Technology Roadmap

Competitive, resilient and sustainable ocean-going shipping

Contents

1. Description of the Sector

1.1 Definition and scope

Ocean-going shipping refers to long-distance seagoing maritime transport of cargo across ocean basins and global trade routes. For the purposes of this roadmap, the sector comprises commercial seagoing merchant vessels above 1,000 gross tonnage engaged in international and intercontinental cargo transport.[1] Compared with short sea shipping, ferries, cruise, offshore and inland waterway transport, ocean-going shipping is characterized by long voyage duration, high propulsion energy demand, large fuel storage requirements, operational autonomy over several days or weeks, and exposure to global port, fuel and regulatory systems[2].

The European-controlled fleet is defined as the fleet beneficially owned or controlled by companies located in the EU-27 and Norway, regardless of the flag under which the vessels are registered.[3] The segment covered by this roadmap includes container ships, dry bulk carriers, tankers (crude, product, chemical and gas), specialized cargo vessels (Ro-Ro, deep-sea and pure car & truck carriers) and general cargo ships.

These characteristics shape fuel choice, retrofit and newbuild economics, port and bunkering infrastructure, the safety assessment, certification and regulatory approval of new fuels and technologies, digital-compliance systems, financing instruments and international regulatory alignment.

1.2 Strategic role in the European waterborne ecosystem

Ocean-going shipping is critical to the European economy, external trade, industrial competitiveness and strategic autonomy. Waterborne transport handles around 90% of international trade, 81% of EU external trade and 40% of EU internal trade.[4] Ocean-going vessels connect European ports, industries and consumers with global supply chains for manufactured goods, raw materials, energy commodities, agricultural products, chemicals and vehicles. European companies supply almost half of the world's maritime equipment and play a leading role in designing and developing most of the global fleet's power systems.[5] The sector is therefore a core enabling system for European economic resilience and global connectivity.

Europe's share of global merchant fleet carrying capacity is nevertheless declining. Between 2019 and 2024, EU-27 controlled tonnage fell from 35.0% to 30.2% of the world fleet, while Asia/Oceania-controlled tonnage rose from 931.8 million dwt to 1,186.0 million dwt over the same period (Table 1).[6]The absolute European controlled fleet has continued to grow in tonnage terms, but at a slower pace than the Asia-Pacific expansion. This is relevant for the roadmap because scale affects fuel procurement, shipyard access and retrofit capacity and technology contracting. It therefore reinforces

[1] Institute of Shipping Economics and Logistics (ISL), Shipping Statistics and Market Review, Volume 68 (Bremen: ISL, 2024), threshold of 1,000 GT following Clarkson Research Services Limited convention; Waterborne Technology Platform, Waterborne Technology Leadership – Towards a Competitive, Resilient and Sustainable Waterborne Sector (Brussels: Waterborne TP, January 2026), 6, https://www.waterborne.eu/images/260115_Waterborne_Technology_Leadership_final.pdf.
[2] Waterborne Technology Platform, Waterborne Technology Leadership, 6 (differentiation of vessel types and services by power requirements, operational profiles and autonomy).
[3] ISL, Shipping Statistics and Market Review, definition of "controlled fleet" (beneficially owned or controlled fleet, regardless of flag).
[4] Waterborne Technology Platform, Waterborne Technology Leadership, 6 (distinction between intercontinental and other waterborne segments; long voyages, high propulsion energy demand, global port exposure).
[5] Waterborne Technology Platform, Waterborne Technology Leadership, 5.
[6] Waterborne Technology Platform, Waterborne Technology Leadership, 5 (European maritime technology sector supplies almost half of the world's maritime equipment)

the need for coordinated European industrial and R&I action that links fleet renewal, fuel supply, port readiness, equipment manufacturing and deployment support.

World region	2019	2021	2024
Europe	843.1	871.8	894.7
— of which EU-27	654.9	680.4	674.3
North America	93.2	91.7	86.9
Latin America	27.8	29.8	17.1
Asia/Oceania	931.8	1,037.4	1,186.0
Africa	15.2	15.3	15.8
World total	1,872.8	2,024.4	2,235.1
EU-27 share of world total	35.0%	33.6%	30.2%

Table 1: Merchant fleet controlled by world region, 2019–2024 (million dwt, ships of 1,000 GT and over)

Source: ISL, based on quarterly updates from Clarkson Research Services Limited.[7]

Beyond aggregate capacity share, European ownership retains strong positions in vessel segments that are central to the technological and energy transition. European shipowners control 45% of global container ship capacity, 34% of oil tanker capacity, 32% of LNG carrier capacity and 28% of bulk carrier capacity.[8] Their scale, fuel demand and associated compliance and investment needs give these segments a particularly important role in driving demand for European solutions in propulsion, alternative fuel systems, energy efficiency technologies, digital optimization, safety, retrofitting and lifecycle services.

1.3 Operational profile

Ocean-going shipping operates through two co-existing business models, both of which are considered in this roadmap: liner shipping and bulk/tramp shipping. The distinction is important because deployment mechanisms, fuel-availability requirements, financing structures, digital compliance needs and SME participation differ substantially between the two. It therefore directly affects the design of the technology and implementation pathway.[9]

Liner shipping operates on published schedules and structured trade lanes. It dominates the container segment and part of the Ro-Ro deep-sea trade. Because routes, port calls and cargo flows are relatively predictable, liner shipping can support corridor-based deployment, long-term fuel offtake agreements, cargo owner aggregation, green shipping lanes, standardised digital reporting and

[7] ISL, Shipping Statistics and Market Review, EU Merchant Fleet by world region 2019–2024 (based on Clarkson Research Services Limited, quarterly updates); Europe includes EU-27, EFTA, UK, Monaco, Gibraltar, Andorra, Türkiye, Western Balkan countries, Russia, Ukraine, Moldova and Georgia from 2023.

[8] European Community Shipowners' Associations (ECSA), *The Economic Value of European Shipping: 2026 Update*, prepared by CE Delft (Brussels: ECSA, May 2026), §2.2 ("European fleet by vessel type and global comparison"), pp. 11–13 (European-controlled shares: 45% of world container ship capacity, 34% of oil tankers, 32% of LNG carriers, 28% of bulk carriers), citing Clarksons Research, *World Fleet Register*, November 2024.

[9] Waterborne Technology Platform, Waterborne Technology Leadership, 6 (business-model distinction between liner and bulk/tramp shipping and their respective business models); European Commission, Zero-Emission Waterborne Transport Partnership, SRIA 2.0 – Strategic Research and Innovation Agenda for the Zero-Emission Waterborne Transport Partnership (Brussels: Waterborne TP, June 2021), Part 2 (differentiation of ship categories by operational profile), https://www.waterborne.eu/images/210601_SRIA_Zero_Emission_Waterborne_Transport_1_2_final_web_low.pdf.

coordinated port fuel infrastructure planning. European operators hold a leading position in this segment, with 45% of global container ship capacity under European control.

Bulk and tramp shipping operates differently. It dominates the dry bulk and tanker segments, has no fixed routes, follows global cargo demand and calls at ports worldwide. In 2025, the Greek-controlled bulk/tramp fleet alone recorded over 175,000 port calls in 171 countries, illustrating the geographic breadth on which this operating model depends.[10] Bulk/tramp shipping operates in highly competitive and price sensitive markets, composed largely of small and medium-sized enterprises. At EU-27 and Norway level, more than 4,000 shipping companies are active, of which around 90% control fewer than ten vessels.[11]

This industry structure is a defining characteristic of ocean-going shipping's implementation pathway. It means that the transition cannot rely only on fixed green corridors or on deployment models designed for large liner operators. For bulk and tramp shipping, sustainable fuels must become available globally, in sufficient quantities and at affordable prices. In parallel, energy efficiency measures, retrofit packages, fuel flexible designs, flexible compliance mechanisms, verified performance methodologies and accessible finance become critical deployment conditions.

Both liner and bulk/tramp shipping depend on international fuel availability, IMO regulation, port readiness and interoperable digital-compliance systems. Both are also subject to FuelEU Maritime and EU ETS Maritime obligations for calls at EU/EEA ports.

1.4 Sector baseline and market characteristics

Fleet composition: Table 2 shows that European-controlled tonnage is concentrated in the vessel types most relevant for the transition to climate neutral deep-sea shipping. In deadweight tonnage terms, the largest European-controlled cargo segments are bulk carriers (256 million dwt), container ships (144 million dwt) and tankers (111 million dwt). These vessel categories differ significantly in route structure, cargo profile, fuel demand, port call patterns, safety requirements and retrofit potential. The roadmap must support differentiated technology packages for liner shipping, bulk carriers, tankers, Ro-Ro cargo vessels and general cargo operations.

Ship type	World number	EU-27 number	EU-27 share	World dwt (thousand)	EU-27 dwt (thousand)	EU-27 share (dwt)
Total fleet	50,257	12,314	25%	2,235,096	674,258	30%
Tankers	14,569	1,858	13%	805,114	111,197	14%
Bulk carriers	13,212	3,196	24%	968,665	256,135	26%
Container ships	6,083	2,387	39%	328,568	143,503	44%
General cargo	13,691	2,652	19%	125,176	28,636	23%
Ro-Ro cargo	963	292	30%	14,382	8,538	59%

[10] Union of Greek Shipowners, *Annual Report 2025–2026* (Athens: UGS, 2026), pp. 18–19 (Greek-owned vessels made more than 175,000 port calls in 171 countries in 2025, excluding passenger, cruise and service vessels; Greek shipping serves the external trade of third countries, with more than 98% of capacity transporting goods between third countries), citing Clarksons Research, March 2026, https://ugs.gr/media/14186/ugs_annualreport_2526_eng.pdf.

[11] European Community Shipowners' Associations (ECSA), *The Economic Value of European Shipping: 2026 Update*, prepared by CE Delft (Brussels: ECSA, May 2026), §2.3 ("European shipping companies by size"), p. 15 (4,153 EU-27 and Norway shipping company groups in 2024; 90% control fewer than ten vessels), citing Clarksons Research, *World Fleet Register*, November 2024.

Ship type	World number	EU-27 number	EU-27 share	World dwt (thousand)	EU-27 dwt (thousand)	EU-27 share (dwt)
Passenger and passenger cargo	2,702	750	28%	48,428	15,549	32%

Table 2:World and EU-27 controlled fleet by ship type, 1 January 2024 (ships of 1,000 GT and over)
Source: ISL, based on Clarkson Research Services Limited.[12]

Passenger and passenger-cargo vessels are included in Table 2 for consistency with the source dataset, but they are not part of the core scope of this roadmap. They are addressed in separate Waterborne technology roadmaps.

