WATERBORNE

WATERBORNE TECHNOLOGY ROADMAP

Competitive, resilient and sustainable ocean-going shipping

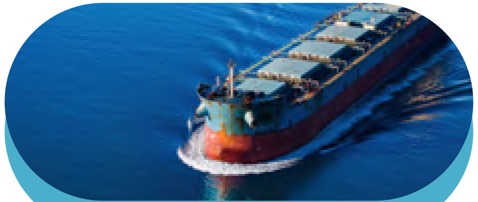
September 2026

OCEAN-GOING SHIPPING TECHNOLOGY ROADMAP

01 DESCRIPTION OF THE SECTOR

This roadmap covers commercial seagoing merchant vessels above 1,000 gross tonnage in intercontinental cargo transport. The segment is defined by long voyages, high propulsion energy demand, large fuel storage, autonomy over weeks and exposure to global port, fuel and regulatory systems. The European-controlled fleet is owned or controlled by EU-27 and Norway companies, regardless of the flag under which the vessels are registered


CONTAINER · 44% EU-CONTROLLED


BULK · 256 M DWT


TANKERS · 111 M DWT


LNG · 32% OF WORLD CAPACITY

WORLD TRADE
90% international trade moves by water — 81% of EU external trade, 40% of internal

EU-27 FLEET
674 m dwt by water — 81% of EU external trade, 40% of internal

DECLINING SHARE
35.0–30.2 % EU-27 share of the world fleet, 2019–2024, as Asia/Oceania grew 254 m dwt

TECHNOLOGY SUPPLY
~50% world maritime equipment is supplied by European companies, which lead on power systems

Figure 1: European-controlled share of global capacity by segment, 2024; bars scaled to 50%.

320 vessels with battery systems — 2.5% of the fleet

26 methanol-capable ships — 63% of the world total

46% of the world LNG-ready fleet, excluding LNG carriers

11 fuel-cell vessels on order for delivery within five years

Alternative-fuel capability of the EU-flagged fleet, 2024: real, but not yet at scale.
The Greek orderbook holds 725vessels, 70 m dwt, USD 60 bn.

TWO OPERATING MODELS

Liner shipping runs published schedules on structured lanes, which supports corridor deployment and long-term offtake. Bulk and tramp shipping has no fixed routes — the Greek-controlled fleet alone made over 175,000 port calls in 171 countries in 2025 — and, being mainly SME-based, needs worldwide fuel availability and affordable retrofits.

Table 1: Controlled fleet by region, ships of 1,000 GT and over; Latin America (17.1) and Africa (15.8) complete the2024 total.
Table 2: EU-27 controlled fleet by ship type; passenger vessels excluded.
Table 3: Share of EU-27 controlled tonnage; 83.7% flies a foreign flag. The EU-flagged fleet is younger than theworld fleet in every cargo segment, but vessels serve 25–30 years, so retrofit matters as much as newbuilds.

MERCHANT FLEET BY WORLD REGION (MILLION DWT)

REGION	2019	2021	2024
Europe	843.1	871.8	**894.7**
— of which EU-27	654.9	680.4	**674.3**
Asia / Oceania	931.8	1 037.4	**1 186.0**
North America	93.2	91.7	**86.9**
World total	1 872.8	2 024.4	**2 235.1**
EU-27 share of world	35.0%	33.6%	**30.2%**

FLEET BASELINE — WORLD AND EU-27, 1 JANUARY 2024

SHIP TYPE	EU no.	share	EU k dwt	dwt sh.
Bulk carriers	3 196	24%	256 135	26%
Container ships	2 387	39%	143 503	44%
Tankers	1 858	13%	111 197	14%
General cargo	2 652	19%	28 636	23%
Ro-Ro cargo	292	30%	8 538	59%
Total fleet	12 314	25%	674 258	30%

TOP FIVE EUROPEAN-CONTROLLED FLEETS, 2024

COUNTRY	SHARE	FGN FLAG
Greece	60.9%	86.8%
Germany	11.1%	90.1%
Italy	8.2%	88.5%
Denmark	6.0%	48.1%
France	3.3%	82.9%

02 POLICY DRIVERS AND CONSTRAINTS

2.1. DRIVERS

EU Climate Law and the 2040 trajectory.
Climate neutrality by 2050 is binding; the framework adopted in March 2026 sets a 2040 target of 90% net GHG reduction against 1990.

IMO 2023 GHG Strategy.
MEPC.377(80) requires carbon intensity to fall at least 40% by 2030 compared to 2008, and net zero by or around 2050, on a well-to-wake basis.

FuelEU Maritime and EU ETS Maritime.
A declining GHG-intensity limit — 14.5% by 2035,80% by 2050 — plus carbon pricing since 2024 and MRV. The July 2026 ETS proposal reserves up to 110 m allowances for 2028–2040.

Sustainable Transport Investment Plan.
COM(2025) 664 confirms differentiated fuel pathways and puts investment need for bio-and e-SMF production by 2035 at EUR 34.7–46.7 bn.

EU Industrial Maritime Strategy.
COM(2026)111 addresses build, equip and repair capacity, MRV simplification, green shipping lanes,resilience, and access to innovation, finance and skills.

EU Ports Strategy.
COM(2026) 112 positions ports as multi-fuel, electrified, digital and secure nodes, with OPS deployment, AFIR-driven fuel infrastructure and CEF3 finance.

Industrial competitiveness and technology sovereignty.
A strategic market for European propulsion, engines, retrofits, equipment,digital platforms and lifecycle services.

Geopolitical resilience and strategic autonomy.
Energy security, critical raw materials, supply-chain resilience and maritime chokepoints shape fleet investment, fuel sourcing and route planning.

Critical-infrastructure protection.
Vessels increasingly count as critical infrastructure; NIS2 mandates cybersecurity, a prerequisite for digital integration and remote operations.

Cargo owners, charterers, lenders and insurers.
Decisions increasingly turn on emissions transparency, verifiable carbon intensity and technology readiness.

2.2 CONSTRAINTS AND BOTTLENECKS

Fuel-supply gap and cross-sector competition.
European owners lead LZCF-capable orders, but Asia-Pacific dominates projected production and under a fifth of Europe's hydrogen pipeline goes to maritime use. Maritime demand competes with steel, refining, fertilisers and aviation fuels.

Cost of ownership and investment uncertainty.
Methanol- or ammonia-powered vessels cost up to twice an oil-fuelled ship, and under half of the twenty major bunkering ports are alternative-fuel ready. Pathway ambiguity and split incentives delay decisions.

Scale, fragmentation and industrial capacity.
European merchant shipyard share fell from 60% in 2010 to about 15% in 2020–2024, and 90% of EU-27/Norway companies run under ten vessels, limiting balance sheets for retrofits and long-tenor offtake.

Retrofit complexity and interoperability.
A heterogeneous fleet needs custom engineering per vessel; standardised kits do not exist. Vessels combine systems from 50 to 100-plus manufacturers with no common data models or APIs.

Regulation, cyber exposure, safetyvalidation and skills.
Simultaneous FuelEU, ETS, MRV and IMO measures create timing and cost-allocation frictions, and NIS2 exposure grows. Safety tests repeat per project, flag, class and port, and trained crews are scarce.

OCEAN-GOING SHIPPING TECHNOLOGY ROADMAP

03 TARGET CAPABILITIES

CURRENT STATE-OF-PLAY AND ACHIEVED DEVELOPMENTS

The challenge is structural. Most of the long-distance fleet bunkers thousands of tonnes of fuel and needs weeks of autonomy, so early green propulsion is expected to rely on combustion engines running on sustainable alternative fuels, supported by wind propulsion, with a later transition to fuel cells on hydrogen-based fuels.

Target capability therefore cannot be simple electrification: it is the ability to combine fuel flexibility, efficiency gains, retrofitting, newbuild readiness, digital optimisation, safety management and interoperable port-fuel infrastructure.

