisation strategies	Rationale	Strengths and Weaknesses
Most probable: • Full electric propulsion (battery-based) • Battery-hybrid systems (for extended flexibility) • Hydrogen Fuel Cells (selective use for long corridors / heavy-duty profiles) • Full integration with shore-side energy infrastructure (charging + smart grids)	Most probable: • Predictive energy management based on fixed routes • Speed optimisation vs river current and water depth • Charging optimisation and grid interaction • Digital twin-based route and energy planning • Fleet-level energy coordination (vessel-infrastructure integration) • Low-speed hull optimisation and shallow-water efficiency	Rationale for the most probable technologies: • Infrastructure proximity: inland vessels operate in continuous interaction with shore-based energy systems, enabling full electrification. • Predictable operations: fixed routes and schedules allow precise energy planning and battery sizing. • Environmental constraints: operations in urban and ecologically sensitive areas require zero air and water pollution. • System-level optimisation: integration between vessels and grid infrastructure enables efficient energy use at network level. • Hydrogen as extender: used where battery-only solutions are insufficient due to route length or payload constraints.	Strengths: • Zero direct emissions (TtW) and near-zero noise • Very high energy efficiency • Strong compatibility with EU environmental policies • High degree of operational predictability • Scalability across large parts of the inland fleet Weaknesses: • Strong dependence on charging infrastructure availability • Grid capacity constraints in some corridors • Battery weight impacting payload in certain cases • Hydrogen infrastructure required for extended operations
Less probable / niche: • Ammonia-based propulsion • LNG and fossil-based fuels • Wind Assisted Propulsion Systems (WAPS)	Less probable / niche: • Fuel-centric optimisation without electrification • Long-range endurance optimisation strategies • Wind-driven propulsion optimisation • Standalone onboard energy systems without grid integration	Rationale for the less probable technologies: • Ammonia: unacceptable safety risks in densely populated and confined inland environments. • Fossil fuels: incompatible with zero-emission requirements for inland transport. • WAPS: ineffective due to low speeds and constrained waterways.	Weaknesses: • Limited operational relevance • High safety and regulatory barriers • Poor alignment with inland operational profiles • Lack of economic justification

UC5: Special Operation Vessels -2050 Technology Uptake scenario			
Energy & Propulsion Solutions	Optimisation strategies	Rationale	Strengths and Weaknesses
Most probable: - Hybrid electric architectures (battery-dominant systems) - Hydrogen Fuel Cells (primary or auxiliary energy source) - Hydrogen ICE (selective use for high-power peaks) - Full electric operation for port and low-load conditions	Most probable: - Peak shaving and spinning reserve replacement - Real-time power demand forecasting and load smoothing - Dynamic positioning optimisation and thrust allocation - Digital twin-based energy and mission optimisation - Smart charging and shore-side energy integration - Autonomous or semi-autonomous energy management systems	Rationale for the most probable technologies: - Load profile matching: vessels operate with long low-load periods and short high-power peaks, making hybrid systems essential. - Instant power requirement: batteries provide immediate torque and response, while hydrogen systems ensure energy availability over time. - Zero-emission operations in ports: frequent operations near populated areas require elimination of local emissions. - System flexibility: hybrid architectures allow dynamic allocation between batteries, fuel cells, and combustion systems. - Operational optimisation: digital control systems enable real-time adjustment of energy flows and propulsion response.	Strengths: - Excellent matching between energy system and operational profile - Significant reduction of idle emissions - Immediate torque delivery for critical operations (e.g. towing, DP) - High operational flexibility across different missions - Strong suitability for port and nearshore zero-emission zones Weaknesses: - High system complexity (multi-source energy architecture) - High CAPEX for batteries and hydrogen systems - Space constraints on compact vessels - Dependence on port-based hydrogen and charging infrastructure
Less probable / niche: - Ammonia-based propulsion - Pure fuel-based systems without hybridisation - Full battery-electric systems for all mission profiles - LNG and fossil-based fuels	Less probable / niche: - Fuel-centric optimisation without hybrid control - Large-scale onboard energy storage without dynamic management - Conventional propulsion without digital integration	Rationale for the less probable technologies: - Ammonia: slow dynamic response and safety concerns make it unsuitable for high-reactivity operations such as towing or DP. - Full electric: battery-only solutions struggle to sustain repeated high-power peaks over extended operations. - Fossil fuels: incompatible with zero-emission port and coastal requirements. - Non-hybrid systems: unable to efficiently handle highly variable load profiles.	Weaknesses: - Limited operational flexibility - Inefficient response to dynamic load conditions - High operational risk in critical manoeuvring phases - Poor alignment with 2050 decarbonisation targets

