Technology Roadmap

Competitive, resilient and sustainable port ecosystems

Contents

1. Description of the Sector

1.1 Definition and scope

Port ecosystems comprise the physical infrastructure, operational actors, digital systems, energy interfaces, logistics services and governance arrangements through which ports connect waterborne transport with the European economy, hinterland networks, industrial clusters, cities, regions and global supply chains. They include seaports, inland ports and mixed ports, together with port authorities, terminal operators, tug operators, maritime pilots, bunkering and port reception-facility providers,logistics and hinterland operators, public authorities, customs and security actors, digital-service providers, port equipment and technology manufacturers, industrial users and urban or regional stakeholders[1].

The trans-European transport network includes 283 seaports, 223 inland ports and 44 mixed ports[2]. For the purposes of this roadmap, port ecosystems are addressed as system nodes in European waterborne, energy and logistics networks. The roadmap covers port-side infrastructure, terminal operations, shore power, vessel charging, alternative-fuel bunkering and handling, digital and data systems, multimodal integration, resilience, security, circularity, workforce transformation and port-city or port-region integration.

Vessel propulsion, onboard systems and vessel-specific technologies are addressed in the relevant vessel roadmaps. However, port-vessel interfaces are included where they determine the deployment of onshore power supply, charging, sustainable alternative fuel bunkering, safety procedures, digital reporting, berth planning and operational coordination.

Because European ports differ substantially in size, function, governance model, traffic profile, hinterland role, energy function, digital maturity and investment capacity, a single uniform deployment model is not appropriate. The roadmap therefore defines common technology pathways, while recognising that capability development must be differentiated across large gateway and transhipment hubs, core TEN-T ports, comprehensive and regional ports, small and medium-sized ports, island and outermost-region ports, inland and mixed ports, and energy-industrial ports.

These port types face different deployment conditions. Large gateways and energy-industrial ports can act as reference sites for automation, multi-energy supply, digital twins, cybersecurity and industrial integration. Core TEN-T ports are central to compliance-driven deployment[3] of shore power, sustainable alternative fuel infrastructure and corridor interoperability. Comprehensive, regional, small, island, inland and mixed ports require modular, affordable and scalable solutions adapted to their traffic, grid capacity, investment capacity, hinterland role and territorial function[4].

The roadmap treats ports as multifunctional ecosystems whose transformation depends on the coordinated development of clean energy, digitalisation, automation, resilience, safety, security, multimodal integration, skills, finance, governance and the European technology-supply base.

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[1] 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, p. 1.
[2] EU Ports Strategy, COM(2026) 112 final, p. 1.
[3] European Commission, *Annex II: List of Nodes of the Trans-European Transport Network* (Brussels: European Commission, 2023), https://transport.ec.europa.eu/document/download/91a49a1e-d350-4295-84e3-3f67038fefcc_en?filename=TEN-T-revision-2023-annex-2.pdf. [transport.....europa.eu]
[4] EU Ports Strategy, COM(2026) 112 final, p. 1.

1.2 Strategic role in the European economy and energy system

European ports are strategic gateways between the internal market, global trade and the wider waterborne transport system. EU ports handle more than 3.4 billion tonnes of goods, around 74% of goods entering or leaving Europe, and around 395 million passengers each year. They record almost 3 million port calls, corresponding to around 23% of the world total, and generate an economic footprint of around EUR 90 billion in turnover and approximately 423,000 direct jobs[5].

Ports provide critical links between maritime transport, inland waterways, rail, road, pipelines, logistics centres, industrial clusters and energy networks. Their performance is therefore directly connected to European competitiveness, supply-chain resilience, territorial cohesion and strategic autonomy. They are particularly important for islands, outermost regions and remote areas, where port connectivity is often essential for passengers, goods, energy supply and basic services.

Ports are also becoming central nodes in the energy transition. Around 40% of commodities handled in EU ports are energy-related[6], and ports are the shore-side interface for onshore power supply, vessel charging, sustainable alternative-fuel bunkering, renewable-energy flows, offshore wind deployment, hydrogen and hydrogen-derived fuels, CO_2 logistics, circular material flows and industrial decarbonisation. The transition away from fossil fuels is therefore changing both port traffic and port infrastructure needs.

The Strategic Research Agenda assigns ports the role of system nodes that enable the energy transition, promote modal shift, advance decarbonisation and support military mobility.[7]

1.3 Traffic and performance

European port traffic provides the operational baseline for the roadmap. Aggregate EU-27 port traffic is stable to declining in tonnage, marginally increasing in container volumes, and broadly recovered in passenger movements after the pandemic. EU-27 ports handled 3,355.9 million tonnes of goods in 2024, below the 2019 level of 3,582.6 million tonnes[8]. Container throughput reached 100.9 million TEU in 2024, above the 2019 level of 97.8 million TEU[9]. Passenger traffic recovered to 417.8 million passengers in 2024, close to the 2019 level of 418.2 million passengers[10].

Table 1. EU-27 port traffic, 2019–2024

Metric (EU-27)	2019	2020	2021	2022	2023	2024	Trend
Goods handled (million tonnes)	3 582.6	3 315.8	3 453.0	3 512.1	3 363.3	3 355.9	declining, −6.3%
Containers (million TEU)	97.8	95.5	99.8	96.6	96.7	100.9	flat to up, +3.2%
Passengers (million)	418.2	230.2	267.9	373.6	393.5	417.8	recovered, −0.1%

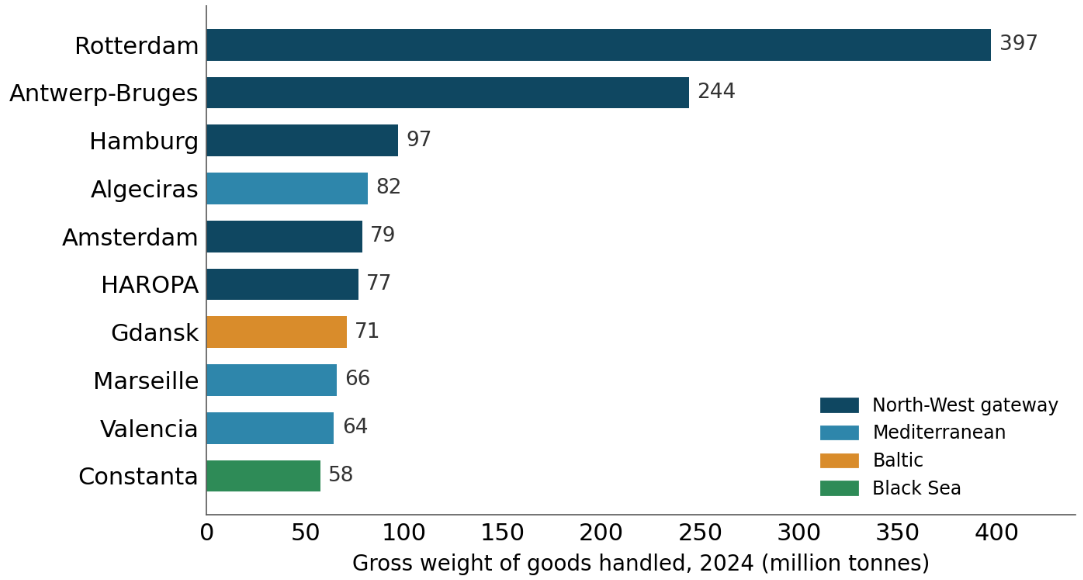
Source: Eurostat, online data codes mar_mg_aa_cwh, mar_mg_am_cvh and mar_mp_aa_cph, extracted 30 June 2026.

Traffic is highly concentrated in a relatively small number of gateway ports, as shown in Figure 1 and Table 2. Rotterdam handled 397.3 million tonnes in 2024, followed by Antwerp-Bruges at 244.2 million tonnes[11]. The top

[5] EU Ports Strategy, COM(2026) 112 final, p. 1.
[6] EU Ports Strategy, COM(2026) 112 final, p. 7.
[7] Strategic Research Agenda (June 2025), p. 16.
[8] Eurostat, gross weight of goods handled in all ports, online data code mar_mg_aa_cwh, extracted 30 June 2026, reference year 2024.
[9] Eurostat, volume of containers handled in main ports by loading status, online data code mar_mg_am_cvh, extracted 30 June 2026, reference year 2024.
[10] Eurostat, passengers embarked and disembarked in all ports, online data code mar_mp_aa_cph, extracted 30 June 2026, reference year 2024.
[11] Eurostat, gross weight of goods handled in the top 20 EU ports by direction, online data code mar_mg_aa_pwhd, extracted 30 June 2026, reference year 2024.