2035

DEPLOYMENT READINESS AND FIRST OPERATIONAL SCALE

First class-approved low- and zero-emission solutions operating on selected international routes

Certified sustainable fuels in use — advanced biofuels, e-fuels and hydrogen-derived fuels

Transitional dual-fuel systems, wind-assisted propulsion and substantial efficiency gains integrated

Industrial-scale retrofit capability: engine conversion, energy management, waste-heat recovery, coatings

Compliance with the first mature phase of FuelEU Maritime and EU ETS Maritime, with standardised monitoring and reporting of fuel use and GHG intensity

Digital twins, voyage optimisation, predictive maintenance and weather routing in practical use, with cyber-physical testing at approval and commissioning

2040

SYSTEM INTEGRATION ACROSS VESSELS, PORTS AND FUEL SUPPLY

Broader commercial deployment of low- and zero-emission operations across major trade lanes

An integrated operating system of ships, ports, fuel suppliers, cargo owners, regulators and platforms

Multi-fuel, route-adaptive capability rather than lock-in to one immature pathway, with multi-fuel system safety at scale

Mature safety capability for toxicity, fire, explosion, cryogenic, cyber and software interoperability risk

Real-time data exchange, predictive traffic management and interoperable ship-port-fuel digital assurance, fuel traceability and machinery health

Distributed digital energy orchestration across the fleet and cyber-risk monitoring

2050

FULLY INTEGRATED, ZERO-EMISSION, AUTONOMOUS

Zero-emission, resilient and digitally integrated mode of global transport

Long-distance voyages on zero-emission or climate-neutral energy carriers, with global or corridor fuel availability, safe bunkering and mature certification

Universal zero-emission propulsion across all vessel categories

Large-scale autonomous operations with human-centred oversight

Circular lifecycle models, full digital integration with ports, hinterland and energy networks, and a fully skilled workforce

Strategic autonomy: diversified supply chains and continuity under disruption

04 TECHNOLOGY PATHWAYS

OPERATIONAL OBJECTIVES — FIVE PATHWAYS

4.1 Future propulsion and energy systems	Safe, cost-competitive and globally deployable zero-emission propulsion for long intercontinental voyages, minimising energy demand through integrated design, hydrodynamics and energy-saving technologies, with modular retrofit-ready architectures and certification readiness from the design stage.
4.2 Intelligent safety, security and resilience	Integrated safety frameworks, validated through real-world testing, evolving alongside new fuels and addressing fuel-and energy-system hazards, cyber-physical risks, degraded operation and safe recovery where external assistance may be delayed.
4.3 Connected, automated and data-driven deep-sea systems	Constant data flows to optimise vessels and fleets, enable autonomous operation and de-risk new energy solutions —predictive maintenance, remote diagnostics, AI-assisted decisions, automated compliance and secure ship-to-shore coordination.
4.4 Human-centred design and a future-ready workforce	Adaptive real-time decision support tailored to human operators, with competences for safe fuel handling, hybrid energy systems and digital tools, ensuring automation supports rather than replaces human decisions on safety-critical operations
4.5 Forward-looking regulation and standardisation	Stable, predictable frameworks accounting for dependencies between vessels, energy supply and infrastructure; global standards for emissions footprints; common interfaces for system integration; and aligned approval pathways for emerging fuels and modular systems.

05 ENABLERS AND DEPLOYMENT

5.1 Route, corridor and global-network deployment. Structured trade lanes and green corridors for liner shipping, plus Clean Energy Marine Hubs, flexible bunkering, FuelEU pooling and charter-party clauses for vessels without fixed routes.

5.2 Sustainable fuel supply and bunkering. Global multi-fuel hubs for methanol,ammonia, biofuels, e-fuels and e-methane,with interoperable certification and lifecycle GHG accounting.

5.3 Fleet renewal, retrofit and efficiency. Fuel-flexible, retrofit-ready newbuilds plus priority retrofit packages; energy efficiency treated as a primary pathway, not a supporting measure.

5.4 Bulk and tramp conditions. SME instruments, pooled procurement, credit guarantees, standardised retrofits, coordinated international fuel volumes and systematic rather than first-of-a-kind support.

5.5 Ports, bunkering hubs and logistics. Multi-fuel, electrified, digital and secure energy hubs, with standardised vessel-port interfaces and attention to carbon-leakage risk.

5.6 Finance and demand aggregation. Market-formation mechanisms, green freight contracts, fuel-cost sharing and consistent business-case methodologies for SMEs and large operators alike.

5.7 Regulation, standards and safety approval. IMO-EU-national alignment to avoid double payment, priority standardisation areas, and safety evidence that transfers across class and flag.

5.8 Digital deployment and interoperability. Aligned reporting for ETS, FuelEU and IMO, secure APIs, trusted data spaces and cybersecurity as an operational safety requirement.

5.9 Workforce and human-centred deployment. Training built before deployment using simulation, digital twins and XR; human-centred bridge, alarm and automation design that reduces workload.

5.10 Governance, coordination and monitoring. Ecosystem-wide governance, a shift from fragmented projects to deployment programmes, and monitoring of price gaps, retrofit uptake, approvals and SME access.

06 EXPECTED IMPACTS

CLIMATE & ENVIRONMENT

2035 Measurable cuts in fuel use and lifecycle-GHG intensity through efficiency and first commercial sustainable-fuel deployment; the 2035 FuelEU requirement is the reference point.

2040 Significant lifecycle-GHG reductions through broader sustainable fuel use, energy-saving technologies, wind assistance and, where appropriate, onboard carbon capture.

2050 Climate-neutral ocean-going shipping at scale, with very low lifecycle GHG emissions and substantially reduced air pollutants.

TECHNOLOGY AND OPERATIONS

2035 Commercial sustainable-fuel and hybrid vessels on selected routes; bankable retrofit packages; verified efficiency; digital twins and AI optimisation deployed.

2040 Industrial-scale retrofits; mature multi-fuel and modular architectures; interoperable ship-port-logistics systems; broader remote support and automated compliance.

2050 Mature zero- and net-zero propulsion, globally interoperable digital ecosystems and resilient, highly automated operations with human oversight.

ECONOMIC AND INDUSTRIAL

2035 Growing demand for European retrofit engineering, propulsion, efficiency and digital technologies; reduced risk for early adopters.

2040 Expanded shipyard and retrofit capacity; shorter integration and approval times; stronger European supply chains and technology competitiveness.

2050 Sustained European leadership in high-value maritime technologies and services, with resilient, diversified supply chains and global deployment capacity.

SAFETY, SECURITY ANDRESILIENCE

2035 Representative safety validation and reusable evidence for sustainable fuels, batteries, hybrid systems and automated functions; improving cyber resilience.

2040 Integrated predictive safety, emergency response and cyber-resilient architectures; less downtime and faster recovery.

2050 Equivalent or improved safety relative to conventional operations,with continuous assurance under technical, cyber and fuel-supply disruption.

WORKFORCE AND SOCIAL

2035 Competence frameworks and training scaled for personnel in sustainable-fuel, hybrid, digital and safety-critical roles.

2040 Continuous upskilling and human-machine teaming in normal operations, with better crew support through digital and remote assistance.

2050 Continuous competence development across maritime professions, with human-centred automation, safe working conditions and attractive career pathways.

CONTENT

LIST OF TABLES

ROADMAP POSITIONING WITHIN THE WATERBORNE TECHNOLOGY LEADERSHIP FRAMEWORK

This roadmap operationalises the Technology Leadership[1] framework for ocean-going shipping. It translates the overarching objectives, including competitiveness, resilience, sustainability, zero-emission operations[2], digitalisation, safety and security, human-centred innovation, standards, skills and deployment at scale, into the specific conditions of ocean-going shipping. It reflects the Technology Leadership document's ecosystem approach, linking shipowners, shipyards, equipment manufacturers, ports, energy, infrastructure and service providers, classification societies, financial institutions, authorities, research organisations and logistics users into a coordinated deployment pathway.

The roadmap on ocean-going shipping is closely interlinked with the following dedicated Technology Roadmaps: maritime technology sector and port ecosystems.

1 Waterborne Technology Platform, Waterborne Technology Leadership: Towards a Competitive, Resilient and Sustainable Waterborne Sector - A Co-programmed Partnership under Framework Programme 10, January 2026

2 Throughout this roadmap, references to zero-emission may, depending on the context, encompass broader environmental performance objectives, including the elimination of local pollutant emissions. Net-zero emission refers specifically to greenhouse gas emissions from a lifecycle perspective and may include carbon neutral fuels, carbon capture pathways and other net-zero solutions

1. DESCRIPTION OF THE SECTOR

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.[3] 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.[4] Therefore, ocean-going shipping electrical and propulsion systems must be specifically designed for long intercontinental voyages with extended energy autonomy (weeks), global fuel diversity, and operation across multiple regulatory jurisdictions.

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.[5] 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. Operational profiles, power systems and retrofit economics differ significantly between the different segments of ocean-going shipping.

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.[6] 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.[7] The sector is therefore a core enabling system for European economic resilience and global connectivity.

3 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.
4 Waterborne Technology Platform, Waterborne Technology Leadership, 6 (differentiation of vessel types and services by power requirements, operational profiles and autonomy).
5 ISL, Shipping Statistics and Market Review, definition of "controlled fleet" (beneficially owned or controlled fleet, regardless of flag).
6 Waterborne Technology Platform, Waterborne Technology Leadership, 6 (distinction between intercontinental and other waterborne segments; long voyages, high propulsion energy demand, global port exposure).
7 Waterborne Technology Platform, Waterborne Technology Leadership, 5.

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).[8] 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 the need for coordinated European industrial and research, development and innovation (RD&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.[9]

Beyond aggregate capacity share, European ownership retains strong positions in vessel segments that are central to the technological and energy transition. Furthermore, these segments are key for energy security and strategic supply chains. 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.[10] 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.

8 Ibid.,
9 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.
10 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.