4.1. Use Case 2050–UC1: General Cargo Vessels

Main differences compared to the 2030 scenario

The most significant evolution concerns the **propulsion system architecture and fuel integration strategy**. In the 2030 scenario, internal combustion engines operating on drop-in fuels such as biofuels or LNG represented the most scalable pathway, primarily within a retrofit logic. In the 2050 timeframe, propulsion systems are instead expected to be **natively designed around carbon-neutral energy carriers**, with ammonia representing the most likely primary option and methanol considered in configurations where lifecycle emissions are effectively neutralised through renewable production pathways or integrated carbon management solutions. As a consequence, vessel design is no longer constrained by legacy fuel systems, and layouts are optimised from the outset to accommodate **alternative fuel storage, safety zoning, fuel handling systems, and advanced automation requirements**. This results in increased volumetric allocation for fuel storage, redesigned machinery spaces, and a stronger integration between propulsion and auxiliary systems compared to 2030 vessels.

A second major difference lies in the **system-level integration of energy efficiency and optimisation technologies**. In 2030, solutions such as Wind Assisted Propulsion Systems (WAPS), air lubrication, and digital voyage optimisation were primarily considered as modular or retrofit-based enhancements. By 2050, these technologies are fully embedded within the naval architecture and energy system design. Hull forms are developed in synergy with aerodynamic propulsion devices, propulsion systems are dimensioned accounting for continuous auxiliary thrust contribution, and air lubrication is treated as a baseline design feature. In parallel, **digital twin-based energy management systems** become intrinsic to vessel operation, enabling real-time optimisation of speed, routing, and energy flows, and allowing continuous alignment with carbon-intensity targets and operational constraints.

From an operational perspective, the overall mission profile of general cargo vessels remains broadly consistent in terms of trading patterns and range. However, the **operational paradigm shifts from fuel consumption optimisation to integrated carbon and energy management**. Vessel performance is continuously monitored and dynamically adjusted through digital systems interfaced with port infrastructure and fuel supply networks. By 2050, it is assumed that **bunkering infrastructure for carbon-neutral fuels is widely available and standardised**, removing the logistical constraints that characterised the transition phase around 2030 and enabling full deployment of zero-emission propulsion solutions at scale.

4.2. Use Case 2050–UC2: Tanker Ships

Main differences compared to the 2030 scenario

The most significant evolution concerns the **propulsion system architecture and its integration with cargo-specific operational constraints**. In the 2030 scenario, tanker vessels relied primarily on internal combustion engines operating on conventional fuels or transitional solutions such as LNG and biofuels, within a retrofit-oriented framework. By

2050, propulsion systems are expected to be **natively designed around carbon-neutral fuels**, with ammonia representing the most probable primary energy carrier, while methanol may be considered in specific configurations where lifecycle emissions are effectively neutralised. The adoption of these fuels introduces substantial implications for vessel design, particularly in relation to **safety zoning, segregation between fuel and cargo systems, and hazardous area management**, which are more critical for tankers than for other vessel categories.

A second major difference lies in the **integration between propulsion systems and cargo-handling energy demand**. Tanker vessels are characterised by significant auxiliary loads associated with cargo operations, including pumping, heating, and inert gas systems. In the 2030 scenario, these systems were largely treated as separate energy consumers supplied by auxiliary engines. In the 2050 configuration, propulsion and auxiliary systems are integrated within a **unified energy architecture**, where alternative fuels supply both propulsion and cargo-related energy demand through optimised distribution systems. This enables improved overall efficiency and facilitates the adoption of zero-emission or near-zero-emission operation across both navigation and cargo-handling phases.

From a design perspective, the transition to alternative fuels results in **reconfigured tank arrangements and increased volumetric requirements for fuel storage**, particularly in the case of ammonia. Unlike 2030 vessels, where fuel storage was a secondary constraint, 2050 tanker designs must balance **cargo capacity, fuel storage volume, and safety requirements**, leading to revised layouts and potential impacts on deadweight utilisation. Additionally, the coexistence of hazardous cargoes and alternative fuels requires advanced containment systems, enhanced monitoring, and stricter compliance with safety regulations.