Fleet age: The EU Member State-flagged fleet is, on average, younger than the world fleet across the main cargo-carrying segments (Table 3). EU-flagged bulk carriers average 12 years against a world average of 13; container ships average 13 against 14; and tankers 14 against 18.[13] A younger fleet supports earlier retrofit and newbuild deployment of alternative-fuel systems, energy-saving devices and digital-compliance equipment. However, ocean-going vessels typically remain in service for 25 to 30 years. The transition must therefore combine fuel flexible newbuilds, retrofit-ready designs, modular upgrade packages and operational efficiency measures for the existing fleet.[14]

Ship type	EU Member State flag	World fleet
Bulk carriers	12	13
Container ships	13	14
Tankers (all)	14	18
— Oil tankers	14	20
— Chemical tankers	14	15
— Gas tankers	10	14
Ro-Ro cargo	18	20
General cargo	22	26

Table 3: Average age of EU Member State-flagged and world fleets by ship type, 2023 (years)
Source: European Maritime Safety Agency, European Maritime Safety Report 2025.[15]

Alternative-fuel capability: In 2024, 320 vessels in the EU Member State-flagged fleet operated with battery systems, corresponding to 2.5% of the fleet. In addition, 26 vessels were methanol-capable, representing 63% of the world methanol-fueled fleet; 46% of the world LNG-ready fleet, excluding LNG carriers, was EU Member State-flagged, and eleven fuel-cell vessels were in the orderbook for delivery

[12] European Community Shipowners' Associations (ECSA), *The Economic Value of European Shipping: 2026 Update*, prepared by CE Delft (Brussels: ECSA, May 2026), §2.3 ("European shipping companies by size"), p. 15 (4,153 EU-27 and Norway shipping company groups in 2024; 90% control fewer than ten vessels), citing Clarkson's Research, *World Fleet Register*, November 2024.
[13] ISL, Shipping Statistics and Market Review, World Merchant Fleet by Ship Type, 1 January 2024, based on Clarkson Research Services Limited.
[14] European Maritime Safety Agency (EMSA), The 2025 European Maritime Safety Report (EMSAFE) (Lisbon: EMSA, 2025), Table 21, Average age by ship type of ships with an EU Member State flag compared with that of the world fleet, p. 84.
[15] EMSA, The 2025 European Maritime Safety Report, Table 22, Average age by tanker type of tankers with an EU Member State flag compared with that of the world fleet, p. 84.

within five years.[16] These figures show that the transition is no longer purely conceptual, but also that large-scale deployment has not yet been achieved.

Fleet concentration by Member State: The European-controlled fleet is concentrated in a small number of Member States (Table 4). Greece controls 410 million dwt, equivalent to 61% of the EU-27 controlled fleet by tonnage, followed by Germany, Italy, Denmark and France. Together, these five countries account for the great majority of European-controlled ocean-going tonnage.[17] Norway, although outside the EU-27, remains a major European maritime power and is relevant to the wider European controlled fleet.

The fleet is highly internationalized in terms of flag as 83.7% of EU-27 controlled tonnage operates under foreign registries. This ratio ranges from 48.1% for Denmark to over 90% for Germany, reflecting competitive pressures on national registries in taxation, crewing rules and administrative requirements, and is a persistent feature of the ocean-going implementation environment.[18]

Country	Controlled fleet (dwt)	Share of EU-27 controlled fleet	Foreign flag share (dwt)
Greece	410,317	60.9%	86.8%
Germany	74,534	11.1%	90.1%
Italy	55,336	8.2%	88.5%
Denmark	40,662	6.0%	48.1%
France	22,366	3.3%	82.9%

Table 4: Top five European-controlled fleets, 2024 (thousand dwt)

Source: ISL, based on Clarkson Research Services Limited. Norway (83 million dwt) is a leading European maritime power but is not included in EU-27 totals. Full Member State breakdown is available in Annex I.[19]

The distinction between ownership, control and flag is important for the roadmap. European influence in ocean-going shipping is exercised not only through EU flags, but also through ownership, chartering, finance, technology supply, ports, classification, regulation and fuel market leadership. Deployment instruments must therefore be designed for a globally operated fleet, while still mobilising European industrial, regulatory and innovation capacity.

1.5 Ocean-going shipping as a technology-leadership opportunity

Ocean-going shipping is central to the European industrial and climate agenda. It is one of the most difficult waterborne segments to decarbonise because of its long voyage distances, high propulsion energy demand, large fuel storage requirements, long asset lifetimes and global operating environment. At the same time, it is one of the most important segments for European technology leadership, because solutions proven in deep-sea shipping can influence global maritime markets.

Continued industrial demand from ocean-going shipping is a essential for the retention and growth of Europe's high-value equipment, propulsion and digital-service capacity. Without the ocean-going market — including its bulk and tramp segment — the European maritime technology sector would lose

[16] European Maritime Safety Agency (EMSA), *The 2025 European Maritime Safety Report (EMSAFE)* (Lisbon: EMSA, 2025), §2.3.4 ("Age of ships"), p. 84.
[17] EMSA, The 2025 European Maritime Safety Report, Table 21 (source: EMSA services), p. 84.
[18] EMSA, The 2025 European Maritime Safety Report, §2.3.5 (Alternative fuels uptake), p. 85 (320 battery-equipped vessels; 26 methanol-capable vessels; 46% of LNG-ready fleet; 11 fuel-cell vessels in orderbook).
[19] ISL, Shipping Statistics and Market Review, Fleet by Member State 2024, based on Clarkson Research Services Limited.

a significant share of its addressable market. European companies already supply close to half of the world's maritime equipment and play a leading role in many of the global fleet's power systems.[20]

Fleet-renewal signals confirm the scale of the opportunity. European shipowners are investing in low- and zero-carbon fuel (LZCF)-capable tonnage, energy saving technologies and environmentally sustainable technologies. The Greek-controlled orderbook alone stands at 725 vessels totaling around 70 million dwt and USD 60 billion, and the corresponding fleet ranks as the world's largest alternative-fuel-capable and environmentally sustainable technology (EST)-fitted fleet.[21] Together with the wider European-controlled orderbook, this pipeline provides the demand signal that European propulsion, fuel-system, digital, retrofit and lifecycle-service industries need to reach scale.

The roadmap builds on this position by connecting European fleet-renewal decisions with European fuel production, port and bunkering readiness, digital-compliance infrastructure, safety regulation and the industrial capacity of European shipyards and equipment suppliers. Section 2 identifies the drivers and constraints; Section 3 sets the target capabilities for 2035, 2040 and 2050; Sections 4 to 6 translate those into technology pathways, deployment conditions and expected impacts.

2. Drivers and Constraints

2.1 Policy and market drivers

The transformation of ocean-going shipping is driven by the interaction of binding global and EU climate regulation, fuel and infrastructure policy, port and industrial strategy, and the need to preserve European technological sovereignty in a globally exposed segment. The most important drivers are set out below.

- **EU Climate Law and 2040 trajectory.** Regulation (EU) 2021/1119 establishes a binding objective of Union climate neutrality by 2050 and a Union obligation to take the necessary measures at Union and Member State level to achieve it collectively.[22] The political agreement reached in December 2025 between the European Parliament and the Council, formally adopted in March 2026, sets a 2040 headline target of a 90% net reduction in greenhouse gas emissions relative to 1990, with an adequate contribution of up to 5% from high-quality international credits.[23]The agreed framework consolidates the trajectory towards 2050 and provides a stable policy signal for investment, innovation and the timely deployment of decarbonization technologies across sectors, including ocean-going shipping, in line with the long-term temperature goal of the Paris Agreement.[24]
- **IMO 2023 GHG Strategy.** Resolution MEPC.377(80) requires the carbon intensity of international shipping to fall by at least 40% by 2030 against a 2008 baseline, sets a 5%–10% striving share for zero- and near-zero-GHG energy by 2030, and targets net-zero by or around 2050, with indicative checkpoints of at least 20% (striving 30%) absolute GHG reductions by 2030 and 70% (striving 80%)

[20] Waterborne Technology Platform, Waterborne Technology Leadership, 5 (European maritime technology sector supplies almost half of the world's maritime equipment); Waterborne Technology Platform, Bulk/Tramp Shipping – Follow-up to the October 2025 meeting (Brussels: Waterborne TP, January 2026), section "Furthermore, during exchanges regarding the upcoming industrial maritime strategy" (oceangoing bulk/tramp fleet as key market for European maritime equipment sector).

[21] Union of Greek Shipowners, Annual Report 2025–2026, 26–27 (orderbook: 725 vessels, 70 million dwt, USD 60 billion), 28–29 (largest alternative-fuel-capable and EST-fitted fleet globally), https://ugs.gr/media/14186/ugs_annualreport_2526_eng.pdf.

[22] Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 (European Climate Law), OJ L 243, 9 July 2021, Articles 1–2, https://eur-lex.europa.eu/eli/reg/2021/1119/oj.

[23] Council of the European Union, "2040 Climate Target: Council Gives Final Green Light," press release, 5 March 2026, https://www.consilium.europa.eu/en/press/press-releases/2026/03/05/2040-climate-target-council-gives-final-green-light/.