20 ports account for about 80% of EU container throughput, with Rotterdam and Antwerp-Bruges handling 13.4 and 12.4 million TEU respectively in 2024[12].

Figure 1. Busiest EU ports by gross tonnage handled, 2024



Source: Eurostat, online data code mar_mg_aa_cwh; port ranking mar_mg_aa_pwhd, extracted 30 June 2026.

At the same time, port activity is redistributing across sea basins. North-West gateway ports have eased compared with 2019, while selected Baltic, Black Sea and Mediterranean transhipment ports have grown[13]. As shown in Table 2 and Figure 2, Gdansk, Constanta and Gioia Tauro recorded strong increases, while Riga, Klaipeda, Amsterdam, Piraeus and Hamburg declined. These shifts reflect changes in trade geography, geopolitical disruption, energy flows and corridor dynamics.

Table 2. Performance of leading EU ports, 2019 and 2024

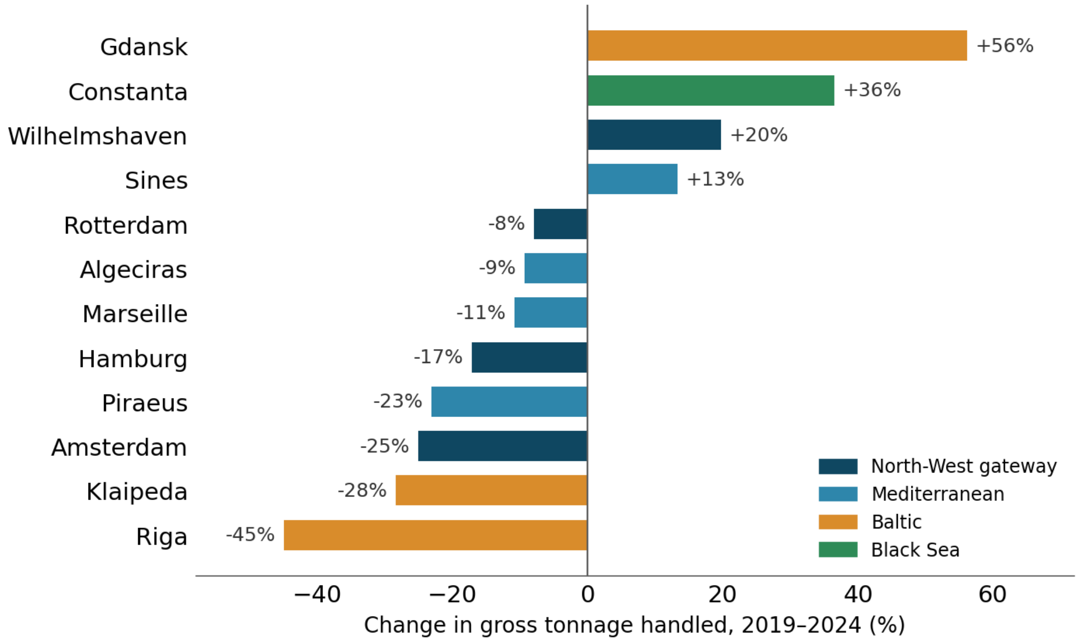
Port	2019 (Mt)	2024 (Mt)	Δ %	2024 (000 TEU)	Signal
Rotterdam	431.8	397.3	−8.0	13 354	NW gateway easing
Antwerp-Bruges *	243.0	244.2	+0.5	12 418	stable
Hamburg	117.2	97.0	−17.2	7 828	NW gateway decline
Amsterdam	105.2	78.8	−25.1	–	NW gateway decline
Algeciras	89.9	81.5	−9.3	5 366	Med gateway
HAROPA †	–	76.7	–	3 102	merger break
Gdansk	45.5	71.0	+56.1	2 051	Baltic growth
Constanta	42.2	57.6	+36.5	963	Black Sea growth
Piraeus	56.8	43.7	−23.1	4 677	Med gateway decline
Gioia Tauro	22.7	38.5	+69.7	5 813	Med transhipment
Klaipeda	42.7	30.6	−28.4	1 070	lost transit
Riga	30.6	16.9	−45.0	–	lost transit

*Sources: Eurostat, online data codes mar_mg_aa_pwhd (gross tonnage) and mar_mg_am_pvh (containers), extracted 30 June 2026. * 2019 combines Antwerp and Zeebrugge, merged from 2022. † 2019 reports Le Havre only; the Rouen component is not separable and the change is not computed.*

Figure 2. Change in gross tonnage handled by leading EU ports, 2019–2024

[12] Eurostat, volume of containers handled in the top 20 EU main ports by loading status, online data code mar_mg_am_pvh, extracted 30 June 2026, reference year 2024.

[13] Eurostat, mar_mg_aa_pwhd, extracted 30 June 2026, reference year 2024.



Source: Eurostat, online data code mar_mg_aa_pwhd, extracted 30 June 2026.

These trends confirm that port technology deployment cannot be based only on historical traffic volumes and that ports must be able to respond to changing trade geography, energy transition, geopolitical disruption, modal-shift objectives, climate impacts and security risks.

1.4 Infrastructure and technological capacity

The existing technological and energy infrastructure base in European ports is uneven and concentrated. Onshore power supply, LNG bunkering, digital platforms, sustainable alternative-fuel projects, automation and resilience measures are advancing, but deployment differs significantly by port size, network status, traffic profile, governance model and investment capacity. This is the starting point for the technology pathways in Chapter 4.

Table 3. Alternative-fuels port infrastructure, EU-27 (2023)

Indicator	EU-27
Onshore power supply — ports equipped	58 (34 Core, 23 Comprehensive)
Onshore power supply — installations	99
Onshore power supply — equipped berths	435 (356 Core / 78 Comprehensive)
Onshore power supply — berths by voltage	low 276 / high 101 / mixed 6 / not stated 52
LNG bunkering — ports	44
LNG bunkering — facilities	61
LNG bunkering — by method	port-to-ship 21 / ship-to-ship 18 / truck-to-ship 18 / other 4

Source: European Alternative Fuels Observatory, Maritime infrastructure portal, 2023 dataset, extracted 30 June 2026. Counts cover EU-27 ports only; European Economic Area ports are excluded. Figures are installed-base counts and are not merged with the survey shares reported by ESPO, which measure a different universe.

As shown in Table 3, onshore power supply is present at 58 EU-27 ports across 99 installations and 435 equipped berths. Of these berths, 276 are low voltage and 101 are high voltage, while 356 are located at Core network ports[14]. LNG bunkering is available at 44 ports across 61 facilities. Survey evidence from European ports is consistent with this picture: shore-side electricity is increasingly present, but often concentrated in low-voltage installations[15], while high-voltage supply for larger vessels remains limited.

[14] European Alternative Fuels Observatory (EAFO), Maritime infrastructure portal: onshore power supply and LNG bunkering installations, extracted 30 June 2026, 2023 dataset.
[15] European Sea Ports Organisation, Environmental Report 2025 – EcoPortsinSights 2025 (Brussels: ESPO, October 2025), pp. 22–23.

The infrastructure baseline indicates that ports are moving towards shore-side energy provision, digitalisation and resilience, but that deployment remains uneven and far from the scale required for the transition. This creates cross-cutting requirements for the roadmap: scalable energy infrastructure, interoperable digital systems and resilience-by-design across port operations, energy systems and hinterland connections.

1.5 The technology-leadership opportunity

European ports have a major technology-leadership opportunity in the transition from infrastructure providers to system orchestrators. Future port competitiveness will depend on the capacity to integrate clean energy, smart logistics, automation, digital platforms, security, resilience, circularity and workforce transformation into coherent port ecosystems. Ports will increasingly compete not only on location and capacity, but also on energy readiness, data connectivity, operational reliability, climate resilience and integration with zero-emission maritime and hinterland transport chains.