Energy efficiency technologies also evolve from optional enhancements to **fully integrated design features**. In 2030, solutions such as air lubrication, hull optimisation, and digital voyage optimisation were implemented as incremental improvements. By 2050, these technologies are embedded within the vessel design, with hull forms, propulsion systems, and operational strategies co-optimised to minimise total energy demand. While Wind Assisted Propulsion Systems (WAPS) may be applicable to certain tanker configurations, their integration is more constrained compared to dry cargo vessels due to deck operations and safety considerations, and therefore requires case-specific evaluation.

Another key difference is the **full integration of digital and automation systems**. Advanced digital twins and energy management platforms enable real-time optimisation of propulsion, cargo operations, and energy flows, ensuring compliance with carbon intensity targets and enhancing operational efficiency. These systems also support predictive maintenance and improved safety monitoring, which are particularly critical for vessels transporting hazardous cargoes.

From an operational standpoint, tanker vessels maintain similar long-haul and regional trading patterns compared to 2030. However, the operational paradigm shifts towards **integrated energy and emissions management across the entire mission**, including cargo handling and port operations. By 2050, it is assumed that **global infrastructure for carbon-neutral fuels is widely available and standardised**, enabling tanker vessels to operate without the fuel availability constraints that characterised earlier transition phases.

4.3. Use Case 2050–UC3: Passenger Ships

Main differences compared to the 2030 scenario

In the 2050 scenario, the cruise ship use case transitions from a hybrid and port-emission–focused decarbonisation approach to a **fully integrated zero-emission energy architecture**, designed to address both propulsion and hotel loads as a single, tightly coupled system. While the 2030 description was centred on the use of batteries for peak shaving and port stays, combined with LNG or biofuels for navigation, the 2050 horizon assumes that cruise vessels are predominantly **newbuild platforms conceived around climate-neutral energy carriers and fully electrified onboard systems**.

The most relevant shift concerns the role of electrical power generation and distribution. In 2030, electrical systems were primarily optimised to reduce auxiliary engine operation and local emissions in port. By 2050, cruise ships are expected to adopt **electric-dominant architectures**, where propulsion and hotel services are supplied through a common high-capacity electrical backbone. Hydrogen-based systems, primarily fuel cells integrated within hybrid configurations, move from pilot-scale demonstrations to **structural base-load providers**, supplying continuous power with minimal noise and vibration. This evolution directly responds to the defining characteristics of cruise vessels, namely continuous hotel loads, passenger comfort requirements, and operation in environmentally sensitive tourist destinations.

Another key difference lies in the treatment of energy efficiency and demand reduction. In the 2030 scenario, optimisation strategies focused on operational measures such as load management, peak shaving, and selective waste heat recovery. In 2050, **hotel load reduction becomes a design driver**, not merely an operational improvement. HVAC systems are fully electrified and integrated with high-efficiency heat pumps, thermal storage, and advanced insulation concepts. Waste heat recovery is embedded within the overall energy system design rather than treated as an auxiliary feature, contributing to space heating, domestic hot water, and ancillary services.

From an operational perspective, port stays evolve from emission-reduction opportunities to **zero-emission operational baselines**. Shore power integration, already relevant in 2030, becomes fully standardised and seamlessly interoperable with onboard energy systems. Cruise itineraries and operational planning are increasingly aligned with energy availability and carbon accounting constraints, supported by digital twin platforms that continuously optimise energy flows, passenger services, and propulsion requirements across the entire voyage.

Finally, the 2050 scenario reflects a shift in risk perception and regulatory maturity. Technologies that were considered marginal or constrained by safety, certification, or public acceptance in 2030 are assumed to have reached a sufficient level of maturity through design standardisation, automation, and regulatory harmonisation. As a result, the decarbonisation strategy for cruise ships in 2050 is no longer driven by incremental substitution of fuels, but by a **holistic redesign of the vessel as a zero-emission floating hospitality platform**, where energy generation, storage, and consumption are fully integrated into the core naval architecture.