[24] United Nations Framework Convention on Climate Change (UNFCCC), Paris Agreement (Paris: UNFCCC, 2015), Article 2(1)(a), https://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf.

by 2040.[25] The Strategy adopts a well-to-wake lifecycle perspective and drives demand for sustainable marine fuels, fuel-flexible engines, wind-assisted propulsion, onboard efficiency systems and digital voyage optimisation.[26] The mid-term measures basket combines a goal-based marine fuel standard with a maritime GHG pricing mechanism, creating a coordinated investment signal for dual-fuel engines, retrofits, energy-saving devices and low- or zero-carbon supply chains.[27] The Strategy also identifies ports and logistics chains as integral to the transition and mobilises R&D, first-mover incentives and capacity-building for LDCs and SIDS.[28]

- **FuelEU Maritime and EU ETS Maritime.** Regulation (EU) 2023/1805 (FuelEU Maritime) imposes a declining GHG-intensity limit on energy used onboard for ships above 5,000 GT calling at EU/EEA ports, with a 14.5% reduction by 2035 and 80% by 2050, and a possible 2% RFNBO quota from 2034 if uptake remains below 1% by 2031.[29] Directive (EU) 2023/959 extends the EU Emissions Trading System to maritime transport from 1 January 2024, adding carbon-pricing obligations based on monitored and verified emissions.[30] Together with Regulation (EU) 2015/757 on MRV, these instruments strengthen the business case for energy efficiency, sustainable maritime fuels and zero-emission technologies, while exposing the segment to compliance complexity across jurisdictions.[31]
- **Sustainable Transport Investment Plan.** COM(2025) 664 final translates FuelEU Maritime demand into a structured package of fuel production, infrastructure, finance and certification.[32] It confirms differentiated fuel pathways for ocean-going vessels — wind-assisted propulsion, a broad basket of sustainable marine fuels, transitional LNG with methane-slip mitigation, biomethane and prospective e-methane, with possible shifts in major hubs towards biodiesel, e-methanol and ammonia — and identifies the core market failure of price gap, e-fuel scarcity and offtake uncertainty.[33] The Plan estimates EUR 34.7–46.7 billion in investment needs for bio-SMF and e-SMF production by 2035 and mobilises Innovation Fund support, a Hydrogen Bank maritime and aviation window, InvestEU, EIB/TechEU, Horizon Europe, ETS-based support for EU-produced SMF, double-sided auctions, an Early Movers Alliance, a possible IPCEI, tradable SMF certificates and book-and-claim options.[34]The international dimension is reinforced through Global Gateway Green Shipping Corridors and Hubs, SMF bunkering hubs in Latin America, Sub-Saharan Africa and Asia, and continued IMO engagement on lifecycle certification.[35]
- **EU Industrial Maritime Strategy.** COM(2026) 111 final addresses the structural barriers specific to ocean-going decarbonisation through six pillars. The *Build, Equip & Repair* measures — the EU Industrial Maritime Value Chains Alliance, "Shipyards of the Future", export-credit tools, fair-

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[25] International Maritime Organization, Resolution MEPC.377(80), 2023 IMO Strategy on Reduction of GHG Emissions from Ships, adopted at the 80th session of the Marine Environment Protection Committee, 7 July 2023, §3 (Levels of Ambition).
[26] MO, Resolution MEPC.377(80), §3.2 (well-to-wake approach) and §4 (Guiding Principles).
[27] IMO, Resolution MEPC.377(80), §5 (Candidate mid-term GHG reduction measures); see also IMO, Report of the Marine Environment Protection Committee on its 83rd session, MEPC 83, April 2025.
[28] IMO, Resolution MEPC.377(80), §5.2 (Safety and the human element), §5.3 (R&D) and §6 (Supportive measures, including ports, logistics chains, capacity-building, technology cooperation, LDCs and SIDS).
[29] Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport (FuelEU Maritime), OJ L 234, 22 September 2023, Articles 4–5.
[30] Directive (EU) 2023/959 of the European Parliament and of the Council of 10 May 2023 amending Directive 2003/87/EC establishing a system for greenhouse gas emission allowance trading within the Union, OJ L 130, 16 May 2023; European Commission, Report from the Commission on Monitoring of the implementation of Directive 2003/87/EC in relation to maritime transport, COM(2025) 110 final, Brussels, 18 March 2025.
[31] Regulation (EU) 2015/757 of the European Parliament and of the Council of 29 April 2015 on the monitoring, reporting and verification of carbon dioxide emissions from maritime transport, OJ L 123, 19 May 2015, as amended.
[32] European Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Sustainable Transport Investment Plan, COM(2025) 664 final, Brussels, 5 November 2025, §2.3 ("Roadmap for the energy transition in waterborne transport"), p. 6.
[33] European Commission, Sustainable Transport Investment Plan, COM(2025) 664 final, §2.1 ("Market challenges") and §2.3, pp. 5–7.
[34] European Commission, Sustainable Transport Investment Plan, COM(2025) 664 final, §3 ("Actions to boost investments") and Investment needs box, pp. 7–8.
[35] European Commission, Sustainable Transport Investment Plan, COM(2025) 664 final, international dimension and Global Gateway Green Shipping Corridors and Hubs, pp. 7–10.

competition instruments and circularity provisions — strengthen technological sovereignty over propulsion, fuel systems, retrofitting and end-of-life circularity.[36] The *Transport & Connect* measures simplify and streamline MRV for EU ETS Maritime and FuelEU Maritime, develop a European network of green shipping lanes and hubs, and pursue IMO alignment to avoid double payment.[37] Resilience measures address shadow-fleet monitoring, binding IMO cybersecurity rules and EU presence around maritime chokepoints[38] *Access to Innovation, Finance and Skills* provides a dedicated maritime Innovation Fund call, possible ETS-based support, Taxonomy revision and skills measures for safe management of alternative fuels and digital systems.[39]

- **EU Ports Strategy.** COM(2026) 112 final positions ports as multi-fuel, electrified, digital and secure nodes in global shipping networks. Its funding principles prioritise supply-chain resilience, green fuels, onshore power supply, port electrification, grid connections, physical and digital security and circularity.[40]Global connectivity measures include guiding principles for EU-supported port projects in third countries and a safeguard where third-country projects could affect EU ports within 300 nautical miles, limiting traffic diversion and carbon leakage.[41]Port energy-transition measures cover OPS deployment, the Electrification Action Plan, OPS price transparency, accelerated AFIR-driven alternative-fuels infrastructure and an assessment by the Renewable and Low-Carbon Fuels Alliance.[42] Security and resilience measures address FDI screening, cyber and hybrid threats, customs cooperation and critical-entity protection, while finance instruments mobilise CEF3 (EUR 51.5 billion transport budget) and EIB Group support.[43]

The European Community Shipowners' Associations frames ocean-going shipping as a strategic competitiveness asset and calls for demand-pull tools that close the offtake gap between European fleet investment and European fuel production. The Union of Greek Shipowners underlines the scale of the cross-trader function on which European ocean-going shipping depends. SEA Europe highlights retrofit and newbuild industrial capacity. ESPO and FEPORT identify ports and terminals as the critical deployment partners for OPS, alternative-fuel bunkering, digitalisation and resilience. The Waterborne Technology Platform identifies systematic deployment, ecosystem coordination and economic viability across all segments — including bulk and tramp — as the conditions for credible uptake.[44]

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[36] European Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, on the EU Industrial Maritime Strategy, COM(2026) 111 final, Brussels, 4 March 2026, §2 ("Build, Equip & Repair"), pp. 2–7.

[37] European Commission, EU Industrial Maritime Strategy, COM(2026) 111 final, §3 ("Transport & Connect"), §3.2 (energy transition and decarbonisation) and §3.4 (simplification of administrative procedures and MRV streamlining for EU ETS Maritime and FuelEU Maritime), pp. 7–11.

[38] European Commission, EU Industrial Maritime Strategy, COM(2026) 111 final, §3.3 (Safety, security and shadow-fleet operations) and §3.5 (Pursuing EU interests at international level: maritime chokepoints, Arctic routes, IMO cybersecurity), pp. 10–12; Annex Summary of Measures – Pillar II, p. 25.

[39] European Commission, EU Industrial Maritime Strategy, COM(2026) 111 final, §§4–6 ("Access to Innovation", "Access to Finance and Investment", "Access to Skills and Quality Jobs"), pp. 12–22.

[40] European Commission, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, EU Ports Strategy, COM(2026) 112 final, Brussels, 4 March 2026, Annex 1 ("Funding principles"), pp. 19–20.

[41] European Commission, EU Ports Strategy, COM(2026) 112 final, §2.1 ("Maintain global competitiveness"), pp. 2–3, and Annex 1.B ("Guiding principles for support to port projects in third countries", including the 300-nautical-miles competitiveness check), p. 20.

[42] European Commission, EU Ports Strategy, COM(2026) 112 final, §3 ("Advance energy transition, sustainability & clean industries"), §3.1 (Ports as enablers of the energy transition), pp. 7–9; Regulation (EU) 2023/1804 of the European Parliament and of the Council of 13 September 2023 on the deployment of alternative fuels infrastructure (AFIR), OJ L 234, 22 September 2023.

[43] European Commission, EU Ports Strategy, COM(2026) 112 final, §2.2 ("Ensuring economic security of EU ports"), pp. 3–4; §4 ("Protect & secure ports"), pp. 13–15; §5 ("Access to finance & investment": CEF3 transport budget of EUR 51.5 billion; EIB Group support of approx. EUR 2.8 billion 2014–2025), pp. 15–17; §6 ("Social cohesion, skills & quality jobs"), pp. 17–18.

[44] Waterborne Technology Platform, Waterborne Technology Leadership, 9–11 (ecosystem approach; systematic deployment; economic viability across all segments including bulk/tramp); Waterborne Technology Platform, Bulk/Tramp Shipping – Follow-up to the October 2025 meeting (Brussels: Waterborne TP, January 2026), Section "Next steps".

2.2 Technology and deployment drivers

Technology trends strengthen the case for an accelerated ocean-going roadmap, but must be interpreted in terms of deployment readiness as well as technology readiness. Energy-efficiency technologies — wind-assisted propulsion, hull and propeller optimisation, waste-heat recovery, advanced coatings, voyage and weather routing — are deployable now and remain the only currently feasible lever for deep-sea vessels operating long voyages at high energy density.[45] Dual-fuel engines and methanol-capable vessels are entering the market faster than ammonia and hydrogen systems, while LNG and biomethane remain transitional options subject to methane-slip and lifecycle performance. Ammonia, hydrogen, fuel cells, onboard carbon capture and advanced autonomy require further safety validation, standards, bunkering infrastructure and corridor-based demonstration before broad ocean-going uptake. The roadmap therefore distinguishes between technologies that should be deployed now, technologies that should be scaled through corridor and green shipping lane pilots, and technologies that still require targeted RD&I and regulatory development.

2.3 Constraints and bottlenecks

European ocean-going shipping faces five binding constraints for decarbonization and competitiveness. The main constraints are set out below.

