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Sakellariadou, F., Wooldridge, C., Kitsiou, D. et al (2026). The role of mega ports in climate change (IUPAC Technical Report). *Pure and Applied Chemistry*, 98(5): 791-826.
<http://dx.doi.org/10.1515/pac-2024-0246>

N.B. When citing this work, cite the original published paper.



IUPAC Technical Report

Fani Sakellariadou*, Chris F. Wooldridge, Dimitra Kitsiou, Marti Puig, Kareem Mahmoud Tonbol, Nikitas Nikitakos, Ida-Maja Hassellöv and Mohamed Elbawab

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<https://doi.org/10.1515/pac-2024-0246>

Received July 3, 2024; accepted March 11, 2026

Abstract: Ports play a vital role in global trade yet pose significant environmental threats to marine and coastal ecosystems from which pollution and habitat alienation are of prime concern. This report investigates the multi-faceted challenges of environmental sustainability within port operations, highlighting the urgent necessity for the removal of pollution sources, including ballast water discharge, antifouling applications, and metal and hydrocarbon contamination. A definitive overview of International and European regulatory frameworks [e.g., Water Framework Directive (WFD), Marine Strategy Framework Directive (MSFD)] is presented in this context, to assess their effectiveness in promoting sustainable port management and marine environmental protection. Additionally, the paper explores the crucial role of bioindicators, particularly invertebrate bivalves and mollusks, for monitoring marine environment health and assessing the impact of anthropogenic pollution. The evolution of port planning toward a more inclusive, stakeholder-driven approach is assessed, marking the transition from traditional top-down models toward a participatory strategy, which involves local communities, environmental organizations, and port authorities. The findings suggest that an integrated approach to management, stakeholder integration, and rigorous environmental regulation are all cornerstones of the successful attainment of sustainable development goals. This paper supports the dialogue on sustainable port management which calls for a harmonious blend between economic growth and environmental stewardship, advocating a framework, which will elevate environmental quality standards, thereby promoting joint port planning and management strategies.

Keywords: Chemistry-based environmental performance indicators; climate change; greenhouse gases; port sustainability.

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Article note: This manuscript was prepared in the framework of IUPAC project 2021-026-3-600.

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1 Introduction

The marine industry has historically played a crucial role in facilitating international trade. However, its notable impact on the release of greenhouse gases (GHGs), particularly in port areas, highlights the pressing requirement for sustainable management approaches. In light of global environmental challenges, it is imperative to reconsider the functioning of port operations.¹ Ports have high energy demands to cover their essential activities which made port authorities need to implement a vigilant energy management system to respond to the current environmental pressure.² Air pollutants from port activities aside from GHGs like common air contaminants (CAC) reduce the human body's immunity against viruses and bacteria and cause respiratory system problems which leads to extra externalities costs on ports hosting cities.³ Implementing the green port concept will result in environmental (climate change combating), operational (operating at higher efficiency), and commercial (lower operational cost and cut the mentioned medical externality cost) benefits.⁴ An Italian study that analyzed three

years of records for pollutants in the surrounding Civitavecchia port-city indicated the port-city interaction regarding air quality and the measured nitrogen dioxide, particle matter with diameter $\leq 10 \mu\text{m}$ (PM_{10}) and sulfur dioxide share from port activities, respectively, were found to be 33 %, 43 %, and 60 %; the study ends to the fact that even while using low sulfur, ports cannot quit emitting ultra-fine particle or black carbon.⁵

From the scientific perspective of a Port Environmental Manager, greenhouse gases (GHGs) are recognized as those that absorb and emit radiant energy within the thermal infrared range, causing the so-called greenhouse effect. They include water vapor, carbon dioxide, methane, dinitrogen oxide (nitrous oxide), trioxygen (ozone), chlorofluorocarbons, hydrofluorocarbons, and perfluorocarbons. In the context of this project, it is recognized that the use of GHGs may be of assistance to the challenge of Port Environmental Management by virtue of their function as environmental performance indicators (EPIs).

These environmental impacts are significantly magnified in the context of mega ports, defined as port facilities with extremely high cargo-handling capacity, extensive and diversified operational infrastructures, and a substantial geographical extension.