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.[11]

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 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.[12] 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.[13]

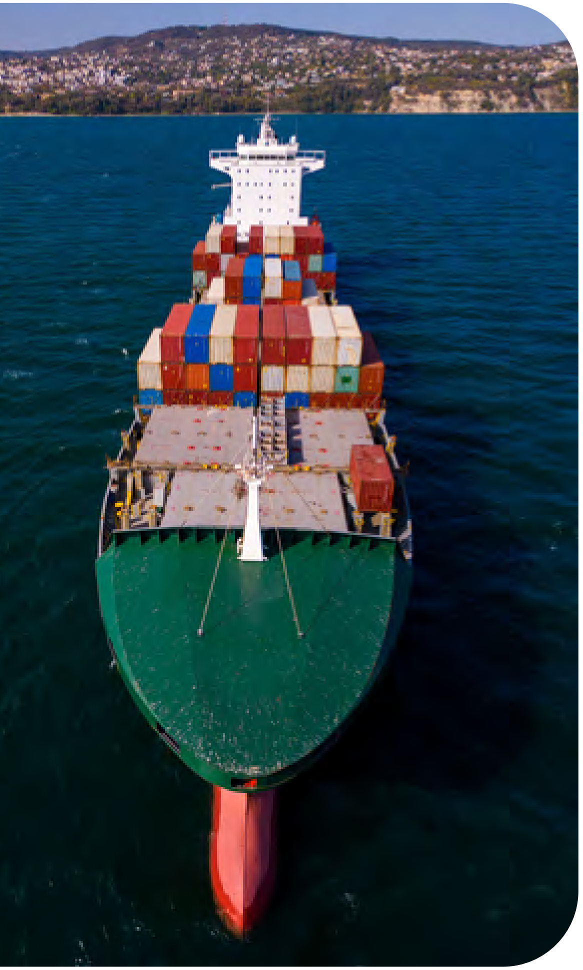
This industry structure is a defining characteristic of ocean-going shipping's implementation pathway. It means that the transition cannot rely only on fixed green corridors or on deployment models designed for large liner operators. For bulk and tramp shipping, sustainable fuels must become available 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.

11 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.

12 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.

13 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.



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 ocean-going 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%
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: SL, based on Clarkson Research Services Limited.[14]

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.

14 Ibid.

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.[15] A younger fleet supports earlier retrofit and newbuild deployment of sustainable 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, operational efficiency measures for the existing fleet,[16] and end-of-life recycling.

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.[17]

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 within five years.[18] 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.[19] Norway, although outside the EU-27, remains a major European maritime power and is relevant to the wider European controlled fleet.

15 ISL, Shipping Statistics and Market Review, World Merchant Fleet by Ship Type, 1 January 2024, based on Clarkson Research Services Limited.
16 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.
17 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.
18 European Maritime Safety Agency (EMSA), The 2025 European Maritime Safety Report (EMSAFE) (Lisbon: EMSA, 2025), §2.3.4 ("Age of ships"), p. 84.
19 EMSA, The 2025 European Maritime Safety Report, Table 21 (source: EMSA services), p. 84.

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.[20]

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: SL, 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.[21]

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. Commercial actors (charterers, cargo owners and ship managers) increasingly influence technology and fuel adoption, whilst class societies, flag, statutory approval, survey, certification and in-service verification are critical for deployment. Deployment instruments must therefore be designed for a globally operated fleet, while still mobilising European industrial, regulatory and innovation capacity.

20 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).
21 ISL, Shipping Statistics and Market Review, Fleet by Member State 2024, based on Clarkson Research Services Limited.

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 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 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.[22]

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 totalling around 70 million dwt and USD 60 billion, and the corresponding fleet ranks as the world's largest sustainable alternative-fuel-capable and environmentally sustainable technology (EST)-fitted fleet.[23] On 11 September 2026, Danish-owned A.P. Møller-Mærsk announced plans to expand its fleet with orders for up to 42 newbuildings as part of a USD 8.9 billion fleet-expansion drive.[24] 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.

22 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).

23 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.

24 Adam Corbett, "A.P. Møller-Mærsk Set to Order Its Largest-Ever Vessels as Part of USD 9bn Spree," Tradewinds, 11 September 2026, https://www.tradewindsnews.com/containers/ap-moller-maersk-set-to-order-its-largest-ever-vessels-as-part-of-9bn-spree/2-1-2040801.

2. DRIVERS AND CONSTRAINTS

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.[25] 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.[26] 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.[27]
- **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%) by 2040.[28] 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.[29] 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.[30] 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.[31]
- **Fuel EU 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.[32] 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.[33] 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.[34] The proposal for a revised EU ETS Directive presented by the Commission on 17 July 2026, COM(2026) 616 final, reinforces this trajectory: it aligns the ETS with the Union's 2040 target of a 90% net emissions reduction, reserves up to 110 million allowances for the period 2028–2040 to support the use of sustainable maritime fuels and the deployment of zero-emission propulsion technologies, and explicitly recognizes

25 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.

26 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/.

27 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.

28 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).

29 IMO, Resolution MEPC.377(80), §3.2 (well-to-wake approach) and §4 (Guiding Principles).

30 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.

31 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).

32 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.

33 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.

34 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.

electric and wind-assisted propulsion systems as eligible technologies under the new Article 3gaa.[35] The proposal confirms that resources from the allowances paid, could support the maritime sector's sustainable alternative fuels and zero-emission propulsion, but not the improvement of the energy efficiency of ships, ports and enabling infrastructure.[36] Together with the parallel proposal to simplify and streamline the MRV framework, COM(2026) 620 final, and the delegated and implementing acts foreseen under Article 6(6) and Annex III of Fuel EU Maritime on the criteria for the acceptance of zero-emission technologies, these instruments converge into a regulatory package that could potentially address the operational needs of today while preserving the technological horizon of tomorrow.[37]

- **Sustainable Transport Investment Plan.** COM(2025) 664 final translates FuelEU Maritime demand into a structured package of fuel production, infrastructure, finance and certification.[38] 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, ethanol and ammonia — and identifies the core market failure of price gap, e-fuel scarcity and offtake uncertainty.[39] 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.[40] 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.[41]
- **Global Gateway Partnerships.** Ocean-going shipping is increasingly tied to EU external relations strategy. Geopolitical partnerships affect bunkering hub development, port access and green shipping corridor viability.
- **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-competition instruments and circularity provisions — strengthen technological sovereignty over propulsion, fuel systems, retrofitting and end-of-life circularity.[42] 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.[43] Resilience measures address shadow-fleet monitoring, binding IMO cybersecurity rules and EU presence around maritime chokepoints[44] 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.[45]

35 European Commission, Proposal for a Directive of the European Parliament and of the Council amending Directive 2003/87/EC and Decision (EU) 2015/1814 as regards driving competitiveness and cost-effective decarbonisation, COM(2026) 616 final, Brussels, 17 July 2026, new Article 3gaa ("Reservation and allocation of allowances for the use of sustainable maritime fuels and zero-emission propulsion technologies", including electric and wind-assisted propulsion systems); amendment to Article 9 (extension of ETS coverage to non-CO2 maritime emissions from 1 January 2026 and to offshore ships from 1 January 2027).

36 European Commission, Proposal for a Directive, COM(2026) 616 final, Brussels, 17 July 2026, amendments to Article 10a on Innovation Fund eligible investments (measures to decarbonise the maritime sector, including the improvement of the energy efficiency of ships, ports, innovative technologies and infrastructure, electrification and sustainable alternative fuels, and zero-emission propulsion technologies).

37 European Commission, Proposal for a Regulation of the European Parliament and of the Council amending Regulation (EU) 2015/757 and Regulation (EU) 2023/1805 to simplify and streamline monitoring, reporting and verification and to align with revisions of the EU Emissions Trading System, COM(2026) 620 final, Brussels, 17 July 2026; Regulation (EU) 2023/1805 (Fuel EU Maritime), OJ L 234, 22 September 2023, Article 6(6) and Annex III (zero-emission technologies for use at berth) and Article 28 (review clause).

38 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.

39 European Commission, Sustainable Transport Investment Plan, COM(2025) 664 final, §2.1 ("Market challenges") and §2.3, pp. 5–7.

40 Ibid., §3 ("Actions to boost investments") and Investment needs box, pp. 7–8.

41 European Commission, Sustainable Transport Investment Plan, COM(2025) 664 final, international dimension and Global Gateway Green Shipping Corridors and Hubs, pp. 7–10.

42 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.

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

44 Ibid., §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.

45 Ibid., §§4–6 ("Access to Innovation", "Access to Finance and Investment", "Access to Skills and Quality Jobs"), pp. 12–22.

