WATERBORNE

WATERBORNE TECHNOLOGY ROADMAP

Competitive, resilient and sustainable port ecosystems

September 2026

PORT ECOSYSTEMS TECHNOLOGY ROADMAP

01 DESCRIPTION OF THE SECTOR

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, emergency-response organisations, fire and rescue services, safety-engineering and validation providers, and urban or regional stakeholders.

3.4 bn t goods handled by EU ports, around 74% of goods entering or leaving Europe

€90 bn economic footprint in turnover, and approximately 423,000 direct jobs

395 m passengers each year, alongside almost 3 million portcalls — around 23% of the world total

40% commodities handled in EU ports are energy-related; ports are becoming central nodes in the energy transition

Dot area gross tonnage, 2024: 397 Mt (Rotterdam) to 17 Mt (Riga).

Hollow grey dot: Odessa, outside the EU-27 series.

Red line: waterways of the five river-port systems.

Red ring: ports with a stated inland-waterway modal share.

Figure 1: Busiest EU ports by gross tonnage handled, 2024. Lambert conformalconic. Geometry: Natural Earth 1:110m coastlines, 1:10m rivers.

TRAFFIC AND PERFORMANCE — EU-27, 2019–2024

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 recovering in passenger movements after the pandemic.

METRIC (EU-27)	2019	2024	TREND
Goods handled (Mt)	3 582.6	**3 355.9**	declining, −6.3%
Containers (m TEU)	97.8	**100.9**	flat to up, +3.2%
Passengers (m)	418.2	**417.8**	recovered, −0.1%

LEADING EU PORTS, 2019 AND 2024

PORT	2019 Mt	2024 Mt	Δ %	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

HINTERLAND CONNECTIVITY AND MODAL SPLIT

Port competitiveness depends also on hinterland connectivity, in which inland waterways are a core component. Inland-waterway transport carried 35.7% of total throughput at the Port of Rotterdam in 2023, ahead of road and rail, and reached a 51% share of maritime throughput at the Port of Antwerp in 2024, the highest share since 2019.

This modal share is the mechanism through which ports deliver the modal-shift objective of Union transport policy.

THE TECHNOLOGY LEADERSHIP OPPORTUNITY

European ports have a major technology leadership opportunity in the transition from infrastructure providers to system orchestrators. 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, and the corresponding port infrastructure mission: bunkering and shore-power supply, smart port communication and information systems, and city-port-nature planning.

02 POLICY DRIVERS AND CONSTRAINTS

2.1. DRIVERS

Climate neutrality and decarbonisation. The European Climate Law sets a 2030 target of at least 55% net emission reduction against 1990, a 2040 milestone of 90% and climate neutrality by 2050. Ports are implicated as emission sources, enablers of vessel decarbonisation and energy nodes.

Maritime fuel and infrastructure regulation. FuelEU Maritime, ETS extension to maritime transport and AFIR create direct demand for shore-side electricity, low-carbon fuels and compliant port-vessel interfaces. Onshore power for larger container and passenger ships from 2030 makes the berth a compliance point.

Competitiveness and changing trade geography. Ports must respond to shifting cargo flows, supply-chain restructuring, geopolitical disruption, changing energy imports and evolving corridor dynamics.

Resilient logistics chains and continuity of port services. Cargo owners, operators, insurers and authorities need evidence that ports can prevent, contain and recover from fire, hazardous releases, cyber incidents, grid failures and extreme weather.

Energy-system transformation. Ports link shore power, vessel charging, fuel bunkering, renewables, offshore wind, hydrogen and its derivatives, CO_2 logistics and industrial decarbonisation, increasingly with distributed generation where grids are constrained.

Corridor-based decarbonisation. Port ecosystems are assessed not only on maritime capacity but on their ability to connect clean maritime transport with rail, road, inland waterways, logistics platforms, industrial areas and energy networks.

Digitalisation, automation and data-driven logistics. Performance depends on interoperable port community and terminal operating systems, digital twins, AI-enabled planning, automated equipment and trusted data exchange.

Security, resilience and military mobility. Ports face cyber threats, hybrid risks, organised crime, sabotage, drones, underwater threats, energy disruption and climate events, making security and resilience core design requirements.

Industrial strategy and circular economy. Ports provide the physical base for ship repair, retrofitting, recycling, offshore energy, renewable fuels, carbon management, the blue economy and circular value chains.

Territorial cohesion and connectivity. Ports are essential for islands, outermost regions and remote territories, requiring deployment models proportionate to traffic demand, grid capacity and local investment capacity.

2.2 CONSTRAINTS AND DEPLOYMENT CHALLENGES

Grid capacity and electrification. Demand rises faster than grid capacity; OPS reaches 62% of surveyed seaports, mostly low-voltage.

Standardisation of mobile battery handling. Divergent procedures, interfaces and fire-safety protocols block seamless transfer between ports.

Fuel readiness and bunkering safety. LNG at 51% of surveyed ports; hydrogen 43%, ammonia 16%, methanol 14%.

Climate resilience and exposure. 69% report operational disruption, 77% reinforce assets, 86% embed adaptation in new development.

Heterogeneity, small ports, insularity. Low investment capacity and weak grids require modular, scalable, affordable solutions.

Spatial competition and permitting. Land and water space is contested; faster permitting for greening terminals is key.

Digital fragmentation and data sovereignty. Port, terminal and national systems lack interoperability and common semantic models.

Security and cyber-physical exposure. Automation enlarges the attack surface; underwater assets face sabotage and hybrid threats.

Fragmented risk ownership. Simultaneous bunkering, charging and cargo operations are not always assessed together.

Intermodal coordination bottlenecks. Impact depends on actors beyond the port perimeter.

Investment and financing. Around EUR 80 bn needed to 2034, EUR 7–9 bn a year, against some EUR 10 bn of EU deployment support.

Fragmented governance. Port authorities do not control all assets and processes needed for port-wide solutions.

Skills and workforce shortages. New fuels, electrification and automation depend on trained personnel, emergency responders and inspectors.

03 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 Technology Leadership framework, which requires ports to evolve from infrastructure providers into system orchestrators delivering resilient, zero-emission services by 2050. 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.

LNG 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%). 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. Regulation sets the near-term anchor, with onshore power supply required for larger container and passenger ships at TEN-T maritime ports by 2030.

2035

SMART AND CLEAN FOUNDATIONS

- Shore power, ship charging and electrified equipment widely deployed
- Hydrogen, ammonia and methanol bunkering procedures in widespread use
- CO_2 handling systems and early nuclear-vessel procedures
- Port Community Systems exchanging secure standardised data
- AI-supported operations, digital twins and predictive maintenance
- Trusted maritime data spaces and cyber-secure port systems
- Integrated multimodal traffic management
- Autonomous vessel-traffic coordination on port platforms
- Adaptive and nature-based infrastructure demonstrated
- Multi-hazard baselines and joint emergency plans in place

2040

SYSTEM INTEGRATION AND LARGE-SCALE AUTOMATION

- Zero-emission core port operations near complete
- Consolidated multi-energy hubs specified to each port's needs
- Ammonia, hydrogen and renewable electricity dynamically converted and stored
- Reduced dependence on external grid capacity
- Logistics platforms fully integrated across vessels, terminals, corridors and energy networks
- Harmonised protocols for autonomous vessel operations
- Mature automation and robotics in handling, inspection, maintenance and security
- Resilient, adaptive infrastructure models across main corridors
- Port digital safety twins for predictive risk and response
- Corridor stress tests and mutual-aid arrangements

2050

FULLY INTEGRATED, ZERO-EMISSION, AUTONOMOUS

- Fully integrated, zero-emission, resilient and autonomous port ecosystems
- Intelligent decision-support systems
- Integrated energy hubs and circular infrastructure
- Secure European digital infrastructure
- Integration into zero-emission logistics chains and industrial corridors
- Autonomous operations across terminals, waterways and logistics nodes
- Central hubs for renewable energy, renewable fuels and CO_2 management
- Fully circular material flows with advanced reuse and recycling
- Highly resilient and cyber-secure port systems
- Continuous assurance and adaptive recovery

04 TECHNOLOGY PATHWAYS

OPERATIONAL OBJECTIVES — SEVEN PATHWAYS

4.1 Zero-emission port operations and clean energy integration	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, sustainable alternative fuel bunkering and handling, multimodal charging infrastructure, on-site renewable generation, energy storage and advanced energy management.
4.2 Smart, automated and data-driven logistics ecosystems	Enable ports to operate integrated, standardised and data-driven logistics ecosystems allowing real-time optimisation and coordination of vessels, terminals, cargo flows and hinterland transport, supported by automation, AI-enabled decision support and trusted data sharing, while maintaining safety, security and operational resilience.
4.3 Resilient and adaptive infrastructure	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.
4.4 Ports as energy hubs and circular economy engines	Enable ports to function as integrated multi-energy 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.
4.5 Enhanced security and (cyber-)resilience for critical port infrastructure	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, proportionate to the risk profile, function and technological maturity of each port.
4.6 Human-centered port innovation and workforce transformation	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 organisational frameworks required to safely and effectively supervise, interact with and optimise advanced port systems.
4.7 Forward-looking regulation, standardization and multimodal integration	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. Priority standards required for large-scale deployment should be substantially advanced by 2035.

05 ENABLERS AND DEPLOYMENT

5.1 Differentiated deployment. Port-specific plans aligned with masterplans, energy and digitalisation strategies; proportionate, interoperable and scalable rather than uniform adoption.

5.2 Energy-system readiness. Coordinated OPS, charging, electrified equipment, bunkering, renewables, storage, smart grids and microgrids, with grid capacity addressed beyond the port boundary.

5.3 Digital interoperability. Community and terminal systems, digital twins, customs and energy platforms interoperable by design, accessible at every level of digital maturity.

5.4 From pilots to scale. Solutions tested as integrated port-system capabilities, using shared testing environments and regulatory sandboxes.

