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# RETHINKING EEA-EMSA'S EUROPEAN MARITIME TRANSPORT ENVIRONMENTAL REPORT 2025-A MARITIME DECARBONIZATION PERSPECTIVE*

## *EEA-EMSA'NIN 2025 AVRUPA DENİZ TAŞIMACILIĞI ÇEVRE RAPORU'NU YENİDEN DÜŞÜNMEK: DENİZCİLİKTE KARBONSUZLAŞTIRMA PERSPEKTİFİ*

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## ABSTRACT

On February 4, 2025, the European Environment Agency and European Maritime Safety Agency published the second in a series of reports on the environmental impact of European maritime transport. This highly important report, which forms the basis for future efforts for a cleaner and livable environment, also contains important information that will guide global efforts for maritime decarbonization. This study aims to provide comparative information on the content of the report and future projections by analyzing the report from the perspective of International Maritime Organization supported by scientific findings.

**Keywords:** •Maritime decarbonization •International Maritime Organization •Maritime policy •Shipping emissions

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## ÖZ

4 Şubat 2025'te Avrupa Çevre Ajansı ve Avrupa Denizcilik Güvenliği Ajansı, Avrupa deniz taşımacılığının çevresel etkisine ilişkin rapor serisinin ikincisini yayınlamıştır. Daha temiz ve yaşanabilir bir çevre için gelecekteki çabalara temel oluşturan bu önemli rapor, aynı zamanda denizcilik sektörünün karbondan arındırılmasına yönelik küresel çabalara rehberlik edecek önemli bilgiler de içermektedir. Bu çalışma, Uluslararası Denizcilik Örgütü'nün bilimsel bulgularla desteklenen bakış açısıyla raporu analiz ederek, raporun içeriği ve geleceğe yönelik tahminler hakkında karşılaştırmalı bilgiler sunmayı amaçlamaktadır.


**Anahtar Kelimeler:** •Denizcilikte karbonsuzlaştırma •Uluslararası Denizcilik Örgütü •Denizcilik politikaları •Gemi emisyonları

## INTRODUCTION

The purpose of this report is to update the data of the 2021 report and provide information for European Union (EU) policy makers, national maritime and environmental administrations of EU Member States, industrial and academic institutions, business and environmental non-governmental organizations, and the public. The report provides an overview of the EU's current maritime traffic and trade and focuses on atmospheric emissions, marine pollution, marine litter, and hazards and physical disturbance of seabed. In addition, decarbonization efforts are covered under a separate title, addressing the EU basket of measures, climate neutral energy solutions and energy transition projections. Finally, topics that need to be studied in more depth are included.

The report, published on the 4th of February 2025, shortly before the International Maritime Organization (IMO) Marine Environment Protection Committee (MEPC) 83 meeting, provides a comprehensive overview of the EU's maritime sector from an environmental perspective. The report examines various types of pollutants and includes a separate assessment of the fisheries sector, physical pollutants as well as underwater noise pollution and physical destruction of the seabed.

Decarbonization efforts is the main subject of the current study. In addition to carbon emissions, other atmospheric emissions are also considered. Based on the data and comments presented in the report, the current study presents the status quo and future projections for the maritime decarbonization in the EU context and in the light of the MEPC 83 decisions.

# I. METHODOLOGY AND ANALYTICAL FRAMEWORK

This study employs a structured qualitative content analysis approach to examine the findings of the EEA–EMSA Maritime Transport 2025 report and compare them with the recent decisions adopted under MEPC 83. The methodological framework consists of three main stages:

Descriptive Assessment: Identification and summarization of the key findings reported in the EEA–EMSA publication, with a focus on emissions trends, fuel transition pathways, and operational efficiency indicators.

Comparative Policy Analysis: Systematic evaluation of the alignment and divergence between the European Union's maritime decarbonization framework and the IMO's global regulatory landscape. This stage considers regulatory instruments, timelines, policy ambition levels, and enforcement mechanisms.

Critical Evaluation via Literature Integration: The report findings are interpreted in light of recent academic literature, industry data, and policy documents. This enables an assessment of the robustness, feasibility, and sectoral implications of the projections and recommendations.