2 The state-of-the art critical review of the current knowledge and understanding of port activities and operations that produce greenhouse gases

2.1 Port activities generating greenhouse gases

The emissions in the shipping industry, mainly come from ships and ports. The shipping industry accounts for 2.3 % of global emissions by generating around 800 to 850 million tons of carbon dioxide emissions per year. Some researchers consider port emissions to be a small part of shipping emissions;⁶ however, ports are the hubs of global international shipping and account for around 3 % of global gas emissions.⁷ This contribution increased by 5.6 % to 740 million tones over the period of 2012–2018 and is expected to increase by up to 50 % until 2050.⁸ The *International Council on Clean Transportation* (ICCT) 2025 report “Greenhouse Gas Emissions and Air Pollution from Global Shipping, 2016–2023” states that greenhouse gas emissions from shipping increased by about 12 % between 2016 and 2023, with shipping’s share of global anthropogenic CO_2 emissions at around 2.3 % during 2017–2023.⁸ The 2023 IMO GHG Strategy emphasizes continued growth in shipping emissions unless deep decarbonization measures are adopted, and it lays out ambitions to peak and reduce shipping GHGs toward net-zero by ~2050.

The wide range of port activities and operations that contribute to greenhouse emissions include activities such as cargo handling, vessel movements, onshore operations, and energy consumption. Here are some key activities commonly associated with emissions at ports:

Vessel operations: Shipping vessels, including container ships, tankers, and cargo vessels, typically use fossil fuels like marine diesel or bunker fuel. These vessels emit greenhouse gases such as carbon dioxide, nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter (PM) during their operations.

Port equipment: Equipment used for loading and unloading cargo, such as cranes, forklifts, and trucks, often run on diesel or other fossil fuels. These vehicles and machinery emit carbon dioxide, NO_x , and PM during their operation.

Table 1: Emissions by pollutant (t) of vessels at EU ports (2018–2019).¹²

Pollutant type	Emissions (10^6 t)
CO_2	140
SO_2	1.63
NO_2	4.46
$\text{PM}_{2.5}$	0.26

Cargo handling and storage: Handling and storage of various types of cargo, especially those that require refrigeration or processing, can also produce emissions. Refrigeration units, warehouses, and processing facilities may rely on electricity generated from fossil fuels.

Port infrastructure: The construction, maintenance, and operation of port infrastructure, including buildings, roads, and utilities, may require energy derived from fossil fuels. Emissions can result from construction activities, energy usage, and transportation associated with maintaining the port facilities.

Rail and truck transport: Ports often serve as hubs for transferring cargo between ships and other modes of transportation such as trains and trucks. Rail and truck transport to and from ports can emit greenhouse gases from diesel engines.

Power generation: Ports may have their power generation facilities to meet their energy needs. If these facilities rely on fossil fuels like coal or natural gas, they will emit greenhouse gases during electricity generation.

Waste management: Improper handling and disposal of waste generated in ports can result in methane emissions from decomposing organic matter in landfills or wastewater treatment facilities.

2.2 Ship emissions in ports

The emission from ships at ports represents a small ratio of the total shipping emission; however, it is the main source of port emission (about 55–77 %).⁹ Emissions from ships while in port mainly come from the auxiliary engines, which are used to produce power in loading, unloading and hoteling operations.¹⁰ Marine propulsion systems on commercial ships are primarily powered by diesel engines, which make up the majority of the available fleet, and steam or gas turbines.¹¹

The most important emissions from ships in ports in the European Union (EU) or in the European Economic Area, as shown in Table 1, were CO₂ and around 40 % was produced by voyages between ports of EU Member States;¹² 6 % being when ships are at berth.

A total of 70 % of ship emissions are detected within 400 km of land. Since a total of 90 % of European ports are spatially connected to cities, the harmful effects of these pollutants affect almost 40 % of the European population, who live within 50 km of the sea.¹³

Elaboration of data sets on ship emissions in ports is a quite difficult process. The major difficulty is their poor homogeneity. Data sets on emissions may be acquired either as global data or divided according to the main vessel categories: passenger and commercial. The global data set regarding emissions is not very useful, since there is a strong dependence on the percentage of contribution of passenger and commercial ships; therefore, elaboration and comparison with other ports becomes quite difficult. On the other hand, data sets on emissions of passenger ships can be specified for cruise ships or other categories (ferries, hydrofoils, or other). In principle, the more the data set is referred to a specific category, the higher its utility. It should be also noted that data sets on commercial ships are generally rarer than data on passenger ships.¹⁴

Table 2: Port-related emission source classifications.¹⁷

Source type	Emissions source classifications	Cargo movement-related
Mobile	Seagoing vessels	Yes
	Domestic vessels	Yes
	Cargo handling equipment	Yes
	Heavy-duty vehicles	Yes
	Locomotive	Yes
	Light-duty vehicles	Yes
Stationary	Electrical grid	Associated
	Power plant	No
	Industrial facilities	No
	Manufacturing facilities	No
	Administrative offices	Associated