5.5 Safety, security and regulatory readiness. Harmonised safety procedures, safety zones, emergency plans, permitting pathways, certification and cyber-secure architectures.

5.6 Investment and business models. Public funding combined with private investment, de-risking instruments, technical assistance, project bundling and shared services.

5.7 Workforce and organisational capacity. Skills in electrification, alternative fuels, automation, cybersecurity, data governance and resilience planning embedded in deployment projects.

5.8 Governance and monitoring. Governed across port, corridor and European levels, aligned with TEN-T, AFIR, FuelEU Maritime and the EU Ports Strategy.

06 EXPECTED IMPACTS

CLIMATE & ENVIRONMENT

2035 Widespread OPS, vessel charging, electrified equipment and renewable integration; measurable cuts in GHG and air pollutants at berth.

2040 Integrated port energy systems combine electrification, renewables, storage and alternative fuels; further emission and efficiency gains.

2050 Climate-neutral port ecosystems with near-zero emissions from port-controlled activities and mature circular resource flows.

ENERGY AND INDUSTRIAL TRANSITION

2035 Grid, charging, storage, energy-management and fuel capabilities develop with initial new value chains.

2040 Ports operate as integrated energy nodes with stronger grid integration, flexibility and industrial-cluster links.

2050 Mature energy and industrial nodes supporting clean maritime energy, circular value chains and strategic autonomy.

COMPETITIVENESS AND LOGISTICS

2035 Better berth planning, call coordination and cargo visibility reduce waiting and congestion and improve reliability.

2040 Integrated port and corridor platforms improve asset utilisation, multimodal performance and response to disruption.

2050 Highly integrated port, maritime and hinterland ecosystems support European supply-chain competitiveness.

RESILIENCE, SAFETY AND SECURITY

2035 Port-wide risk assessment, joint emergency planning and continuity arrangements support safer deployment.

2040 Predictive risk management, digital safety tools and joint stress testing improve resilience across corridors.

2050 Continuous assurance and adaptive recovery embedded across port, energy, digital and hinterland systems.

INNOVATION, SKILLS AND LEADERSHIP

2035 Digital twins, AI decision support, smart energy and automation advance alongside workforce training.

2040 Scalable, interoperable European port technologies and business models widen market deployment.

2050 European ports form a leading market for sustainable port technologies, with highly skilled workers and common standards.

TERRITORIAL COHESION

2035 Modular, scalable solutions let small, island, inland and outermost-region ports participate to their capability.

2040 Deployment gaps narrow through replication, shared services and capacity building.

2050 A resilient, interconnected European port network maintains essential connectivity across port types.

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ROADMAP POSITIONING WITHIN THE WATERBORNE TECHNOLOGY LEADERSHIP FRAMEWORK

This roadmap operationalises the Technology Leadership[1] framework for port ecosystems. 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 port ecosystems. 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 port ecosystems is closely interlinked with the following dedicated Technology Roadmaps: maritime technology sector, inland waterway transport, short sea shipping, ferries, cruise, oceangoing, offshore and blue economy.

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

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, emergency-response organisations, fire and rescue services, safety-engineering and validation providers, and urban or regional stakeholders.[3]

The trans-European transport network includes 283 seaports, 223 inland ports and 44 mixed ports[4]. 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, sustainable 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, safe navigation in the port area, 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[5] 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[6].

3 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.
4 EU Ports Strategy, COM(2026) 112 final, p. 1.
5 Regulation (EU) 2024/1679 of the European Parliament and of the Council of 13 June 2024 on Union guidelines for the development of the trans-European transport network, amending Regulations (EU) 2021/1153 and (EU) No 913/2010 and repealing Regulation (EU) No 1315/2013, OJ L, 2024/1679, 28 June 2024, Annex I (core and comprehensive network), http://data.europa.eu/eli/reg/2024/1679/oj.
6 EU Ports Strategy, COM(2026) 112 final, p. 1.

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

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[7].

Ports provide critical links between maritime transport, inland waterways, rail, road, pipelines, logistics centres, industrial clusters, energy networks and digital systems in constrained areas, often close to cities and industrial sites. 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 act as active energy-system nodes, interfacing port infrastructure, vessel energy demand, grid connection, local energy storage, charging systems, shore power, safety systems and operational coordination between port, vessel operator, terminal operator, grid operator and energy provider. Furthermore, ports are enabling high-power charging.

Ports are also becoming central nodes in the energy transition. Around 40% of commodities handled in EU ports are energy-related[8], and ports are the shore-side interface for onshore power supply, vessel charging, sustainable alternative fuel bunkering, renewable energy flows, offshore wind deployment, offshore energy, CO_2 logistics, circular economy activities and industrial decarbonisation. The transition away from fossil fuels is therefore changing both port traffic and port infrastructure needs.

The Technology Leadership framework assigns ports the role of system nodes that enable the energy transition, promote modal shift, advance decarbonisation and support military mobility.[9]

7 EU Ports Strategy, COM(2026) 112 final, p. 1.
8 EU Ports Strategy, COM(2026) 112 final, p. 7.
9 Waterborne Technology Leadership (January 2026), p. 21.

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 recovering 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[10]. Container throughput reached 100.9 million TEU in 2024, above the 2019 level of 97.8 million TEU[11]. Passenger traffic recovered to 417.8 million passengers in 2024, close to the 2019 level of 418.2 million passengers[12].

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%

Table 1: EU-27 port traffic, 2019–2024
Source: Eurostat, online data codes mar_mg_aa_cwh, mar_mg_am_cvh and mar_mp_aa_cph, extracted 30 June 2026.

Port traffic is concentrated in a small number of gateway ports and is redistributing across sea basins. Table 2 sets out the leading EU ports by gross tonnage handled in 2024, the largest nodes on which port-technology deployment will concentrate; figure 2 sets out the ports with the largest change in gross tonnage between 2019 and 2024. The two selections differ by design: the first ranks ports by scale, the second by movement. Rotterdam handled 397.3 million tonnes in 2024, close to a quarter of the top-20 total, followed by Antwerp-Bruges at 244.2 million tonnes.[13] The top 20 ports account for about 80% of EU container throughput, with Rotterdam and Antwerp-Bruges handling 13.4 and 12.4 million TEU respectively.[14]

The two views converge on the same ports. Rotterdam and Antwerp-Bruges lead by scale yet are static or easing, while the movement is concentrated a tier below: Gdansk and Constanța rising on Baltic and Black Sea flows, Hamburg, Amsterdam and Piraeus declining. So the sector's largest nodes are stable while its traffic geography shifts around them.

10 Eurostat, gross weight of goods handled in all ports, online data code mar_mg_aa_cwh, extracted 30 June 2026, reference year 2024.
11 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.
12 Eurostat, passengers embarked and disembarked in all ports, online data code mar_mp_aa_cph, extracted 30 June 2026, reference year 2024.
13 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.
14 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.

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[15]. 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.

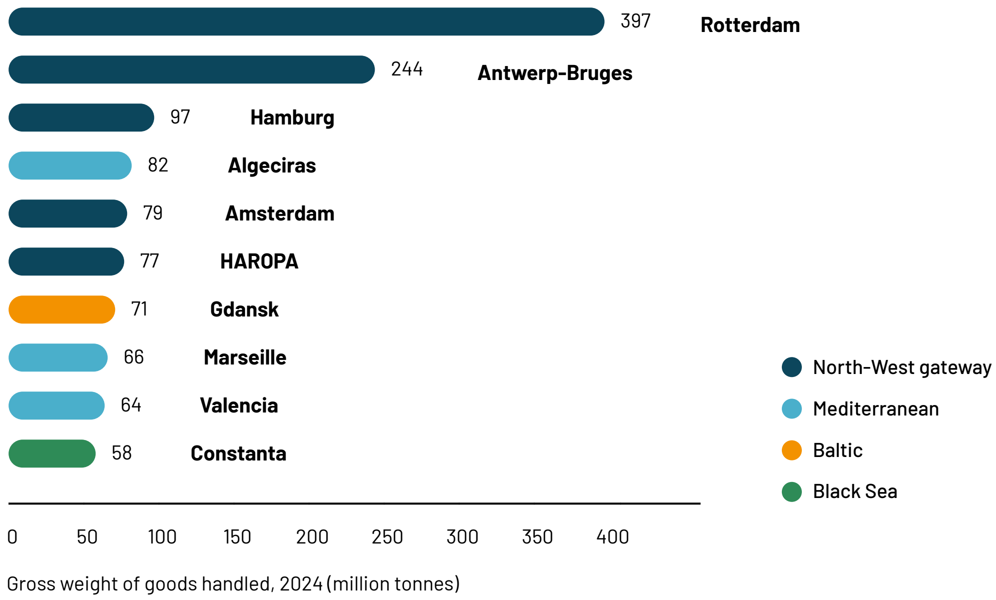

Figure 1: Busiest EU ports by gross tonnage handled, 2024
Source: Eurostat, online data code mar_mg_aa_cwh; port ranking mar_mg_aa_pwhd, extracted 30 June 2026.