To ensure a coherent and systematic assessment, the analysis is organized under five thematic pillars commonly employed in maritime decarbonization research:

Emissions Dynamics: $CO_2$, $CH_4$, BC and other pollutant trends across the EU fleet.

Energy Transition Pathways: Alternative fuels, technological readiness, and adoption barriers.

Regulatory Architecture: Comparative evaluation of EU and IMO frameworks (FuelEU, ETS, LCA Guidelines, MEPC 83 outcomes, etc.).

Sectoral Implications: Impacts on shipping companies, ports, and global maritime logistics chains.

Policy Implications: Strategic recommendations addressing governance gaps, implementation challenges, and potential synergies.

# II. A BRIEF SUMMARY OF THE REPORT AND SOME COMMENTS ON THE KEY OUTCOMES

- 74% of the EU's total trade products are exported and imported by sea.

- Maritime activities excluding fishing and port activities generated a gross added value of €44.3 billion in 2021.
- By 2022, 31% of total carbon dioxide (CO2) emissions were produced by bulk carriers, 15% by oil tankers, 14% by container ships, 11% by chemical tankers, and 9% by general cargo ships.→Since the findings of the report reveal that bulk carriers predominantly produce more GHG emissions, prioritizing these ships can be considered the right approach. On the other hand, each ship needs a different decarbonization roadmap, depending on its age and carrying capacity. Therefore, it would be correct to consider the measures proposed by the IMO and the EU as the main arteries and the GHG reduction measures actually implemented as capillaries. Shipowners should pay attention to the general framework provided by the reports and roadmaps when decarbonizing individual ships.
- According to 2022 data, the EU fleet consists of around 13,000 ships and produced a total of 137.5 million tons of $CO_2$. This value corresponds to 14.2% of the total transport sector. By 2022, maritime transport is responsible for 26% of the total methane ($CH_4$) emissions produced by the EU's transport sector. This is equivalent to 14,000 t. $SO_x$ from maritime transport is estimated at 267,000 t in 2022. While maritime transport was responsible for 96% of total sulphur oxides ($SO_x$) emissions from transportation in 2005, this rate decreased to 88% in 2022. In 2022, the share of nitrogen oxides ($NO_x$) emissions from maritime transport in total transport emissions is 39%, corresponding to 1,577,000 t. Particulate matter (PM) emissions are 43% of transport emissions in 2022, equivalent to 88,000 t. Black carbon (BC) emissions from shipping account for 17% of total transport emissions in 2022, equivalent to 9,000 t. Table 1 presents the regional changes in ship traffic and emissions.→Although the findings indicate a reduction in the proportion of shipborne $SO_x$ emissions, ships are still the most dominant source of $SO_x$. It is obvious that the reduction is due to the presence of Emission Control Area (ECA) regions, but it seems that more drastic measures are needed. Similarly, $NO_x$ and PM emissions from ships are also very high and need to be controlled. Table 1 shows that ship traffic in Europe is generally on an upward trend. The decline in Black Sea and North Sea traffic is not at high levels and the decline in the Black Sea is considered to be due to the Russian-Ukrainian War. The increase in Atlantic and Arctic routes is particularly noteworthy. This increase

brings with it an increase in $CO_2$ and $CH_4$ emissions. It is highly likely that the increase in $CH_4$ emissions is due to the widespread use of LNG (see Fig. 1). A significant reduction in $SO_x$ and PM emissions was observed due to the presence of ECA zones. The Arctic route has been activated by the melting of permanent sea ice due to global warming and is emerging as a short natural waterway between East Asia and Western Europe. The findings suggest that around 2050, Arctic waters will remain open for polar-class vessels 200-250 days a year and open-water vessels 100-150 days a year.[1] While some studies have shown that the Arctic route remains uncertain[2]or even inadequate[3] in terms of cost-benefit, the findings of the report clearly show that traffic tends to increase. The Arctic region has a different significance compared to other regions. In this region, atmospherically released BC adheres to the ice sheet, causing the ice to lose its purity and thus its whiteness, weakening the albedo effect.[4] Albedo is the rate at which solar energy reaching the Earth's surface is reflected back and plays an important role in maintaining surface temperature.[5] Therefore, the decreasing purity of Arctic ice means a decrease in its reflectivity, contributing to global warming. Although the report shows a reduction in BC emissions between 2015 and 2023, the GWP20 impact of BC is considerably higher at the local scale.[6] Considering the sensitivity of the Arctic region, it is essential to carry out studies to reduce the values. The declaration of the Canadian Arctic and the Norwegian Sea as ECAs at MEPC 82 and the designation of the Northeast Atlantic from Greenland to the Strait of