- **European industrial competitiveness and technology sovereignty.** Ocean-going shipping is a strategic market for European propulsion systems, engines, retrofit solutions, digital platforms, maritime equipment and lifecycle services. Maintaining and strengthening Europe's global leadership in these areas is a major driver for innovation, investment and deployment.
- **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.[46] 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.[47] Port energy-transition measures cover OPS deployment, the Electrification Action Plan, OPS price transparency, accelerated AFIR-driven sustainable alternative fuels infrastructure and an assessment by the Renewable and Low-Carbon Fuels Alliance.[48] 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.[49]
- **Geopolitical resilience and strategic autonomy.** Shipping is increasingly influenced by concerns related to energy security, critical raw materials, supply-chain resilience and maritime chokepoints. These factors affect fleet investment, fuel sourcing, route planning and technology choices, and should be recognised alongside climate objectives as long-term strategic drivers.
- **Critical infrastructure protection.** Ocean-going vessels increasingly operate as critical infrastructure. NIS2 mandates cybersecurity for operators of maritime critical infrastructure. Cybersecurity is a prerequisite for digital integration and remote operations.
- **Customer, cargo-owner, charterers, lenders and insurers demand.** Commercial decisions are increasingly influenced by emissions transparency, verifiable carbon intensity, fuel lifecycle emissions and technology readiness, low-carbon transport solutions and verifiable lifecycle reporting. This demand-side pressure is becoming an important driver for fuel transition, energy-efficiency technologies and digital monitoring capabilities.

The European Community Shipowners' Association 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.[50]

46 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.

47 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.

48 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.

49 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.

50 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. CONSTRAINTS AND BOTTLENECKS

European ocean-going shipping faces 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 sustainable 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.[51] 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.[52] 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.[53] Competition to secure affordable and reliable supplies of sustainable fuels is likely to influence fleet-renewal decisions, technology selection and long-term investment strategies across the sector. This is further constrained by the fragmentation of global infrastructure and fuel interoperability.
- **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.[54] 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.[55] Cross-sectoral competition is intensifying: hydrogen-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.[56] 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.[57]
- **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.[58] 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.[59] 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.[60] Furthermore large-scale deployment may be constrained by limited manufacturing capacity for engines, fuel systems, retrofit packages, specialised components, shipyards slots and skilled labour.

51 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.

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

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

54 IEA, Energy Technology Perspectives 2026, Chapter 2, p. 94.

55 Ibid., p. 106.

56 Ibid., p. 94.

57 IEA, Energy Technology Perspectives 2026, Chapter 3 ("Technology deployment dashboards"), "Ammonia and methanol propulsion ships", p. 129.

58 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.

59 ECSA, The Economic Value of European Shipping: 2026 Update, §2.3, p. 15, citing Clarksons Research, World Fleet Register, November 2024.

60 European Commission, EU Industrial Maritime Strategy, COM(2026) 111 final, §2.1 ("EU maritime manufacturing: fostering growth and competitiveness in lead markets"), p. 3.

- **Investment uncertainty.** Investment uncertainty is arising from technology pathway ambiguity. Shipowners are being asked to make long-lived investment decisions while significant uncertainty remains regarding future fuel availability, fuel prices, infrastructure development and the eventual winning technology pathways. This delays investment decisions. In many cases, the party investing in efficiency improvements or new technologies is not the party capturing the full economic benefit. Misaligned incentives between shipowners, charterers, cargo owners, fuel suppliers and infrastructure providers continue to slow the business case for investment and deployment. Furthermore, banks are unwilling to finance first-of-a-kind alternative-fuel vessels without long-term contracts, which specifically for bulk/tramp operators and SME shipowners complicates decision making.
- **Complexity of retrofitting.** The highly heterogeneous ocean-going fleet requires integrating multi-fuel engines, batteries, waste-heat recovery and digital systems into legacy electrical architectures. This requires custom engineering per vessel, as standardised retrofit kits do not exist.
- **Regulatory architecture and compliance complexity.** The simultaneous entry into force of Fuel EU Maritime,[61] the extension of the EU Emissions Trading System to maritime transport from January 2024,[62] and the MRV framework,[63] 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.[64]
- **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.[65] 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.[66] The eFTI Regulation extends this trajectory to the wider logistics chain, signalling that ocean-going competitiveness will increasingly depend on end-to-end digital trade and enforcement interoperability.[67] Fragmented digital standards and a lack of harmonised international standards for e.g. remote operational support further constrain implementation.

61 Regulation (EU) 2023/1805 (FuelEU Maritime), OJ L 234, 22 September 2023.

62 Directive (EU) 2023/959, OJ L 130, 16 May 2023; European Commission, COM(2025) 110 final, Brussels, 18 March 2025.

63 Regulation (EU) 2015/757, OJ L 123, 19 May 2015, as amended.

64 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.

65 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".

66 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.

67 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.

- **Digital twin standardisation and equipment interoperability.** Vessels integrate systems from 50 – 100+ manufacturers with no standardised data models or API specifications. Integrated digital twins for energy management, predictive maintenance and emissions monitoring require standardised interfaces not yet defined.
- **Fragmented and insufficient representative-scale safety validation.** Deep-sea systems must manage fire, explosion, toxicity and cryogenic hazards potentially for weeks. External emergency assistance may be distant and vessels operate across jurisdictions. Tests and safety cases are often repeated for each project, flag, class and port. This increases approval time, cost, insurance uncertainty and first-mover risk.
- **Skills availability and workforce shortages are cross-cutting constraints.** The safe deployment of new fuels, electrification, digital systems, automation and remote operations depends on the availability of suitably trained crews, shore operators, port personnel, emergency responders, inspectors and maintenance teams.[68] Automation, remote technical support and digital decision-support tools can improve safety, reduce workload and make ocean-going operations more attractive for future generations of maritime professionals. Skills gaps may slow deployment or increase operational risk. Training systems, competence standards and certification requirements will need to evolve in parallel with fleet and infrastructure renewal, while human-centred design will be necessary to ensure that digital and automated systems support rather than overburden crews and shore-based operators.

2.3. 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.

68 European Tug owners Association, consultation (2026); European Maritime Safety Agency, Safety Analysis 2025 (2025).

3. TARGET CAPABILITIES

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.[69]

The following sections set out the current state of development and the target capabilities required for 2035, 2040, and 2050.

3.1 CURRENT STATE-OF-PLAY AND ACHIEVED DEVELOPMENTS

Ocean-going shipping is already progressing along several technology pathways, although technology maturity and deployment readiness differ significantly between solutions. Energy-efficiency technologies — including wind-assisted propulsion, hull and propeller optimisation, waste-heat recovery, advanced coatings, voyage and weather routing — are available for deployment and constitute an important near-term means of reducing fuel consumption and emissions from deep-sea vessels. Dual-fuel engines and methanol-capable vessels are increasingly entering the market, while LNG and biomethane remain transitional options subject to methane-slip and lifecycle-performance considerations. Ammonia, hydrogen, fuel cells, onboard carbon capture and advanced autonomy require further safety validation, standards, bunkering infrastructure and representative-scale demonstration before broad ocean-going uptake.

Digital technologies are also becoming increasingly embedded in ocean-going operations. Digital twins, voyage optimisation, predictive maintenance, emissions monitoring, weather routing and port-call optimisation and increasingly capable AI-enabled decision support tools can support improved energy efficiency, operational performance and reliability. At the same time, increasing reliance on software-intensive and interconnected ship systems, together with higher capacity and lower latency ship-shore connectivity, strengthens the need for interoperable data exchange, cybersecurity, cyber-safety, secure communications and robust system assurance throughout the vessel lifecycle.

The operational challenge remains structural. Most existing long-distance cargo vessels bunker large quantities of fuel and require several weeks of autonomy. For these vessels, early green propulsion is expected to rely primarily on internal combustion engines using sustainable alternative fuels, potentially supported by wind propulsion, with a possible later transition towards fuel cells using green hydrogen-based fuels. The transition of ocean-going shipping will therefore require a combination of fuel flexibility, energy-efficiency improvements, retrofitting, newbuild readiness, digital optimisation, safety management and interoperable port and fuel infrastructure.

69 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.

The current state of development therefore spans technologies that can already be deployed, technologies requiring accelerated scale-up and system integration, and technologies that still require targeted RD&I, demonstration, regulatory development and infrastructure deployment. This differentiated maturity provides the baseline for the target capabilities defined for 2035, 2040 and 2050.

3.2. BY 2035 — DEPLOYMENT READINESS AND FIRST OPERATIONAL SCALE

By 2035, ocean-going shipping should be capable of operating first low- and zero-emission class-approved solutions on selected international routes where fuel supply, port infrastructure, cargo flows, regulatory conditions, safe bunkering procedures and crew training 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 integrating transitional dual-fuel systems, wind-assisted propulsion and substantial energy-efficiency improvements. This requires trusted lifecycle economics, performance-verification capability and global fuel interoperability & certification standards.

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.[70] 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, wind-assist integration and standardised electrical architectures. This requires industrial-scale retrofit capability and class-approval of solutions identified.

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.[71] 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 Waterborne Technology Leadership document's linkage between digital twins, zero-emission decision-support systems and green ship operations.[72] In 2035, ships are protected from cyber-attacks and testing cyber-physical systems during approval and commissioning will be a common practice.

70 Waterborne Technology Platform, Waterborne Technology Leadership, 8 (retrofitting and newbuild replacement both required, given long vessel lifetimes of around 30 years).

71 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).