15 Eurostat, mar_mg_aa_pwhd, extracted 30 June 2026, reference year 2024.

Port	2019 (Mt)	2019 (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
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Table 2: Performance of leading EU ports, 2019 and 2024

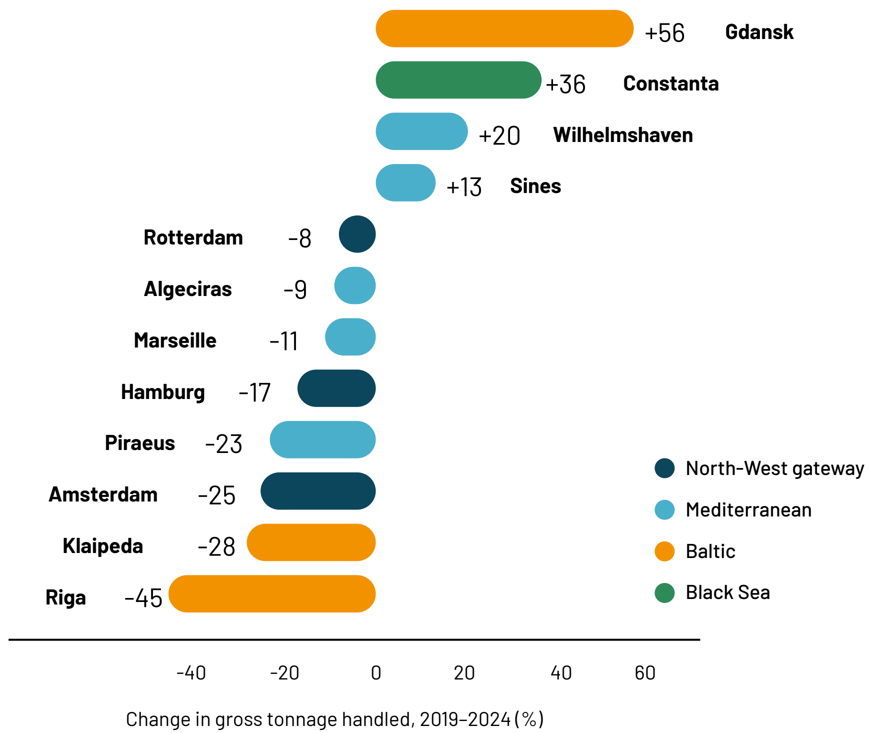


Figure 2: Change in gross tonnage handled by leading EU ports, 2019–2024
Table 3: Change in gross tonnage handled by leading EU ports, 2019–2024
Source: Eurostat, online data code mar_mg_aa_pwhd, extracted 30 June 2026. HAROPA is not shown: the 2019 series reports Le Havre only, so no comparable base exists for a change calculation.

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. HINTERLAND CONNECTIVITY AND MODAL SPLIT

Port competitiveness depends also on hinterland connectivity, in which inland waterways are a core component. Inland-waterway transport carried 35.7% of total throughput at the Port of Rotterdam in 2023, ahead of road and rail, and reached a 51% share of maritime throughput at the Port of Antwerp in 2024, the highest share since 2019.[16] This modal share is the mechanism through which ports deliver the modal-shift objective of Union transport policy, and it conditions the port-side infrastructure required for barge handling, bunkering and digital coordination.

Inland-waterway cargo handling is organised around five river-port systems, which together frame the hinterland dimension of the sector.[17] The Rhine, Dutch and French Belgian systems grew in 2024, while the Danube and Sava systems contracted.

Inland-waterway port system	2024 (Mt)	Δ 2024/2023
Dutch ports	278.8	+1.2%
French and Belgian ports	202.6	+3.1%
Traditional Rhine ports	106.3	+4.8%
Danube ports	58.9	−20.4%
Sava ports	2.8	−49.5%

Table 4: Inland-waterway cargo handling by river-port system, 2024
Source: Central Commission for the Navigation of the Rhine, Market Observation – Annual Report 2025, Tables 1–6. Figures are inland-waterway (barge) cargo handling by river system and are not comparable with the maritime throughput in Tables 1 and 2. System totals cover the ports listed in the source and are not national totals; some ports appear in more than one basin.

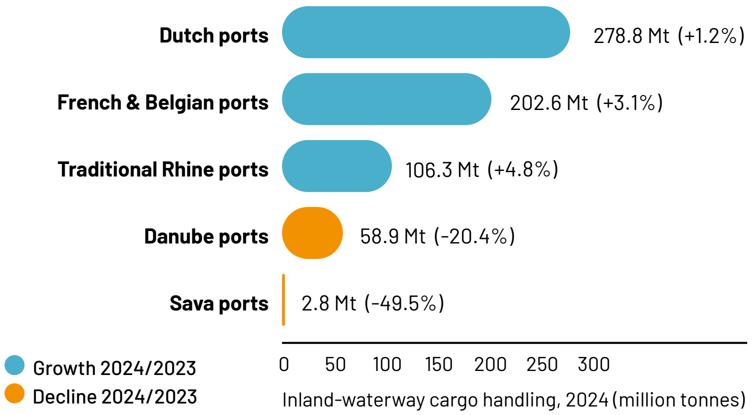


Figure 3: Inland-waterway cargo handling by river-port system, 2024 **Source:** CCNR, Market Observation – Annual Report 2025, Tables 1–6.

The Danube system illustrates the exposure of hinterland networks to geopolitical change. Inland-waterway handling at Danube ports fell 20.4% in 2024, as the resumption of activity at the Port of Odessa reduced the grain traffic previously diverted through Constanta.[18] This is the river-side counterpart of the maritime growth recorded at Constanta in the same period, and it shows that hinterland volumes respond to corridor shifts as sharply as maritime volumes.

16 Central Commission for the Navigation of the Rhine, Market Observation – Annual Report 2025, chapter 5 (Inland waterway cargo handling in ports) (Strasbourg: CCNR, 2025), pp. 85, 87.
17 CCNR, Market Observation – Annual Report 2025, pp. 94–104.
18 CCNR, Market Observation – Annual Report 2025, pp. 90, 102.

1.5. 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.

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

Table 5: Alternative-fuels port infrastructure, EU-27 (2023)
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[19]. 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[20], while high-voltage supply for larger container and passenger vessels remains limited.

The infrastructure baseline indicates that ports are moving towards shore-side energy provision, 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, circularity and new raw materials, interoperable digital systems and resilience-by-design across port operations, energy systems and hinterland connections.

19 European Alternative Fuels Observatory (EAFO), Maritime infrastructure portal: onshore power supply and LNG bunkering installations, 2023 dataset, extracted 30 June 2026..

20 European Sea Ports Organisation, Environmental Report 2025 – EcoPortsinSights 2025 (Brussels: ESPO, October 2025), pp. 22–23.

1.6. 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. As key TEN-T nodes, they will play a central role in Europe's decarbonisation, energy security and industrial competitiveness by enabling climate-neutral, resilient and digitally connected port ecosystems.

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[21]. It identifies the corresponding port infrastructure mission: bunkering and shore-power supply, smart port communication and information systems, and city-port-nature planning.[22]

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.

21 Waterborne Technology Leadership (January 2026), p. 21.
22 Waterborne Technology Leadership (January 2026), pp. 22-23.

2. DRIVERS AND CONSTRAINTS

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 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, sustainable alternative-fuel supply and infrastructure renewal.[23]
- **Maritime fuel and infrastructure regulation.** FuelEU Maritime, the extension of the EU Emissions Trading System to maritime transport[24] and the Alternative Fuels Infrastructure Regulation[25] 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 from 2030 makes the berth a critical compliance point[26].
- **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[27]. 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.
- **Resilient, autonomous, safe logistics chains and continuity of port services.** Ports must sustain trade, energy supply, mobility and emergency logistics while introducing sustainable alternative fuels, charging, automation and interconnected data systems. Cargo owners, operators, financiers, insurers and public authorities increasingly need evidence that ports can prevent, contain and recover from fire, hazardous releases, cyber incidents, grid failures and extreme weather. Demonstrated resilience protects revenue and corridor reliability, reduces congestion and downtime, and strengthens the business case for clean-energy traffic and infrastructure.
- **Energy-system transformation.** Ports are becoming energy nodes linking shore power, vessel charging, sustainable alternative fuel bunkering, renewable energy flows, offshore wind, CO_2 logistics, circular material flows and industrial decarbonisation. Growing electricity demand from shore power, vessel charging, electrified terminals, energy production and industrial decarbonisation is increasing the strategic importance of local electricity production and energy-flexible solutions. Ports may increasingly rely on distributed zero-emission power generation, to supplement constrained grid connections, improve energy resilience and support new mobility and industrial applications. This changes port infrastructure needs, land-use priorities, business models and the relationship between ports, energy providers and industrial clusters.

23 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).
24 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.
25 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.
26 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.
27 EU Ports Strategy, COM(2026) 112 final, p. 1.

- **Corridor-based decarbonisation and demand for low-carbon logistics chains.** Growing demand from cargo owners, industrial users and public authorities for low-carbon, traceable and resilient logistics chains. Port ecosystems are increasingly assessed not only by their maritime capacity, but by their ability to connect clean maritime transport with rail, road, inland waterways, inland logistics platforms, industrial areas and energy networks. This creates a market and policy driver for technologies that integrate port decarbonisation with corridor performance, modal shift, verified emissions data and reliable hinterland connectivity.
- **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, foreign investments in ports 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.[28]
- **Industrial strategy and circular economy.** Ports provide the physical base for ship repair, maintenance, retrofitting, recycling, offshore energy, the blue economy 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[29]. 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.

28 EU Ports Strategy, COM(2026) 112 final, pp. 10–15.
29 EU Ports Strategy, COM(2026) 112 final, p. 1.

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 (at national level). This is a substantial limitation to investments in shore power installations, and connection is constrained by missing physical connections, substation limits and frequency conversion.[30] Onshore power supply reaches 62% of surveyed European seaports, but this is mainly concentrated in low-voltage installations. High-voltage connections for larger ships remains scarce.[31] Electrification depends on grid expansion and reinforcement, smart-grid and non-wire solutions and demand management, grid permitting and connection availability, in particular for small and medium ports. Furthermore, affordable electricity availability is both a constraint and a driver, as well as port energy system readiness.
- **Standardisation on handling mobile battery/energy systems.** The deployment of battery-charging systems is challenged by the absence of common standards across ports and terminals. Differences in (battery) handling procedures, charging interfaces, safety requirements, and terminal equipment limit the ability to roll-out electrification in both seagoing and inland shipping. Without harmonised standards, operators may face increased costs, reduced operational flexibility, lower asset utilisation, and slower market adoption.
- **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.[32] 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, draughts 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.[33] Regional conditions diverge, with winter navigation constraints in the north and heat-stress conditions in the south.[34] 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.[35] Regional conditions diverge, with winter navigation constraints in the north and heat-stress conditions in the south.[36] Solutions must be modular, scalable and affordable rather than uniform.