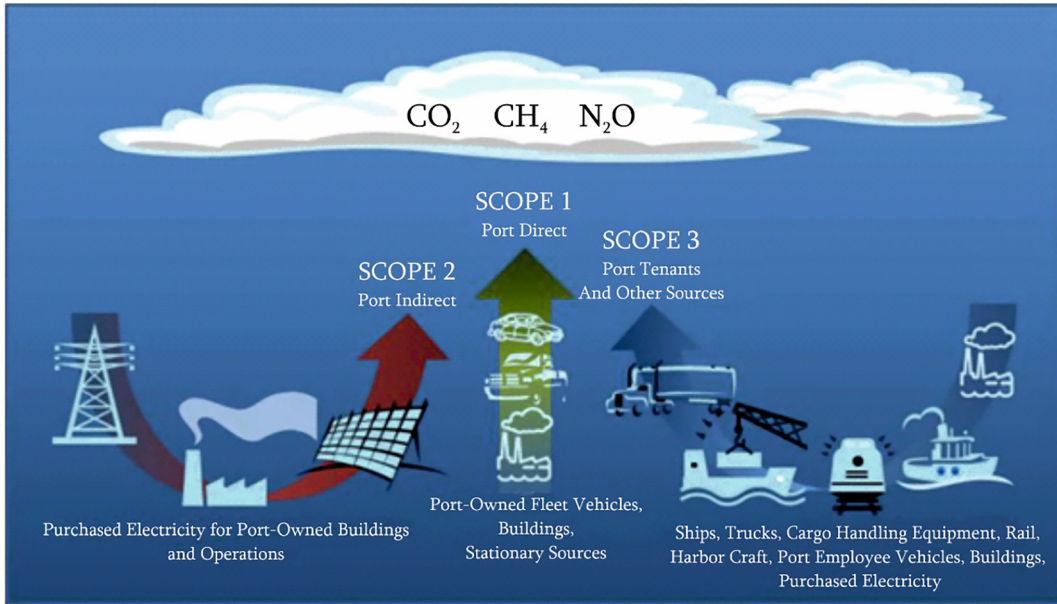


Fig. 1: Port-related greenhouse gases emissions sources by scope.¹⁷

Another important issue is how emission data are attributed to the different activities in ports. In general, specific activities in ports are grouped as hotelling, maneuvering or navigation. Hotelling refers to the state that the ship is stopped at wharves but emit exhaust gases from engines to produce heat and electrical power for all the services necessary. Maneuvering and navigation in port refer to the movement of the ship inside the port or in its proximity. In particular, maneuvering represents the high non-stationary phase where the ship changes speed or direction to approach the dock. Navigation refers to the movement of the ship with a quite constant and reduced speed inside the port area. The length of the route of the navigation phase is quite variant. However, the hotelling phase represents generally the largest fraction of total emissions in port: NO_x 90.1%; $\text{PM}_{2.5}$ 78.0%; and SO_x 88.5%.¹⁵ Nevertheless, the above-mentioned percentages vary depending mainly on time at hotelling and length of maneuvering phase.

2.3 Multiple emission sources from port operations

Port operations involve multiple emission sources, and during their assessment, the specific characteristics of each port should be considered. Some ports are mainly engaged in international maritime transportation while others are responsible for national and inland river coastal transportation.

Sources of emissions from port activities (other than ships) include loading and unloading of petroleum products that produce volatile organic compound emissions, dry docks (evaporative volatile organic compound emissions), passenger car traffic (combustion products and evaporative volatile organic compound emissions), heavy vehicle traffic (combustion products emission), railway traffic (combustion products emission), and demolition or main modification of ships (iron and other metals, hydrocarbons, ozone depleting substances, and others). In addition, port areas are always linked to industrial activities to benefit of the proximity of loading and unloading vessels and to avoid costly load breakdowns. Industrial activities include generally heavy activities such as power plants, ships building plants, iron and steel plants, non-ferrous metal industry, paper and paper pulp plants, oil refineries, chemical and petrochemical plants, and airports. Therefore, all such sources should be evaluated in the framework of an integrated emission inventory approach.¹⁶

Port-related emission sources concerned with the works controlled or influenced by the port are classified according to the types of emission source and energy.¹⁷ Port emission sources are primarily mobile and stationary equipment related to cargo movement and are presented in Table 2.

According to the ownership or control of port emission sources in the World Port Climate Initiative (WPCI) ‘Carbon Footprint’ guidelines, port activities that generate emissions are divided into three categories, or rather, ‘ranges’.¹⁸

Category 1 – direct sources of the port. They are controlled and operated by port management entities; port-owned fleet vehicles, vehicles owned or leased by port management, boilers and furnaces in buildings, cargo handling equipment of the port, and any other sources of emissions.