72 Waterborne Technology Platform, Waterborne Technology Leadership, 17 (Demonstration of integration of digital twins across design, production and maintenance for mainstream vessel classes)

3.3. 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.[73]

Fuel capability by 2040 should be multi-fuel and route adaptive. Ocean-going vessels should be able to use different sustainable alternative fuel options depending on route, bunkering availability, vessel type and cargo profile. This requires multi-fuel system safety at scale. The Strategic Research and Innovation Agenda of the Partnership on Zero-Emission Waterborne Transport states that there is no single cost-effective and globally available sustainable alternative fuel today, and that future fuel choices depend on social, economic, technical and environmental conditions.[74] 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, whilst fully exploiting the potential of energy-efficiency technologies.

Safety capability must become mature by 2040. Sustainable alternative fuels, digitalisation and automation introduce new operational risks, including toxicity, fire, explosion, cryogenic handling, cyber risk and 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 sustainable alternative fuels, digitalisation and automation.[75]

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, interoperable ship-port-fuel digital assurance, emissions fuel traceability, machinery health, cybersecurity, compliance data exchange, distributed digital energy orchestration across fleet 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.[76]

3.4. 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 Waterborne Technology Leadership document's 2050 vision for European waterborne transport is a safe, secure and resilient mode of transport delivering zero harmful emissions, zero pollution and zero fatalities.[77]

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.[78]

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73 Waterborne Technology Platform, Waterborne Technology Leadership, 9 (integration of vessels, ports, infrastructure and the broader ecosystem as precondition for the waterborne transition).

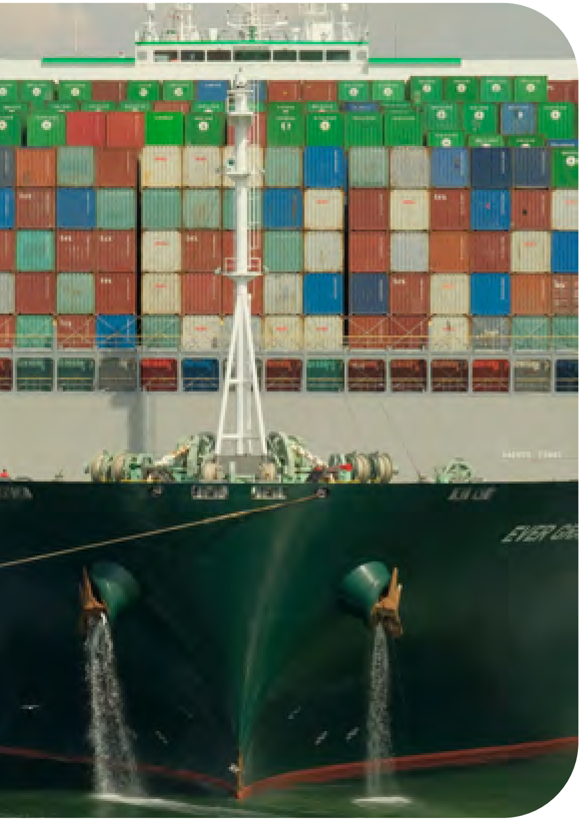
74 European Commission, ZEWT Partnership, SRIA 2.0, Part 1 (Vision) and Part 2 (Sustainable Alternative Fuels): no single cost-effective and globally available alternative fuel today; future fuel choices depend on social, economic, technical and environmental conditions.

75 European Commission, EU Industrial Maritime Strategy, COM(2026) 111 final, Brussels, 4 March 2026, §3.3 (Safety, security), pp. 10–11.

76 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).

77 Waterborne Technology Platform, Waterborne Technology Leadership, 18 (Vision: by 2050, European waterborne transport will be a force of European competitiveness as a safe, secure and resilient mode of transport, delivering zero harmful emissions, zero pollution and zero fatalities).

78 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).



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, where safety, reliability, cyber resilience and lifecycle circularity are standard supported by human-centred automation rather than automation alone.[79]

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 sustainable alternative fuels, the capacity to maintain operations under geopolitical, climatic, energy market, cyber and technical disruptions. The Waterborne Technology Leadership document links waterborne transformation to resilience, cybersecurity, supply-chain reliability, integration into Europe's energy and logistics systems, and strategic autonomy.[80]

3.5 CROSS-CUTTING CAPABILITY IMPLICATIONS

The progression towards the 2035, 2040 and 2050 target capabilities depends on a set of cross-cutting capabilities that must develop in parallel with propulsion and energy technologies. Increasing digitalisation, AI-enabled decision support, automation and ship-shore connectivity require interoperable data environments, secure communications, cybersecurity and cyber-safety, robust system assurance and human-centred design. These capabilities must support safe and reliable operation under normal as well as degraded or disrupted conditions.

Ocean-going shipping must also strengthen operational and supply-chain resilience. This includes secure and diversified technology and energy supply chains, reliable access to sustainable alternative fuels, reduced critical dependencies, internationally interoperable infrastructure and standards, and a suitably skilled workforce capable of operating increasingly complex fuel, digital and automated systems.

These cross-cutting capabilities apply across vessel types and business models and should therefore be developed as integral elements of the propulsion, safety, digitalisation, workforce, regulatory and deployment pathways set out in Chapters 4 and 5.

79 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).

80 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).

4. TECHNOLOGY PATHWAYS

4. TECHNOLOGY PATHWAYS

The transformation of ocean-going shipping requires coordinated progress across propulsion and energy systems, safety and resilience, digitalisation and automation, human capabilities, and regulation and standardisation. These pathways are closely interdependent: new fuels and propulsion systems require corresponding advances in safety, digital integration, workforce competence, infrastructure and regulatory approval. The following sections identify the main technology pathways, target capabilities, required enablers and research gaps for 2035, 2040 and 2050, taking account of the different operational and deployment conditions of liner and bulk/tramp shipping.

4.1 FUTURE PROPULSION AND ENERGY SYSTEMS ENABLING A CLIMATE-NEUTRAL OCEAN-GOING 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. Fuel flexibility, retrofitability, safety assurance and verification of actual operational performance will also be important to enable deployment across the existing and future fleet. Advanced energy intelligence, predictive optimization and vessel-level digital twins will underpin Europe's long-term technological advantage.

4.1.1. Operational objective

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, and enabling modular and retrofit-ready architectures that can accommodate future fuel and technology developments over the vessel lifetime. Safety, assurance, certification and regulatory approval readiness should be integrated from the design stage.

4.1.2. Target capability 2035, 2040 and 2050

By 2035:

- Safe handling and operation of new technologies and fuels to be adopted, supported by verified and adequate training, procedures and safety assurance approaches. TRL will remain technology and fuel specific; mature technologies should increasingly move towards large scale deployment, while genuinely novel concepts require further demonstration and validation. For example, some biofuels are already in use at TRL9 while other technologies remain at demonstration stage.

- Untapping the potential of "out of spec" biofuels and blends thereof. Cost, availability, fuel quality, compatibility and safety come into play. As long as sustainable biofuels are more affordable than synthetic (green hydrogen based) fuels, new biofuel pathways will emerge. TRL 1-9 depending on fuel pathway.
- Flexible fuel blending widely in use – Ocean-going shipping on the path of transition, including drop-in biofuels during the early transition. Fuel quality specifications, blend compatibility and verification methodologies should support safe use. TRL 7-9, depending on the fuel component and blend.
- Dual/multi fuelled transitional fleets expanded TRL 9
  - New dual/multi fuel concepts, building on diesel-LNG and diesel-methanol systems already deployed
- Proven Energy Saving Devices increasingly deployed, while novel Energy Saving Devices are demonstrated and validated under representative ocean-going operating conditions
  - Including, 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
  - Proven solutions: TRL 8-9; novel concepts: TRL 6-7.
- Proven Energy Saving Operations increasingly deployed, while novel operational concepts are demonstrated and validated
  - Including virtual arrival, weather routing, energy efficient routing, trim/cargo optimisation etc.
  - Proven solutions: TRL 8-9; novel concepts: TRL 6-7.
- Novel Hybrid Concepts demonstrated, including DC-based onboard power distribution and flexible voltage architectures TRL 6-7
- Novel Upgrade kits for using sustainable fuels demonstrated TRL 6
  - Total cost of ownership optimized, enabling deployment and scalability
  - Retrofit solutions should increasingly use modular and standardised interfaces where technically appropriate
- Novel Vessel efficiency upgrade kits demonstrated TRL 6-7
- Novel cost competitive propulsion system(s) demonstrated TRL 6
  - Including, but not limited to wind propulsion with 30+% energy savings and other renewable assisted propulsion concepts.
- Novel Emission Saving Devices demonstrated TRL 6-7
  - Including, but not limited to onboard carbon capture, SCRs, methane catalysts and other emission control systems
- Onboard carbon capture demonstrated at representative scale, including vessel integration, energy penalty, captured CO_2 storage, handling and offloading requirements TRL 6-7.
- Verified methane slip monitoring and mitigation demonstrated for relevant fuel and engine pathways, supporting reliable emissions and lifecycle performance assessment TRL 7-8.
- Nuclear propulsion holistic feasibility completed - commercial (OPEX + CAPEX), social, safety & security, regulatory and certification pathways, liability and insurance, port and coastal state acceptance, emergency arrangements and port-access implications:
  - system components TRL 5
  - consequential safety measures TRL 6
  - implementation roadmap TRL 4
- Initial large-scale validation of energy saving technologies (ESDs) and operational efficiency measures, providing verified data on actual performance under representative vessel, route weather and duty cycle conditions, cost and emission reduction. TRL 7