- **Fuel-supply gap.** European shipowners lead global investment in low- and zero-carbon fuel (LZCF)-capable tonnage, yet the demand signal is not matched by a credible European production pipeline. The European-controlled fleet accounts for the largest share of orderbook investment in dual-fuel and alternative-fuel vessels, but Asia-Pacific represents the dominant share of projected global LZCF production capacity, and less than a fifth of Europe's announced low-carbon hydrogen pipeline is allocated to maritime use.[46]The Union of Greek Shipowners illustrates the paradox: the Greek-owned orderbook stands at 725 vessels, 70 million dwt and USD 60 billion, and the fleet ranks as the world's largest alternative-fuel-capable and EST-fitted fleet, while production capacity for the corresponding fuels remains predominantly outside Europe.[47] The Sustainable Transport Investment Plan estimates investment needs of EUR 34.7–46.7 billion for bio-SMF and e-SMF production by 2035 to meet FuelEU Maritime demand.[48]
- **Upstream energy systems and cross-sectoral competition.** The low-emissions fuels market remains marginal: in 2024, low-emissions hydrogen supplied less than 1% of total hydrogen use, while demand for low-emissions ammonia and methanol in shipping remains limited and awaiting new-vessel deliveries.[49] As of September 2025, only 15% of hydrogen and hydrogen-based fuel production potentially operational by 2030 had offtake agreements in place, and only one-quarter of those were on firm long-term terms.[50] Cross-sectoral competition is intensifying: hydrogen-

[45] Waterborne Technology Platform, Bulk/Tramp Shipping – Follow-up to the October 2025 meeting (Brussels: Waterborne TP, January 2026), Section "Items raised reconfirmed during the meetings", points 1–2 (zero-emission technologies not yet technically or commercially available for ocean-going ships; energy efficiency as currently the only feasible lever; choice of solution depending on vessel type, route and business model).

[46] European Community Shipowners' Associations (ECSA), *The Economic Value of European Shipping: 2026 Update*, prepared by CE Delft (Brussels: ECSA, May 2026), Annex 1 ("Low- and Zero-Carbon Shipping: Fleet Investment and the Fuel Availability Gap"), pp. 11–14 (European-controlled fleet leads global orderbook investment in LZCF-capable tonnage; Asia-Pacific accounts for around 74% of projected global LZCF production capacity against around 10% in Europe; less than 5% of Europe's projected LZCF pipeline currently allocated to maritime use); International Energy Agency, *Energy Technology Perspectives 2026* (Paris: OECD/IEA, 2026), Chapter 2 ("Outlook for deployment of clean energy technologies"), pp. 94–106.

[47] Union of Greek Shipowners, Annual Report 2025–2026, 26–29, https://ugs.gr/media/14186/ugs_annualreport_2526_eng.pdf.

[48] European Commission, Sustainable Transport Investment Plan, COM(2025) 664 final, §3 and Investment needs box, pp. 7–8.

[49] IEA, Energy Technology Perspectives 2026, Chapter 2, p. 94.

[50] IEA, Energy Technology Perspectives 2026, Chapter 2, p. 106.

based fuels for shipping, aviation and power generation account for around 40% of firm offtake volumes for low-emissions hydrogen, placing maritime demand in direct competition with steel, refining, fertilisers and synthetic aviation fuels.[51] On the deployment side, the total cost of ownership of methanol- or ammonia-powered vessels is today up to twice that of oil-fuelled ships, and fewer than half of the world's twenty major bunkering ports are alternative-fuel ready.[52]

- **Scale, fragmentation and business-model exposure.** Europe retains strategic positions across vessel segments: European shipowners control 45% of global container ship capacity, 34% of oil tankers, 32% of LNG carriers and 28% of bulk carriers.[53] Overall capacity share is declining as Asia-Pacific shipowners expand more rapidly. Scale is decisive for decarbonisation, since larger operators diversify technology risk, optimise compliance and secure stronger terms in fuel procurement and shipyard access. European industry structure works against this logic: around 90% of EU-27/Norway shipping companies control fewer than ten vessels, limiting pooled balance-sheet capacity for retrofits, first-of-a-kind newbuilds and long-tenor offtake contracts, and constraining bulk/tramp SMEs in particular.[54] European shipyards have lost merchant-segment global market share over the last decades, declining to around 15% in 2020–2024 from 60% in 2010, with leadership challenged in ferries and offshore-wind installation vessels.[55]
- **Regulatory architecture and compliance complexity.** The simultaneous entry into force of FuelEU Maritime,[56] the extension of the EU Emissions Trading System to maritime transport from January 2024,[57] and the MRV framework,[58] together with the parallel IMO 2023 GHG Strategy and its mid-term measures basket, creates timing, jurisdictional and cost-allocation frictions that translate into investment uncertainty for long-lifetime assets. The EU Industrial Maritime Strategy commits to simplifying and streamlining MRV for EU ETS Maritime and FuelEU Maritime, while pursuing alignment at IMO to avoid double payment.[59]
- **Digital readiness and cybersecurity.** Compliance is increasingly operationalised through digital infrastructure: the European Maritime Single Window environment became applicable from 15 August 2025, EMSA's THETIS-MRV centralises monitoring, reporting and verification, and the integration of FuelEU into THETIS-MRV connects monitoring plans, reporting and verification cycles.[60]Uneven digital readiness among smaller operators raises compliance costs and verification error risk. Reliance on interconnected reporting platforms elevates cybersecurity exposure under the NIS2 Directive.[61] The eFTI Regulation extends this trajectory to the wider

[51] IEA, Energy Technology Perspectives 2026, Chapter 2, p. 94.
[52] IEA, Energy Technology Perspectives 2026, Chapter 3 ("Technology deployment dashboards"), "Ammonia and methanol propulsion ships", p. 129.
[53] European Community Shipowners' Associations (ECSA), *The Economic Value of European Shipping: 2026 Update*, prepared by CE Delft (Brussels: ECSA, May 2026), §2.2 ("European fleet by vessel type and global comparison"), pp. 11–13, citing Clarksons Research, *World Fleet Register*, November 2024.
[54] ECSA, The Economic Value of European Shipping: 2026 Update, §2.3, p. 15. citing Clarkson's Research, *World Fleet Register*, November 2024.
[55] European Commission, EU Industrial Maritime Strategy, COM(2026) 111 final, §2.1 ("EU maritime manufacturing: fostering growth and competitiveness in lead markets"), p. 3.
[56] Regulation (EU) 2023/1805 (FuelEU Maritime), OJ L 234, 22 September 2023.
[57] Directive (EU) 2023/959, OJ L 130, 16 May 2023; European Commission, COM(2025) 110 final, Brussels, 18 March 2025.
[58] Regulation (EU) 2015/757, OJ L 123, 19 May 2015, as amended.
[59] European Commission, EU Industrial Maritime Strategy, COM(2026) 111 final, §3.2 and §3.4, pp. 8–11; Annex Summary of Measures – Pillar II, p. 25.
[60] Regulation (EU) 2019/1239 of the European Parliament and of the Council of 20 June 2019 establishing a European Maritime Single Window environment and repealing Directive 2010/65/EU, OJ L 198, 25 July 2019 (applicable from 15 August 2025); European Maritime Safety Agency, "THETIS-MRV Information System to Support Regulation (EU) 2015/757"; EMSA, "Integration of FuelEU in THETIS-MRV".
[61] Directive (EU) 2022/2555 of the European Parliament and of the Council of 14 December 2022 on measures for a high common level of cybersecurity across the Union (NIS2 Directive), OJ L 333, 27 December 2022.

logistics chain, signalling that ocean-going competitiveness will increasingly depend on end-to-end digital trade and enforcement interoperability.[62]

2.4 Implications for roadmap design

The ocean-going roadmap is organised around deployable capabilities under conditions of global exposure. The decisive question is whether vessels, ports, fuel suppliers, charterers, regulators and digital platforms can operate long-distance corridors safely, competitively and reliably in line with FuelEU Maritime, EU ETS Maritime and the IMO 2023 GHG Strategy. For this reason, the roadmap prioritises integrated deployment: vessels and ports developed together; fuel demand aggregated at corridor and hub level; book-and-claim and tradable certificate mechanisms bridging the price gap; financing tools structured for SMEs alongside large operators; and digital reporting systems designed to reduce rather than shift administrative burdens.

3. Target Capabilities

Ocean-going shipping must maintain Europe's long-distance maritime connectivity while progressively moving from fossil-fueled operations to zero-emission, digitally integrated and resilient global transport services. The Waterborne Technology Leadership document identifies large intercontinental merchant ships as vessels with high power requirements and long operational autonomy for which key technologies still require further development to reach technological maturity, and therefore as a priority for deployable zero-emission solutions.[63]

The operational challenge is structural. Most of the existing long-distance cargo fleet typically bunkers thousands of tonnes of fuel and requires several weeks of autonomy. For these vessels, early green propulsion is expected to rely primarily on internal combustion engines using sustainable fuels, potentially supported by wind propulsion, with a possible later transition towards fuel cells using green hydrogen-based fuels. Target capability cannot therefore be defined as simple electrification. It must be defined as the ability to combine fuel flexibility, energy-efficiency gains, retrofitting, newbuild readiness, digital optimisation, safety management and interoperable port-fuel infrastructure.[64]

3.1 By 2035 — Deployment readiness and first operational scale

By 2035, ocean-going shipping should be capable of operating first low- and zero-emission solutions on selected international routes where fuel supply, port infrastructure, cargo flows and regulatory conditions can be coordinated. The operational priority is to move beyond demonstration and establish first-of-a-kind deployment at route, fleet and corridor level. This includes vessels capable of using certified sustainable maritime fuels — advanced biofuels, e-fuels and hydrogen-derived fuels — while

[62] Regulation (EU) 2020/1056 of the European Parliament and of the Council of 15 July 2020 on electronic freight transport information (eFTI), OJ L 249, 31 July 2020.

[63] Waterborne Technology Platform, Waterborne Technology Leadership – Towards a Competitive, Resilient and Sustainable Waterborne Sector (Brussels: Waterborne TP, January 2026), 10 (ship types with high power requirements and long operational autonomy require further development to reach technological maturity), https://www.waterborne.eu/images/260115_Waterborne_Technology_Leadership_final.pdf.

[64] European Commission, Zero-Emission Waterborne Transport Partnership, SRIA 2.0 – Strategic Research and Innovation Agenda for the Zero-Emission Waterborne Transport Partnership (Brussels: Waterborne TP, June 2021), Part 2 ("Research and Innovation Strategy"), pathway for large intercontinental vessels (early reliance on internal combustion engines using sustainable fuels; wind propulsion; later transition to fuel cells with green hydrogen-based fuels), https://www.waterborne.eu/images/210601_SRIA_Zero_Emission_Waterborne_Transport_1_2_final_web_low.pdf

integrating transitional dual-fuel systems, wind-assisted propulsion and substantial energy-efficiency improvements.