The Technology Leadership framework sets the vision of fully integrated, zero-emission, digitally enabled and climate-resilient port ecosystems at the heart of global supply chains and the energy transition[16]. The Strategic Research Agenda identifies the corresponding port infrastructure mission: bunkering and shore-power supply, smart port communication and information systems, and city-port-nature planning[17].

Industry associations, standardisation bodies and collaborative platforms are also part of this technology-leadership capacity. Organisations such as ESPO, EFIP, FEPORT, PEMA, TIC4.0, PIANC, IAPH and relevant ISO technical committees contribute to common terminology, data models, operational standards, interoperability frameworks and deployment practices, particularly in areas such as terminal digitalisation, automation, data exchange, port-vessel interfaces and multimodal integration.

This opportunity spans clean energy provision, zero-emission port operations, smart logistics, automation, resilience, cyber-secure systems, circularity and port-based industrial integration. The roadmap builds on this opportunity by defining the capabilities, technology pathways, enablers and deployment conditions needed to move from isolated projects towards integrated, interoperable and resilient port ecosystems.

2. Drivers and Constraints

The transformation of European port ecosystems is driven by a combination of regulatory, market, technological, environmental, security and territorial factors. These drivers interact with structural constraints that determine the speed, cost and unevenness of deployment across different port types.

2.1 Main drivers

- **Climate neutrality and decarbonisation:** The European Climate Law establishes a 2030 target of at least a 55% net reduction in greenhouse gas emissions relative to 1990, a 2040 milestone of a 90% net reduction, and climate neutrality by 2050. Ports are implicated as emission sources, as enablers of vessel decarbonisation, and as energy nodes. The target framework fixes the long-term horizon for port electrification, alternative-fuel supply and infrastructure renewal.[18]

[16] Waterborne Technology Platform, Waterborne Technology Leadership (Brussels: Waterborne TP, January 2026), p. 21.
[17] Strategic Research Agenda (June 2025), p. 18.
[18] Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 establishing the framework for achieving climate neutrality (European Climate Law), OJ L 243, 9 July 2021, Arts. 2 and 4 (climate neutrality by 2050; 2030 target of at least a 55% net reduction relative to 1990); complemented by the 2040 target of a 90% net reduction relative to 1990 adopted as an amendment to that Regulation (Council, March 2026). L

- **Maritime fuel and infrastructure regulation:** FuelEU Maritime, the extension of the EU Emissions Trading System to maritime transport[19] and the Alternative Fuels Infrastructure Regulation[20] create direct demand for shore-side electricity, low-carbon fuels, energy-efficiency measures and compliant port-vessel interfaces. The requirement for larger containerships and passenger ships to use onshore power supply at quay from 2030 makes the berth a critical compliance point[21].
- **Port competitiveness and changing trade geography**: Ports must respond to shifting cargo flows, supply-chain restructuring, geopolitical disruption, changing energy imports and evolving corridor dynamics[22]. Competitiveness will increasingly depend not only on location and capacity, but also on energy readiness, digital connectivity, reliability, resilience, hinterland integration and the ability to support low-emission logistics chains.
- **Energy-system transformation**: Ports are becoming energy nodes linking shore power, vessel charging, sustainable alternative-fuel bunkering, renewable-energy flows, offshore wind, hydrogen and hydrogen-derived fuels, CO_2 logistics, circular material flows and industrial decarbonisation. This changes port infrastructure needs, land-use priorities, business models and the relationship between ports, energy providers and industrial clusters.
- **Digitalisation, automation and data-driven logistics**: Port performance increasingly depends on interoperable digital systems, port community platforms, terminal operating systems, digital twins, AI-enabled planning, zero-emission and automated equipment and trusted data exchange with vessels, authorities and hinterland networks. Digitalisation is therefore a competitiveness driver, but also a condition for resilience, safety, energy optimisation and multimodal integration.
- **Security, resilience and military mobility**: Ports face growing exposure to cyber threats, hybrid risks, organised crime, sabotage, terrorism, drones, underwater threats, energy disruption and climate-related events. Their role in supply chains, energy systems and military mobility makes security and resilience core design requirements for future port systems. note 26: EU Ports Strategy, COM(2026) 112 final, pp. 10–15]
- **Industrial strategy and circular economy**: Ports provide the physical base for ship repair, maintenance, retrofitting, recycling, offshore energy, renewable fuels, carbon management and circular value chains. Port-based industrial capacity is therefore linked to European competitiveness, strategic autonomy, decarbonisation and the development of new maritime and energy value chains.
- **Territorial cohesion and connectivity**: Ports are essential for islands, outermost regions, inland regions and remote territories[23]. In these contexts, port transformation must preserve affordable connectivity, passenger and freight continuity, energy supply and access to essential services. This requires deployment models that are proportionate to traffic demand, grid capacity and local investment capacity.

2.2 Constraints and deployment challenges

The drivers meet structural constraints that determine the speed, cost and unevenness of deployment across European ports.

- **Grid capacity and electrification:** Electricity demand in ports is rising faster than available grid capacity, and connection is constrained by missing physical connections, substation limits and frequency conversion.[24] Onshore power supply reaches 62% of surveyed European seaports, concentrated in low-voltage installations while high-voltage supply for larger ships remains scarce.[25] Electrification depends on grid reinforcement, smart-grid and non-wire solutions and demand management, in particular for small and medium ports.

[19] 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 (inclusion of maritime transport), OJ L 130, 16 May 2023.
[20] Regulation (EU) 2023/1804 of the European Parliament and of the Council of 13 September 2023 on the deployment of alternative fuels infrastructure and repealing Directive 2014/94/EU (AFIR), OJ L 234, 22 September 2023, Art. 9.
[21] 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, Arts. 4 and 6.
[22] EU Ports Strategy, COM(2026) 112 final, p. 1.
[23] EU Ports Strategy, COM(2026) 112 final, p. 1.
[24] EU Ports Strategy, COM(2026) 112 final, p. 7.
[25] ESPO, Environmental Report 2025, pp. 22–23.

- **Sustainable alternative fuel readiness and bunkering safety:** Hydrogen, ammonia and methanol bunkering require harmonised safety standards, operational procedures and reception facilities that are not yet established at scale; liquefied natural gas bunkering is offered by 51% of surveyed ports, while hydrogen, ammonia and methanol projects remain at 43%, 16% and 14% respectively.[26] Multi-fuel and retrofit infrastructure is required, certain fuels may be restricted at specific ports for safety reasons, and the transition changes hazardous-waste streams and reception requirements.
- **Climate resilience and physical exposure:** Ports face rising sea levels, storm surge, heat stress and changing navigation conditions that threaten fixed assets and operational continuity. Operational disruption from climate change is reported by 69% of surveyed European ports, while 77% are reinforcing existing infrastructure and 86% integrate adaptation into new development.[27]Regional conditions diverge, with winter navigation constraints in the north and heat-stress conditions in the south.[28] Adaptation must be embedded in asset design and port planning given long infrastructure lead-times
- **Heterogeneity, small ports and insularity:** The diversity of ports in size, location, market segment and governance prevents a single technology pathway. Inland, island and small-market ports combine low investment capacity, weak grid connections and higher energy costs, which the energy transition intensifies.[29] Regional conditions diverge, with winter navigation constraints in the north and heat-stress conditions in the south.[30] Solutions must be modular, scalable and affordable rather than uniform.
- **Spatial competition and environmental permitting:** Port development competes with urban and environmental uses for limited land and water space, and the energy transition adds demand for generation, storage and industrial areas.[31] Climate change, air quality and energy efficiency are the three highest-ranked environmental priorities of European ports, and stricter air-quality and water-quality requirements raise the compliance and permitting burden.
- **Digital fragmentation and data sovereignty:** Port community systems, terminal systems and national reporting environments are insufficiently interoperable, and data standardisation across the logistics chain is low. Secure data sharing among operators and with customs and other authorities requires common semantic models and data-sovereignty safeguards. Fragmentation limits real-time optimisation and the deployment of digital twins.
- **Security and cyber-physical exposure:** Increasing automation and connectivity enlarge the cyber-attack surface of port operations and energy systems. Critical infrastructure, including underwater assets, is exposed to sabotage and hybrid threats. Resilience must be designed into system architecture rather than added afterwards.
- **Investment and financing:** Estimated investment needs for European ports reach around EUR 80 billion, against EU support of approximately EUR 10 billion for deployment and more than EUR 200 million for research and innovation since 2014.[32] Funding bottlenecks include access to secure finance, rising costs and lengthy permitting. Closing the gap requires a mix of EU, national and private funding with de-risking instruments.
- **Skills and workforce transition:** Port personnel require new competences in electrification, sustainable alternative fuels, automation, artificial intelligence and cyber security. New operational roles and organisational models are needed to support human oversight of automated systems.