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1 Elena Rovenskaya and others, 'Future Scenarios of Commercial Freight Shipping in the Euro-Asian Arctic' (2024) 163 Futures 103446.

2 Frédéric Lasserre, 'Case Studies of Shipping along Arctic Routes. Analysis and Profitability Perspectives for the Container Sector' (2014) 66 Transportation Research Part A: Policy and Practice 144.

3 Abel Meza and others, 'Relevance and Potential of the Arctic Sea Routes on the LNG Trade' (2023) 50 Energy Strategy Reviews 101174.

4 Linfei Yu and Guoyong Leng, 'Identifying the Paths and Contributions of Climate Impacts on the Variation in Land Surface Albedo over the Arctic' (2022) 313 Agricultural and Forest Meteorology 108772.

5 Hao Yan and others, 'Forest Greening Increases Land Surface Albedo During the Main Growing Period Between 2002 and 2019 in China' (2021) 126 JGR Atmospheres e2020JD033582.

6 Jinlei Chen and others, 'Projected Emissions and Climate Impacts of Arctic Shipping along the Northern Sea Route' (2024) 341 Environmental Pollution 122848.

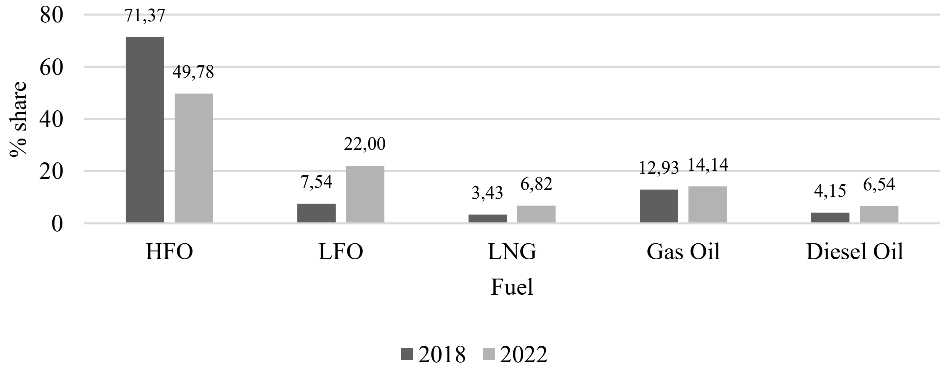
Gibraltar as an ECA at MEPC 83 are considered to be very important steps towards the protection of the Arctic region.

**Table 1**: Regional changes in ship traffic and emissions between 2015-2023

| Region | Ship Traffic | $CO_2$ | $CH_4$ | $SO_x$ | $NO_x$ | PM | BC |
|---|---|---|---|---|---|---|---|
| **Atlantic** | %45 | %46 | %454 | -%75 | %33 | -%58 | -%36 |
| **Baltic Sea** | %7 | %6 | %375 | <-> | -%6 | %6 | %21 |
| **Mediterranean Sea** | %19 | %15 | %211 | -%76 | %8 | -%61 | -%48 |
| **Black Sea** | -%12 | %1 | %291 | -%71 | -%7 | -%58 | -%48 |
| **North Sea** | -%7 | %8 | %97 | -%11 | -%17 | -%9 | -%5 |
| **Arctic** | %48 | %62 | %108 | -%57 | %32 | -%38 | -%16 |

- According to projections, in the business-as-usual scenario, these emissions could increase by around 14% between 2015-2030 and by 34% between 2015-2050.
- Figure 1 presents the fuel change rates between 2018-2022.→The decrease in the rate of heavy fuel oil (HFO) in the four-year period is striking. The main reason for this is considered to be the IMO 2020 Sulphur Cap implementation. Since alternative fuels are not yet widely used, HFO has been replaced mainly by light fuel oil (LFO). The use of gas oil and diesel oil has also partially increased. After LFO, the most dramatic increase was realized in LNG with a nearly doubling. This supports the $CH_4$ increase rates in Table 1.