30 EU Ports Strategy, COM(2026) 112 final, p. 7.
31 ESPO, Environmental Report 2025, pp. 22-23.
32 ESPO, Environmental Report 2025, pp. 24-25.
33 ESPO, Environmental Report 2025, pp. 16-17.
34 Waterborne Technology Platform, Strategic Research Agenda for the European Waterborne Sector (Brussels: Waterborne TP, June 2025), p. 14.
35 OECD, Policy Pathways Beyond the Shoreline: Enhancing Resilience and Innovation in Island Economies, OECD Rural Studies (Paris: OECD Publishing, 2025).
36 Strategic Research Agenda (June 2025), p. 14.

- **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.[37] 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. Furthermore, speeding up permitting processes for greening and renovating port terminals will be key.
- **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.
- **Fragmented risk ownership across port, terminal, vessel and energy actors.** Bunkering, charging, shore power and cargo handling will likely occur simultaneously. Combined fire, release, grid, digital and physical risks are not always assessed together. Responsibilities, safety evidence and emergency interfaces vary between ports. This delays approval and creates cascading operational disruption.
- **Port-hinterland and intermodal coordination bottlenecks.** There is a coordination gap between port-side investments and hinterland/intermodal capacity. A port authority may develop OPS, electrification, sustainable alternative fuel infrastructure, terminal digitalisation or energy-management systems, but the decarbonisation impact depends on coordinated deployment with terminal operators, railway infrastructure managers, logistics platforms, transport operators, grid operators, energy providers, industrial users and public authorities. Bottlenecks outside the port perimeter can limit the impact of port-side innovation: insufficient rail capacity, weak last-mile connections, lack of interoperable data, grid connection delays, fragmented responsibilities and uncertainty on who bears demand and investment risk.

37 ESPO, Environmental Report 2025, pp. 20-21.

- **Investment and financing.** Estimated investment needs for European ports reach around EUR 80 billion over the ten years to 2034, equivalent to roughly EUR 7–9 billion annually, against EU support of approximately EUR 10 billion for deployment and more than EUR 200 million for research and innovation since 2014.[38] Funding bottlenecks include access to secure finance, rising costs, lengthy permitting and a lack of support for brownfield reconversions. Closing the gap requires a mix of EU, national and private funding with de-risking instruments. Attracting more and faster investment from partners with a proven track record of long-term developed based on sound business plans and parameters will be critical.

- **Fragmented governance, unclear allocation of responsibilities and limited capacity to coordinate multi-actor investments.** Fragmented governance and the division of responsibilities for infrastructure, data and investment among port authorities, terminal concessionaires and operators, energy and grid operators, infrastructure managers, customs authorities, municipalities and other public bodies. Port authorities do not always directly control all the assets and operational processes required for electrification, digital interoperability, cybersecurity and hinterland integration. Different investment cycles, procurement procedures, legal competences and commercial priorities can delay decisions and prevent port-wide solutions from progressing beyond individual pilots.

- **Skills availability and workforce shortages are cross-cutting constraints.** The safe deployment of new fuels, electrification, circularity, digital systems, automation and remote operations depends on the availability of suitably trained port personnel, shore operators, crews, emergency responders, inspectors and maintenance teams.[39] Skills gaps may slow deployment or increase operational risk. Training systems, competence standards and certification requirements will need to evolve in parallel with innovations, while human-centered design will be necessary to ensure that digital and automated systems support rather than overburden port personnel and crew.

38 ESPO estimates a EUR 80 billion investment need for European ports over the ten years to 2034, equivalent to around EUR 7–9 billion annually: European Sea Ports Organisation, Port Investments Study 2024: The Investment Pipeline and Challenges of European Ports, prepared by Peter de Langen (Brussels: ESPO, 2024), pp. 19, 24, https://www.espo.be/media/ESP-3217_InvestmentStudyReport2024_LR.pdf, as cited in European Commission, EU Ports Strategy, COM(2026) 112 final, Brussels, 4 March 2026, p. 15, n. 54; EU support figures at p. 15.

39 European Tugowners Association, consultation with the Waterborne Technology Platform (2026); European Maritime Safety Agency, Annual Overview of Marine Casualties and Incidents (Lisbon: EMSA, 2025).

3. TARGET CAPABILITIES

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 Technology Leadership framework, which requires ports to evolve from infrastructure providers into system orchestrators delivering resilient, zero-emission services by 2050.[40] 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.[41] 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%).[42] 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.[43] Regulation sets the near-term anchor, with onshore power supply required for larger container and passenger ships at TEN-T maritime ports by 2030.[44] 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 have established smart and clean operational foundations.[45] Shore power, electric-ship charging, electrified equipment and energy-efficient terminal operations are widely deployed and planned against port-wide electricity demand. Operational procedures for hydrogen, ammonia and methanol bunkering are in widespread use, alongside CO_2 handling systems and early procedures for nuclear-powered vessels. Ports deploy modular zero-emission microgrids integrating renewable generation, energy storage and ammonia-to-power or hydrogen-based power systems to support shore power, charging and critical infrastructure. Ports are able to measure and report the decarbonisation impact of port-side technologies on the wider logistics chain. Interoperable digital port and hinterland ecosystems are becoming mainstream. Port Community Systems exchange standardised and secure data with the European Maritime Single Window environment, customs and security authorities, terminal systems, railway and road operators, multimodal freight terminals and energy-management platforms. AI-supported port operations, digital twins, predictive maintenance, trusted maritime data spaces, cyber-secure port systems and integrated multimodal traffic management are in place. Harmonised data procedures enable exchange between European port stakeholders, and port digital twins and AI-enabled traffic coordination are in initial deployment across terminal clusters. Autonomous vessel-traffic coordination is integrated with port digital platforms, integrated cybersecurity platforms rolled out, and adaptive and nature-based port infrastructure demonstrated. Joint port, terminal, vessel and responder emergency plans are in place. Digital and sustainable alternative fuel training programmes for port operators are introduced.

40 Waterborne Technology Leadership (January 2026), p. 21.
41 ESPO, Environmental Report 2025, pp. 22–23.
42 ESPO, Environmental Report 2025, pp. 24–25.
43 ESPO, Environmental Report 2025, pp. 16–17.
44 AFIR, Regulation (EU) 2023/1804, Art. 9.
45 Waterborne Technology Leadership (January 2026), p. 22.

3.3. 2040 – SYSTEM INTEGRATION AND LARGE-SCALE AUTOMATION

By 2040, ports achieve system integration and large-scale automation.[46] Electrification and zero-emission core port operations are near complete, supported by consolidated multi-energy hubs supplying sustainable alternative fuels, green electricity and hydrogen-based products, specified to each port's needs. Ports operate integrated multi-energy systems where ammonia, hydrogen and renewable electricity can be dynamically converted, stored and supplied according to operational demand, reducing dependence on external grid capacity. Furthermore, adequate climate crisis adaptability is in place. Logistics platforms are fully integrated, linking vessels, terminals, hinterland corridors and energy networks, and protocols for autonomous vessel operations are harmonised.
Ports operate integrated port-corridor coordination systems linking vessels, terminals, rail, road, logistics platforms and energy networks, supported by interoperable data and common emissions accounting. Ports are becoming fully interoperable smart ports with automated energy management, integrated sustainable alternative fuel infrastructure and seamless digital connectivity between ships, terminals and hinterland transport. Mature automation and robotics are deployed in cargo handling, inspection, maintenance and security operations, and resilient and adaptive port-infrastructure models in place across Europe's main corridors. Port digital safety twins for predictive risk and response have been developed and corridor stress tests and mutual-aid arrangements across ports will be in place. Workforce transformation is supported by digital control rooms, advanced simulation training and new operational roles.

46 Waterborne Technology Leadership (January 2026), pp. 22-23.

3.4. 2050 – FULLY INTEGRATED, ZERO-EMISSION, AUTONOMOUS PORT ECOSYSTEMS

By 2050, European ports function as fully integrated, zero-emission, resilient and autonomous ecosystems, supported by intelligent decision-support systems, circular infrastructure, integrated energy hubs and secure European digital infrastructure.[47] Port ecosystems are fully integrated into zero-emission logistics chains and industrial corridors, with autonomous operations functioning safely across terminals, waterways and integrated logistics nodes and mature clean energy services, resilient infrastructure, secure digital systems and measurable contribution to European competitiveness and strategic autonomy. Ports serve as central hubs for renewable energy import and export, renewable fuels distribution and CO_2 management, and material flows are fully circular, supported by advanced digital, reuse and recycling systems. Port systems are highly resilient and cyber-secure, protecting critical waterborne and energy infrastructure. The Technology Leadership framework sets the corresponding infrastructure end-state, with ports operating as Smart Ports and as hubs of sustainable alternative energy under city-port-nature planning. Continuous assurance and adaptive recovery across port ecosystems will be deployed by 2050.

3.5. CROSS-CUTTING CAPABILITY IMPLICATIONS

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

The capability model is therefore 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.

47 Waterborne Technology Leadership (January 2026), p. 23.

4. TECHNOLOGY PATHWAYS

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, Development and Innovation (RD&I) 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 requires integrated approaches combining full or partial electrification of port equipment, shore-side power supply, high-capacity vessel charging, renewable energy generation, advanced energy storage systems, smart grids and microgrids, demand side management and digital energy management. Particular attention should be given to grid constraints, peak demand management, local generation and storage, non-wire solutions and the resilience of port energy systems under disruptions. Infrastructure for hydrogen, ammonia, methanol, CO_2 logistics, offshore energy import/ export and other relevant energy carriers should be developed according to port function, traffic demand, safety requirements, available space and regional energy system conditions. Not all ports will need to accommodate all energy carriers or technologies, and deployment pathways should therefore remain modular, scalable and demand driven.