2.3 Implications for roadmap design

The roadmap is organised around deployable capabilities at the level of the port as a system node. The decisive question is whether a port, its energy suppliers, terminal operators, logistics actors and authorities can deliver zero-emission energy services, smart logistics and resilient operations safely and at acceptable cost. Capability development is differentiated by port typology, because grid access, fuel demand, digital maturity and financing capacity differ across port categories. Energy demand is aggregated and planned at

[26] ESPO, Environmental Report 2025, pp. 24–25.
[27] European Sea Ports Organisation, Environmental Report 2025 – EcoPortsinSights 2025 (Brussels: ESPO, October 2025), pp. 16–17.
[28] Strategic Research Agenda (June 2025), p. 14.
[29] OECD, Policy Pathways Beyond the Shoreline (2025).
[30] Strategic Research Agenda (June 2025), p. 14.
[31] ESPO, Environmental Report 2025, pp. 20–21.
[32] EU Ports Strategy, COM(2026) 112 final, p. 15.

port-system and corridor level, data systems are interoperable by design, and financing is structured for operators of all sizes.

3. Target Capabilities

3.1 Current state of play and achieved developments

The target capabilities build on the current state of technology, regulation and deployment, and on the mission set for ports in the Strategic Research Agenda, which requires ports to evolve from infrastructure providers into system orchestrators delivering resilient, zero-emission services by 2050.[33] Onshore power supply is available at one or more berths in 62% of surveyed European seaports, predominantly at low voltage, while high-voltage supply for container, passenger and cruise vessels remains limited.[34] Liquefied natural gas bunkering is offered by 51% of surveyed ports, and next-generation fuel projects are under development for hydrogen (43%), biofuels (28%), ammonia (16%) and methanol or methane (14%).[35] Climate adaptation is advancing: 69% of surveyed ports report operational disruption from climate change, 77% are reinforcing existing infrastructure and 86% integrate adaptation into new development.[36] Regulation sets the near-term anchor, with onshore power supply required for larger container and passenger ships at TEN-T maritime ports by 2030.[37] Deployment remains uneven across sea basins, port sizes and governance models, and mature solutions still require port-scale validation and integrated safety cases.

3.2 2035 – Smart and clean foundations

By 2035, European ports should have established smart and clean operational foundations.[38] Shore power, electric-ship charging, electrified equipment and energy-efficient terminal operations should be widely deployed and planned against port-wide electricity demand. Operational procedures for hydrogen, ammonia and methanol bunkering should be in widespread use, alongside CO_2 handling systems and early procedures for nuclear-powered vessels. Harmonised data procedures should enable exchange between European port stakeholders, and port digital twins and AI-enabled traffic coordination should be in initial deployment across terminal clusters. Autonomous vessel-traffic coordination should be integrated with port digital platforms, integrated cybersecurity platforms should be rolled out, and adaptive and nature-based port infrastructure should be demonstrated. Digital and alternative-fuel training programmes for port operators should be introduced.

3.3 2040 – System integration and large-scale automation

By 2040, ports should achieve system integration and large-scale automation.[39] Electrification and zero-emission core port operations should be near complete, supported by consolidated multi-energy hubs supplying sustainable alternative fuels, green electricity and hydrogen-based products, specified to each port's needs. Logistics platforms should be fully integrated, linking vessels, terminals, hinterland corridors and energy networks, and protocols for autonomous vessel operations should be harmonised. Mature automation and robotics should be deployed in container handling, inspection, maintenance and security operations, and resilient and adaptive port-infrastructure models should be in place across Europe's main corridors. Workforce transformation should be supported by digital control rooms, advanced simulation training and new operational roles.

[33] Strategic Research Agenda (June 2025), p. 16.
[34] ESPO, Environmental Report 2025, pp. 22–23.
[35] ESPO, Environmental Report 2025, pp. 24–25.
[36] ESPO, Environmental Report 2025, pp. 16–17.
[37] AFIR, Regulation (EU) 2023/1804, Art. 9.
[38] Waterborne Technology Leadership (January 2026), p. 22.
[39] Waterborne Technology Leadership (January 2026), pp. 22–23.

3.4 2050 – Fully integrated, zero-emission, autonomous port ecosystems

By 2050, European ports should function as fully integrated, zero-emission and autonomous ecosystems.[40] Port ecosystems should be fully integrated into zero-emission logistics chains, with autonomous operations functioning safely across terminals, waterways and integrated logistics nodes. Ports should serve as central hubs for renewable-energy import and export, renewable fuels distribution and CO_2 management, and material flows should be fully circular, supported by advanced digital, reuse and recycling systems. Port systems should be highly resilient and cyber-secure, protecting critical waterborne and energy infrastructure. The Strategic Research Agenda sets the corresponding infrastructure end-state, with ports operating as Smart Ports and as hubs of sustainable alternative energy under city-port-nature planning.[41]

The capability model is differentiated by port typology. A small island port serving territorial-cohesion functions will not follow the same pathway as a large gateway hub integrating offshore-energy import, a core TEN-T port on a hydrogen corridor, or an energy-industrial port hosting circular value chains. Capability selection, funding design and the sequencing of infrastructure investment follow port size, network status, energy role, digital maturity and operator capacity.

4. Technology Pathways

4.1 Zero-emission port operations and clean energy integration

Zero-emission port operations require a systematic transformation of port energy systems, infrastructure and operations. Research and Innovation will be essential to enable the large-scale deployment of electrification, sustainable alternative fuels and renewable energy while ensuring reliability, safety, affordability, interoperability and operational resilience across diverse European port environments. Future RD&I and investment activities should therefore evolve beyond isolated infrastructure deployment and address integrated ecosystem-level coordination, enabling ports to evolve from (passive) energy consumers into active, intelligent and flexible nodes within decarbonised energy, industrial and logistics networks. The development of solutions enabling zero-emission port operations is requiring integrated solutions combining full electrification of equipment, shore-side power supply and high-capacity charging systems renewable energy systems, advanced storage systems, and smart grids and microgrid integration . Particular attention should be devoted to scalable infrastructure for hydrogen, ammonia, methanol, CO_2 logistics, offshore energy import/ export and multimodal energy exchange.

4.1.1 Operational objective(s)

Enable ports to provide reliable, safe, resilient and cost-efficient zero-emission energy services to vessels, terminal equipment, industry and hinterland operations by integrating shore-side electricity (OPS), sustainable alternative fuel bunkering and handling, multimodal charging infrastructure, on-site renewable generation and advanced energy management. This includes the capability to dynamically balance highly variable energy demand and supply while maintaining operational continuity and resilience.

4.1.2 Target capability 2035, 2040 and 2050

By 2035:

- Ports operate hybrid energy systems combining grid electricity, local renewable generation and energy storage, supporting widespread shore power use, initial fast-charging solutions for battery-electric and hybrid vessels.
- Advanced digital energy twins, underpinned by industry-backed standards. enable predictive optimisation of energy flows, maintenance and resilience.

[40] Waterborne Technology Leadership (January 2026), p. 23.
[41] Strategic Research Agenda (June 2025), p. 18.

- Energy governance models are deployed at port level to optimise energy demand, charging operations, bunkering coordination, and multimodal energy flows while reducing peak loads and operational inefficiencies.