**Figure 1**: Fuel change rates between 2018-2022




- 98% of water discharge volumes are wash water, mostly from open-loop Exhaust Gas Cleaning Systems (ECGS) (74% of scrubbers are open-loop).→There are two modes of wet scrubbers: Closed-loop and open-loop. In closed-loop mode, seawater is mixed with NaOH and recirculated, while in open-loop mode, seawater is sprayed into the exhaust gas to convert $SO_x$ gases into sulfuric acid ($H_2SO_4$). Scrubber wash water has been observed to stimulate the microplankton community and it has been stated that it is very difficult to predict the environmental impacts of scrubber wash water, which mainly contains metals and polycyclic aromatic hydrocarbons (PAHs). It has also been indicated that scrubber wash water may increase the nutrition in marine environment.[7] Although the contribution of scrubber wash water to the total environmental impact of the ship was assessed as very low in another study, it was concluded that the impact of marine eutrophication should be further investigated.[8] These findings suggest that there should be some restrictions on the discharge of wash water from scrubber utilization. In particular, the sludge-like substance released into the sea as a result of the use of open-loop mode may cause unpredictable and irreversible impacts on the marine ecosystem due to its harmful components.

- The recently adopted EU ′Fit for 55′ package extends the EU Emissions Trading System (ETS) to maritime transport. Shipping companies will surrender allowances for part of their GHG emissions: 40% of their verified emissions by 2024, 70% by 2025, and 100% by 2026. The FuelEU Maritime Regulation stipulates that the average annual GHG intensity of energy used on board ships should be reduced by at least 2% by 2025, 6% by 2030 and then by 80% by 2050 in 5-year steps compared to the 2020 baseline.→ETS is an increasingly widespread practice in the world and the average auction price in the EU for 2024 is 64.74 EUR and the average secondary market price is 65.23 EUR.[9] FuelEU foresees a penalty of 2400 EUR per ton of very low sulphur fuel oil (VLSFO) and adopts the tank-to-wake (TtW) approach.[10] IMO proposed a two-tier

7 Erik Ytreberg and others, 'Effects of Scrubber Washwater Discharge on Microplankton in the Baltic Sea' (2019) 145 Marine Pollution Bulletin 316.

8 Alba Martínez-López and others, 'Environmental Assessment Model for Scrubbers versus Alternative Mitigation Systems for Feeder Vessels in Liner Shipping' (2022) 321 Journal of Environmental Management 115954.

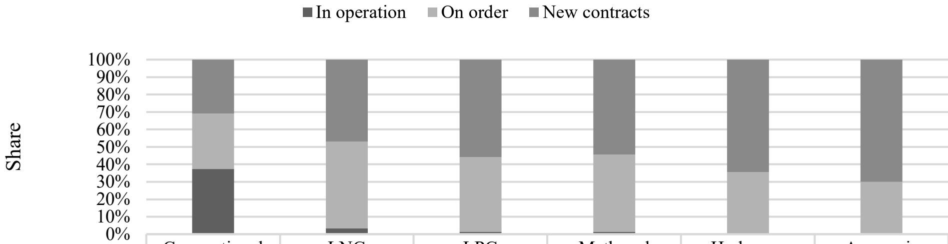
9 'International Carbon Action Partnership' <https://icapcarbonaction.com/en/ets> accessed 11 May 2025.

10 'DNV' <https://www.dnv.com/news/fueleu-maritime-how-to-prepare-for-compliance/> accessed 11 May 2025.

carbon pricing solution to achieve the IMO 2023 GHG Strategy targets at the MEPC 83 meeting. Accordingly, if the ship can achieve a reduction between the annual reduction rates determined for the two tiers, it will have to pay the first tier (100 USD/t $CO_2$eq) penalty, and if it cannot achieve the first tier, it will have to pay the second tier (380 USD/t $CO_2$eq) penalty. The approach focused on well-to-wake (WtW)emissions.