4.4. Use Case 2050–UC4: Inland Waterway Vessels

Main differences compared to the 2030 scenario

In the 2050 scenario, inland waterway vessels retain largely unchanged **external dimensional constraints** compared to the 2030 baseline, as these are dictated by fixed infrastructural limits such as locks, bridges, channel depth, and air-draft restrictions. Length overall, beam, and maximum design draft therefore remain within the same regulatory envelopes, typically defined by the European inland navigation classes. The principal evolution with respect to 2030 is not geometric, but rather related to **internal arrangement, mass distribution, and energy system integration**.

Compared to 2030 vessels—where electrification was often implemented through partial hybridisation or battery retrofits—the 2050 configuration assumes **purpose-designed hulls optimised for full electric or hydrogen-electric propulsion**. Battery systems increase significantly in installed capacity, leading to a higher proportion of displacement being allocated to energy storage. As a result, lightweight structural solutions and optimised scantlings become more critical to offset the added mass of batteries and maintain payload capacity within allowable limits.

For vessels operating on longer corridors or under higher payload demands, **hydrogen storage systems** are integrated into the hull, typically in the form of pressurised or liquid tanks located within dedicated compartments. This introduces new volumetric constraints compared to 2030 designs and requires a reallocation of internal space that would previously have been used for cargo or ballast. The longitudinal and vertical positioning of these tanks has a direct impact on trim and stability, necessitating refined weight management and careful control of the vertical centre of gravity to preserve compliance with inland stability criteria.

Propulsion architecture evolves from diesel-mechanical or hybrid arrangements to **fully electric drive systems**, with electric motors directly coupled to propellers or azimuthing units. This reduces the footprint of traditional engine rooms but introduces distributed electrical spaces, power electronics rooms, cooling circuits, and safety zones. Consequently, machinery spaces become more modular and decentralised compared to the 2030 layout, improving redundancy while increasing integration complexity.

The removal of conventional fuel tanks, exhaust systems, and associated piping allows partial recovery of internal volume; however, this is largely offset by the space required for batteries, hydrogen storage, thermal management systems, and safety equipment. Overall displacement therefore increases moderately relative to 2030 vessels of comparable size, with a corresponding emphasis on **hydrodynamic optimisation at low speeds** to preserve energy efficiency and transport capacity.

4.5. Use Case 2050–UC5: Special Operations Vessels

Main differences compared to the 2030 scenario

In the 2050 scenario, the reference tug and service vessel maintains a broadly similar operational role and size envelope compared to the 2030 baseline; however, **key dimensional, volumetric, and mass-distribution characteristics are modified** to accommodate zero-emission propulsion systems and associated energy storage. While in 2030 vessel design remained largely constrained by conventional machinery layouts, the 2050 configuration assumes **purpose-designed hulls and machinery spaces optimised for electrified and hydrogen-based systems**.

From a dimensional standpoint, overall length and beam are not expected to increase significantly relative to the 2030 fleet, remaining within the typical ranges required for port manoeuvrability and escort operations. Instead, changes are primarily internal, with **increased allocation of volume within the hull** for energy storage systems. Battery compartments and hydrogen storage tanks are integrated below deck, leading to revised internal arrangements and altered longitudinal weight distribution. As a result, displacement increases moderately compared to 2030 vessels of similar size, requiring careful optimisation of hull form and stability margins.

The propulsion architecture evolves from hybridised mechanical systems to **electric-dominant configurations**, with propulsion units driven by electric motors supplied by batteries and, where required, hydrogen fuel cell systems. This shift reduces the footprint of conventional engine rooms but introduces new requirements for electrical rooms, power electronics, cooling systems, and ventilation. Consequently, machinery spaces are more distributed than in 2030 designs, improving redundancy but increasing integration complexity.

Weight sensitivity becomes a defining design constraint. Compared to 2030 hybrid tugs, 2050 vessels must balance the additional mass of batteries and hydrogen systems against the need to preserve bollard pull and dynamic response. This leads to greater emphasis on **lightweight structural design, compact energy storage solutions, and optimised centre-of-gravity positioning**, ensuring that manoeuvring performance and stability remain compliant with escort and harbour regulations.

Auxiliary systems are also affected. The transition to zero-emission propulsion enables the removal of exhaust gas systems and reduces fuel handling complexity, but introduces additional requirements for thermal management, gas detection, and safety zoning. Deck layouts and superstructure arrangements are adapted accordingly, with minimal impact on external dimensions but noticeable changes in internal volume utilisation.