By 2040:

- Ports achieve near-complete electrification and zero-emission core operations, supported by mature smart-grid integration, high-capacity charging infrastructure and multi-fuel energy hubs for hydrogen, ammonia and methanol and biofuels of residual origin. This should be specified to their needs, since not all ports will need to accommodate all energy carriers.
- Develop solutions for localised energy supply to meet local demand or to deal with net congestion. Plan of nuclear energy to be adopted in small-modular reactors

By 2050:

- Ports function as fully zero-emission and resilient energy and logistics ecosystems, seamlessly integrated into zero-emission maritime and hinterland transport chains.
- Energy systems operate autonomously and adaptively, balancing electricity, renewable fuels, energy storage and carbon management.

4.1.3 Required enablers

- Significant increase in grid capacity combined with advanced smart-grid technologies, microgrids, local flexibility markets, and non-wire solutions at port scale.
- Safety standards and operational guidelines for large-scale handling of sustainable alternative fuels for bunkering and battery systems. Most notably, regulations need to be developed for use of nuclear as a fuel.
- Harmonised standards for high-power shore-side electricity, fast charging for vessels and sustainable alternative fuel bunkering interfaces (vessel-port energy alignment). Standards are already developed for onshore power supply for most vessel types. What is currently lacking are standards for charging batteries onboard a vessel.
- Digital port energy management platforms enabling real-time and predictive coordination between vessels, terminals, other connected facilities and energy suppliers.
- Interoperable energy data models and APIs that cover OPS connection events, charging sessions, fuel bunkering operations, energy source, equipment consumption, emissions, location, time windows and operational status.
- Clarity on stakeholders' roles, governance responsibilities and business models related to supplying shore power. Solutions should be scalable, affordable, and modular rather than one-size-fits-all approaches.
- Skills development and new organizational models enabling ports to manage complex multi-energy systems.

4.1.4 Key research gaps

- Development of scalable electrification solutions. - Research is needed on modular, mobile and scalable Onshore Power Supply (OPS) systems that can be adapted to different berth types, vessel sizes and port layouts, including solutions suitable for small and medium-sized ports. Solutions should consider Onshore Power Supply for vessel outside of the currently regulated vessel categories, including different tanker segments and bulk carriers.
- Develop solutions for (fast) charging for (short sea) vessels with battery-electric propulsion - Development of ultra-fast, high-capacity charging systems for short-sea shipping and work vessels, addressing challenges related to grid impact, power electronics, standardization and battery degradation.

- Further development of smart/ intelligent grid solutions and energy storage integration - Further RD&I is required on intelligent energy management, combining batteries, hydrogen-based storage and thermal storage to manage peak loads, intermittency of renewables and operational flexibility at port scale.
- Ports and nuclear power (implications on space, security and operations) - EG rules of entry through rules on sailing on sustainable alternative fuels instead of through exemption rules.
- Vessel - port energy alignment and energy management. This requires communication and standard data interfaces between the energy management systems of the vessel and of the different stakeholders in the port (including port equipment, charging infrastructure for trucks and passenger cars and industry).
- Concepts for the demand and requirements of an energy bunkering vessel.
- System-level energy optimization and digital twins - Development of port-wide digital energy twins capable of simulating, predicting and optimizing energy demand, supply and infrastructure investment decisions under different traffic, weather and market scenarios.
- Development of multi-charging solutions, where charging equipment can be used for charging vessels but also other applications.
- Research into looking for a business model that is replicable for all ports that includes demand-side uncertainties.

- Developing sustainable alternative fuel bunkering infrastructure standards and safe and cost-efficient multi-fuel bunkering at EU ports, going beyond the state-of-play of the different available solutions. Focus lies on development of multi-use or retrofit infrastructure and implementation of solutions, especially for small and medium sized ports
- Harmonized standards and regulatory frameworks for multi-fuel bunkering, CO_2 handling and circular resource flows. Research on possibilities, challenges and opportunities of EU-wide clear guidelines for standards and regulatory frameworks.
- Solutions supporting and facilitating offloading and processing of Ship Based Carbon Capture. To go from technical pilots to real world operational demonstrators (integration of technology port operations and logistics processes) to scale up
  - Development of scalable and modular business models and market mechanisms - Innovation is required in energy-related business models, including energy-as-a-service, shared infrastructure, flexibility markets and collaborative investment schemes involving ports, energy providers and shipping companies
  - Resilience and cybersecurity of port energy systems - Research on resilient-by-design energy infrastructure, addressing cyber-physical risks, extreme weather events and cascading failures across interconnected energy and logistics systems. Research on needs for resilience-by-redundancy systems.

4.2 Smart, automated and data-driven logistics ecosystems

Intelligent, autonomous and data-driven logistics ecosystems will become a foundational pillar for the competitiveness, sustainability, resilience and strategic autonomy of future European port ecosystems. Research and innovation will be required to move beyond fragmented digital solutions, isolated automation pilots and siloed logistics optimisation towards fully integrated, interoperable and intelligent logistics systems spanning vessels, terminals, ports and hinterland corridors. Future R&I must therefore address not only technological development, but also system and process integration, trust, governance and the safe coexistence of human and automated operations. Advanced digital ecosystems enabling real-time optimisation of vessels, terminals, cargo flows and hinterland transport inside and between ports is pursued. R&I needs to concentrated on automation, robotics, sensor development, AI-enabled scheduling, predictive capacity management, and digital twins of port operations. Data sharing enables this. Data sharing must be seamless amongst logistics actors themselves, but also with customs and other authorities. Data sharing must also be secure. Data sovereignty is important to ensure data owners remain in control of how their data is accessed, used and processed by others.

4.2.1 Operational objective(s)

Enable ports to operate integrated, standardised and data-driven logistics ecosystems that allow real-time optimisation and coordination of vessels, terminals, cargo flows and hinterland transport, supported by automation, AI-enabled decision support and trusted data sharing across all relevant stakeholders, while maintaining safety, security and operational resilience.

4.2.2 Target capability 2035, 2040 and 2050

By 2035:

- There are developed plans and first operating pilots that lay the foundation of a scalable, standardised and interoperable digital ecosystem that enables secure data sharing between key European port stakeholders, including terminals, shipping lines, authorities and hinterland operators. Data security and sovereignty is ensured by design for all participants.
- Leveraging the digital ecosystem, there is an initial deployment of port community systems and digital twins that support maritime and hinterland traffic coordination, berth planning and terminal operations (including logistics information such as customs compliance and track and trace). Transport and port operations are tracked in real-time and incidences are automatically identified. AI-based decision support tools assist human operators in scheduling, ordering and rescheduling, congestion management, operational deviations and resources allocation.
- Deployment of autonomous vessel traffic coordination systems integrated with port digital ecosystems and innovation focused on large-scale operational pilots. These systems should incorporate solutions for mixed traffic which includes autonomous and manned vessels.
- Deployment of coordination of autonomous port handling equipment with systems integrated with autonomous and manned vessels and port digital ecosystems (including Terminal operating systems and Port Community Systems).

By 2040:

- Ports operate fully integrated logistics ecosystems linking maritime operations, terminal automation and hinterland corridors and energy networks. The number of participants to the digital ecosystem has increased significantly.
- Harmonised protocols for autonomous vessel operations, autonomous port handling equipment, autonomous trucks and autonomous trains.
- Deployment of mature automation and robotics in inspection, maintenance and security operations that integrates seamlessly with the digital ecosystem.
- Digital twins evolve into predictive and prescriptive tools, enabling proactive capacity management and disruption mitigation. Port digital twins are widely integrated and used by operators and port authorities.
- Research increasingly targets system-of-systems optimization, cross-port coordination and scalable deployment across European corridors.

By 2050:

- Port logistics ecosystems function with a high degree of physical and digital autonomy (autonomous port operations) supported by trusted AI systems coordinating MASS vessels, terminals and multimodal flows across regions.
- AI and autonomous systems run ports and logistics corridors on routine business while human operators supervise, intervene and optimize complex systems through advanced control rooms.
- Continuous learning systems adapt operations in real time, ensuring safe, efficient and resilient logistics chains under changing economic, environmental and geopolitical conditions.