- The global energy consumption of the maritime sector is about 14 EJ/year, equivalent to 3.2% of the global primary energy consumption of 442 EJ/year (in 2022). To achieve the expected emission reductions and energy intensity by 2030 from IMO and EU provisions, fossil fuel consumption needs to be limited to around 11.28EJ of total energy demand.
- Figure 2 presents the share of conventional and alternative fuels in total number of ships.→The overwhelming majority of ships in operation run on conventional fuels. Even the share of liquefied natural gas (LNG), the most widely used alternative fuel, is 0.57%. On the other hand, the share of conventional fuels in ships on order has fallen dramatically and the share of LNG and liquefied petroleum gas (LPG) has increased significantly. The situation is similar for new contracts. While the use of hydrogen and ammonia is very low for ships on order, the demand for these fuels has increased in new contracts. In this context, since it takes approximately 1-2 years to build a ship (taking into account the capacities of shipyards and the aging and decommissioning of ships), it can be predicted that by mid-2030, the proportion of ships using conventional fuels may drop to around 90%.

**Figure 2**: Share of conventional and alternative fuels in total number of ships




| | Conventional | LNG | LPG | Methanol | Hydrogen | Ammonia |
|---|---|---|---|---|---|---|
| New contracts | 82 | 8 | 6 | 2 | 1 | 1 |
| On order | 84,33 | 8,49 | 4,58 | 1,63 | 0,54 | 0,43 |
| In operation | 99,23 | 0,57 | 0,14 | 0,05 | 0,01 | 0 |

Fuel Types

- Wind propulsion systems have already been installed on more than 30 ships and 26 more in progress.→The use of wind energy on ships is a long-established method, but has been virtually rediscovered by decarbonization efforts. The use of wind energy as auxiliary propulsion can reduce operational greenhouse gas (GHG) emissions by 30-40%[11] and meet 8-27% of a ship's power needs.[12] Wind propulsion is therefore considered to have a very important place in carbon intensity indicator (CII) mitigation and is particularly highlighted as an important alternative for the realization of the CII mitigation (Z) factors set out in MEPC 83. Wind propulsion is expected to be used on more ships in the near future.
- Maritime activities, excluding fishing and port activities, employ a total of 380,000 people. According to the scenario prepared by Lloyds Register (LR) and University Maritime Advisory Services (UMAS), 450,000 seafarers will need additional training by 2030 and 800,000 by the mid-2030s, assuming net zero GHG target will be achieved by 2050, while alternative fuel use increases in the 2020s.→ The number of seafarers who will need training is expected to reach 1.8 million by

[11] Elizabeth Lindstad and others, 'Ship of the Future – A Slender Dry-Bulker with Wind Assisted Propulsion' (2022) 3 Maritime Transport Research 100055; James Mason and others, 'Quantifying Voyage Optimisation with Wind Propulsion for Short-Term CO2 Mitigation in Shipping' (2023) 289 Ocean Engineering 116065.

[12] Saeid Hassankhani Dolatabadi, Aykut I Ölçer and Seyedvahid Vakili, 'The Application of Hybrid Energy System (Hydrogen Fuel Cell, Wind, and Solar) in Shipping' (2023) 46 Renewable Energy Focus 197.

2050.[13] Green transition is a long-term process that needs to be taken seriously from an education perspective, and if seafarers are not interested in alternative fuels and/or energy efficiency methods due to lack of education and awareness, it can lead to wasted efforts. Findings show that there is a lack information on which training activities are more effective.[14] Therefore, it is important to implement comprehensive training projects and put green transition in the context of social-life cycle assessment (S-LCA). In this way, a sustainable transformation can be guaranteed by taking into account the demands and needs of all stakeholders involved in the transition.

## FURTHER RECOMMENDATIONS

The treatment of methane emissions in the report appears conservative, particularly given recent evidence showing higher upstream and operational methane leakage associated with LNG usage. A more comprehensive evaluation requires incorporating well-to-wake analyses and acknowledging uncertainties inherent in $CH_4$ quantification methodologies. Similarly, the aggregation of BC emissions into a single total indicator may underrepresent high-risk regions, particularly the Arctic. This omission can weaken the policy relevance of BC projections.