The sector should also be capable of retrofitting a significant share of the existing fleet. Given the long lifetime of vessels, greening the fleet requires both retrofitting and newbuild replacement, rather than relying only on future new vessels.[65] For ocean-going shipping, this means operational capability for engine conversion, dual-fuel operation, onboard energy-management systems, waste-heat recovery, hydrodynamic optimisation, advanced coatings and wind-assist integration.

By 2035, the segment must also be capable of complying with the first mature phase of FuelEU Maritime and EU ETS Maritime requirements. The Sustainable Transport Investment Plan confirms that FuelEU Maritime requires a 14.5% greenhouse-gas intensity reduction by 2035, with sustainable maritime fuels expected to play a substantial role in meeting that target.[66] Vessels must be able to monitor, verify and report fuel use, greenhouse-gas intensity and operational emissions in a reliable and standardised manner.

Digital capability by 2035 should be practical rather than fully autonomous. Ocean-going vessels should be able to use digital twins, voyage optimisation, predictive maintenance, emissions monitoring, weather routing and port-call optimisation to reduce fuel consumption and improve reliability, consistent with the Strategic Research and Innovation Agenda's linkage between digital twins, zero-emission decision-support systems and green ship operations.[67]

3.2 By 2040 — System integration across vessels, ports and fuel supply

By 2040, ocean-going shipping should be capable of broader commercial deployment of low- and zero-emission operations across major trade lanes. The target is not only cleaner vessels, but an integrated operating system in which ships, ports, fuel suppliers, cargo owners, regulators and digital platforms function together. The Waterborne Technology Leadership document states that the waterborne transition depends on integration across vessels, ports, infrastructure and the broader ecosystem, because waterborne assets have long lifespans, operate globally, require specialised fuels and equipment, and depend on interoperable port logistics systems.[68]

Fuel capability by 2040 should be multi-fuel and route-adaptive. Ocean-going vessels should be able to use different sustainable fuel options depending on route, bunkering availability, vessel type and cargo profile. The Strategic Research and Innovation Agenda states that there is no single cost-effective and globally available alternative fuel today, and that future fuel choices depend on social, economic, technical and environmental conditions.[69] By 2040, this should translate into operational flexibility: vessels should not be locked into one immature pathway but should be designed and operated to manage different fuel options safely.

Safety capability must become mature by 2040. Alternative fuels, digitalisation and automation introduce new operational risks, including toxicity, fire, explosion, cryogenic handling, cyber risk and

[65] Waterborne Technology Platform, Waterborne Technology Leadership, 8 (retrofitting and newbuild replacement both required, given long vessel lifetimes of around 30 years).
[66] European Commission, Sustainable Transport Investment Plan, COM(2025) 664 final, Brussels, 5 November 2025, §2.3 ("Roadmap for the energy transition in waterborne transport"), p. 6 (FuelEU Maritime 14.5% GHG-intensity reduction by 2035).
[67] European Commission, ZEWT Partnership, SRIA 2.0, Part 2, R&I priorities on digital green shipping and zero-emission decision-support systems.
[68] Waterborne Technology Platform, Waterborne Technology Leadership, 9 (integration of vessels, ports, infrastructure and the broader ecosystem as precondition for the waterborne transition).
[69] European Commission, ZEWT Partnership, SRIA 2.0, Part 1 (Vision) and Part 2 (Sustainable Alternative Fuels): no single cost-effective and globally available alternative fuel today; future fuel choices depend on social, economic, technical and environmental conditions.

software interoperability risk. The EU Industrial Maritime Strategy underlines that safety protocols must evolve to manage new operational, technological and cybersecurity risks as shipping transitions towards alternative fuels, digitalisation and automation.[70]

By 2040, ocean-going shipping should also be capable of high levels of digital integration with ports and logistics chains. This includes real-time data exchange, predictive traffic management, standardised data formats, secure ship-shore communication and cyber-risk monitoring, aligned with the Waterborne Technology Leadership document's identification of real-time coordination, predictive traffic management, software interoperability and workforce digital skills as milestones before full 2050 maturity.[71]

3.3 By 2050 — Full zero-emission ocean-going shipping

By 2050, ocean-going shipping must be capable of operating as a zero-emission, resilient and digitally integrated mode of global transport. The Strategic Research and Innovation Agenda's overall 2050 vision is for Europe to lead and accelerate the transformation of global waterborne transport into a zero-emission mode that eliminates harmful environmental emissions, including greenhouse gases, air pollutants, water pollutants and underwater noise.[72]

For ocean-going shipping, this means full operational capability to complete long-distance voyages using zero-emission or climate-neutral energy carriers, supported by global or corridor-based fuel availability, safe bunkering systems, mature certification and interoperable international standards. The 2050 capability includes the full system: fuel production, bunkering, vessel design, digital monitoring, safety regulation, port infrastructure, crew competence, cyber resilience and lifecycle circularity.[73]

The Waterborne Technology Leadership document defines the 2050 transformation as universal deployment of zero-emission propulsion across all vessel categories, including long-distance maritime transport, combined with large-scale autonomous operations, circular vessel lifecycle models, full digital integration between vessels, ports, hinterland logistics and energy networks, and a fully skilled workforce. For ocean-going shipping, this translates into a target capability of zero-emission deep-sea operations at scale, supported by human-centred automation rather than automation alone.[74]

By 2050, ocean-going shipping should also be capable of supporting European strategic autonomy and resilience. This includes secure and diversified supply chains, reduced technological dependency, cyber-secure digital systems, reliable access to alternative fuels, and the capacity to maintain operations under geopolitical, climatic or technical disruption. The Waterborne Technology Leadership

[70] European Commission, EU Industrial Maritime Strategy, COM(2026) 111 final, Brussels, 4 March 2026, §3.3 (Safety, security), pp. 10–11.
[71] Waterborne Technology Platform, Waterborne Technology Leadership, 18–19 (real-time coordination, predictive traffic management, monitoring of software interoperability and cyber risks, and workforce digital skills as milestones for waterborne transformation).
[72] European Commission, ZEWT Partnership, SRIA 2.0, Part 1, Vision 2050 (Europe to lead and accelerate the transformation of global waterborne transport into a zero-emission mode).
[73] Waterborne Technology Platform, Waterborne Technology Leadership, 18–19 (full-system 2050 capability across fuel production, bunkering, vessel design, digital monitoring, safety regulation, port infrastructure, crew competence, cyber resilience and lifecycle circularity).
[74] Waterborne Technology Platform, Waterborne Technology Leadership, 20 (universal deployment of zero-emission propulsion across all vessel categories, including long-distance maritime transport; large-scale autonomous operations; circular vessel lifecycle models; full digital integration; fully skilled workforce).

document links waterborne transformation to resilience, cybersecurity, supply-chain reliability, integration into Europe's energy and logistics systems, and strategic autonomy.[75]

4. Technology Pathways (Task theme leader(s))

4.1 Future propulsion and energy systems enabling a climate-neutral ocean-going (deep sea) fleet

Develop scalable, safe and efficient zero-emission propulsion technologies, including but not limited to hydrogen-, ammonia- and methanol-based systems, advanced batteries, fuel cells, hybrid architectures and renewable-assisted propulsion. Given the expected constraints on availability and cost of climate-neutral fuels and energy at global scale, systematic reduction of energy demand becomes a primary pathway alongside fuel transition. This constraint will play a key role in determining the relative viability of different fuel pathways, where solutions combining lower energy demand with scalable fuel availability are likely to emerge as the most competitive. Emphasis will be placed on energy efficiency, cost competitiveness, system integration and global market readiness. Advanced energy intelligence, predictive optimization and vessel-level digital twins will underpin Europe’s long-term technological advantage.

4.1.1 Operational objective(s)

Enable safe, cost competitive, flexible, scalable, globally deployable zero-emission propulsion and power systems suitable for long intercontinental voyages. This includes minimising overall energy demand through integrated vessel design, hydrodynamics, energy saving technologies and operational optimisation

4.1.2 Target capability 2035, 2040 and 2050

By 2035 – searching for the most cost competitive solutions

- Safe handling and operation of all of new technologies and fuels to be adopted – verified, sufficient and adequate trainings and procedures in place. TRL is technology and fuel specific. For example some bio fuels are already in use TRL9 and some technologies are in the pilot phase, wind assisted propulsion TRL7
- Untapping the potential of “out of spec” bio fuels and blends thereof. Cost, availability and safety comes into play. As long as the bio fuels are more affordable than synthetic (green hydrogen based) fuels, new bio fuels will emerge.
- Flexible fuel blending widely in use – Deep sea shipping on the path of transition. New bio fuels from drop-in at the beginning of the transition. TRL 1-9 (bio component dependent)
- Dual/multi fuelled transitional fleets expanded TRL9
    - New dual/multi fuel concept (diesel-LNG, diesel-methanol already deployed)
- Novel Energy Saving Devices demonstrated TRL6
    - But not limited to waste heat recovery/utilisation, resistance reduction through hull optimisation, advanced hull surface treatments, antifouling solutions and novel drag-reduction technologies including both incremental improvements and novel low-friction concepts, DC, low-medium or high voltage
- Novel Energy Saving Operations demonstrated TRL6
    - But not limited to virtual arrival, weather routing, energy efficient routing, trim/cargo optimisation etc.
- Novel Hybrid Concepts demonstrated TRL 6, including DC-based onboard power distribution and flexible voltage architectures
- Novel Upgrade kits for using sustainable fuels demonstrated TRL6

[75] Waterborne Technology Platform, Waterborne Technology Leadership, 7 (waterborne transformation linked to resilience, cybersecurity, supply-chain reliability, integration into Europe's energy and logistics systems, and strategic autonomy).