4.2.3 Required enablers

- Easy onboarding to the digital ecosystem for all participants, including small and medium sized ports and businesses with lower digital maturity levels and investment capacity.
- Post-quantum cryptography and Privacy Enhancing Technologies (PET) to secure the digital ecosystem and all its participants from attacks. Data encryption must ensure safety of communication channels to make the logistics ecosystem resilient under cyberattacks that are targeting the performance of the sector. Privacy Enhancing Technologies (PET) are a prerequisite when sharing (sensitive) data amongst a larger number of parties to allow for digital twins, predictive modelling and optimisation.
- Harmonized, interoperable standards and digital tools to support the uptake of automation, especially for Small and Medium sized ports. A common digital foundation is essential to prevent isolated port systems and enable seamless interoperability.
- Many technologies are currently in the stage of a technical pilot. It is required to take the leap to real world operational demonstrators (integration of technology port operations and logistics processes) and to scale up.
- Digital infrastructure capable of supporting high-volume, low-latency data exchange through 5G/6G, edge computing technologies for fast, comprehensive data exchange.
- Aerial/surface/underwater drones for maintenance and inspection.
- Automation of processes to enable autonomous vessels and vehicles to function without (new) manual tasks (e.g., twist-lock handling, intelligent container storage/smart containers, automated entry and exit processes at terminal gates).
- Safety frameworks and certification processes for automated and AI-driven port operations.
- Organizational change and skills development to support human–machine collaboration and new operational roles.
- Business model innovations and collaboration agreements that support fair yield distributions that fit the next level optimalisations in the port ecosystem.

4.2.4 Key research gaps

- Digital ecosystem - Digital interoperability and harmonisation is hindered by a low level of data standardisation across the supply chain and varying digital maturity levels. Support is needed to boost common standards and progress towards interoperable data spaces. Many of the data space initiatives and developments are still siloed by sector and seamless data sharing in the port ecosystem will require interoperability between for example initiatives in mobility (EMDS) and energy (CEEDS). An example of the need for common semantic models is the harmonisation / standardisation on all the data that can be gathered on a vessel (similarly to what happened with the Canbus in the automotive industry).
- Port-scale digital twins - Further RD&I is required to develop high-fidelity digital twins that integrate vessel traffic, terminal operations, energy systems and hinterland logistics, moving from descriptive models to predictive and prescriptive decision-support tools.
- Scalable automation and robotics - Research into modular, flexible automation solutions that can be deployed incrementally across different terminal types and cargo segments, including mixed human–robot environments and legacy infrastructure.
- Autonomous vessel–port interaction - Further development of technologies and operational concepts enabling safe and efficient interaction between autonomous or semi-autonomous vessels and port systems, including traffic management, berthing and cargo operations.
- Artificial intelligence - Further RD&I is required to leverage artificial intelligence for predictive, prescriptive and autonomous decision-making across port and logistics operations. This includes the development of AI models for demand forecasting, anomaly detection, optimisation of vessel calls, yard and hinterland operations, as well as energy management. A key challenge is ensuring access to high-quality, standardised data and addressing issues related to explainability, trust, governance and ethical

use of AI. Integration of AI across different data spaces and systems will be essential to unlock its full potential within the port ecosystem. Cybersecurity - Improve resilience on the overall digital corridor in terms of cybersecurity and data integrity in automated logistics- RD&I is needed on secure-by-design architectures that ensure data sovereignty, post-quantum cryptography and PET, resilient digital corridors and protection of automated systems., Especially as automation and autonomy increases in the system, the security of the system becomes of critical importance.

- Human-centric automation and organizational innovation - Research on new roles, training concepts and organizational models that enable effective human oversight, trust and accountability in highly automated logistics ecosystems, ensuring social acceptance and workforce resilience.

4.3 Resilient and adaptive infrastructure

Ports are strategic gateways to Europe and need to be resilient to different types of threats. This includes safety and security risks such as disruptions of communication systems or drug traffic, but also other risks such as effects of climate change (sea-level rise, extreme weather), energy disruptions (blackouts, cascading failures between grid, ports and the logistics system) and changes in global trade patterns (nearshoring, changes in sourcing strategies). RD&I will support advanced materials, modular construction, structural health monitoring and integrated resilience planning linking ports, waterways and coastal zones. RD&I activities must focus on both physical infrastructure and decision-support tools enabling ports to plan, invest and operate under deep uncertainty.

4.3.1 Operational objective(s)

Enable ports to design, operate and upgrade port and hinterland infrastructure that is resilient to climate change impacts, extreme events, man-made hazards and evolving operational requirements, while maintaining safety, continuity of operations and cost-effectiveness across the full lifecycle of port assets.

4.3.2 Target capability 2035, 2040 and 2050

By 2035:

- Demonstration of adaptive port infrastructure that is able to meet future challenges both in terms of physical lay-out (modular quays designs, redundancies in electric systems, climate-resilient surfaces, etc) as well as digital systems.
- Decision support tools are available to assess different risks, infrastructure vulnerabilities and adaptation options at port-system level. Ports are able to define acceptable disruption levels through planning, risk assessment, and prioritised investments.

By 2040:

- Deployment of resilient and adaptive port-infrastructure across Europe's main corridors.
- Roll-out of best practices from large ports to small and medium sized ports.
- Infrastructure systems incorporate continuous monitoring and predictive maintenance capabilities, enabling proactive adaptation to changing environmental and operational conditions.

By 2050:

- Port infrastructure operates as an adaptive system, capable of self-assessment and dynamic response to long-term climate trends and acute disruptions.
- Nature-based solutions and engineered infrastructure are fully integrated, supporting resilience, biodiversity and sustainability objectives.

4.3.3 Required enablers

- Integrated risk assessment and adaptation planning at port and regional level.
- Monitoring technologies and data ecosystems for structural health, environmental conditions and asset performance.
- Standards and guidelines supporting modular, adaptive and nature-based infrastructure solutions.
- Skills and organizational capabilities enabling ports to plan and manage infrastructure under uncertainty.

4.3.4 Key research gaps

- Fit for purpose architecture to enable a data ecosystem for monitoring infrastructure and asset conditions versus risks. This monitoring requires access to a variety of proprietary data sources, including sensors, in combination with AI and uniformed KPIs for performance and health monitoring for prevention and action.
- Decision support tools that enable small and medium size ports to perform system impact analysis for identifying threats which enables them to make strategic decisions on acceptable disruption levels and assists in prioritising investments.
- Adaptive and modular infrastructure concepts - Research into modular designs, adaptable materials and construction methods that allow phased upgrades and functional flexibility over long infrastructure lifecycles.
- Solution development on specific threats, such as, climate change and transformation of workers' skills.
- Development of novel surveillance techniques, such as development of drones for (underwater) surveillance.
- Innovation in sensor technologies, data analytics and predictive models supporting early detection of degradation, climate impacts and emerging risks.

4.4 Ports as energy hubs and circular economy engines

Support the development of networks of ports as major nodes for alternative sustainable energy carriers, renewable energy, CCS/CCUS logistics and circular value chains. Focus in this area will be primarily on deployment of best practices throughout European ports. This may require different financial instruments than research funding. Topics to be considered include advance multi-energy terminals, circular waste and recycling solutions, and digitally managed resource flows linking waterborne, industrial and urban sectors.

4.4.1 Operational objective(s)

Enable ports to function as integrated multi-fuel production and supply hubs and circular economy engines, supporting sustainable alternative fuels, renewable energy flows, carbon management and circular material streams, while ensuring safe operations, efficient spatial use and seamless integration with maritime, industrial and urban systems.

4.4.2 Target capability 2035, 2040 and 2050

By 2035:

- Identification and roll out of best practices that link the energy systems of ports with the local industrial cluster.
- Circular economy activities focus on activities such as reuse of excavated materials, circular procurement, industrial symbiosis, waste heat utilisation, recycled construction materials and digital product passports.

By 2040:

- Ports operate mature multi-energy terminals combining renewable electricity, alternative fuels and CO_2 logistics, integrated with industrial clusters, nearby city activities and offshore energy systems.
- Circular value chains are increasingly digitized and optimized, enabling higher-value reuse and recycling.

By 2050:

Ports serving as central hubs for renewable energy import/export, hydrogen distribution and CO_2 management.

- Fully circular material flows supported by advanced digital tracking, such as in Digital Product Passports (DPPs), reuse and recycling infrastructures supporting closed-loop and climate-neutral logistics and industrial systems.