Category 2 – indirect sources of the port. Electricity purchased for the consumption of the buildings and the management operations of the port. In this category, the electricity and energy purchased by tenants are not included.

Category 3 – other indirect sources of the port. These sources are associated with tenant operations, including ships, trucks, cargo handling equipment, rail locomotives, harbor craft, tenant buildings, tenant purchased electricity, and the vehicles of the port employees. In case of a port with many tenants, this would be an enormous source of greenhouse gas emissions.

The scopes are illustrated in Fig. 1.

Table 3: The ranking of European countries regarding the maritime supply chain emissions associated with ports.²¹

Ranking	Country	Million tons of CO ₂ per year
1	Netherlands	17.6
2	Spain	13.9
3	UK	11.1
4	Italy	10.4
5	Germany	9.5
6	Belgium	8.8
7	France	7.5
8	Norway	4.5
9	Greece	4.2
10	Sweden	4.0

Netherlands is ranked 1st with 17.6 Mt of carbon dioxide per year, followed by Spain and UK, while Norway, Greece, and Sweden are met at the last places.

Table 4: The ranking of European countries regarding the emissions from ship activities at port.²¹

Ranking	Country	Thousand tons of CO ₂ per year
1	Italy	1165
2	Spain	1039
3	Netherlands	1001
4	UK	918
5	France	604
6	Belgium	591
7	Germany	484
8	Greece	456
9	Norway	256
10	Sweden	254

2.4 Difficulties in assessing emissions in ports

The estimation of emissions in ports is a quite complex process since mathematical models and algorithms should be applied by considering all different variables relevant to the emission sources. Furthermore, the specific nature and characteristics of each port in the world should be considered, since each one has different size and functions relevant to its specific business environment.³ Other potential difficulties consist in the scarcity and unavailability of relevant data sets. Modern technology has been exploited in several cases for detecting emissions in ports. For instance, a good example is that of China where a study envisages the use of a sort of drones called Unmanned Aerial Vehicles (UAVs) for this purpose.¹⁹

2.5 Which are the ports with the highest carbon dioxide emissions?

Most of the shipping emissions in ports are concentrated in Asia and Europe, e.g., 58 % of the carbon dioxide emissions, since most of world's port activity is carried out there: Asia and Europe represent 70 % of total port calls.²⁰ A port call means an intermediate stop for a ship on its scheduled journey for cargo operation or transporting supplies or fuel; it is a port where a ship stops except its home port. European ports have much less emissions of SO_x (5 % of world total), PM₁₀ (7 %) PM₁₀ means particle matter with diameter ≤10 μm), and PM_{2.5} (8 %) (PM_{2.5} means particle matter with diameter ≤2.5 μm), and PM_{2.5} (8 %) than their share of port calls (22 %) would suggest. The latter could be explained by the EU regulation to use low sulfur fuels at berth. Ports with high emissions relative to their port traffic can be found in Africa, the Middle East, Latin America, and – to a slightly lesser extent – in North America. The ports with the largest absolute emission levels due to shipping are Singapore, Hong Kong (China), Tianjin (China), and Port Klang (Malaysia). The distribution of shipping emissions in ports is skewed: the 10 ports with the largest emissions represent 19 % of total carbon dioxide emissions in ports and 22 % of SO_x emissions.²⁰

A recent high-resolution global ship emission inventory; however, not explicitly *only ports* but shipping around ports and coastal waters) provides disaggregated data for CO₂ emissions by region in 2021:²¹

- **Asian ports/shipping regions** account for ~45.5 % of global CO₂ emissions from shipping at berth/near ports.
- **European ports/shipping regions** account for ~27.5 % of global CO₂ emissions.
- The remaining emissions are distributed among regions such as North America, South America, Africa, and Oceania.

Table 5: The top-10 priority environmental issues for mega-ports, as identified by EcoPorts members. Those with significance to climate change are marked with an asterisk^a.

Mega ports >100 mt. Europe	Priority	Mega ports >100 mt. Rest of the World
Climate change (energy efficiency, GHG emissions reduction, and adaptation) ^a	1	Relationship with local community ^a
Air quality ^a	2	Air quality ^a
Noise	3	Port development (land related) ^a
Relationship with local community ^a	4	Ship exhaust emissions ^a
Port development (water related) ^a	5	Port development (water related) ^a
Energy efficiency ^a	6	Dust
Dredging: operations	7	Hazardous cargo (handling/storage) ^a
Garbage/port waste	8	Vehicle exhaust emissions (including cargo handling) ^a
Ship exhaust emissions ^a	9	Water quality
Conservation areas	10	Garbage/port waste ^a

Table 6: The top-10 priority environmental issues for smaller ports, as identified by EcoPorts members. Those with significance to climate change are marked with an asterisk^a.