5. RECOMMENDATIONS FOR REFINEMENT AND VALIDATION

The use cases developed within this deliverable currently represent the most robust and consistent approximation of the European fleet segmentation, based on the available datasets and the methodological framework defined in Deliverable D1.1. The adopted approach, combining statistical representativeness, dimensional clustering, and operational profiling, ensures that each use case captures the most recurrent configurations observed across the European maritime and inland navigation sectors. As such, the UC set can be considered, at this stage, a reliable and sufficiently accurate representation of fleet diversity for the purposes of scenario analysis and technology assessment.

The definition of each use case through dimensional ranges and operational envelopes is a deliberate methodological choice, aimed at preserving representativeness and flexibility while avoiding overfitting to specific vessel configurations. This approach is particularly appropriate in the context of early-stage comparative assessments, where the objective is to identify consistent technological trends and cross-segment implications rather than to model individual vessels with high granularity.

Further refinement of the use cases is therefore not required at this stage from a structural or methodological perspective. However, a targeted refinement process will be developed in subsequent phases of the project where required by downstream analyses, in particular in the context of Life Cycle Assessment (LCA) and techno-economic evaluations. In these cases, the use of parameter ranges may need to be complemented or replaced by more specific, point-based values in order to ensure numerical consistency, model convergence, and comparability of results.

Such refinements will be implemented selectively and only where strictly necessary, maintaining full traceability with the original use case definitions. The transition from range-based to point-based parameters will follow a controlled approach, ensuring that selected values remain fully representative of the corresponding vessel segment and do not compromise the overall coherence of the methodological framework.

In this perspective, refinement should be understood not as a revision of the use cases themselves, but as a functional adaptation of their parametrisation to meet the requirements of specific analytical tools. This ensures continuity between qualitative scenario definition and quantitative assessment, while preserving the integrity and representativeness of the UC framework as the reference baseline for the ZEWT analysis.

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ANNEX I - 2030 TIME HORIZON USE CASES FRAMEWORK

Use Case 2030–UC1: General Cargo Vessels

Table 1 – General Ship's features

Parameter	Reference Value / Range	Notes / Rationale
Vessel type	Dry cargo (bulk-dominant reference vessel)	Representative of bulk + general cargo + medium container
Deadweight (DWT)	70,000 - 80,000 t (~75,000 t)	Dominant IMO size class
Length overall (LOA)	210 - 230 m	Typical Panamax/Kamsarmax
Beam	30 - 36 m	Consistent with bulk carrier geometry
Draft	12.5 - 14.5 m	Fully laden condition
Hull type	Full-form displacement (Cb > 0.80)	Optimised for capacity and efficiency
Cargo configuration	5 – 7 holds (bulk/multipurpose)	Allows variability in cargo types
Propulsion system	2-stroke low-speed diesel	Dominant fleet technology
Installed power	10 - 13 MW	Typical for 75k DWT
Propulsion layout	Single shaft, FPP	Conventional architecture
Service speed	13 – 15 knots	Efficiency-driven operation
SFOC	165 - 175 g/kWh	Post-2010 vessels
Fuel	HFO / MGO (baseline)	No alternative fuels in reference
Electrical system	Diesel generators (no EMS)	Conventional setup
Thermal availability	High (exhaust + cooling)	Suitable for WHR
Materials	Steel hull	Standard construction
Retrofit margins	Moderate (deck + internal volume)	Enables WAPS + auxiliary systems
Age	~10-15 years (2010–2015 build)	Fleet peak construction

Table 2 – Technology under investigation

Parameter	Reference Value / Range	Notes / Rationale
Fuel strategy	Biofuels, LNG	Retrofit-compatible solutions
Dual-fuel capability	Optional	Where feasible (long-term flexibility)
Energy efficiency – hull	Coatings, appendage optimisation	Immediate energy reduction
Energy efficiency – propulsion	Propeller/rudder optimisation	Mature technologies
Air lubrication	Applicable	Reduces frictional resistance
Waste Heat Recovery (WHR)	Applicable	High potential on 2-stroke engines
Hybridisation	Limited (battery + shaft gen)	Peak shaving / auxiliary optimisation
Battery system	Small-scale	Not for propulsion
Energy management system	Advanced EMS	Optimises load distribution
Wind Assisted Propulsion (WAPS)	Rotor sails / suction sails	Auxiliary propulsion contribution
Digital optimisation	Voyage optimisation, monitoring	Enables WAPS + routing synergy