4.4.3 Required enablers

- Effective identification and distribution of best practices throughout the European port community.
- Spatial planning tools supporting the integration of energy, logistics and circular economy functions within ports.
- Digital solutions enabling monitoring, traceability and optimization of energy and material flows, both in terms of tracking product origins and emissions but also in tracking reuse potential and availability of (scarce) resources.
- Skills and organizational capabilities to manage complex energy and circular systems safely and efficiently.

4.4.4 Key research gaps

- Circular economy system integration - RD&I into design of infrastructure, digital architecture and processes linking ports with industrial, urban and maritime circular value chains, including advanced sorting, processing and reuse machinery while also allowing for digital traceability (e.g. in DPPs).
- Digitalization of energy and material flows – RD&I into digital tools enabling real-time monitoring, certification and optimization of multi-energy and circular flows across port ecosystems and connected regions

4.5 Enhanced security and (cyber-)resilience for critical port infrastructure

Strengthen security of digital port-critical infrastructure and networks, including energy systems and digital platforms. RD&I will focus on identifying key risks to port operations and activities (including underwater assets), smart prevention, secure-by-design architecture, intelligent detection and response systems, recovery and integrated cyber-physical resilience strategies.

4.5.1 Operational objective(s)

Enable ports to protect critical infrastructure and operations through integrated security and cyber-resilience solutions that ensure continuity, safety and trust across increasingly interconnected digital, energy and logistics systems.

4.5.2 Target capability 2035, 2040 and 2050

By 2035:

- Implementation of state-of-the-art cybersecurity technology, such as post-quantum encryption, through dedicated tools aimed at small and medium sized ports and their stakeholders.
- Initial integration of cyber and physical security monitoring supports improved situational awareness and incident response.
- Adoption of Zero Trust Architecture in port environments ensures that no user, device, or system is trusted by default, requiring continuous verification of identities, devices, and access requests across all maritime and logistics operations.

By 2040:

- Ports operate integrated cyber-physical security systems capable of detecting, responding to and recovering from complex attacks and disruptions across digital, energy and operational domains.

By 2050:

- Port ecosystems achieve an important level of autonomous resilience, with self-monitoring, self-healing and adaptive security mechanisms embedded in critical infrastructure.
- Human operators supervise and govern resilient systems supported by advanced decision-support tools.

4.5.3 Required enablers

- Security-by-design principles embedded in the digital ecosystem (as described in 4.2), energy and automation systems as well as in human operated procedures.
- Harmonized cybersecurity standards, guidelines and certification schemes for port ecosystems.
- Skills development and awareness for port authorities and operators.
- Coordination of mechanisms between ports, authorities and critical infrastructure operators.
- Digital security ecosystem that is connected to critical digital and physical components for on-going monitoring of security levels and risks, and detection of threats and disruptions.
- Algorithms and AI agent solutions that respond to complex attacks and disruptions and recover the port ecosystem to minimum performance levels without or with minimum human intervention.

4.5.4 Key research gaps

- Port Specific cybersecurity solutions - Determine which cyber security technologies that exist are most suitable for uptake in port ecosystems, especially in small and medium sized ports.
- Focus on systems that enable smart prevention (because detection and response only occur when an attack is already underway).
- Autonomous cyber resilience. This includes, for example, self-healing technology and AI-supported resilience management that can anticipate threats and support human decision making before disruptions escalate (reasoning about courses of action to advise the human, etc.)

4.6 Human-centered port innovation and workforce transformation

Just as in other European sectors, port ecosystems face labour challenges such as scarcity in key positions, increasing competition for intersectoral relevant professionals (e.g. IT, commercial) and an aging workforce, both for blue-collar and white-collar roles due to demographic change. This creates a critical need for both replacing retirees and in upscaling current workers, including preserving, transforming and passing-on relevant sectoral know-how.

There is a need to develop new operational concepts, ergonomic systems and training models for automation, alternative fuels, digital control rooms and resilience management. Furthermore, innovations are needed in organisational aspects, such as creation of new business models and collaboration methods. R&I will promote advanced simulation, XR- enabled training, competence frameworks and safe human machine cooperation across port operations.

4.6.1 Operational objective(s)

Enable ports to manage the transition towards highly automated, digital and energy-integrated operations through human-centred innovation, ensuring that port workers are equipped with the skills, tools and organizational frameworks required to safely and effectively supervise, interact with and optimize advanced port systems.

4.6.2 Target capability 2035, 2040 and 2050

By 2035:

Introduction of digital and alternative fuel training programs for port operators

- Early digital control rooms and simulation-based training environments support new operational roles.

By 2040:

- Deploying workforce transformation with digital control rooms, advanced simulation training and new operational roles
- Workforce transformation is embedded in organizational models, supported by continuous learning.

By 2050:

- Port operations rely on highly skilled human operators supervising autonomous and adaptive systems.
- Human-centred design principles are fully embedded in port technologies and governance, ensuring trust, safety and long-term workforce sustainability.

4.6.3 Required enablers

- Competence frameworks and certification schemes aligned with future port roles.
- Advanced simulation, training and decision-support technologies.
- Organizational innovation supporting new roles, collaboration models and change management.
- Collaboration of port stakeholders with universities and professional trainers.
- Social dialogue and stakeholder engagement supporting workforce acceptance.

4.6.4 Key research gaps

- Human–machine cooperation in port operations: Research on safe, transparent and effective interaction between humans and automated or AI-driven systems, including workload management and decision authority.
- Training and skills development for future ports
- Organizational and business model innovation
- Social acceptance and workforce resilience - Research into change management, trust in automation and long-term impacts of digitalization and decarbonization on port employment and working conditions.
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4.7 Forward-looking regulation, standardization and multimodal integration

Support regulatory innovation, data governance models and harmonized standards enabling cross-border, port-port, port-vessel and port-hinterland interoperability. Develop tools for energy system integration, alternative fuel certification, operations telemetry and monitoring, automated operations and coordinated multimodal planning. Assure that the regulatory burden is solved as soon as possible to unblock all standards and protocols by 2035.

4.7.1 Operational objective(s)

Enable ports to operate within harmonized, future-proof regulatory and standardization frameworks that support cross-border interoperability, multimodal integration and the safe deployment of digital, automated and zero-emission solutions.

4.7.2 Target capability 2035, 2040 and 2050

By 2035:

- Initial alignment of standards and regulatory approaches supporting data sharing, sustainable alternative fuels, automation and multimodal operations. Introduction of standards at some major European TEN-T ports"
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By 2040:

- Full deployment of harmonized regulatory frameworks and standards enable seamless port–port, port–vessel and port–hinterland interoperability across European corridors.

By 2050:

- Adaptive, innovation-friendly regulatory ecosystems support fully integrated, zero-emission and autonomous transport and logistics systems.

4.7.3 Required enablers

- Sandboxes for large-scale pilots in several areas.
- Coordination between regulators, standardization bodies and industry.
- Data governance and certification frameworks supporting trust and interoperability.
- Tools enabling integrated multimodal and cross-sector planning.

4.7.4 Key research gaps

- Regulatory innovation and sandboxes
- Standardization for interoperability
- Multimodal system integration

5. Enablers and Deployment

The technology pathways identified in Chapter 4 require deployment at the level of the port ecosystem. Ports are multi-actor environments requiring coordination in terms of investment, operations, data sharing, safety and land use. Deployment must therefore combine technology readiness with governance, permitting, finance, operational continuity and port-community coordination.

5.1 Differentiated deployment across port types

For each technology pathway, deployment should be assessed against port function, traffic demand, grid capacity, land availability, governance model, concession structure, digital maturity, safety requirements and investment capacity. The key enablers are port-specific deployment plans aligned with masterplans, energy plans, digitalisation strategies and hinterland-connectivity plans. Further considerations include modular and scalable solutions adapted to different port sizes and operating profiles; common interoperability requirements to avoid fragmented energy, digital and operational systems; technical assistance and capacity-building for small, medium-sized, island, inland and regional ports; financing mechanisms adapted to different project scales, including project bundling, shared procurement and de-risking instruments; concession, lease and procurement clauses that embed energy readiness, digital interfaces, data sharing, cybersecurity, resilience and environmental performance; safety and permitting guidance proportionate to local risk profiles; and monitoring indicators that track progress by port type. The objective is not uniform technology adoption across all ports, but proportionate, interoperable and scalable deployment that allows each port to contribute to climate-neutral, digital, resilient and secure European waterborne transport according to its role in the network.