4.1.1. Operational objective

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, energy storage and advanced energy management. This includes the capability to dynamically balance highly variable energy demand and supply, reduce peak loads, coordinate energy use across port stakeholders and maintain operational continuity under grid, market or infrastructure disruptions. Vessel-port energy alignment should enable interoperable coordination between vessel energy management systems, port infrastructure, terminal equipment, hinterland charging systems and relevant industrial users.

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, and 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, infrastructure use and resilience.

- 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.
- Scalable and modular energy solutions, including mobile or flexible shore power and charging systems where appropriate, support deployment across ports with different traffic volumes, berth configurations and grid capacities.

By 2040:

- Ports achieve widespread electrification and zero-emission core operations, supported by mature smart-grid integration, high-capacity charging infrastructure and multi energy hubs supplying the energy carriers required by each port's traffic and industrial role.
- Localised energy supply, storage and flexibility solutions are deployed where appropriate to meet local demand, reduce grid congestion and strengthen port energy resilience.
- Local renewable generation, energy storage, smart grid solutions and demand side flexibility increasingly complement grid reinforcement and improve port energy resilience.
- Port and vessel energy management systems exchange standardised operational and energy data, supporting optimised charging, shore power use, bunkering and wider port energy system coordination.
- Where relevant to specific port and regional energy strategies, the potential role of emerging energy technologies, including small modular reactors, may be assessed subject to appropriate safety, regulatory, security, spatial, environmental and waste management requirements.

By 2050:

- Ports function as zero-emission and resilient energy and logistics ecosystems, integrated into zero-emission maritime and hinterland transport chains, with deployment pathways adapted to port function, traffic demand, energy role and local conditions.
- Energy systems operate autonomously and adaptively, balancing electricity, renewable fuels, energy storage, flexible demand and carbon management systems.
- Port energy systems are designed for high operational resilience, with appropriate redundancy, local flexibility and recovery capability to maintain critical functions during grid or infrastructure disruptions.

4.1.3. Key research gaps

- 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, island, inland and regional ports. Solutions should also consider vessel categories not currently subject to mandatory Onshore Power Supply requirements where operational demand justifies deployment.
- High-capacity vessel charging. Further development and demonstration of fast and ultra-fast charging systems for short-sea shipping, inland waterway transport and work vessels and other suitable vessel segments, addressing grid impact, power electronics, safety, interoperability, connection systems and battery degradation.
- Smart grid, storage and flexibility solutions. Further RD&I on intelligent energy management combining batteries, hydrogen-based storage, thermal storage, local renewable generation, demand side management and other flexibility solutions to manage peak loads, renewable intermittency and operational requirements at port scale.

- Energy system resilience. Research on resilient-by-design port energy infrastructure, including redundancy, local generation and storage, island or off-grid capability where appropriate, recovery strategies and cascading failures across interconnected energy and logistics systems.
- Vessel - port energy alignment. Development of common communication and data interfaces between the energy management systems of the vessel and of the different stakeholders in the port (including port equipment, vessel and hinterland charging infrastructure and industrial users).
- System-level energy optimization and digital twins. Development of port-wide digital energy twins capable of simulating, predicting and optimizing energy demand, supply, grid constraints and infrastructure investment decisions under different traffic, weather, disruption and market scenarios.
- Multi-use charging and energy infrastructure. Development of solutions allowing infrastructure to support vessels and, where technically appropriate, other port and hinterland applications, improving utilisation and investment efficiency.
- Sustainable alternative fuel and carbon management infrastructure. Development of harmonised standards and safe, cost-efficient solutions for multi-fuel bunkering, CO_2 handling, Ship Based Carbon Capture offloading and processing, and circular resource flows, including scalable and retrofit solutions suitable for different port types.
- Nuclear related port requirements. Research is needed on the safety, security, spatial, operational, emergency response and regulatory implications for ports associated with nuclear powered vessels and, where relevant, potential small modular reactor applications, without assuming their applicability across all port types.
- Energy infrastructure business models. Development and demonstration of scalable and replicable business models, including energy-as-a-service, shared infrastructure, flexibility markets and collaborative investment arrangements that account for demand uncertainty and differences between port types.

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, development 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 RD&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. RD&I needs to concentrate on automation, robotics, sensor development, AI-enabled scheduling and decision support, predictive capacity management, predictive maintenance and digital twins of port operations.

Digital twins should progressively evolve from asset-specific applications towards integrated port-system applications covering maritime and hinterland traffic coordination, berth planning, terminal operations, energy systems, infrastructure and logistics information. Data sharing enables this. Data sharing must be seamless amongst logistics actors themselves, but also with customs and other authorities, including information supporting customs compliance, track and trace and multimodal coordination. 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. The availability, quality, standardisation and interoperability of data are equally important prerequisites for effective AI, digital twin and optimisation applications.

4.2.1. Operational objective

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. European resilience should also be supported through secure and reliable digital architectures and, where feasible, by reducing strategic dependencies in technologies supporting critical port infrastructure.

4.2.2. Target capability 2035, 2040 and 2050

By 2035:

- There are developed plans and increasingly operational implementations 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.
- Building on existing Port Community Systems and other operational digital platforms, a significant share of European ports move beyond first stage pilots towards structural deployment of integrated digital systems and digital twins supporting maritime and hinterland traffic coordination, berth planning and terminal operations, including customs compliance and track and trace information. Transport and port operations are tracked in real time and incidents or operational deviations are automatically identified.
- AI-based decision support tools are increasingly integrated into operational workflows, assisting 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.
- Initial large-scale 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, hinterland corridors and energy networks. The number of participants in the digital ecosystem has increased significantly.
- Harmonised protocols support autonomous vessel operations, autonomous port handling equipment, autonomous trucks and autonomous trains.
- Mature automation and robotics are deployed 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, predictive maintenance 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, supported by interoperable data spaces and common semantic models.

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 routine port and logistics corridor operations 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. Key research gaps

- Digital ecosystem. Digital interoperability and harmonisation are 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 interoperable data spaces. Existing data space initiatives and developments are still siloed by sector, and seamless data sharing in the port ecosystem will require interoperability between mobility (EMDS), energy (CEEDS), customs and logistics data environments. Common semantic models are required to enable consistent exchange of vessel, cargo, infrastructure, operational and energy data.
- Port-scale digital twins. Further RD&I is required to develop high-fidelity digital twins integrating vessel traffic, terminal operations, infrastructure, energy systems, environmental conditions and hinterland logistics, moving from asset specific and descriptive models towards predictive and prescriptive decision-support tools.
- Scalable automation and robotics. Research into modular and 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 AI models for demand forecasting, anomaly detection, predictive maintenance, optimisation of vessel calls, yard and hinterland operations, emissions monitoring and energy management. Key challenges include access to high-quality, standardised data, explainability, trust, governance and ethical use of AI.
- Cybersecurity and trusted digital corridors. RD&I is needed on secure-by-design architectures that ensure data sovereignty, post-quantum readiness, cryptography and PET, resilient digital corridors and protection of automated systems. As automation and autonomy increase, cyber resilience and data integrity become critical requirements across the port and logistics ecosystem.
- 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, including the implications of automation for workload, job profiles, working conditions 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. Resilience unfolds across four interconnected capacities: planning and preparation, absorption and response, recovery and adaptation, and transformation towards enhanced performance. This includes safety and security risks such as disruptions of communication systems or drug traffic, but also other risks such as effects of sudden-onset disruptive events (floods, heatwaves & droughts, extreme precipitation events, storm surges, wildfires) and slow-onset events (sea level rise, salinisation, loss of biodiversity and invasive species, changing precipitation patterns and changes in water availability) as well as energy disruptions such as blackouts and cascading failures between the grid, ports and the logistics system, and changes in global trade patterns such as nearshoring and 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. Adaptation should consider both engineered and nature-based solutions, including measures addressing heat, flooding, water level variability and other location specific climate impacts.

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

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. This includes adaptation to location specific impacts such as heat stress, flooding, sea level rise and low water conditions affecting inland port and hinterland operations.

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, heat-resilient and greener climate-resilient surfaces, flood protection measures and other climate adaptation solutions) 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.
- Initial demonstration and uptake of nature-based and hybrid nature-engineered solutions for climate adaptation, where appropriate to local port and coastal conditions.

By 2040:

- Deployment of resilient and adaptive port-infrastructure across Europe's main corridors.
- Identification, exchange, and wider deployment of proven resilience and adaptation practices across different port types, allowing solutions developed in large, medium-sized, small, inland, island or regional ports to be transferred where relevant.
- Infrastructure systems incorporate continuous monitoring and predictive maintenance capabilities, enabling proactive adaptation to changing environmental and operational conditions.

- Predictive climate and risk modelling tools increasingly support preparedness for heat, flooding, extreme weather, water level vulnerability and other location specific hazards.
- Nature based and hybrid adaptation solutions are increasingly integrated into port infrastructure and spatial planning strategies where technically and environmentally appropriate.

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.
- Critical port functions are supported by mature preparedness, emergency response and recovery arrangements capable of maintaining or rapidly restoring essential services following major disruptions.