Table 3 – Operational scenario

Parameter	Reference Value / Range	Notes / Rationale
Mission type	Regional + interregional cargo	EU-relevant, globally consistent
Voyage range	1,000 - 3,000 nm	Representative trade routes
Navigation duration	3 – 10 days	Per leg
Port call frequency	Every 1 – 2 weeks	Bulk trading pattern
Port stay duration	12 – 48 hours	Cargo operations
Speed	13 – 15 knots	Steady-state regime
Engine load	70 – 85% MCR	Efficient operating range
Propulsion power	8 - 10 MW (in operation)	From installed 10–13 MW
Daily propulsion energy	190 - 240 MWh/day	Main energy consumer
Auxiliary load (navigation)	10 - 20 MWh/day	5–10% of total
Total energy (navigation)	200 - 260 MWh/day	Combined demand
Manoeuvring loads	Peak (short duration)	Thrusters, transients
Port power demand	0.5 - 2 MW	Auxiliary only
Port energy per call	10 - 50 MWh	Depends on duration
Energy distribution	85–90% propulsion	Dominant consumption
Regulatory framework	CII, EEXI, SEEMP	IMO + EU alignment

Use Case 2030–UC2: Tanker Ships

Table 1 – General Ship's features

Category	Parameter	Reference Value / Range
General	Vessel Type	Product / Chemical Tanker (MR class)
Dimensions	DWT	40,000 - 50,000 t
	LOA	180 - 200 m
	Beam	30 - 32 m
	Draft	10 - 12 m
Propulsion	Engine Type	2-stroke low-speed diesel
	Installed Power	8 - 10 MW
	Service Speed	13 – 15 knots
Energy System	Fuel Type (baseline)	HFO / MGO
	Electrical Generation	Diesel generators
	Thermal Availability	High (engine exhaust & cooling)
Cargo System	Cargo Type	Liquid bulk (products, chemicals)
	Auxiliary Loads	Pumps, heating, inert gas systems
Structure & Layout	Hull Type	Double hull, full-form
	Deck Constraints	Limited (piping & safety zones)
Fleet Profile	Vessel Age	~10-15 years

Table 2 – Technology under investigation

Category	Parameter	Reference Value / Approach
Propulsion & Fuels	Fuel Transition	Biofuels (drop-in), LNG (where feasible)
	Propulsion Architecture	Conventional ICE with dual-fuel flexibility (limited cases)
Energy Efficiency	Hull Optimisation	Low-friction coatings, hull cleaning strategies
	Propulsion Efficiency	Optimised propeller and rudder configurations
	Energy Saving Devices	Air lubrication systems
Thermal Systems	Waste Heat Recovery	Integration with cargo heating systems
Cargo Systems	Energy Optimisation	Efficient pumping systems and cargo heating control
	Thermal Management	Improved insulation of cargo tanks
Hybridisation	Electrical Integration	Shaft generators for auxiliary optimisation
	Energy Storage	Limited batteries for peak shaving and load balancing
Digital Systems	Energy Management	Advanced EMS for propulsion and cargo load coordination
Wind Assistance	WAPS	Limited applicability due to deck and safety constraints

Table 3 – Operational scenario

Category	Parameter	Reference Value / Range
Mission Profile	Voyage Range	800 - 2,500 nm
	Voyage Duration	2 – 7 days
	Port Call Frequency	Every 5 – 10 days
	Port Stay Duration	18 – 60 hours
Navigation	Service Speed	13 – 15 knots
	Engine Load	65–85% MCR
Energy Demand (Nav.)	Propulsion Energy	150 - 210 MWh/day
	Auxiliary Energy	20 - 40 MWh/day
	Total Energy	170 - 250 MWh/day
Port Operations	Power Demand	2 - 6 MW
	Energy per Port Call	40 - 150 MWh
Energy Breakdown	Propulsion Share	70 – 80%
	Auxiliary Share	20 – 30%
Operational Phases	Manoeuvring	Peak loads (thrusters + propulsion)
Regulatory Context	Compliance Framework	CII, EEXI, SEEMP