By 2040:

- Updated safe handling and operation of new technologies and fuels to be adopted
- Energy Saving Devices deployed and scaled TRL 8-9
- Energy Saving Operations deployed and scaled TRL 8-9
- Hybrid Concepts deployed and scaled TRL 8-9
- Upgrade kits for using sustainable deployed and scaled TRL 8-9
- Vessel efficiency upgrade kits deployed and scaled TRL 8-9
- Cost competitive propulsion deployed and scaled TRL 8-9
- Ammonia-capable ocean-going vessels operational on selected corridors where fuel supply, bunkering infrastructure and safety approval are available TRL 8
- Modular fuel tank integration optimised for minimal cargo loss TRL 7
- Standardised modular dual- or multi-fuel propulsion and energy system architectures available for newbuild and retrofit applications across relevant vessel classes TRL 8-9
- Wind assisted propulsion deployed and scaled where vessel type, route and operating profile make it technically and commercially suitable TRL 8-9
- Onboard carbon capture deployed in suitable commercial applications where lifecycle performance, energy requirements, economics and CO_2 handling and offloading infrastructure support its use TRL 8-9.

By 2050:

- updated safe handling and operation of 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, supporting future fuel, energy and technology upgrades throughout vessel lifetimes
- Wind assisted propulsion used in vessel segments and operating profiles where it provides a cost-effective contribution to energy demand reduction, including non-time-critical cargo operations
- Globally interoperable fuel, energy and emissions verification supports lifecycle certification and compliance across climate-neutral propulsion pathways

4.1.3. Key research gaps

- Biofuels: what organic waste/side product could be turned into fuel at a cost competitive price with synthetic green hydrogen-based fuels, while meeting lifecycle sustainability requirements?
- Fuel quality characterisation, stability, compatibility and safe blending methodologies for emerging biofuels and fuel blends, including internationally compatible specifications and onboard verification where required
- 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" and other wind-assisted propulsion concepts across different vessel types, routes and operating profiles

- Standardised modular propulsion, fuel, electrical and control system architectures enabling cost-effective retrofit and future conversion across vessel classes.
- Onboard carbon capture integration, including capture performance, energy penalty, space and weight requirements, storage, CO_2 offloading, downstream handling, lifecycle emissions and cost effectiveness
- Measurement and mitigation of methane slip and other relevant non- CO_2 emissions
- Lifecycle emission modelling, including harmonised lifecycle GHG assessment, fuel certification and chain-of-custody methodologies interoperable across IMO, EU and global fuel supply systems
- Setting criteria for allowable under water radiated noise
- Next-generation and not-yet-identified energy saving concepts beyond currently known technologies including improved prediction of performance and cost-benefit for such technologies
- Real world verification of energy saving technology performance under representative vessel, route, weather, loading and operational conditions
- 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

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 meets both operational and sustainability objectives.

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

These frameworks should address fuel- and energy-system hazards, cyber-physical risks, degraded modes of operation and safe recovery, including situations where external assistance may be limited or delayed.

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 TRL 6
- Automatic safety incident communication concepts vessel to vessel, shore to vessels and shore to shore communication TRL 6
- Automatic re-routing guidance system based on risk of incident and/or occurred incidents considering current traffic and weather conditions TRL 6
- Cyber security resilience – cyber redundancy and cyber-physical resilience concepts TRL 8
- Resilient navigation & degraded-mode navigation TRL 6
- Representative scale validation of safety concepts for sustainable alternative fuels, hybrid systems and autonomous functions under real operational conditions, including relevant fire, explosion, toxicity, cryogenic and battery hazards. TRL 6-7
- Safe fallback and recovery concepts demonstrated for loss or degradation of critical functions, including power, propulsion, navigation and communications. TRL 6-7

By 2040:

- Collision avoidance deployment utilising automatic vessel to vessel, shore to vessels and shore to shore communication TRL 8
- Automatic safety incident communication deployment vessel to vessel, shore to vessels and shore to shore TRL 8
- Automatic re-routing guidance system based on risk of incident and/or occurred incidents considering current traffic and weather conditions deployment TRL 8
- Cyber redundancy and resilient cyber-physical architectures deployed TRL 9
- Autonomous navigation deployed in corridors TRL 7
- Integrated safety systems for sustainable alternative fuels and hybrid energy systems deployed, combining detection, containment, shutdown, mitigation and emergency response functions as appropriate to the fuel and system concerned. TRL 8-9.

By 2050:

- Autonomous navigation deployed in corridors TRL 9
- Integrated predictive safety and resilience systems deployed across relevant ocean-going operations, supporting safe operation, degraded modes and recovery from technical, environmental and cyber disruptions TRL 9.

4.2.3. Key research gaps

- Barriers of introducing assisted and automated operation.
- Introduction pathways for assisted and automated operation.
- Safety of sustainable alternative fuels and hybrid energy systems under representative ocean-going conditions, including fire, explosion, toxicity, cryogenic and battery hazards and interactions between different onboard energy systems.
- Cyber-physical resilience, degraded mode operation and recovery following loss or degradation of critical vessel functions.
- Safety assessment of compound failures involving combinations of technical failure, hazardous release, fire, adverse weather, loss of communications or cyber disruption.
- Validation methodologies for integrated safety systems under representative scale and real operational conditions, including operations where external assistance may be delayed.
- Methods for developing reusable and transferable safety evidence and safety case components across vessels and technology applications.

4.3. FULLY CONNECTED, AUTOMATED AND DATA-DRIVEN DEEP-SEA SYSTEMS

4.3.1. Operational objective

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. They should also support predictive maintenance, remote diagnostics and assistance, AI-supported decision making, automated reporting and compliance, and secure ship-to-shore and ship-to-port coordination.

4.3.2. Target capability 2035, 2040 and 2050

By 2035:

- Develop and disseminate data standards to facilitate interoperability of software solutions and data transfers. TRL 7
- Virtual arrival concept demos. TRL 7
- Automatic communication concepts between marine traffic supervision hubs. TRL 8
- Emission data and reporting available for customer according to ISO14083. TRL 9
- Use of digital twins and operational data to verify performance, emissions and economic viability of new technologies. TRL 6-8
- Predictive maintenance and remote diagnostic systems demonstrated using operational vessel data, supporting reduced downtime and improved lifecycle performance. TRL 7-8
- AI-supported decision support systems demonstrated for voyage, energy and operational optimisation, with appropriate human oversight. TRL 6-8
- Secure and interoperable ship-to-shore and ship-to-port data exchange demonstrated for operational safety and compliance related information. TRL 7-8

By 2040:

- Virtual arrival deployed. TRL 9
- Interoperable digital architectures deployed across vessels, ports, shore control centres and relevant logistics and operational actors, enabling real-time exchange of operational and performance data. TRL 8-9
- Digital twins deployed for vessel and fleet performance optimisation, predictive maintenance and lifecycle management. TRL8-9
- AI-supported operational decision support and optimisation systems deployed at scale, with validated performance and appropriate human oversight. TRL8-9
- Remote diagnostics and specialist support integrated into normal ocean-going operations. TRL8-9
- Automated emissions, performance and compliance reporting increasingly integrated into vessel and fleet digital systems. TRL8-9

By 2050:

- Globally interoperable and secure digital maritime ecosystems support continuous data exchange between vessels, ports, shore control centres and relevant maritime and logistics actors. TRL9
- Advanced AI-supported and increasingly automated vessel and fleet operations are deployed across relevant ocean-going applications, with human oversight and validated safety and performance. TRL9
- Digital twins and operational data support continuous vessel optimisation, predictive maintenance, technology performance verification and lifecycle management. TRL9
- Continuous assurance and adaptive recovery support resilient digital operations under degraded communication, cyber or system conditions. TRL9

4.3.3. Key research gaps

- Interoperability of vessel, fleet, port and shore systems, including common data models and interfaces.
- Validation, explainability and human oversight of AI-supported maritime decision support and optimisation systems.
- Digital twin methodologies for vessel performance, predictive maintenance, energy optimisation and lifecycle management.
- Remote diagnostics and technical support systems suitable for long duration ocean- going operation.
- Automated verification and reporting of operational, emissions and compliance data.
- Reliable digital operation under degraded connectivity, data quality limitations and cyber disruption.

4.4. HUMAN-CENTRED DESIGN AND A FUTURE-READY DEEP-SEA WORKFORCE

4.4.1. Operational objective

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 sustainable alternative fuels, operation of complex hybrid energy systems, interaction with advanced digital support tools and continuous training. Human-centred design should ensure that increasing levels of automation and digitalisation support, rather than replace, effective human decision making, with clear human oversight of safety critical operations.