<5 mt. Europe	Priority	<5 mt. Rest of the World
Energy efficiency ^a	1	Air quality ^a
Air quality ^a	2	Water quality
Climate change (energy efficiency, Greenhouse gases emissions reduction, and adaptation) ^a	3	Garbage/port waste ^a
Ship waste ^a	4	Relationship with local community ^a
Noise	5	Dust ^a
Water quality	6	Energy consumption ^a
Relationship with local community ^a	7	Noise
Garbage/port waste ^a	8	Port development (land related) ^a
Port development (land related) ^a	9	Hazardous cargo (handling/storage) ^a
Dust ^a	10	Ship waste ^a

It should be noted that the above mentioned of year 2021 dataset does not precisely separate *port emissions alone* from *near-port emissions*, but it is currently among the most detailed regionally disaggregated estimates available in literature.

As far as the port maritime supply chain emissions ranking in Europe is concerned, Rotterdam is associated with almost 14 million tons of carbon dioxide per year.²¹ Antwerp, with 7.4 million tons of carbon dioxide per year, and Hamburg, with 4.7 million tons of carbon dioxide per year, are in the second and third place, respectively. Following are ranked Algeciras (4th), Barcelona (5th), Piraeus (6th), and Valencia (7th). Spanish ports are responsible for the emission of almost 14 million tons of carbon dioxide. At the last places, the ports of Bremerhaven, Marseille, and Amsterdam are ranked. In addition, the ports of Barcelona, Palma, and Venice are responsible for a high portion of carbon dioxide emissions, since that they are popular destinations with a significant number of cruise ships each year.

The ranking of European countries regarding the maritime supply chain emissions associated with ports is given in Table 3.

Regarding emissions from ship activities at port (Table 4), Italy comes first with 1165 thousand tons of carbon dioxide per year followed by Spain, Netherlands, and UK. In the last place is ranked again Sweden.

3 Perspective and context of port environmental management concerning climate change

3.1 Change and transition

Successive reviews of the EcoPorts Network (the environmental initiative of the European Sea Ports Organisation (ESPO), which supports ports across the European Union and neighboring European countries in improving their environmental management) and recent reports by European Sea Ports Organization (ESPO)²² and Eco Sustainable Logistics Chain Foundation (ECOSLC)²³ confirm that the Environmental Management priorities of the port sector are:

- i) Compliance with legislation
- ii) Cost and risk reduction
- iii) Environmental protection
- iv) Sustainable development

Environmental Management may be defined as the functional organization necessary to deliver environmental protection and sustainable development to the highest possible standards of compliance and accountability. The challenge for the Port Environmental Manager is to control impacts of the ports Environmental Aspects. These, in turn, are defined as those activities, products, and services that may impact on the environment directly or indirectly. The impacts may be beneficial or adverse.

The tests of significance are i) aspects for which the Port Authority/terminal has strict liability or responsibility in law, ii) those over which (as a landlord) it may reasonably be expected to be able to bring influence to bear (e.g., over tenants/operators), and iii) aspects that are deemed to be of local, regional, or national importance.

The port sector has demonstrated its policy commitment to manage its environmental liabilities and responsibilities, based on sector-wide collaboration between a wide range of key stakeholders, including the networked cooperation facilitated by EcoPorts (see www.ecoport.com for Europe) and www.ecoslc.eu for Rest of the World).

The port sector recognizes that environmental management has evolved from very local, quayside activities, and operations to nowadays including the whole port area, port-city links, and considerations of the Logistics Chain throughout the hinterland. The transboundary and dynamic circumstances of climate change are widely accepted by the sector as is the need for collaboration between multiple stakeholders (Table 5).

The issues are very much interrelated, and the identification and selection of key chemistry-based EPIs is obviously crucial to management and mitigation of climate change. In comparison, it is interesting to note the perceived priority environmental issues of small ports – note the same issues and the commonality of the concerns involved. It may be suggested that although each port may be considered unique in terms of its commercial profile, geography and hydrography, a sector-wide and global approach is required to deal with the transboundary and all-embracing effect of climate change (Table 6).

3.2 Challenges and objectives for port authorities

Major ports worldwide must comply with an extensive body of environmental legislation and regulation aimed at controlling the impacts of their activities, products, and services. Although compliance is not negotiable, port authorities face increasing pressure to demonstrate that they are taking all necessary steps and maintaining a precautionary approach. The situation is particularly complex because, in many cases, the port authority operated under a ‘landlord’ model, meaning that the overall environmental impact of the port area results not only from the port authority’s own activities but also from those of its often-extensive list of tenants and operators.