4.3.3. Key research gaps

- Infrastructure monitoring and risk intelligence. Fit for purpose architectures are needed for data ecosystems monitoring infrastructure and asset conditions against evolving risks. This requires access to a variety of proprietary data sources, including sensors, in combination with AI and uniformed KPIs for asset performance, condition monitoring, prevention and intervention.
- Decision-support and predictive resilience models. Further development of decision support and predictive models enabling ports, including small and medium sized ports, to assess system impacts, identify emerging threats, evaluate disruption scenarios and adaptation options, define acceptable disruption levels and prioritise investment.
- 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.
- Climate adaptation solutions. Further research and demonstration addressing location specific climate hazards, including sea-level rise, flooding, storm surge, extreme heat, low water conditions and other changing hydrological or meteorological conditions affecting port and hinterland operations.
- Nature-based and hybrid resilience solutions. Research is needed on the performance, scalability, lifecycle costs and operational integration of nature-based and hybrid nature-engineered solutions for flood protection, heat mitigation, coastal resilience and biodiversity enhancement in different port environments.
- Emergency preparedness, response and recovery. Development and validation of predictive tools, emergency response concepts, and recovery strategies supporting continuity or critical port functions under climate, infrastructure, energy and other major disruptions.
- Surveillance and inspection technologies. Development of novel surveillance and inspection technologies, including aerial, surface and underwater drones, for infrastructure monitoring and early detection of damage or emerging risks.
- Sensors, analytics and predictive maintenance. Innovation in sensor technologies, data analytics and predictive models supporting early detection of infrastructure 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, according to their function, location, demand and links with surrounding industrial and energy systems. 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 advancing multi-energy terminals, circular waste and recycling solutions, and digitally managed resource flows linking waterborne, industrial and urban sectors. Circularity should be addressed across the lifecycle of port infrastructure, equipment and material flows, prioritising resource efficiency, life extension, reuse, refurbishment and repurposing before recycling and final recovery.

4.4.1. Operational objective

Enable ports to function as integrated multi-energy 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. Enable ports to identify, optimise and progressively close material and resource loops across port infrastructure, equipment, logistics activities and connected industrial 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 clusters.
- Port level mapping of relevant energy, material and resource flows supports identification of opportunities for industrial symbiosis, reuse, refurbishment, repurposing and recycling.
- Circular economy activities focus on reuse of excavated materials, circular procurement, industrial symbiosis, waste heat utilisation, recycled construction materials and digital product passports, together with lifecycle extension and reuse of port infrastructure, equipment and components where feasible.

By 2040:

- Ports with an appropriate energy and industrial role 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, refurbishment, repurposing and recycling.
- Lifecycle and circularity principles are increasingly embedded in the design, procurement, maintenance, upgrade and renewal of port infrastructure and equipment.

By 2050:

- Ports with relevant energy functions serve as central hubs for renewable energy import/export, hydrogen distribution and CO_2 management.
- Circular material flows are highly developed, supported by advanced digital tracking, such as in Digital Product Passports (DPPs), reuse, refurbishment, repurposing and recycling infrastructure, contributing to closed-loop and climate-neutral logistics and industrial systems.
- Port infrastructure and equipment are increasingly designed, operated and renewed according to lifecycle and circularity principles, maximising asset life, reuse and material recovery.

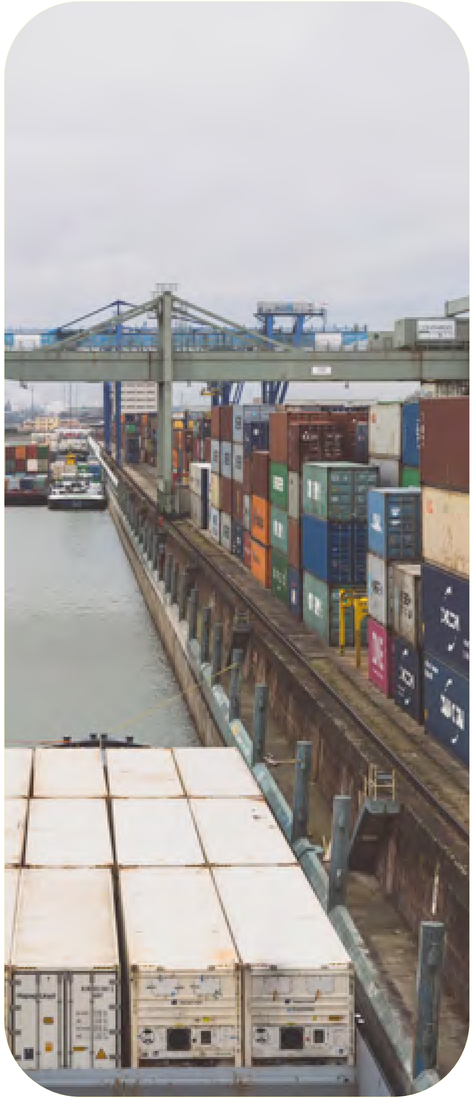
4.4.3. Key research gaps

- Circular economy system integration. RD&I into design of infrastructure, digital architectures 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).
- Lifecycle circularity of port infrastructure and equipment. Research into design, maintenance and asset management approaches that extend service life and enable repair, refurbishment, repurposing, reuse and high value material recovery of port infrastructure, equipment and components.
- Mapping and optimisation of circular resource flows. Development of methods and digital tools to identify, quantify and optimize material, waste, energy and secondary resource flows within ports and between ports, industrial clusters and surrounding regions.
- 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.
- Industrial symbiosis and cross sector circularity. Research and demonstration of scalable approaches enabling ports, industries, cities and logistics actors to exchange energy, heat, materials, by products and secondary resources, including assessment of technical, spatial regulatory and business model requirements.

4.5. ENHANCED SECURITY AND (CYBER-)RESILIENCE FOR CRITICAL PORT INFRASTRUCTURE

Strengthen security of digital port-critical infrastructure and networks, including energy systems, digital platforms, operational systems and underwater assets. 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.

Particular attention should be given to maintaining continuity of critical port functions under cyber, physical, energy and hybrid disruptions, and to ensuring that ports of different sizes and digital maturity levels can implement appropriate baseline levels of security and resilience.



4.5.1. Operational objective

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.

Ports should be able to prevent, detect, respond to and recover from cyber-physical disruptions while maintaining or rapidly restoring critical operational functions. Security and resilience measures should be proportionate to the risk profile, function and technological maturity of each port.

4.5.2. Target capability 2035, 2040 and 2050

By 2035:

- Implementation of state-of-the-art cybersecurity technologies and common baseline security and resilience measures, supported by dedicated tools and guidance suitable for small and medium sized ports and their stakeholders.
- Initial integration of cyber and physical security monitoring supports improved situational awareness, early detection and incident response.
- Adoption of Zero Trust Architecture in relevant port digital 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.
- Business continuity and recovery arrangements are in place for critical port functions, including procedures for operation under degraded digital, communication or energy conditions.
- Joint exercises and representative disruption scenarios are increasingly used to test coordination between port authorities, terminal operators, public authorities, emergency services and critical infrastructure operators.

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.
- Security information and situational awareness are increasingly coordinated across port communities and, where relevant, between ports and connected logistics and critical infrastructure networks.
- Resilience systems support continuity of essential operations through redundancy, alternative operating modes and coordinated recovery procedures.
- Cross port and corridor level exercises validate response and recovery capabilities for large scale cyber, physical and hybrid disruptions.

By 2050:

- Port ecosystems achieve a high 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.
- Critical port functions can continue or be rapidly restored under complex and cascading disruptions, supported by integrated cyber-physical monitoring, redundancy, adaptive response and recovery systems.

4.5.3. Key research gaps

- Port Specific cybersecurity and resilience solutions. Determine which existing and emerging cyber security technologies and resilience approaches are most suitable for uptake in different port ecosystems, especially in small and medium sized ports, with limited technical and financial capacity.
- Smart prevention and early warning. Further development of systems that move beyond detection and response towards anticipation and prevention of cyber, physical and hybrid threats through continuous monitoring, anomaly detection, risk intelligence and predictive analytics.
- Integrated cyber-physical security. Research on architectures that combine cyber, physical, operational and energy system security, including protection of critical infrastructure, underwater assets, automated equipment and interconnected logistics systems.
- Business continuity and recovery. Development and validation of methods, technologies and operational procedures that enable ports to maintain critical functions under degraded conditions and recover rapidly following cyber, energy, communication, physical and hybrid disruptions.
- Autonomous cyber resilience. Development of self-monitoring, self-healing and AI-supported resilience management systems that can anticipate threats, assess possible courses of action and support human decision making before disruptions escalate (reasoning about courses of action to advise the human, etc.)
- Cross-port and corridor resilience. Research on shared situational awareness, coordinated response, mutual support and recovery mechanisms between ports and connected transport, energy and logistics networks, including joint exercises and large-scale disruption scenarios.
- Resilience metrics and validation. Development of common methods and indicators for assessing cybersecurity, operational continuity, recovery time, minimum service levels and overall cyber-physical resilience across different types.

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, engineering, 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 upskilling and reskilling current workers, including preserving, transforming and transferring relevant sectoral know-how.

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

Automation and digitalisation will change the content and organisation of port work but should not be assumed to translate directly into reduced employment. They may reduce exposure to hazardous or repetitive tasks while creating new technical, supervisory, maintenance, data and system integration roles. Workforce transformation should therefore focus on evolving job profiles, skills requirements, working conditions and effective human oversight of increasingly automated systems.

4.6.1. Operational objective

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.

The objective also includes ensuring that workforce transformation accompanies electrification, circular economy activities and new energy systems, while preserving operational knowledge, safety, job quality and the capacity for effective human intervention.

4.6.2. Target capability 2035, 2040 and 2050

By 2035:

- Wider uptake of digital, electrification, energy transition and alternative fuel training programs for port operators
- Digital control rooms and simulation-based training environments are more widely deployed to support new and evolving operational roles.
- Competence frameworks increasingly address automation, high voltage systems, energy management, circularity, cybersecurity and human-machine interaction alongside conventional port operational skills.
- Workforce transition plans identify changing job profiles and reskilling needs associated with automation and digitalisation, while considering impacts on workload, safety and working conditions.

By 2040:

- Workforce transformation is supported by digital control rooms, advanced simulation training and new operational roles
- Continuous learning and reskilling are embedded in organisational models.
- Human-machine cooperation is mature across automated terminal, energy, maintenance, and logistics operations, with clearly defined responsibilities for supervision, intervention and decision making.
- Training and career pathways increasingly combine maritime and port operational knowledge with digital, electrical, energy, circular economy and cyber resilience competences.

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.
- Continuous skills development supports workers throughout successive technological transitions, while preserving critical operational knowledge and enabling adaptation to new roles and technologies.