4.4.2. Target capability 2035, 2040 and 2050

By 2035:

- AR/VR assisted navigation concepts demonstrated in open sea, congested areas, narrow straights, shallow waters, arrival/departure operations.
- AR/VR assisted concepts demonstrated for decision making support in harsh conditions and incidents.
- Crew competence frameworks covering relevant sustainable alternative fuels, hybrid and electrical energy systems, digital systems and increasingly automated operations.
- Alarm management.
- Fuel handling.
- Emergency response.
- Safe operational procedures.
- Simulation based and immersive training increasingly used for complex, safety-critical and infrequent operational scenarios.
- Human factors considerations, including workload, fatigue and interface usability, integrated into the design and validation of new digital and automated systems.

By 2040

- Autonomous navigation and operation demonstrated in corridors with appropriate human oversight and clearly defined responsibilities (not equivalent to unmanned operation).
- Advanced human-machine teaming deployed for voyage planning, operational decision support, safety monitoring and maintenance.
- Shore based specialist and remote support functions integrated into relevant ocean-going operations.
- Competence and continuous upskilling frameworks established for personnel operating or supervising alternative fuel, hybrid, digital and increasingly automated systems.

By 2050:

- Autonomous navigation and operation demonstrated globally where operationally and regulatorily appropriate, with human oversight retained for safety-critical functions (not equivalent to unmanned operation).
- Human centred design principles embedded across increasingly automated vessel systems and shore-based operational support.
- Continuous competence development and recurrent training embedded across relevant maritime roles, enabling personnel to adapt to evolving fuels, technologies and levels of automation.

4.4.3. Key research gaps

- Human-machine interaction and human-AI teaming in increasingly automated ocean-going operations.
- Workload, fatigue, situational awareness, alarm management and cognitive performance under increasing levels of automation and digital support.
- Effectiveness of simulation, AR/VR and other immersive training approaches for sustainable alternative fuels, emergency scenarios and complex vessel operations.
- Competence requirements and role evolution for onboard personnel and shore-based operators as automation and remote support increase.
- Trust, accountability and appropriate levels of human oversight in AI-supported and autonomous operations.
- Impacts of new technologies and operating models on working conditions, workforce attractiveness and retention.

4.5. FORWARD LOOKING REGULATION, STANDARDIZATION AND SYSTEM-LEVEL INTEGRATION

4.5.1. Operational objective

Forward looking regulation in a maritime environment is key. Stable and predictable regulatory frameworks are important to provide investment certainty and avoid disruptive changes in direction. 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 the calculation of the emissions footprint 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, so that different systems and modules can communicate and operate together through compatible interfaces. Predictable and internationally aligned approval and certification pathways will also be needed for emerging fuels, modular systems and increasingly digital vessel technologies.

4.5.2. Target capability 2035, 2040 and 2050

By 2035:

- Global, or at least European, standards of calculating emission footprints of goods shipped and persons travelled, based on example ISO 14083. Even where standards exist, common interpretation and application are needed to enable fair comparison of cumulative emissions per tonne-nautical-mile and other relevant transport performance metrics.
- Harmonised methodologies for lifecycle-GHG assessment and fuel sustainability certification, supporting consistent treatment of different fuel production pathways and internationally interoperable compliance.
- Initial standardisation and type approval approaches for modular propulsion, energy and retrofit systems, enabling certified components and modules to be integrated or upgraded without unnecessary repetition of case-by-case approval.

By 2040:

- Standardised communication, electrical, digital and other relevant system interfaces widely applied across onboard equipment, enabling interoperability, modular integration and retrofitability.
- Predictable certification and approval pathways established for modular and reconfigurable vessel systems, sustainable alternative fuels and increasingly digital technologies.
- Mutual recognition of validated safety and technical evidence increasingly applied between relevant classification, flag-state and regulatory frameworks, where appropriate.
- Interoperable digital reporting and certification systems support emissions, fuel, lifecycle and compliance information exchange across relevant jurisdictions.

By 2050:

- A mature and highly harmonised international regulatory and standardisation framework supports zero-/net-zero ocean going vessel operations, modular vessel architectures and globally interoperable digital systems.
- Technology-neutral approval and certification frameworks enable the introduction of new fuels, propulsion, energy and digital technologies without unnecessary case-by-case regulatory barriers, while maintaining equivalent or improved levels of safety.

4.5.3. Key research gaps

- Interpretation and application of standards to ensure fair and harmonised comparison between vessel types, technologies and operating profiles.
- Regulatory and certification pathways for modular and reconfigurable propulsion, energy and retrofit systems.
- Methods for harmonised lifecycle-GHG accounting, fuel sustainability certification and interoperable compliance across different regulatory regimes.
- Approaches for digital certification, automated compliance verification and remote inspection where technically and regulatorily appropriate.
- Regulatory treatment and assurance of AI-supported and increasingly automated vessel systems, including the evidence required for approval and continued operation.

5. ENABLERS AND DEPLOYMENT

5. ENABLERS AND DEPLOYMENT

The technology pathways identified in Section 4 show that the transformation of 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.[81]

A large share of the intercontinental fleet, however, especially bulk tramp shipping, does not operate on fixed routes. For these vessels, the technology pathways identified in Section 4, including global sustainable 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,[82] flexible bunkering access, Fuel EU Maritime pooling of compliance balances, and charter-party clauses allocating responsibilities and costs between owners, operators and charterers.[83, 84]

Deployment models should therefore combine corridor-based early markets with mechanisms that can progressively support worldwide access to sustainable alternative fuels and verified environmental attributes for vessels operating outside fixed routes.

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81 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.

82 https://www.cleanenergyministerial.org/initiatives-campaigns/hubs/

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

84 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.

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. Fuel deployment will also require internationally interoperable sustainability certification, fuel quality assurance and lifecycle GHG accounting capable of distinguishing relevant production pathways and supporting credible compliance across jurisdictions.

Deployment should therefore prioritise the development of global multi-fuel bunkering hubs for methanol, ethanol, 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 alternative 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, ethanol, biomass, carbon-capture and industrial-policy actors. Sustainable alternative fuel availability for shipping will compete with demand from aviation, chemicals, fertilisers, steel, power generation and other sectors. The roadmap therefore supports system-level planning that clarifies when and where scarce sustainable alternative fuels deliver the highest value and where energy-efficiency measures can reduce demand.

Where physical fuel availability remains geographically uneven, internationally recognised chain-of-custody, mass-balance or equivalent mechanisms may complement physical supply, provided that environmental integrity and avoidance of double counting are ensured.

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[85] 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.

85 European Commission, Sustainable Transport Investment Plan, COM(2025) 664 final, Brussels, 5 November 2025.

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.

Deployment at scale will also require sufficient European shipyard and ship repair yard capacity, manufacturing and installation capability, specialized supplier networks, and maintenance and lifecycle service capacity for retrofit technologies. Standardised and repeatable retrofit packages can reduce engineering effort, installation time, cost and approval uncertainty across similar vessel classes.

Digital engineering, lifecycle digital twins, model-based design and virtual integration and testing should increasingly support retrofit planning. These approaches can help identify space, stability, structural energy and system integration constraints before physical installation and provide evidence supporting design optimisation, approval and certification.

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 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.[86]

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.[87]

5.4. BULK/TRAMP SHIPPING: DEDICATED DEPLOYMENT CONDITIONS

Bulk/tramp ocean-going shipping requires 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 level, around 90% of shipping companies control fewer than ten vessels.[88] 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.[89]

Cooperative or pooled approaches to procurement, retrofit contracting, fuel purchasing and technical services may also help smaller operators achieve scale and reduce transaction costs.

Second, coordinated international action is required to secure sufficient sustainable alternative 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.

86 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.
87 BIMCO, ETS – Emission Trading Scheme Allowances Clause for Time Charter Parties 2022; BIMCO, FuelEU Maritime Clause for Time Charter Parties 2024.
88 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.
89 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

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.[91]

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. 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 ocean-going shipping, even though vessels operate globally. Major European and global ports should evolve into multi-fuel, electrified, digital and secure maritime energy hubs. They should provide sustainable alternative fuel bunkering, shore-side electricity where relevant, safe handling and storage infrastructure, emergency-response capacity, digital reporting interfaces, cybersecurity, emissions monitoring and circularity services.

For new fuels and onboard carbon capture pathways, port readiness should also include safe transfer, temporary storage and onward handling of captured CO_2 and other associated materials.

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.

Vessel-port interfaces for sustainable alternative fuels, electrical systems, digital reporting and emergency response should be standardised where possible to enable scalable deployment across multiple ports and vessel types.

Port deployment should also account for global competitiveness and carbon-leakage risks. If sustainable alternative 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.

91 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

5.6. FINANCE, MARKET FORMATION AND DEMAND AGGREGATION

Ocean-going shipping requires major investment in new vessels, retrofits, sustainable 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.

Investment decisions should be supported by consistent business case assessment methodologies covering total cost of ownership, lifecycle emissions, operational performance, fuel price and availability risks, technology maturity, retrofit downtime and residual value implications. Where benefits and costs fall on different actors, contractual and financial models should support appropriate risk and benefit sharing among owners, charterers, cargo interests, fuel suppliers and financiers.