Use Case 2030–UC3: Passenger Ships

Table 1 – General Ship's features

Parameter	Reference Value / Range	Notes / Rationale
Vessel type	Ro-Pax / medium-size cruise vessel	Representative of EU passenger fleet (ferries + cruise)
Length overall (LOA)	180 - 220 m	Most recurrent EU passenger vessel size
Beam	26 - 30 m	Port and stability constraints
Draft	6.5 - 8 m	Typical operational range
Passenger capacity	800 – 1,800 pax	Covers Ro-Pax and small cruise
Cargo configuration	Vehicles + passenger decks	Multi-deck layout
Propulsion system	Diesel-electric	Dominant for flexibility and redundancy
Installed power	15 - 30 MW	Balanced propulsion + hotel load
Propulsion layout	Electric propulsion motors	Integrated power system
Service speed	18 – 22 knots	Schedule-driven operations
Fuel	MGO / low sulphur fuels (baseline)	Some LNG-ready vessels
Electrical system	Integrated diesel-electric	Enables hybridisation
Thermal availability	Medium–high	Suitable for HVAC integration
Hotel load share	40 – 50% of total energy	Key distinguishing feature
Materials	Steel hull + aluminium superstructure	Weight optimisation
Retrofit margins	Limited–moderate	Constrained by passenger spaces
Age	~10-20 years	Fleet renewal window

Table 2 – Technology under investigation

Category	Parameter	Reference Value / Approach
Propulsion & Fuels	Fuel Transition	Biofuels (drop-in), LNG
	Propulsion Architecture	Diesel-electric with hybrid integration
Energy Efficiency	Hull Optimisation	Coatings, appendage optimisation
	Propulsion Efficiency	Propeller optimisation
Hotel Systems	Energy Optimisation	HVAC efficiency, lighting, insulation
Thermal Systems	Waste Heat Recovery	Integration with HVAC and onboard services
Hybridisation	Electrical Integration	Full system optimisation (diesel-electric)
	Energy Storage	Batteries for peak shaving and port operations
Digital Systems	Energy Management	Advanced EMS for propulsion + hotel loads
Wind Assistance	WAPS	Not applicable (superstructure constraints)

Table 3 – Operational scenario

Category	Parameter	Reference Value / Range
Mission Profile	Voyage Range	100 - 600 nm
	Voyage Duration	4 – 24 hours
	Port Call Frequency	Daily / multiple per day
	Port Stay Duration	1 – 6 hours
Navigation	Service Speed	18 – 22 knots
	Engine Load	60–85% MCR
Energy Demand (Nav.)	Propulsion Energy	250 - 500 MWh/day
	Hotel Load Energy	150 - 300 MWh/day
	Total Energy	400 - 700 MWh/day
Port Operations	Power Demand	3 - 10 MW
	Energy per Port Call	5 - 50 MWh
Energy Breakdown	Propulsion Share	50 – 60%
	Hotel Share	40 – 50%
Operational Phases	Manoeuvring	Frequent peak loads
Regulatory Context	Compliance Framework	CII, EEXI, SEEMP

Use Case 2030–UC4: Inland Waterway Vessels

Table 1 – Reference vessel characteristics

Parameter	Reference Value / Range	Notes / Rationale
Vessel type	Inland waterway cargo vessel	Representative of bulk, container, and general river freight
Length overall (LOA)	80 - 135 m	Governed by European lock systems and bridge clearances
Beam	9 - 17 m	Standardized river infrastructure dimensions
Draft	2.5 - 3.5 m	Strictly limited by seasonal hydrological variability
Cargo capacity	1,500 – 4,000 tonnes / 100 – 300 TEU	Based on hull configuration and river water depths
Propulsion system	Diesel-mechanical configuration	One or two main engines with reduction gearboxes
Installed power	500 kW - 2.5 MW	Tailored to river navigation constraints
Service speed	8 – 13 knots (15-24 km/h)	Modest transit speed favoring safety and efficiency
Hotel load share	Minimal relative to propulsion	Limited to navigation systems and basic accommodation
Hull type & Materials	Conventional steel hull	Optimised for shallow-draft operation and low resistance
Retrofit margins	Comparatively favorable	Driven by lower installed power and constrained ranges