The Port Authority must consider not only the impacts for which it has direct liability and responsibility but also those impacts of its tenants and operators over which, in a court of law, the port authority may be deemed to be in a position to bring influence to bear in its role as ‘landlord’. The Authority may also be expected to take into account specific environmental issues considered to be of international, national, or regional significance. Responses to these liabilities require the identification of relevant Environmental Performance Indicators (EPIs).

The international port sector has made substantive progress in its Environmental Management programs over the last 25 years. The days of commerce-only imperatives have steadily been superseded by the conservation concept, then the environmental protection imperative, followed by wide-spread adoption of Environmental Management Systems (EMS) and now, the essential component of Sustainable Development.

Through the development of its own internationally recognized EMS Quality standard of EcoPorts Port Environmental Review System (PERS) (*ibid*), the sector has demonstrated its willingness to comply on the basis of voluntary, self-regulation but recognizes that it needs specialist advice and guidance on the most relevant EPIs necessary to establish environmental base-line and benchmark performance and to form the basis of monitoring and reporting protocols.

The dilemma for ports is that as ‘Landlords’ they need to be able to monitor the most relevant EPIs related to their own aspects (which may be relatively restricted to considerations of navigation and port development) but

they also need to be sufficiently informed to influence their tenants and operators through collaboration on coordinated programs taking into account the cross-boundary issues comprised of the port area, adjacent city space, and hinterland because of the logistics chain.

3.3 Collaborative approach

Port Authorities are well-placed to coordinate stakeholder response options, disseminate good practice and deliver science-based reports on the quality of the environment. Despite being highly competitive, the free exchange of knowledge and experience on environmental issues is a long-adopted strategy of the sector. Port professionals tasked with environmental management have a wide range of individual backgrounds in terms of qualifications and experience ranging from economic to natural science, and legal to social.

As stated above, Port Authorities have definite liabilities and responsibilities for Environmental Management. In May 2017, the International Association of Ports and Harbors set up a World Ports Sustainability Program (WPSP) (<https://sustainableworldports.org/>) guided by the 17 United Nations Sustainable Development Goals (SDGs, <https://sdgs.un.org/goals>). The program aims to enhance and coordinate future sustainability efforts of ports worldwide and foster international cooperation with partners in the supply chain. The World Ports Sustainability Program (*ibid*) seeks to empower port community actors worldwide to engage with business, governmental, and societal stakeholders in creating sustainable added value for the local communities and wider regions in which their ports are embedded. Their various award winners demonstrate good environmental practice.

Analysis of responses by Port Authorities (all of them members of the EcoPorts Network) to the Self-Diagnosis Methodology (SDM, *ibid*) for Environmental Management shows that 26 of 292 SDM questions identified as significant within established EMS procedures are directly linked to aspects of GHG management. This figure therefore refers to the number of SDM items addressing GHG-related issues, rather than the number of ports responding, and represents a focused subset within the broader EMS structure. Components of the overall EMS are:

- Environmental policy and scope
- Environmental aspects
- Objectives and targets
- Resources and budget
- Managerial organization and personnel
- Awareness and training
- Communication
- Operational management
- Emergency planning
- Issues and monitoring
- Review and audit
- Green Services

The self-diagnosis methodology itself is a checklist of components that are considered fundamental to a practicable and time- and cost-effective EMS that assists the Port Authority in a phased approach to achieving the International Quality Standard of EMS, EcoPorts PERS. The objective is to identify procedures, processes, and capabilities of EMS in terms of dealing with control of impacts. The Self-Diagnosis Methodology and its associated pathway leading to the PERS international standard is recognized by European Sea Ports Organization (ESPO), American Association of Port Authorities (AAPA), International Association of Ports and Harbors (IAPH), World Ports Sustainability Program (WPSP), World Bank (European Investment Bank, and European Bank for Reconstruction and Development), the United Nations Environment Programme (UNEP), the African Ports Association, the Arab Sea Ports Federation, the Taiwan Ports International Corporation (TPIC), and the InterAmerican Committee for Ports (Organization of the American States). Representatives from major insurance companies

Table 7: Percentage of positive responses to specific SDM questions.