A critical challenge identified in the report is the gap between projected fuel-switching trends and the actual technological readiness levels (TRLs) of alternative fuels. While e-fuels and biofuels are highlighted as central long-term options, key issues such as scalability, global supply chain constraints, and certification methodologies require deeper attention.

The priorities of the EU strategic research agenda include;

- Alternative Fuels and Green Technologies→Since it is not yet possible to choose from a large number of alternative fuels and technologies, the fuel/technology-agnostic position is considered to be the most successful

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[13] DNV, 'Energy Transition Outlook 2023-Maritime Forecast to 2050' (DNV 2023).

[14] Mohammud Hanif Dewan and Radu Godina, 'Effective Training of Seafarers on Energy Efficient Operations of Ships in the Maritime Industry' (2023) 217 Procedia Computer Science 1688.

approach.[15] However, production and supply chains, high costs, retrofit requirements, safety standards, bunkering infrastructure, and fuel compatibility are seen as significant risks to be overcome.[16] Following the MEPC 83 carbon pricing decisions, the importance of the LCA method has increased due to the WtW approach.[17] In this context, it is recommended to increase the number of scientific projects and studies based on the LCA approach in order to understand the environmental, economic and social impacts of alternative fuels and innovative technologies in all dimensions.

- Decarbonization, Emissions Monitoring and Mitigation→Maritime decarbonization depends on alternative fuels, innovative and energy-efficient technologies, fuel producers and infrastructure working together with both technological capacity and political will.[18] Emission monitoring and mapping remains important as a guide to preventive work.
- Digitalization and Smart Shipping→ Maritime is considered to be an experience-based and conservative sector and more work is needed to fully understand the environmental impacts of digitalization.[19] Digitalization is predicted to drive four trends in the coming years: economic, environmental, political and technological.[20] Accordingly, it is important to increase the number of studies that comprehensively evaluate all four components, especially the effects on seafarers.
- Port Automation→The main barriers for port digitalization and green technology are the high costs for modifying the infrastructure, lack of

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15 Mohsen Mandegari, Mahmood Ebadian and Jack (John) Saddler, 'The Need for Effective Life Cycle Assessment (LCA) to Enhance the Effectiveness of Policies Such as Low Carbon Fuel Standards (LCFS's)' (2023) 181 Energy Policy 113723.

16 Zhongwei Li and others, 'Marine Alternative Fuels for Shipping Decarbonization: Technologies, Applications and Challenges' (2025) 329 Energy Conversion and Management 119641.

17 Levent Bilgili, 'A Systematic Review on the Acceptance of Alternative Marine Fuels' (2023) 182 Renewable and Sustainable Energy Reviews 113367.

18 Hui Xing and others, 'Alternative Fuel Options for Low Carbon Maritime Transportation: Pathways to 2050' (2021) 297 Journal of Cleaner Production 126651.

19 Clarissa A González Chávez and others, 'Advancing Sustainability through Digital Servitization: An Exploratory Study in the Maritime Shipping Industry' (2024) 436 Journal of Cleaner Production 140401.

20 World Maritime University, 'Transport 2040: Impact of Technology on Seafarers - The Future of Work' (Aykut Ölçer and others eds, World Maritime University 2023) <https://commons.wmu.se/lib_reports/78> accessed 27 January 2026.

standards, and small scale of operating capacity.[21] Experts recommend prioritizing digital solutions, digital business management and digital technology, respectively. In addition, improving port safety, optimizing port transportation, standardization of technology, optimizing port facilities, and digital asset management should be respectively promoted.[22] Besides, it is recommended that scenario analysis, risk assessment, transnational cooperation, and knowledge sharing should be taken into account.[23]

- Zero Pollution and Circular Economy→The circular economy, which aims to provide both economic and environmental gains, especially by keeping non-renewable resources in a closed loop, has been highly recognized in the maritime community. However, low awareness and knowledge, regulations, longevity of marine vessels, barriers in the reverse supply chain and sectoral acceptance level are considered as significant barriers.[24]
- Human Element and Climate Resilience and Adaptation→For decarbonization efforts to achieve sustainable success, it is essential to examine the human factor in detail.[25] Although most of the seafarers have knowledge on the subject, only 47% of them actively participate in the practices.[26] IMO and IMO-affiliated educational institutions in particular have an important role in this regard.[27]
- Maritime Regulatory Issues→The findings of the report underline the increasing need for a more coherent, transparent, and globally

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21 Zheng Wan and others, 'Transforming Ports for a Low-Carbon Future: Innovations, Challenges, and Opportunities' (2025) 264 Ocean & Coastal Management 107636.