Table 2 – Technology under investigation

Category	Parameter	Reference Value / Approach
Propulsion & Fuels	Fuel Transition	Drop-in biofuels or LNG as transitional options
	Propulsion Architecture	Full battery-electric or hybrid-electric drive systems
Energy Efficiency	Hydrodynamic Optimisation	Low-speed hull and shallow-water efficiency upgrades
Hybridisation & Storage	Electrical Integration	Advanced PMS coordinating batteries and propulsion units
	Energy Storage	Batteries sized as main energy source or for hybrid backup
Digital Systems	Energy Management	Predictive routing based on river currents and lock transits
Wind Assistance	WAPS	Not applicable due to bridge interferences and low speeds
Infrastructure	Shore Interface	High integration with port/terminal charging infrastructures

Table 3 – Operational scenario

Category	Parameter	Reference Value / Range
Mission Profile	Voyage Pattern	Predictable, repetitive, and corridor-based operations
	Daily Operating Range	20 – 300 km per day
	Port Call Frequency	High frequency (daily or structured sequence of segments)
	Port Stay Duration	From a few hours to a full day (loading/unloading)
Navigation	Load Profiles	Smoother than port tugs, adjusted for river flow conditions
	Operational Cycles	Frequent stop-and-go cycles due to lock transits
Port Operations	Power & Energy Demand	Minimal propulsion demand; auxiliary-dominated phases
Regulatory Context	Compliance Framework	Environmental zoning, local air quality rules, CII/EEI

Use Case 2030–UC5: Special Operation Vessels

Table 1 – Reference vessel characteristics

Parameter	Reference Value / Range	Notes / Rationale
Vessel type	Special Operation Vessels (OSVs, PSVs, Tugs)	Mission-driven units with highly variable load profiles
Length overall (LOA)	55 - 70 m	Recurrent European service vessel envelope
Beam	12 - 15 m	Consistent with stability and manoeuvrability criteria
Draft	4.0 - 5.0 m	Optimised for port, coastal, and nearshore environments
Propulsion system	Twin-screw or azimuth thruster configuration	Driven by two medium-speed diesel engines
Installed power	3.0 - 4.5 MW	Reduced range avoiding massive construction vessels
Service speed	11 – 13 knots	Focus on precise thrust control rather than transit speed
Load profile	Highly transient and variable	Prolonged low-load periods with short-duration peaks
Auxiliary loads	Mission-driven (winches, cranes, pumps)	Irregular and peak-intensive electrical loads
Retrofit margins	Sizable internal volume allocation	Sufficient for compact BESS and hybrid retrofits
Proxy extensions	Large deep-sea fishing vessels (~5 MtCO ₂ /year)	Partially applicable due to similar operational cycles

Table 2 – Technology under investigation

Category	Parameter	Reference Value / Approach
Propulsion & Fuels	Fuel Transition	Drop-in biofuels for immediate emissions mitigation
	Propulsion Architecture	Hybrid-electric power systems (primary solution)
Energy Efficiency	Thrust Optimisation	High-efficiency azimuth thrusters and CPP systems
	Auxiliaries Electrification	Fully electrified winches, deck machinery, and pumps
Hybridisation & Storage	System Configuration	BESS integrated for load smoothing and peak shaving
	Battery Sizing	Driven by power requirements (kW) rather than capacity (kWh)
Digital Systems	Energy Management	Real-time PMS/EMS coordinating thrusters and dynamic loads
Alternative Fuels	Gas / Disruptive	LNG/H ₂ considered secondary due to extreme volume penalties

Table 3 – Operational scenario

Category	Parameter	Reference Value / Range
Mission Profile	Mission Type	Task-driven and event-based operations
	Geographical Radius	50 – 150 nautical miles from base port
	Port Interface	Frequent daily port returns and interface events
Time Allocation	Low-load / Standby	40 – 60% of time (<20-30% installed capacity)
	Transit Operation	20 – 30% of time (30–60% installed capacity)
	Peak Operations	10 – 20% of time (80–100% capacity - DP/Towing)
Port Operations	Power & Emissions	Main engines inactive; ideal for zero-emission battery/OPS mode
Energy Breakdown	Efficiency Penalties	Heavy mismatch between high installed power and low average load
Regulatory Context	Compliance Framework	IMO compliance (CII, EEXI) + port decarbonisation targets



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