    - Total cost of ownership optimized, enabling deployment and scalability
- Novel Vessel efficiency upgrade kits demonstrated TRL6
- Novel cost competitive propulsion system(s) demonstrated TRL6
    - But not limited wind propulsion with 30+% energy savings
- Novel Emission Saving Devices demonstrated TRL6
    - But not limited to carbon capture, SCRs, methane catalyst etc....
- Nuclear propulsion holistic feasibility completed - commercial (OPEX + CAPEX), social, safety & security
    - o system components TRL5
    - o consequential safety measures TRL 6
    - o implementation roadmap TRL 4
- Initial large-scale validation of energy saving technologies (ESDs) and operational efficiency measures, providing verified data on performance, cost and emission reduction. TRL7

By 2040 – narrowing down on the most cost competitive solutions

- Updated safe handling and operation of new technologies and fuels to be adopted
- Energy Saving Devices deployed and scaled TRL8-9
- Energy Saving Operations deployed and scaled TRL8-9
- Hybrid Concepts deployed and scaled TRL8-9
- Upgrade kits for using sustainable deployed and scaled TRL8-9
- Vessel efficiency upgrade kits deployed and scaled TRL8-9
- Cost competitive propulsion deployed and scaled TRL8-9
- Ammonia-capable ocean-going vessels operational on selected corridors TRL8
- Modular fuel tank integration optimised for minimal cargo loss TRL7
- Standardised dual- or multi-fuel architectures for vessels TRL 8-9
- “TradeWind” concept for wind propulsion – chasing the wind TRL8

By 2050 – operating with the most cost competitive solutions

- updated safe handling and operation new technologies and fuels
- climate-neutral ocean-going vessels operating globally
- Energy saving systems and hydrodynamic optimisation are standard across the fleet, forming a baseline requirement rather than optional add-ons
- standardised zero-emission propulsion systems deployable across vessel classes.
- standardised modular propulsion architecture suitable for both retrofit and newbuild vessels
- Wind assisted propulsion segments for non-time critical cargo utilising 200 year old trade wind routes

4.1.3 Required enablers

- The fuel molecule does not know what colour it is, but the financial impact is dependent on the colour of the molecule. The green transition is not black or white, intermediate steps needed to accelerate the uptake of more sustainable fuels on the journey towards zero emission.
- global alternative fuel bunkering networks
- IMO-aligned safety standards
- Validated methodologies and tools to quantify economic and environmental performance of energy efficiency solutions, supporting investment decisions and large-scale adoption of energy saving technologies
- fuel certification and lifecycle accounting frameworks
- Integrated planning and coordination between energy production, infrastructure development and maritime demand to ensure availability of climate-neutral fuels at scale.
- financing for fleet renewal
- Risk sharing mechanism for introduction of “out of spec” biofuels

- Sector coupling enabling large scale production of sustainable fuels – for example fertilizers
- Safe, reliable and cost competitive small modular reactors available for Marine use
- TradeWind corridors
- Green electricity and charging infrastructure

4.1.4 Key research gaps (linked to achieving the objectives, building on the current state-of-play).

- Bio fuels: what organic waste/side product could be turned into fuel at a cost lower than synthetic (green hydrogen based) fuels
- System-level assessment of competing uses of climate-neutral energy and sustainable biomass across sectors, and implications for fuel prioritisation in maritime transport.
- high energy-density fuels for long haul voyages
- safe ammonia combustion at scale, handing and storing
- hydrogen storage for ocean going vessels
- scalable onboard carbon-neural fuel systems
- Feasibility of "sail ships"
- lifecycle emission modelling
- setting criteria for allowable under water radiated noise
- including next-generation and not-yet-identified energy saving concepts beyond currently known technologies including improved prediction of performance and cost-benefit for such technologies
- Development of advanced hull surface treatments and friction-reduction technologies

4.2 Intelligent safety, security and resilience as foundational enablers

4.2.1 Operational objective(s)

Achieving safe and resilient operations during the energy transition requires regulatory frameworks that evolve alongside new fuels and technologies. Combining digital safety monitoring with environmental protection ensures that deep sea shipping meet both operational and sustainability objectives.

The increasing complexity of alternative fuels, hybrid energy systems and digitalised vessel operations requires integrated safety frameworks that are validated through real-world testing and demonstration.

4.2.2 Target capability 2035, 2040 and 2050

By 2035

- Collision avoidance concepts utilising automatic vessel to vessel, shore to vessels and shore to shore communication TRL6
- Automatic safety incident communication concepts vessel to vessel, shore to vessels and shore to shore communication TRL6
- Automatic re-routing guidance system based on risk of incident and/or occurred incidents considering current traffic and weather conditions TRL6
- Cyber security resilience – cyber redundance concept TRL8
- Resilient navigation & degraded-mode navigation TRL 6
- Initial validation of safety concepts for alternative fuels, hybrid systems and autonomous functions under real operational conditions. TRL 6-7

By 2040

- Collision avoidance deployment utilising automatic vessel to vessel, shore to vessels and shore to shore communication TRL8

- Automatic safety incident communication deployment vessel to vessel, shore to vessels and shore to shore TRL8
- Automatic re-routing guidance system based on risk of incident and/or occurred incidents considering current traffic and weather conditions deployment TRL8
- Cyber redundance deployed TRL9
- Autonomous navigation deployed in corridors TRL7

By 2050

- Autonomous navigation deployed in corridors TRL9

4.2.3 Required enablers

Standard communication protocol for collision avoidance, automatic vessel to port communication. Ports and congested areas to have designated safety zones and procedures in case of emergency.

4.2.4 Key research gaps (linked to achieving the objectives, building on the current state-of-play).

- Barries of introducing assisted and automated operation
- Build introduction pathways for assisted and automated operation

4.3 Fully connected, automated and data-driven deep-sea systems

4.3.1 Operational objective(s)

Connected shipping with constant data flows is a key enabler for vessel and fleet optimisation, safety at sea and above all autonomous and semi-autonomous navigation and operation. Digital systems play a key role in validating, optimising and de-risking the deployment of new propulsion and energy solutions through continuous data collection and analysis.

4.3.2 Target capability 2035, 2040 and 2050

By 20235

- Develop and disseminate data standards to facilitate interoperability of software solutions and data transfers TRL7
- Virtual arrival concept demos TRL7
- Automatic communication concepts between marine traffic supervision hubs TRL8
- Emission data and reporting available for customer according to ISO14083 TRL9
- Use of digital twins and operational data to verify performance, emissions and economic viability of new technologies. TRL 6-8

By2040

- Virtual arrival deployed TRL9

By2050

4.3.3 Required enablers

- Global Maritime Traffic Control similar to aviation

4.3.4 Key research gaps (linked to achieving the objectives, building on the current state-of-play).

4.4 Human-centred design and a future-ready deep-sea workforce

4.4.1 Operational objective(s)
Development of adaptive, real-time decision support systems tailored to human operators. Investigation of real-time simulation and optimization methods that enhance voyage planning and execution through human-centred, data-driven operational models. This includes developing competencies for safe handling of alternative fuels, operation of complex hybrid energy systems, interaction with advanced digital support tools and continuous training.

4.4.2 Target capability 2035, 2040 and 2050
By 2035

- AR/VR assisted navigation concepts demoed, open sea, congested areas, narrow straight, shallow waters, arrival/departure
- AR/VR assisted concepts demoed for decision making support in harsh conditions, incidents
- crew competence
- alarm management
- fuel handling
- emergency response
- safe operational procedures

By 2040

- Autonomous navigation and operation demonstrated in corridors (not equivalent to unmanned)

By 2050

- Autonomous navigation and operation demonstrated globally (not equivalent to unmanned)

4.4.3 Required enablers
AR/VR capability and usability on real life situations, share of VR/AR may depend on route, segment, region etc.

4.4.4 Key research gaps (linked to achieving the objectives, building on the current state-of-play).

4.5 Forward looking regulation, standardization and system-level integration

4.5.1 Operational objective(s)
Forward looking regulation in a maritime environment is key. Staying the course is more important than have ideological shifts every 4-5 years. An uncertain environment will in general decrease the willingness to invest. This includes enabling regulatory frameworks that account for system-level dependencies between vessels, energy supply, infrastructure and cross-sector competition for climate-neutral energy.

Global standards on calculation emission footprints of goods shipped and persons travelled needs to be established in order to have an open and transparent way of stating comparable environmental consequences of each voyage.

Common standards are also needed for system level integration, various systems and module “speak the same language”.

4.5.2 Target capability 2035, 2040 and 2050

By 2035

- Global, or at least European, standards of how calculation emission footprints of goods shipped and persons travelled, based on example ISO 14083. Even if there is a standard, the interpretation of the standard is not black or white. Common practices for the interpretation to enable fair comparison about the cumulative emission/ton/nm (SI would be kg/kg/m)

By 2040

- Standard communication interfaces on all equipment

By 2050

4.5.3 Required enablers

- ICAS, IMO and Flag states to enable introduction of new technologies in a more collaborative manner without endangering safety. Safety is #1, hence pilots and demos should and need to have back-ups until appropriate confidence is reached. Then and only then, can possible safety back-ups be removed – they should not become the industry standard in case they are truly back-ups or back-ups of back-ups.
- Common best practice interpretation of standards, ex ISO 14083
- Standard communication ID for all equipment onboard
- Harmonised methodologies for assessing lifecycle emissions, energy efficiency and system-level impacts across different fuel and propulsion pathway

4.5.4 Key research gaps (linked to achieving the objectives, building on the current state-of-play).

- Interpretation of standards making the comparison between vessel types, technology used fair and harmonised.

5. Enablers and Deployment

The technology pathways identified in Section 4 show that the transformation of intercontinental or ocean-going shipping cannot be delivered through vessel innovation alone. Ocean-going shipping operates globally, requires long-range autonomy, depends on international fuel availability and serves highly competitive markets. Deployment must therefore be organised around the coordinated readiness of vessels, ports, fuel suppliers, cargo owners, charterers, financiers, classification societies, and international regulatory bodies. The aim is to move from isolated pilots and first-of-a-kind projects towards scalable deployment models that can work across vessel types, trade lanes and ownership structures.

For ocean-going shipping, deployment must address two different but complementary operating models. Liner shipping, especially container shipping, operates on structured networks and can support corridor-based deployment, long-term offtake agreements, cargo-owner aggregation and green shipping lanes. Bulk and tramp shipping, by contrast, follows global cargo demand, has no fixed routes, calls at ports worldwide and is often operated by small and medium-sized companies. Its deployment conditions are therefore different and require globally available fuels, flexible compliance instruments, affordable retrofit solutions and simple access to finance.

5.1. Route, corridor and global-network deployment

The first deployment model should be based on structured trade lanes, and green shipping corridors These are most suitable for container shipping, vehicle carriers, selected tanker trades, gas carriers and other services with predictable port pairs or repeated trade flows. Corridor-based deployment should combine fuel-ready vessels, bunkering infrastructure, port readiness and cargo owner demand. Priority should be given to trade lanes where European-controlled fleets, European ports and global partners can aggregate sufficient fuel demand to justify infrastructure investment. These include major Asia-Europe, transatlantic, Mediterranean-Atlantic, North Sea-Baltic, energy import and strategic raw material corridors. Deployment should be linked to Global Gateway partnerships, green shipping lanes, strategic bunkering hubs and cooperation with major non-European ports[76].