4.6.3. 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, decision authority, situational awareness and appropriate levels of human intervention.
- Training and skills development for future ports. Research into competence requirements, training methods and certification approaches for electrification, sustainable alternative fuels, automation, AI, cybersecurity, digital control rooms, circular economy activities and resilience management.
- Workforce impacts of automation and digitalisation. Research on how automation changes job content, task allocation, staffing models, occupational profiles and working conditions, including the balance between reduced exposure to repetitive or hazardous work and the creation of new technical and supervisory roles.
- Organizational and business model innovation. Research into organisational structures, collaboration models and management practices required for increasingly integrated, automated and energy intensive port ecosystems.
- Social acceptance and workforce resilience. Research into change management, trust in automation and long-term impacts of digitalization, decarbonization and circular economy transition on port employment, skills, working conditions and workforce resilience.
- Knowledge retention and transfer. Research into methods for preserving and transferring tacit operational knowledge as experienced workers retire and new digital and automated operating models are introduced

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 and frameworks for energy system integration, sustainable alternative fuel certification, operational telemetry and monitoring, automated operations and coordinated multimodal planning. Interoperability should extend across port community, customs and maritime reporting systems, vessel interfaces and hinterland transport networks, while taking account of relevant international standards and global maritime and logistics interfaces.

Regulatory and standardisation frameworks should evolve sufficiently rapidly to avoid becoming barriers to deployment, while maintaining appropriate levels of safety, security, environmental protection and data governance. Priority standards and protocols required for large scale deployment should be substantially advanced by 2035, rather than assuming that all regulatory and standardisation issues can be fully resolved by that date.

4.7.1. Operational objective

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. The frameworks should support coherent interaction between ports, vessels, customs and other public authorities, terminal and logistics operators, energy systems and hinterland transport, while facilitating interoperability with international shipping and logistics networks.

4.7.2. Target capability 2035, 2040 and 2050

By 2035:

- Initial alignment and operational implementation of priority standards and regulatory approaches supporting data sharing, sustainable alternative fuels, electrification and charging, automation and multimodal operations across European ports.
- Common standards and interfaces are increasingly applied for port-vessel, port-port and port hinterland information exchange, including interaction with Port Community Systems, customs and relevant maritime reporting environments.
- Regulatory sandboxes and large scale operational demonstrations generate evidence for certification, safety requirements and future harmonisation of emerging digital, automated and energy technologies.
- European standards and data frameworks are developed, with compatibility with international maritime and logistics standards to avoid creating isolated regional solutions.

By 2040:

- Harmonized regulatory frameworks and standards enable seamless port-port, port-vessel and port-hinterland interoperability across European corridors.
- Digital, energy and automated operation interfaces are widely standardised, supporting cross border deployment and interoperability among vessels, terminals, authorities, energy systems and multimodal transport networks.
- European approaches are aligned, where appropriate with international standards and regulatory frameworks, supporting interoperability with global shipping and logistics chains.

By 2050:

- Adaptive, innovation-friendly regulatory ecosystems support fully integrated, zero-emission and autonomous transport and logistics systems.
- Regulatory and standardisation frameworks evolve continuously with technological development, allowing new technologies and operating concepts to be introduced while maintaining safety, security, interoperability, environmental performance and human oversight.

4.7.3. Key research gaps

- Regulatory innovation and sandboxes. Development and evaluation of regulatory approaches and controlled testing environments that allow emerging energy, digital and autonomous solutions to be demonstrated under realistic port conditions and generate transferable evidence for wider deployment.
- Standardisation for interoperability. Development and validation of common standards, interfaces and semantic models supporting port-port, port-vessel, port-hinterland and port-energy interoperability, including compatibility with relevant international standards.
- Digital reporting and authority integration. Further integration of port-community and operational data systems with customs, maritime reporting and other public-authority systems, reducing duplication and enabling secure and efficient data exchange across the logistics chain.
- Multimodal system integration. Research on regulatory, digital and operational frameworks supporting coordinated planning and information exchange across maritime, rail, inland-waterway and road transport.
- Standards for emerging automated and energy interfaces. Research and pre-standardisation activities for new operational interfaces associated with autonomous vessels and equipment, high-capacity charging and other emerging port-vessel interactions, building on the more detailed technology requirements identified in Sections 4.1 and 4.2.

5. ENABLERS AND DEPLOYMENT

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. Affordability and long-term economic viability are also essential, particularly for capital intensive energy, digital and infrastructure investments and for smaller ports with more limited investment capacity. deployment also needs to be supported by appropriate standards, interoperable interfaces, skills and organisational capacity, secure and resilient digital and communication infrastructure, operational validation and regulatory frameworks capable of evolving alongside technological development.

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, affordable 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; appropriate contractual, procurement and governance arrangements 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. Deployment planning should also incorporate integrated risk assessment, climate adaptation and infrastructure condition information, enabling investment priorities and acceptable disruption levels to be defined in relation to local conditions and port functions. 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. Deployment should also recognise the role of medium sized regional ports, industrial port clusters and other specialised ports as potential sites for technology demonstration and replication.

5.2 ENERGY-SYSTEM READINESS AND PORT INFRASTRUCTURE

Ports need to enable access to 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. Port-wide energy planning should coordinate port authorities, terminal operators, vessel operators, energy suppliers, grid operators and relevant industrial users and should address both infrastructure investment and operational energy demand. Local markets, energy storage and non-wire solutions should complement conventional grid reinforcement where technically and economically appropriate. Deployment should also consider the affordability of electricity and other energy carriers, grid connection costs and investment conditions needed to make electrification commercially viable. Local generation, storage and flexibility solutions can complement grid reinforcement where appropriate. 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. Appropriate safety, security, emergency response and waste management frameworks will also be required where ports interact with emerging energy technologies, including nuclear powered vessels or related systems where relevant. Common and progressively harmonised interfaces should support high power shore side electricity, high-capacity vessel charging and sustainable alternative fuel bunkering. Port and vessel energy management systems should increasingly exchange interoperable operational and energy data, including information on connection and charging events, bunkering operations, equipment consumption, energy sources, emissions, location, time windows and operational status. For ports acting as energy and industrial hubs, baseline mapping of energy, material and resource flows and appropriate spatial planning should support integration with industrial clusters, renewable energy systems, CO_2 logistics and circular value chains.

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. Participation in these digital ecosystems should be accessible to actors with different levels of digital maturity, including small and medium-sized ports and businesses. Common digital foundations and scalable onboarding solutions are needed to prevent the emergence of isolated systems and new digital divides within the European port network. High-quality, standardised and accessible data should be supported by common semantic models and interoperable data spaces spanning maritime, logistics, customs, energy and hinterland systems. Secure data sharing should combine data sovereignty with appropriate cybersecurity and privacy technologies, including Privacy Enhancing Technologies and, as technologies mature, post-quantum-ready security approaches. Digital infrastructure should provide the connectivity and computational capacity required for increasingly data intensive and time critical applications, including 5G/6G, edge computing and secure resilient communication infrastructure where appropriate. Industry associations, standardisation bodies and platforms should be mobilised to support common terminology, operational definitions, interoperability and deployment practices. Because European ports are part of global maritime and logistics networks, European data and interoperability frameworks should, where appropriate, remain compatible with relevant international standards and systems.

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. Demonstrations should operate under representative real-world conditions and integrate technologies with actual port and logistics processes. They should include, where relevant, automated and autonomous equipment and vehicles, aerial, surface and underwater systems for inspection and maintenance, digital and physical interfaces, and supporting port processes that may otherwise create new manual bottlenecks. 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. Where appropriate, large scale and cross port demonstrations should generate transferable operational, safety, certification, regulatory and business case evidence that supports replication and commercial deployment across ports with different characteristics. Shared testing and validation environments and regulatory sandboxes should be used where necessary to generate evidence for emerging digital, automated and energy technologies and to avoid repeated project specific approval processes.

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. Relevant standards, guidelines and certification schemes should provide common baseline requirements while allowing application across different port types, sizes and risk profiles. Security-by-design and resilience-by-design principles should be embedded in digital, energy, automation and physical infrastructure as well as operational procedures. Safety, security and resilience should be designed into infrastructure, digital systems and operational procedures from the beginning. Critical functions should be supported by secure and resilient communications, positioning and data exchange infrastructure, appropriate redundancy and alternative operating modes. Continuous monitoring should support situational awareness and early identification of evolving cyber, physical and operational risks, increasingly complemented by AI-supported detection, response and recovery tools under appropriate human oversight. Port wide and corridor level resilience arrangements should also include joint stress tests, emergency exercises, business continuity planning, mutual support arrangements and coordinated recovery procedures involving ports terminal operators, public authorities, emergency services and other critical infrastructure actors. Representative disruption scenarios and shared test environments should be used to validate cyber-physical resilience, incident response and recovery procedures. Regulators, standardisation bodies and industry should cooperate to ensure that regulatory and certification frameworks evolve with technological development. Active European participation in relevant international standardisation should support compatibility between European solutions and global maritime and logistics systems.

5.6 INVESTMENT, FUNDING AND BUSINESS MODELS

Investment sequencing and business models must reflect port governance. Many port assets are operated by terminal operators or other private operators rather than by port authorities directly. Where relevant, contractual and governance arrangements should support the implementation of applicable energy, digital, cybersecurity, resilience and environmental requirements, while avoiding fragmented approaches that undermine a level competitive playing field. 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. Funding and de-risking mechanisms should support the full innovation and deployment cycle, from research and demonstration through first industrial deployment and commercial scale-up, helping to bridge the financing gap between successful pilots and market ready solutions. Business models should support shared and multi-user infrastructure, energy-as-a-service approaches, flexibility markets and collaborative investment arrangements where appropriate, while addressing demand uncertainty and fair distribution of costs and benefits across port ecosystem participants. For circular economy deployment, procurement and asset management approaches should increasingly account for durability, lifecycle extension, repair, refurbishment, repurposing, reuse and material recovery. Long term investment and funding approaches should also consider lifecycle costs, including operation, maintenance, software and cybersecurity updates, data management, equipment renewal and the availability of specialised personnel. Stable and predictable policy, permitting and investment conditions are important for capital intensive port energy and infrastructure projects.