SDM number	Issue	% Response yes
A.1	Environmental policy	95.75
A.13	Ref to reduction of consumption	85.90
A.15	Ref to environmental management of operators and tenants	80.45
A.17	Ref. to UN SDGs	86.45
A.19	Inventory of legislation	92.00
A.21	Inventory of aspects	92.55
A.22	Monitoring of bunkering	71.35
A.36	Roll-on/roll-off (Ro-Ro)	46.85
A.73a	Shipping companies	50.00
A.74	Emissions to air	88.85
A.83a	GHG emissions	66.70
A.83b	Air emission targets	33.30
A.83d	Low emission zones or berths	33.30
G.2	Environmental monitoring program	83.05
G.3	Air quality	68.40
G.11	Carbon footprint Port	52.45
G.11a	Carbon footprint Port + Stakeholders	33.30
G.11b	Carbon footprint as G.11 + ships	33.30
G.12	Energy efficiency	77.45
G.21	Waste, fuel, and energy use	71.35
G.24	Operational challenges climate change	49.30
G.25	Infrastructure: climate change	64.25
I.1	Onshore power supplies (OPS) available	54.95
I.14	Liquified natural gas (LNG) available	29.00
I.26	Differentiated fees	50.55

state that a port's environmental performance and especially its risk prevention policy is "factored-in" to calculations of premiums; and those standards such as Port Environmental Review System (PERS) are recognized components of a responsible approach. Such certification may also be a condition for funding to assist port/terminal development.

The percentage positive responses to each component are currently being calculated as a global performance indicator based on the total EcoPorts Network (www.ecoslc.eu, www.ecoport.com).

With reference to Table 7, within the overall components of SDM and PERS, there are clear procedures and processes that indicate the extent to which port authorities can manage the quality of the environment and climate change issues. For example:

- **Environmental Policy.** This may be seen as the most significant strength of a port's preparedness because the policy statement drives the whole environmental management program and the associated Environmental Management System (EMS).
- **Inventory of Legislation.** All quality standards of EMS require the Port to have an inventory of relevant environmental legislation and regulations related to its liabilities and responsibilities. The sector recognizes that compliance is non-negotiable and that recognition of its environmental obligations is critical to its policy of voluntary, self-regulation.
- **Inventory of aspects for the port area.** It is essential that the Port has an Inventory of Significant Environmental Aspects (SEAs) as this is a requirement of the EMS quality standards of ISO 14001, Eco-Management and Audit Scheme (EMAS), and Port Environmental Review System (PERS). It is a highly important document in terms of identifying priorities for action, defining objectives, and monitoring trends of performance. If the port is to identify and manage the impacts of its activities and operations on climate change, then, it is an imperative that it is aware of the nature and origin of such causes. The Inventory of Environmental Aspects is a key document in terms of compliance and control. The Authority should identify its Significant

Environmental Aspects (SEAs) that is, those activities, products, and services that may impact on the environment directly or indirectly. The impacts may be beneficial or adverse. The overall objective of an effective EMS is to control the impacts of the SEAs. Over 92 % of member ports declare such an inventory.

- **Specific aspects.** Certain activities, products, and services may have both direct and indirect impacts on the environment, including influences on climate change. The significance of chemistry is also apparent in many cases.
- **Objectives and targets.** Other key components of a credible EMS include issues directly related to climate change such as whether, or not, the port authority has set up its own GHG reduction target, air emissions reduction target, and response to being bound by the local authority's GHG and air emissions reduction targets, if any such targets have been specified. Similarly, the port is required to state if low emission zones and/or emission berth standards been introduced in the port area. To qualify for an international quality standard of EMS, the port is required to communicate the objectives and to quantify, where appropriate.
- **Environmental issues and monitoring.** Another requirement of the previously referenced EMS is that of operating an environmental monitoring program. Again, as with other facets of the EMS, this has a direct bearing on the port's ability to control impacts and to manage the implications for climate change. The ability to deliver quantified and/or qualitative Environmental Performance Indicators (EPIS) is essential in order to confirm compliance and track progress. Data and information may come from secondary sources (Subject to quality and reliability of data and source) – the Port Authority/Company, itself, does not necessarily need to execute the monitoring surveys or programs. National, regional, or local responsible agencies or Non-Governmental Organizations (NGOs) may well be able to provide relevant information and data. The capacity to address carbon footprint counting only port authority's activities, carbon footprint counting port authority's and port stakeholders' emissions (including terminals, tenants, and contractors), and carbon footprint counting port authority's, port stakeholders', and third parties' emissions (including ships) is obviously directly linked to awareness of influences on climate change generated by the range of port-based activities. Closely correlated with these aspects are those of energy efficiency and use of resources. The implications of climate change for port operations are attracting more attention throughout the sector, and the standards specify that port authorities should i) state if they have experienced any operational challenges that may be related to climate change (e.g., more frequent storms, flooding, changes in wind, or wave conditions?), ii) confirm whether or not the port has taken any action to strengthen the resilience of its existing infrastructure in order to adapt to climate change?, and iii) state if the port has considered climate change adaptation as part of new infrastructure development projects.
- **Green services.** The options and opportunities to influence and encourage 'green shipping' are increasingly recognized as contributions to dealing with climate change. The provision of Onshore Power Supplies (OPS), Liquefied Natural Gas (LNG), and the application of Environmentally Differentiated Port Dues are increasingly being adopted to encourage sustainable development and to reduce the impact of shipping on emissions to air.