A large share of the intercontinental fleet, however, especially bulk tramp shipping, does not operate on fixed routes. For these vessels, the technical enablers identified in Section 4, including global alternative fuel bunkering networks, lifecycle fuel certification and fuel-flexible vessel architectures, must be complemented by deployment mechanisms that address uneven physical fuel availability. These include Clean Energy Marine Hubs[77], flexible bunkering access, Fuel EU Maritime pooling of compliance balances, and charter-party clauses allocating responsibilities and costs between owners, operators and charterers.[78,79]

5.2. Sustainable fuel supply, bunkering and energy-system readiness

The most critical deployment condition for ocean-going shipping is the global availability of sustainable alternative fuels at sufficient scale, at competitive prices and in globally relevant locations. Unlike ferries and some short sea services, intercontinental vessels cannot rely primarily on frequent charging or paired-port infrastructure. They require energy carriers with high energy density, reliable bunkering access and internationally recognised safety and lifecycle-emission standards.

Deployment should therefore prioritise the development of global multi-fuel bunkering hubs for methanol, ammonia, sustainable biofuels, e-fuels, biomethane, e-methane and other certified renewable or low-carbon fuels. LNG and bio-LNG may remain transitional options, while for some vessel types, wind-assisted propulsion, onboard energy efficiency, waste-heat recovery and digital voyage optimisation will reduce fuel demand and improve the business case for sustainable fuels.

Fuel deployment should be planned together with production capacity, port infrastructure, certification, safety approval and offtake mechanisms. This requires coordination between maritime transport, renewable energy, hydrogen, ammonia, methanol, biomass, carbon-capture and industrial-policy actors. Sustainable fuel availability for shipping will compete with demand from aviation,

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[76] International Maritime Organization, Resolution MEPC.377(80), 2023 IMO Strategy on Reduction of GHG Emissions from Ships, adopted at the 80th session of the Marine Environment Protection Committee, 7 July 2023, §5.3 and §6 (Capacity-building, technology cooperation, LDCs and SIDS); European Commission, Sustainable Transport Investment Plan, COM(2025) 664 final, international dimension and Global Gateway Green Shipping Corridors and Hubs, pp. 7–10.

[77] https://www.cleanenergyministerial.org/initiatives-campaigns/hubs/

[78] European Commission, Sustainable Transport Investment Plan, COM(2025) 664 final, Brussels, 5 November 2025, §2.1 and §3, pp. 5-8.

[79] BIMCO, ETS – Emission Trading Scheme Allowances Clause for Time Charter Parties 2022; BIMCO, FuelEU Maritime Clause for Time Charter Parties 2024. BIMCO explains that the ETS clause allocates costs and responsibilities for obtaining, transferring and surrendering GHG emissions allowances, while the FuelEU clause addresses compliance balances, including banking and pooling where applicable.

chemicals, fertilisers, steel, power generation and other sectors. The roadmap should therefore support system-level planning that clarifies when and where scarce sustainable fuels deliver the highest value and where energy-efficiency measures can reduce demand.

For bulk and tramp shipping, the deployment condition rests on a fuel-availability triangle: sustainable alternative fuels can be taken up at scale only when they are available worldwide, in sufficient quantities, at affordable prices in a safe manner. This market failure is recognised by the Sustainable Transport Investment Plan[80] and requires public intervention to bridge the gap between sustainable and conventional fuels

5.3. Fleet renewal, retrofitting and energy-efficiency deployment

Given the long lifetime of ocean-going vessels, fleet transition must combine newbuilds, retrofits and operational efficiency. New vessels ordered in the coming decade should be designed with fuel-flexible engines, retrofit-ready architectures, modular tank and fuel-system layouts, space and stability margins for future conversion, digital energy-management systems and compatibility with future safety and reporting requirements. For the existing fleet, retrofit deployment is essential. Priority retrofit packages should include energy-saving devices, hull and propeller optimisation, advanced coatings, wind-assisted propulsion where suitable, waste-heat recovery, air-lubrication or friction-reduction technologies, onboard energy management, methane-slip reduction, emissions monitoring, digital twins and condition-based maintenance. For some vessels, engine conversion, fuel-system upgrades, carbon-capture readiness or hybrid auxiliary systems may also be relevant.

Energy efficiency should be treated as a primary deployment pathway, not only as a supporting measure. For bulk and tramp vessels, where zero-emission fuels may not be available worldwide in the short term, energy-efficiency measures are often the most immediately deployable option. Stakeholder consultations carried out by the Waterborne Technology Platform with the European Commission and the European Parliament in late 2025 and early 2026 reconfirmed that, for bulk/tramp ocean-going vessels, zero-emission technologies are not yet technically or commercially available at scale; energy-efficiency measures therefore remain, in the short term, the only deployable lever, with the appropriate combination of solutions varying by vessel type, route profile and business model[81]. Their uptake should be supported by the performance verification and cost-benefit methodologies identified in Section 4, complemented by contractual and financing models that share benefits between owners, operators, charterers and cargo interests. This is particularly important because the party investing in an energy-efficiency measure is not always the party benefiting directly from lower fuel consumption[82].

5.4. Bulk/tramp shipping: dedicated deployment conditions

Bulk/tramp ocean going shipping require dedicated deployment conditions within the intercontinental segment. These services operate in a highly competitive global market, with calls in more than 170 countries, no fixed routes and a fleet structure in which smaller companies play a major role. At EU

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[80] European Commission, Sustainable Transport Investment Plan, COM(2025) 664 final, Brussels, 5 November 2025.
[81] Waterborne Technology Platform, Bulk/Tramp Shipping – Follow-up to the October 2025 meeting (Brussels: Waterborne TP, January 2026), section “Items raised reconfirmed during the meetings”, points 1–2.
[82] BIMCO, ETS – Emission Trading Scheme Allowances Clause for Time Charter Parties 2022; BIMCO, FuelEU Maritime Clause for Time Charter Parties 2024.

level, around 90% of shipping companies control fewer than ten vessels[83]. This means that deployment instruments designed only for large liner operators, fixed corridors or individual first-of-a-kind projects will not be sufficient.

The roadmap should therefore mobilise four dedicated deployment conditions for bulk and tramp shipping.

First, dedicated actions for SMEs are needed, including pooled procurement frameworks, credit guarantees, simplified access to funding, standardised retrofit packages and technical assistance. These instruments should reduce administrative complexity and make transition support accessible to smaller operators[84,85].

Second, coordinated international action is required to secure sufficient sustainable fuel volumes worldwide. This should be pursued through IMO processes, Global Gateway partnerships, strategic port cooperation and the development of green energy hubs beyond Europe. For tramp vessels, which may not call regularly at the same ports, geographically broad fuel availability is more important than isolated high-profile fuel hubs.

Third, market formation mechanisms are needed to bridge the price gap between sustainable and conventional fuels. These may include maritime-relevant ETS revenue recycling as foreseen in the Sustainable Transport Investment Plan. In addition, FuelEU Maritime pooling of compliance balances and charter-party clauses can support practical allocation of compliance responsibilities and costs between owners and charterers[86].

Fourth, public support should move from isolated first-of-a-kind projects towards systematic technology deployment. The Innovation Fund, as currently designed, has been identified as limited in its ability to drive systematic uptake across the bulk/tramp fleet because it tends to support first-of-a-kind projects, small numbers of vessels or single port fuel deployments, while its administrative complexity can disadvantage SME applicants[87]. Future instruments should therefore support scale, replication and accessibility across vessel classes and ownership structures.

These dedicated conditions are consistent with the Waterborne Technology Leadership document's call for an ecosystem approach, in which the deployment of innovation is addressed across the full value chain and economic viability is ensured across segments, including bulk and tramp shipping.

5.5. Ports, bunkering hubs and logistics-system integration

Ports are central deployment nodes for intercontinental shipping, even though vessels operate globally. Major European and global ports should evolve into multi-fuel, electrified, digital and secure

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[83] European Community Shipowners' Associations (ECSA), The Economic Value of European Shipping: 2026 Update (Brussels: ECSA / Oxford Economics, May 2026), §2.3, p. 15; Union of Greek Shipowners, Annual Report 2025–2026 (Athens: UGS, 2026), pp. 18–19.

[84] European Community Shipowners' Associations (ECSA), The Economic Value of European Shipping: 2026 Update (Brussels: ECSA / Oxford Economics, May 2026), §2.3, p. 15; Union of Greek Shipowners, Annual Report 2025–2026 (Athens: UGS, 2026), pp. 18–19

[85] Waterborne Technology Platform, Bulk/Tramp Shipping – Follow-up to the October 2025 meeting (Brussels: Waterborne TP, January 2026), section "Items raised reconfirmed during the meetings", points 1–2.

[86] European Commission, Questions and Answers on Regulation (EU) 2023/1805 on the use of renewable and low-carbon fuels in maritime transport, Article 21, pooling of compliance balances

[87] Waterborne Technology Platform, Bulk/Tramp Shipping – Follow-up to the October 2025 meeting (Brussels: Waterborne TP, January 2026), section "Items raised reconfirmed during the meetings"

maritime energy hubs. They should provide sustainable fuel bunkering, shore-side electricity where relevant, safe handling and storage infrastructure, emergency-response capacity, digital reporting interfaces, cybersecurity, emissions monitoring and circularity services.

Deployment should prioritise ports that serve major intercontinental trade lanes, energy import chains, container networks, tanker flows and bulk commodity corridors. Port readiness should be planned together with fuel production, grid capacity, renewable-energy access, storage infrastructure, safety zones, permitting, customs procedures, digital systems and hinterland connectivity.

Port deployment should also account for global competitiveness and carbon-leakage risks. If sustainable fuels, infrastructure or compliance costs are available only in some regions, traffic may shift to competing hubs. European deployment therefore needs international cooperation with third-country ports, Global Gateway corridors, strategic bunkering partnerships and harmonised lifecycle certification.

5.6. Finance, market formation and demand aggregation

Ocean-going shipping requires major investment in new vessels, retrofits, alternative-fuel systems, bunkering infrastructure, fuel production, digital systems and workforce training. The cost gap between sustainable and conventional fuels remains one of the most important barriers. Deployment therefore requires market-formation mechanisms that create demand sufficient to support investment and financing decisions, and reducing first-mover risk. Key instruments should be designed to support both SMEs and large shipping corporations. Cargo owners and charterers must also be part of deployment. Green freight contracts, long-term charter-party clauses, fuel-cost sharing mechanisms, emissions-performance incentives and transparent lifecycle-emission reporting can help create demand for low- and zero-emission services. Without demand aggregation across cargo owners, charterers and logistics providers, vessel owners may face disproportionate investment risk.