22 Yi-Chih Yang and Yun-Hsin Hsieh, 'The Critical Success Factors of Smart Port Digitalization Development in the Post-COVID-19 Era' (2024) 17 Case Studies on Transport Policy 101231.

23 Zhechen Zhang and others, 'Digitalization and Innovation in Green Ports: A Review of Current Issues, Contributions and the Way Forward in Promoting Sustainable Ports and Maritime Logistics' (2024) 912 Science of The Total Environment 169075.

24 Dogancan Okumus and others, 'Circular Economy Approach in the Maritime Industry: Barriers and the Path to Sustainability' (2023) 72 Transportation Research Procedia 2157.

25 Ki Hong Ten and others, 'Automatic Identification System in Accelerating Decarbonization of Maritime Transportation: The State-of-the-Art and Opportunities' (2023) 289 Ocean Engineering 116232.

26 Mohammud Hanif Dewan and Radu Godina, 'Unveiling Seafarers' Awareness and Knowledge on Energy-Efficient and Low-Carbon Shipping: A Decade of IMO Regulation Enforcement' (2024) 161 Marine Policy 106037.

27 Mohammud Hanif Dewan and others, 'Exploring Seafarers' Knowledge, Understanding, and Proficiency in SEEMP: A Strategic Training Framework for Enhancing Seafarers' Competence in Energy-Efficient Ship Operations' (2024) 10 Heliyon e36505.

harmonized maritime regulatory framework. While regional initiatives such as the EU ETS and FuelEU Maritime demonstrate regulatory leadership, the coexistence of multiple regulatory approaches risks fragmenting compliance obligations and creating uneven competitive conditions across global shipping markets. First, greater convergence between regional and global regulatory instruments is essential. The divergence between the EU's TtW approach and the IMO's WtW framework may lead to inconsistent incentive structures, particularly for alternative fuels such as LNG, biofuels, and e-fuels. Aligning life cycle assessment (LCA) methodologies, default emission factors, and fuel certification schemes under IMO guidance would enhance regulatory clarity and reduce the risk of carbon leakage or regulatory arbitrage. Second, $CH_4$ and BC emissions should be more explicitly embedded within mandatory regulatory mechanisms rather than remaining primarily within monitoring or reporting frameworks. Given the disproportionate climate impacts of $CH_4$ and BC, especially in sensitive regions such as the Arctic, the expansion of ECAs and the introduction of differentiated compliance requirements based on regional environmental vulnerability should be considered. Third, regulatory measures should move beyond ship-level compliance and increasingly address system-level integration. This includes coordinated regulation of fuel supply chains, port infrastructure readiness, and bunkering safety standards. Without parallel regulatory obligations on fuel producers and port authorities, ship operators alone cannot deliver the anticipated pace of decarbonization. Finally, the human element must be formally recognized within maritime environmental regulation. Mandatory training requirements, competency standards for alternative fuels, and S-LCA considerations should be integrated into future IMO instruments to ensure that regulatory ambition is matched by operational feasibility and workforce readiness. Overall, future maritime regulation should prioritize global alignment, life cycle-based accountability, regional environmental sensitivity, and human-centered implementation. Such an approach would strengthen the credibility, effectiveness, and long-term resilience of maritime decarbonization policies.

The combined analysis of the EEA–EMSA 2025 report and MEPC 83 decisions reveals significant progress in maritime decarbonization efforts, while also highlighting persistent regulatory, technological, and data-related challenges.

Strengthening global–regional policy alignment, improving methane and BC monitoring, and accelerating alternative fuel infrastructure development emerge as key priorities for achieving sector-wide emissions reductions.

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