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 therefore supports alignment between IMO, EU and national frameworks to avoid duplication, double payment and fragmented compliance.

Priority standardisation areas include lifecycle emission accounting, sustainable alternative fuel certification, bunkering procedures, fuel quality, verified methane-slip measurement and mitigation, ammonia and methanol safety, hydrogen-derived fuels, lifecycle accounting and safe handling and offloading for 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. For prospective nuclear propulsion pathways, further assessment will additionally require coordinated regulatory, safety, security, certification, liability, insurance, emergency response and port and coastal state acceptance frameworks before any potential deployment can be considered. 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.

Representative scale test environments and operational demonstrations should generate robust safety evidence under realistic vessel and voyage conditions, including compound failures and situations where external assistance may be delayed.

Where appropriate, validated safety evidence and reusable safety case elements should support more consistent approval across vessel applications, classification societies and flag administrations, while maintaining the responsibility of the competent approving authority.

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.

Interoperability should also extend to safety-critical vessel-to-vessel, vessel-to-shore and vessel-to-port communications, including collision avoidance, navigational safety and emergency information exchange.

For globally operating vessels, deployment will also depend on reliable and resilient communications connectivity across ocean going routes, including the capability to maintain essential functions under degraded or intermittent connectivity.

International interoperability and progressive coordination of maritime traffic, navigation and information management systems should support safe and efficient vessel-to-vessel, vessel-to-shore and vessel-to-port operations.

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.

Common equipment and data models should support integration across vessel systems and between vessels, ports and shore-based actors. Digital certification and remote inspection should also be enabled where technically mature and accepted by the competent authorities.

AI-supported systems should be deployed within appropriate governance, validation and human oversight frameworks, particularly where they influence safety-critical or compliance-related decisions.

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 sustainable 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.

Competence and training requirements should evolve in alignment with applicable IMO/STCW frameworks and relevant interim or future guidance for alternative fuels, digitalization, automation and remote operations.

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 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. It should also track retrofit and installation capacity, approval and integration times, representative scale safety validation, operational availability and recovery performance, and the uptake of interoperable digital systems. 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

6. EXPECTED IMPACTS

The implementation of this roadmap supports 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 alternative fuels, bunkering infrastructure, safety standards, digital systems, financing mechanisms, port readiness and international cooperation. Impacts should therefore be assessed across environmental, technological and operational, economic and industrial, safety and resilience, and workforce dimensions, and differentiated between the 2035, 2040 and 2050 horizons.

Impact dimension	2035 – Early deployment	2040 – Scale-up and integration	2050 – Full transformation
Climate and environmental	Measurable reductions in fuel use and lifecycle-GHG intensity through energy efficiency, operational optimisation and initial commercial deployment of sustainable alternative fuels. For vessels and voyages within FuelEU Maritime scope, the applicable 2035 GHG-intensity requirement provides a regulatory reference point.	Significant lifecycle-GHG reductions through broader deployment of sustainable alternative fuels, energy-saving technologies, wind-assisted propulsion and, where appropriate, onboard carbon capture.	Climate neutral ocean-going shipping operating at scale, with very low lifecycle GHG emissions and substantially reduced air pollutants.
Technology and operations	Commercial sustainable alternative fuel and hybrid vessels on selected routes; validated and increasingly bankable retrofit packages; verified energy efficiency performance; digital twins, predictive maintenance and AI-supported optimisation increasingly deployed.	Industrial scale retrofits; mature multi-fuel and modular vessel architectures; interoperable ship-port-logistics digital systems; broader remote technical support and automated compliance.	Mature zero-/net-zero propulsion, globally interoperable digital ecosystems, lifecycle digital management and resilient highly automated operations with human oversight.

Table 6: Expected Impacts

Impact dimension	2035 – Early deployment	2040 – Scale-up and integration	2050 – Full transformation
Economic and industrial	Growing demand for European retrofit engineering, propulsion, energy-efficiency, safety and digital technologies; reduced technical and investment risk for early adopters.	Expanded shipyard/retrofit capacity and manufacturing capability; reduced integration and approval time; stronger European supply chains and technology competitiveness.	Sustained European leadership in high value maritime technologies and services, supported by resilient and diversified supply chains and global deployment capacity.
Safety, security and resilience	Representative safety validation and reusable evidence for sustainable alternative fuels, batteries, hybrid systems, onboard carbon capture and increasingly automated functions; improving cyber resilience.	Integrated predictive safety, vessel-port-bunkering emergency response and cyber resilient architectures; reduced operational downtime and faster recovery from disruptions.	Improved safety relative to conventional operations; continuous safety assurance and resilient operations under technical, cyber, fuel supply and other major disruptions.
Workforce and social	Competence frameworks and training scaled for personnel in relevant sustainable alternative fuel, hybrid, digital and safety-critical roles.	Continuous upskilling and advanced human machine teaming integrated into normal operations; improved support for crews through digital and remote assistance.	Continuous competence development embedded across relevant maritime professions, with human-centred automation, safe working conditions and attractive technology-oriented career pathways.

Table 6: Expected Impacts

The first expected impact is a substantial reduction in greenhouse-gas emissions and air pollutants from ocean-going 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 reduces emissions across container ships, bulk carriers, tankers, gas carriers and other ocean-going cargo vessels. In the short and medium term, energy efficiency measures are particularly important, where zero-emission fuels may not yet be globally available, affordable or technically mature at scale. Progress will be assessed through lifecycle-GHG and energy-intensity indicators rather than fuel choice alone. Where regulatory GHG-intensity milestones are referenced, including those under FuelEU Maritime, they should be clearly scoped to the vessels, voyages and energy use covered by the relevant regulation rather than presented as absolute global-fleet emission reductions.

A second impact is the creation of demand for sustainable marine fuels and the acceleration of fuel supply chains serving ocean-going shipping. Implementation of the roadmap aggregates demand across structured liner routes, green shipping corridors, major bunkering hubs and, where possible, bulk/tramp operations. This supports investment in advanced biofuels, e-fuels, methanol, ethanol, ammonia, biomethane, e-methane and other certified renewable or low-carbon fuels. It also addresses 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. Success is also reflected in increasingly diversified fuel supply chains, internationally interoperable sustainability and lifecycle certification, and reduced dependence on individual fuel pathways or geographically concentrated supply sources.

Implementation of the roadmap will strengthen European industrial competitiveness and technology leadership. Fleet renewal, retrofitting and fuel-system deployment will 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 reinforces Europe's influence over global maritime technology and standards. Industrial impact should also be measured through the ability to scale deployment: availability of retrofit and installation capacity, repeatable retrofit packages, manufacturing and supplier capacity, reduced integration and approval times, and the ability of European value chains to support lifecycle maintenance and future upgrades.

A further 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 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 reduce the risk that decarbonisation favours only the largest operators. Progress should be assessed not only by the availability of such instruments, but also by their actual accessibility and uptake among smaller operators.

The roadmap improves the role of ports and bunkering hubs in global maritime decarbonisation. Major European ports and partner ports outside Europe 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 sustainable 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 will support safe deployment. These measures reduce uncertainty for first movers and improve confidence among shipowners, charterers, crews, ports, insurers and regulators. Impact will also be reflected in more efficient and predictable safety approval, wider availability of validated and transferable safety evidence, improved incident-response and recovery performance, reduced unplanned downtime and greater operational continuity under technical, environmental and cyber disruptions. For deep-sea operations, this includes preparedness for incidents where external firefighting, medical or technical assistance may be delayed.

Digitalisation will 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 reduces duplication and administrative burden. If implemented well, digitalisation improves fuel efficiency, reduces waiting time, supports virtual arrival, strengthens cyber-secure ship-shore communication and makes emissions performance more transparent for cargo owners and regulators. Impacts include improved vessel availability and maintenance efficiency through predictive maintenance and remote diagnostics, reduced administrative effort through automated and interoperable reporting, and stronger European capability in maritime digital technologies and services.

The implementation of the roadmap strengthens 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 reduces 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. By 2050, resilience is also reflected in the capacity of ocean-going shipping and its supporting systems to maintain critical functions under major fuel-supply, cyber, infrastructure or geopolitical disruptions, recognising that continuity of individual trade routes cannot always be guaranteed.

Workforce and skills impacts will be substantial. The transition requires new competences among seafarers, shore-based operators, port personnel, emergency responders, surveyors, shipyard workers, fuel suppliers and digital service providers. Training in sustainable 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 improves safety and supports the attractiveness of maritime professions. Simulation, XR, digital twins and harmonised competence frameworks will help prepare crews and shore personnel before large scale deployment. Progress should be measured through competence coverage of personnel in relevant roles and the availability of continuous upskilling, rather than through a blanket numerical target for the entire maritime workforce.

Finally, the roadmap generates 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. Additional indicators should include retrofit and industrial deployment capacity, integration and approval time, operational availability and downtime, representative scale safety validation and recovery performance, uptake of interoperable digital systems, and competence coverage for personnel in relevant roles. Where possible, indicators should be defined against transparent and periodically updated baselines. The results will 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.

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