The design of post-2027 instruments should reflect the specific deployment needs of ocean-going shipping. This includes the proposed European Competitiveness Fund and its clean-transition and industrial-decarbonisation window, the next Connecting Europe Facility cycle, and a strengthened successor to the Zero-Emission Waterborne Transport Partnership under Framework Programme 10.

5.7. Regulation, standards and safety approval

Deployment at scale requires stable, predictable and internationally harmonised regulation. Ocean-going shipping is regulated primarily through the IMO, while EU instruments such as EU ETS Maritime, FuelEU Maritime, MRV and port infrastructure requirements create additional obligations for vessels trading with Europe. The roadmap should therefore support alignment between IMO, EU and national frameworks to avoid duplication, double payment and fragmented compliance.

Priority standardisation areas include lifecycle emission accounting, sustainable fuel certification, bunkering procedures, fuel quality, methane-slip measurement, ammonia and methanol safety, hydrogen-derived fuels, onboard carbon capture, wind-assisted propulsion performance, energy-saving device verification, digital reporting, cyber resilience and data interoperability.

Safety approval is especially important for ammonia, methanol, hydrogen, LNG, bio-LNG, batteries, fuel cells, hybrid systems, onboard carbon capture and autonomous or remotely supported operations. Deployment should be supported by regulatory sandboxes, demonstration corridors, class and flag-state guidance, port emergency-response protocols, crew training requirements and harmonised risk-assessment methodologies.

5.8. Digital deployment, monitoring and interoperability

Digitalisation is a core enabler for ocean-going shipping because compliance, optimisation and market transparency increasingly depend on reliable data. Vessels will need interoperable systems for emissions monitoring, fuel use reporting, lifecycle emission verification, voyage optimisation, weather routing, cargo and port call coordination, predictive maintenance, digital twins and cyber secure ship-shore communication.

Deployment should avoid fragmented digital systems that increase administrative burden. Instead, digital reporting for EU ETS Maritime, FuelEU Maritime, IMO requirements, cargo-owner reporting and port-call optimisation should be aligned as far as possible. Interoperable data standards, secure application programming interfaces, trusted data spaces and automated verification tools can reduce duplication and improve compliance accuracy.

Cybersecurity must be treated as an operational safety and resilience requirement. Ocean-going vessels increasingly depend on digital navigation, cargo, engine, fuel, reporting and shore-support systems. Deployment should therefore include cyber risk assessment, secure-by-design equipment, degraded-mode navigation, incident response, crew training and minimum cyber-resilience baselines across vessels, ports and service providers.

5.9. Workforce, skills and human-centred deployment

The transition of ocean-going shipping will require new competences across the maritime workforce. Seafarers, shore-based operators, port personnel, bunkering teams, emergency responders, shipyard workers, surveyors, class societies, fuel suppliers and digital service providers will need skills in alternative fuels, high-voltage systems, fuel cells, ammonia and methanol safety, methane-slip control, carbon capture, digital monitoring, cybersecurity, automation, remote support and emergency response.

Training should be developed before large-scale deployment, not after. Simulation, digital twins, XR-based training, onboard drills and shore-based training centres should be used to prepare crews and shore teams for complex fuel and digital systems. Human-centred design should guide bridge systems, alarm management, decision-support tools, remote support, digital reporting interfaces and automation, ensuring that new systems reduce rather than increase workload.

The roadmap should also support the attractiveness of seafaring and maritime technical professions. A successful transition will require not only new technologies, but also safe working conditions, clear competence frameworks, continuous upskilling, social dialogue and international recognition of training standards.

5.10. Governance, coordination and monitoring

Deployment of climate-neutral ocean-going shipping requires governance across the full maritime ecosystem. Shipowners, operators, charterers, cargo owners, ports, fuel producers, energy suppliers, shipyards, equipment manufacturers, classification societies, financial institutions, research organisations, seafarer representatives and international organisations should be involved in deployment planning.

At European level, coordination should aim to move from fragmented innovation projects to deployment programmes that are scalable across vessel types, corridors and ownership structures.

Monitoring should track fuel availability, fuel price gaps, lifecycle-emission performance, fleet renewal, retrofit uptake, energy-efficiency gains, bunkering infrastructure, corridor readiness, digital reporting readiness, safety approvals, workforce training and finance mobilised. For bulk and tramp shipping, monitoring should also assess whether deployment instruments are accessible to SMEs and whether global fuel availability is sufficient for vessels without fixed routes.

6. Expected Impacts

The implementation of this roadmap is expected to support the transformation of intercontinental or ocean-going shipping into a climate-neutral, globally connected, digitally integrated, safe and resilient component of the European and international transport system. Because this segment operates across oceans, global trade lanes and multiple regulatory jurisdictions, its impacts will depend, as noted above, not only on vessel technologies, but also on the coordinated deployment of sustainable fuels, bunkering infrastructure, safety standards, digital systems, financing mechanisms, port readiness and international cooperation.

The first expected impact is a substantial reduction in greenhouse-gas emissions and air pollutants from deep-sea shipping. The combination of sustainable marine fuels, fuel-flexible propulsion, energy-saving devices, wind-assisted propulsion, hydrodynamic optimisation, waste-heat recovery, digital voyage optimisation and operational efficiency measures should reduce emissions across container ships, bulk carriers, tankers, gas carriers and other ocean-going cargo vessels. In the short and medium term, energy efficiency measures will be particularly important, where zero-emission fuels may not yet be globally available, affordable or technically mature at scale.

A second expected impact is the creation of demand for sustainable marine fuels and the acceleration of fuel supply chains serving ocean-going shipping. The roadmap should help aggregate demand across structured liner routes, green shipping corridors, major bunkering hubs and, where possible, bulk/tramp operations. This can support investment in advanced biofuels, e-fuels, methanol, ammonia, biomethane, e-methane and other certified renewable or low-carbon fuels. It can also help address the fuel availability challenge identified for bulk/tramp shipping: fuels must become available worldwide, in sufficient quantities, at affordable prices and under safe conditions for bunkering, storage and onboard use.

The roadmap is also expected to strengthen European industrial competitiveness and technology leadership. Fleet renewal, retrofitting and fuel-system deployment can generate demand for European shipyards, repair yards, engine manufacturers, marine equipment suppliers, fuel-system integrators, wind-assist technology providers, digital-service companies, classification societies, safety technology providers and financial institutions. Because Europe controls a significant share of global shipping capacity, including major positions in container ships, bulk carriers, tankers and specialised cargo segments, successful deployment in this roadmap can reinforce Europe's influence over global maritime technology and standards.

A further expected impact is improved competitiveness and transition capacity for bulk and tramp shipping, including SME operators. This segment is highly exposed to global competition, volatile routes, uncertain cargo flows and thin margins. Deployment instruments that move beyond isolated first-of-a-kind projects and support systematic uptake of retrofit packages, energy-efficiency solutions, finance, fuel certification tools and simplified access mechanisms should improve the ability of smaller companies to participate in the transition. Dedicated SME-oriented support, credit guarantees, pooled procurement, book-and-claim options, tradable sustainable-fuel certificates and other market-formation mechanisms can help reduce the risk that decarbonisation favours only the largest operators.

The roadmap should also improve the role of ports and bunkering hubs in global maritime decarbonisation. Major European ports and partner ports outside Europe can become multi-fuel, electrified, digital and secure maritime energy hubs, supporting sustainable fuel bunkering, shore-side electricity where relevant, safe fuel handling, lifecycle emission certification, emissions monitoring, emergency response and circularity services. This impact is particularly important for major container corridors, tanker and gas trades, energy-import routes and strategic raw-material flows. International cooperation through Global Gateway green shipping corridors and hubs can extend these impacts beyond Europe and support global fuel availability.

Safety, security and resilience impacts are expected to be significant. The deployment of alternative fuels, fuel flexible engines, batteries, fuel cells, onboard carbon capture, wind-assisted propulsion and automated or remotely supported functions introduces new risk profiles. Harmonised safety procedures, class and flag-state guidance, port emergency response protocols, cyber-resilience baselines, crew training and regulatory sandboxes should support safe deployment. These measures should reduce uncertainty for first movers and improve confidence among shipowners, charterers, crews, ports, insurers and regulators.

Digitalisation should generate further operational, environmental and compliance impacts. Interoperable digital systems for fuel use reporting, lifecycle emission verification, EU ETS and FuelEU Maritime compliance, IMO reporting, digital port-call coordination, weather routing, predictive maintenance, voyage optimisation and cargo owner reporting can reduce duplication and administrative burden. If implemented well, digitalisation can improve fuel efficiency, reduce waiting time, support virtual arrival, strengthen cyber-secure ship-shore communication and make emissions performance more transparent for cargo owners and regulators.

The roadmap is also expected to strengthen European strategic autonomy and supply chain resilience. Ocean going shipping is essential for energy imports, food security, raw-material flows, industrial supply chains and external trade. By supporting European technological capability, diversified fuel supply, secure port and bunkering infrastructure, cyber-resilient operations and international regulatory leadership, the roadmap can reduce dependency on single suppliers, single fuel pathways or vulnerable maritime chokepoints. This is particularly relevant for container shipping, gas carriers, tankers and bulk carriers serving strategic commodities.

Workforce and skills impacts will be substantial. The transition will require new competences among seafarers, shore-based operators, port personnel, emergency responders, surveyors, shipyard workers, fuel suppliers and digital service providers. Training in alternative fuels, high voltage systems, ammonia and methanol safety, fuel cells, methane slip control, digital monitoring, cybersecurity, remote support, emergency response and human-machine teaming should improve safety and support the attractiveness of maritime professions. Simulation, XR, digital twins and harmonised competence frameworks can help prepare crews and shore personnel before large scale deployment.

Finally, the roadmap should generate evidence for future policy, regulation, standards and investment decisions. Monitoring should cover emissions reduction, fuel availability, fuel price gaps, energy efficiency performance, retrofit uptake, newbuild readiness, bunkering infrastructure, digital reporting readiness, safety approvals, cyber resilience, workforce training, SME access to finance and corridor readiness. The results should feed back into future EU and IMO regulation, Waterborne Technology Platform priorities, FP10, the successor to the Zero-Emission Waterborne Transport Partnership, the next Connecting Europe Facility cycle and post-2027 competitiveness instruments.