5.7 WORKFORCE AND ORGANISATIONAL CAPACITY

Workforce and organisational capacity are also deployment enablers. Ports will need new skills in electrification, sustainable 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. Competence frameworks and, where appropriate, certification schemes should evolve in parallel with new port roles and technologies. Training infrastructure and curricula should cover high-voltage systems, sustainable alternative fuels, energy systems, circularity, automation, AI, cybersecurity and resilience alongside conventional port operational competences. Ports and port stakeholders should cooperate with universities, vocational education and training providers and professional training organisations to develop relevant programmes and pathways. Skills intelligence and workforce planning tools should identify emerging competence requirements and reskilling needs across occupational profiles. Organisational innovation, change management approaches and social dialogue should support workforce acceptance and effective human-machine collaboration. Particular attention should also be given to preserving and transferring operational know-how as experienced workers retire and new digital and automated working models are introduced.

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. This should include coordinated energy planning, integrated risk and adaptation planning, infrastructure and environmental monitoring, spatial planning for new energy and circular economy functions, and clear allocation of responsibilities among public and private actors. At corridor level, ports must coordinate with hinterland networks, inland ports, shipping lines, rail and road operators, energy systems and logistics platforms. This should extend beyond administrative port boundaries to the functional port hinterland, including relevant last mile rail and road infrastructure, port gates, inland terminals, logistics platforms, freight villages, dry ports, industrial areas and other nodes that influence port and corridor performance. Coordinated planning should address transport capacity, energy demand, infrastructure investment, data exchange and allocation of responsibilities across the port industrial and multimodal corridor. Cooperation with industrial clusters, cities, resource- and waste-management actors and energy providers should also support industrial symbiosis, shared energy systems and circular resource flows where relevant. Border control, customs and maritime reporting processes should also be integrated into port system deployment, building on Port Community Systems, European Maritime Single Window environments and evolving European customs and data systems, while avoiding duplicate reporting and fragmented digital processes. Coordination between port authorities, customs and other public authorities, standardisation organisations, terminal and logistics operators and hinterland actors should support coherent deployment of multimodal and cross-sector interfaces. 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. Cross border cooperation between ports should support joint testing, knowledge transfer, exchange or proven practices and replication of successful solutions. 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. Monitoring should increasingly draw on reliable climate, infrastructure condition, energy and resource flow data and support comparison of deployment and resilience performance across port types.

6. EXPECTED IMPACTS

6. EXPECTED IMPACTS

The implementation of this roadmap will strengthen the role of European ports as competitive, resilient and sustainable system nodes in waterborne transport, logistics, energy and industrial networks. Impacts will be realised progressively as technologies move from demonstration and early deployment towards integrated port system and corridor level operation. Because European ports differ substantially in size, function, energy role, traffic profile, governance model and investment capacity, impacts should be assessed according to port type and function rather than through uniform deployment expectations. Realisation of these impacts will also depend on adequate investment and funding, supportive and harmonised regulatory frameworks, affordable energy and deployment conditions that maintain a level competitive playing field across European ports and operators. The following indicative outcomes provide reference points for assessing progress towards 2035, 2040 and 2050.

Impact dimension	2035 – Deployment and foundations	2040 – Scale-up and integration	2050 – Full transformation
Climate and environmental performance	Widespread deployment of OPS, vessel charging, electrified port equipment, energy efficiency measures and renewable energy integration where demand exists. Measurable reductions in GHG emissions and local air pollutants from vessels at berth and port-controlled operations.	Integrated low- and zero-emission port energy systems increasingly combine electrification, renewable generation, storage, smart energy management and sustainable alternative fuels. Further reductions in port and logistics chain emissions and improved energy efficiency.	Climate neutral port ecosystems integrated into zero emission maritime and hinterland logistics chains, with near zero emissions from port-controlled activities where technically and operationally feasible, high renewable energy integration and mature circular resource flows.
Competitiveness and logistics performance	Improved berth planning, vessel call coordination, cargo visibility and hinterland operations reduce waiting and congestion and improve reliability. Increasing digitalisation supports rail, inland waterway and road coordination.	Integrated port and corridor platforms, improved asset utilisation, logistics reliability, multimodal performance and responsiveness to disruption and changing trade patterns.	Highly integrated port, maritime and hinterland logistics ecosystems support efficient multimodal transport, European supply chain competitiveness and strategic connectivity.

Table 6: Expected Impacts

Impact dimension	2035 – Deployment and foundations	2040 – Scale-up and integration	2050 – Full transformation
Energy and industrial transition	Ports progressively develop the grid, charging, storage, energy management and sustainable fuel capabilities required by their traffic and industrial roles. Port industrial energy cooperation and initial new value chains develop around renewable energy, hydrogen derived fuels, CO_2 logistics and circularity.	Ports with relevant energy and industrial functions increasingly operate as integrated energy nodes, with stronger grid integration, local flexibility, renewable energy, storage and links with industrial clusters.	Ports with relevant functions operate as mature energy and industrial nodes within European transport and energy corridors, supporting clean maritime energy, circular value chains, industrial symbiosis and European strategic autonomy.
Resilience, safety and security	Port wide risk assessment, joint emergency planning, interoperable emergency information and business continuity arrangements support safer deployment of new energy, digital and automated systems.	Predictive risk management, digital safety tools, joint stress testing and coordinated recovery arrangements improve resilience across ports and connected corridors.	Continuous assurance and adaptive recovery are embedded across port, energy, digital and hinterland systems, supporting fewer and less severe incidents, shorter disruptions and rapid restoration of critical functions.
Territorial cohesion and port network development	Modular and scalable solutions enable small, medium-sized, island, inland, outermost region and regional ports to participate according to their needs and capabilities.	Deployment gaps between port types are reduced through replication, shared services, capacity building and improved integration into multimodal and energy corridors.	A resilient and interconnected European port network maintains essential connectivity and enables different port types to contribute to climate neutral transport, energy security and territorial cohesion according to their function.
Innovation, skills and European technology leadership	Increased deployment of digital twins, AI-enabled decision support, smart energy systems and automation is accompanied by workforce training in digital, energy, safety and security competences.	Scalable and interoperable European port technologies, services and business models support wider market deployment, new employment opportunities and stronger industrial ecosystems around ports.	European ports provide a leading market for sustainable port technologies and services, supported by highly skilled workers, human-centred automation, common standards and strong European capabilities in energy, digital, infrastructure and resilience solutions.

Table 6: Expected Impacts

6.1 CLIMATE AND ENVIRONMENTAL IMPACTS

The roadmap contributes to 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 are 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. Where direct electrification is feasible, grid reinforcement, local generation, energy storage and flexibility solutions enable greater use of clean electricity while reducing peak demand and grid constraints. The roadmap also supports more climate-resilient infrastructure and greater use of adaptive and nature-based solutions where appropriate. Progress should be monitored through indicators such as GHG and local-pollutant emissions, OPS energy supplied and utilisation, the share of eligible vessel calls using OPS, electrification of port equipment, renewable energy use, energy efficiency and emissions avoided.

6.2 COMPETITIVENESS AND LOGISTICS PERFORMANCE

The roadmap improves 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 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. Better coordination across the functional port hinterland also reduce truck waiting and congestion, improve rail and intermodal planning and strengthen the reliability of end-to-end logistics chains. 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. Progress should therefore include indicators such as vessel, gate and truck waiting times, cargo dwell time, berth and terminal productivity, asset utilisation, rail and inland waterway modal share, service reliability and logistics related emissions.

6.3 ENERGY AND INDUSTRIAL TRANSITION IMPACTS

The roadmap supports the transformation of ports into active energy and industrial nodes. Ports are 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. Investment in grid capacity, storage, energy management systems and affordable electricity supply will be important to realise these impacts and support waterborne and port electrification. Energy industrial ports and major gateways act as early deployment sites, while modular and scalable solutions allow smaller, island, inland and regional ports to participate in the transition according to their role and capacity. The precise role of port authorities in energy generation, storage and governance depends on national governance models and local circumstances and should not be prescribed uniformly across Europe.

6.4 RESILIENCE, SAFETY AND SECURITY IMPACTS

The roadmap strengthens 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 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 sustainable 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.

By progressively introducing port-wide risk baselines, interoperable emergency information, joint plans and exercises, predictive safety tools and corridor level stress testing, the roadmap reduces incident severity, operational downtime and recovery times while improving the continuity and reliability of essential port services. Monitoring should include indicators such as detection and response time, recovery time, duration of service disruption, exercise coverage, safety critical workforce training and availability of critical functions under degraded conditions.

6.5 TERRITORIAL COHESION AND PORT-NETWORK IMPACTS

The roadmap supports a more balanced transformation of the European port network. By promoting modular, affordable and scalable solutions, it prevents 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. Progress should therefore be assessed not only through absolute levels of technology deployment, but also through the reduction of disparities in energy readiness, digital capability, resilience and access to investment across different port types and regions.

6.6 INNOVATION, SKILLS AND EUROPEAN TECHNOLOGY LEADERSHIP

The roadmap strengthens European technology leadership in port ecosystems by supporting the transition from isolated pilots to interoperable, scalable and replicable port-system solutions. It creates 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. The transition also generates demand for new and evolving competences in electrification, energy systems, digital operations, automation, AI, cybersecurity, circularity and resilience.

Expected social impacts include safer and higher quality work, reduced exposure to hazardous or repetitive tasks, new technical and supervisory roles and continuous skills development, while maintaining human oversight of increasingly automated port systems. For port cities and regions, reduced air pollution, noise and environmental pressures also contribute to improved quality of life and stronger acceptance of port activity while maintaining the port's economic and connectivity functions.

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