5.2 Energy-system readiness and port infrastructure

Energy-system readiness is the most important deployment condition. Ports must be able to provide reliable, safe and cost-effective energy services to vessels, terminal equipment, hinterland transport and industrial users. This requires coordinated deployment of onshore power supply, vessel charging, electrified equipment, sustainable alternative fuel bunkering, renewable-energy integration, storage, smart grids, microgrids and energy-management systems. Grid capacity must be addressed beyond the port boundary, in cooperation with transmission and distribution system operators, energy suppliers and industrial users. Not all ports will need all fuels or energy carriers. Deployment of hydrogen, ammonia, methanol, biofuels, LNG, electricity and CO_2 infrastructure should be based on traffic demand, safety constraints, land availability, permitting, emergency-response capacity and corridor-level planning.

5.3 Digital interoperability and port-community data governance

Digital deployment must address the port community as a whole. Port community systems, terminal operating systems, digital twins, customs interfaces, energy-management platforms, vessel-call optimisation tools and hinterland systems should be interoperable by design. Common data models, semantic standards, secure APIs, trusted data spaces and clear data-governance rules are needed to support port-port, port-vessel, port-hinterland and port-energy integration. Industry associations, standardisation bodies and platforms should be mobilised to support common terminology, operational definitions, interoperability and deployment practices.

5.4 From pilots to scalable port-system deployment

Deployment must move from technical pilots to operational demonstrators and scalable solutions. Shore power, charging, smart-grid management, sustainable alternative-fuel bunkering, port digital twins, automated equipment, cyber-resilience, adaptive infrastructure and circular-economy solutions should be tested as integrated port-system capabilities, not as isolated technologies. Demonstrators should include indicators for emissions reduction, energy demand, grid impact, berth productivity, waiting time, safety, cyber resilience, operational continuity, cost and transferability across port types.

5.5 Safety, security and regulatory readiness

Safety, security and regulatory readiness are essential conditions for deployment in port environments. Sustainable alternative fuels, high-voltage systems, batteries, automated equipment, drones, underwater assets, autonomous vessels and interconnected energy systems introduce new risk profiles within constrained land and water areas, often close to cities, industrial zones and environmentally sensitive sites. Ports need harmonised safety procedures, safety zones, emergency-response plans, permitting pathways, training, certification processes, cyber-secure architectures and regulatory sandboxes. Safety, security and resilience should be designed into infrastructure, digital systems and operational procedures from the beginning.

5.6 Investment, concessions and business models

Investment sequencing and business models must reflect port governance. Many port assets are operated by terminal operators or concessionaires rather than by port authorities directly. Requirements for shore power, digital interfaces, cybersecurity, resilience, data sharing and energy efficiency should therefore be reflected in concession agreements, lease conditions, procurement criteria and port-community governance arrangements. Public funding should be combined with private investment, de-risking instruments, technical assistance, project bundling and shared services, especially for small, medium-sized, island, inland and regional ports.

5.7 Workforce and organisational capacity

Workforce and organisational capacity are also deployment enablers. Ports will need new skills in electrification, alternative fuels, automation, AI-enabled decision support, cybersecurity, data governance, energy management, emergency response, circularity and resilience planning. Training, competence frameworks, simulation-based learning, digital control-room skills and human-centred design should be embedded in deployment projects.

5.8 Governance, coordination and monitoring

Deployment should be governed and monitored across port, corridor and European levels. At port level, stakeholders must coordinate investment, data sharing, land use, safety and operational planning. At corridor level, ports must coordinate with hinterland networks, inland ports, shipping lines, rail and road operators, energy systems and logistics platforms. At European level, deployment should align with TEN-T, AFIR, FuelEU Maritime, the EU Ports Strategy, the EU Industrial Maritime Strategy, the Sustainable Transport Investment Plan and relevant research and innovation programmes. Progress should be monitored through indicators covering energy infrastructure, digital interoperability, automation, resilience, emissions reduction, safety, workforce readiness, investment mobilised and deployment gaps across different port types.

6. Expected Impacts

The implementation of this roadmap is expected to strengthen the role of European ports as competitive, resilient and sustainable system nodes in waterborne transport, logistics, energy and industrial networks.

6.1 Climate and environmental impacts

The roadmap will contribute to the zero- emission port operations and waterborne transport by enabling the deployment of shore-side electricity, vessel charging, electrified terminal equipment, smart energy management, renewable-energy integration and sustainable alternative-fuel bunkering. Ports will be better able to support the transition of vessels, terminals and hinterland operations towards zero-emission energy systems.

Expected impacts include zero-emission port operations and vessels at berth, improved energy efficiency, greater use of renewable electricity and sustainable alternative fuels, and improved management of waste, circular material flows and CO_2 logistics. The roadmap will also support more climate-resilient infrastructure and greater use of adaptive and nature-based solutions where appropriate.

6.2 Competitiveness and logistics performance

The roadmap will improve port competitiveness by supporting more efficient, reliable and digitally connected port operations. Integrated port community systems, digital twins, AI-enabled decision support, automation and real-time data exchange will improve berth planning, terminal operations, cargo visibility, hinterland coordination and disruption management.

Expected impacts include reduced waiting times, better asset utilisation, improved reliability of vessel and cargo flows, stronger integration with rail, inland waterways and road transport, and enhanced capacity to respond to changing trade patterns and corridor dynamics. Ports will increasingly compete not only on location and capacity, but also on energy readiness, digital connectivity, operational reliability and integration with low-emission logistics chains.

6.3 Energy and industrial transition impacts

The roadmap will support the transformation of ports into active energy and industrial nodes. Ports will be better positioned to host and coordinate shore power, vessel charging, renewable-energy flows, hydrogen and hydrogen-derived fuels, CO_2 handling, offshore energy activities, circular value chains and industrial symbiosis.

Expected impacts include improved energy-system integration, stronger links between ports and nearby industrial clusters, better planning of port energy demand, increased flexibility in local energy systems and new opportunities for port-based industrial activity. Energy-industrial ports and major gateways can act as early deployment sites, while modular and scalable solutions can allow smaller, island, inland and regional ports to participate in the transition according to their role and capacity.

6.4 Resilience, safety and security impacts

The roadmap will strengthen the resilience of ports as critical infrastructure. Climate adaptation, structural health monitoring, predictive maintenance, cyber-secure architectures, integrated risk assessment and improved emergency-response procedures will increase the ability of ports to prevent, withstand, respond to and recover from disruptions.

Expected impacts include improved continuity of port operations under climate, energy, cyber, security and geopolitical disruptions; better protection of critical port, energy and underwater infrastructure; safer deployment of alternative fuels, high-voltage systems, batteries, automation and drones; and stronger coordination between port authorities, terminal operators, public authorities, emergency services and critical infrastructure operators.

6.5 Territorial cohesion and port-network impacts

The roadmap will support a more balanced transformation of the European port network. By promoting modular, affordable and scalable solutions, it can help prevent the transition from being concentrated only in large gateway ports. Small, medium-sized, island, inland, outermost-region and regional ports will benefit from proportionate deployment models, technical assistance, shared services, project bundling and fit-for-purpose digital and energy solutions.

Expected impacts include improved connectivity for islands and remote regions, greater resilience of essential port services, better integration of inland and mixed ports into multimodal corridors, and reduced deployment gaps between large and smaller ports.

6.6 Innovation, skills and European technology leadership

The roadmap will strengthen European technology leadership in port ecosystems by supporting the transition from isolated pilots to interoperable, scalable and replicable port-system solutions. It will create demand for innovation in port energy systems, digital platforms, automation, AI, cyber-resilience, adaptive infrastructure, circularity, safety procedures and multimodal integration.

Expected impacts include stronger European capabilities in port technologies and services, wider use of common standards and interoperability frameworks, new business models for port energy and digital services, and improved cooperation between ports, technology providers, industry associations, standardisation bodies, universities and training organisations.