3.4 Awareness and implications of climate change for the port sector

As awareness and definition of environmental issues has evolved and changed with time, so has the significance of the interrelated impacts associated with port activities and shipping operations. Historically, it was the influence of weather that impacted upon and constrained navigation. The influence of wind force and direction, the impact of storms, and the overall constraints imposed by tides and general sea conditions, the safety of navigation and the ability to load and discharge cargoes, all controlled port operations. The number of shipwrecks in the approach channels and around salient navigational features are testament to the all-pervading influence of climate and meteorology on port and shipping operations.

With advances in maritime technology, the industrial development of port areas, the development of hinterland connections and the progressive expansion of the logistics chain, arguably the balance changed, and it

was the impact of commercial operations on climate and environment, both locally and globally, that began to make impact and attract attention. Without question, such impacts are profound and universally recognized and acknowledged. There is a certain irony in the fact that in some ways because of such impacts, the results have gone full circle in as much that once again, port operations and navigation are becoming increasingly influenced by meteorological changes largely induced by climate change.

Indicators of the perceived significance of climate change on present and future management decisions are evident from the EcoPorts Network of responses to its review process. From a sample of 214 ports, worldwide, to the question ‘Has your port experienced any operational challenges that may be related to climate change (e.g., more frequent storms, flooding, and changes in wind or wave conditions)?’ 49.3 % of the Network acknowledged such occurrences. In response to the question ‘Has your port taken any action to strengthen the resilience of its existing infrastructure in order to adapt to climate change?’ 64.25 % responded in the affirmative. 68.85 % stated that they had considered climate change adaptation as part of any new infrastructure development projects.

3.5 Port management response options

It is difficult to generalize on reactions for the port sector as a whole because in so many ways, each port (harbor, terminal, authority, company, corporation, etc.) is a unique entity when the sum total of its characteristics are considered such as geography, hydrography, commercial profile, throughput, ownership, local culture, and so forth are taken into account. Of particular importance, of course, are the legal liabilities and regulations with which the port administration should comply. From a global perspective there is a wide range of responses varying from non-compliance to compliance-plus, and from being inactive to demonstrating proactive, good practice initiatives. The selected pathways reflect both organizational and personal attributes, opinions, and attitudes applied within the complex of legal requirements and socio-economic considerations.

Management response options (the act, right, or power to choose) range from doing nothing, to implementing pro-active, best practice programs of compliance-plus and innovation. Willful non-compliance through ignorance or deliberate disregard carries increasing risks as an ever-widening group of stakeholders put the Port Authority under growing scrutiny. Enforcement agencies, Non-Governmental Organizations (NGOs), and Local Community Groups all have duties and expectations about how ports should deal with both global and local environmental issues. The argument that “it is cheaper to pay the fine than to invest in appropriate technology” is steadily becoming harder to justify. It is difficult to generalize on the penalties for breaching environmental legislation for the port sector as a whole given the diversity of such regimes world-wide. However, as summarized by Thompson Smith and Puxon,²⁴ penalties and consequences may include the Notices relating to enforcement and clean-up, fines or imprisonment, Civil sanctions, adverse publicity, insurance rates, relationships with regulators, and the value of the business. They indicate the broad range of punishments that may be applied as a result of non-compliance. Awareness of the provisions of the international, national, and local legal requirements are therefore critically important for mega ports in whichever country they are located. Apart from these formal consequences, there is also the attendant poor public relations and challenge to local, socially driven ‘license to operate’. Climate change and its associated topics are becoming headline issues in the geo-political debate.

The significance of awareness of legislation, compliance, and choice of response options to this research is that the decisions made by the Port Authorities define the pathway along which the port’s management will proceed in its actions to close the gap between policy and practice through effective implementation.

3.6 Current and future trends of the environmental port management procedures to handle climate change

The almost constantly evolving scope, remit, and status of the environmental sustainability imperative means that identifying the most relevant and significant environmental issue is becoming highly significant to considerations of a port’s environmental management program. The remit of Port Environmental Management

has broadened significantly from quayside impacts and the general issue of conservation to now include cross-boundary concerns including challenges related to port-city links, hinterland connections, logistical chain operations, and specifically, and with increasing significance, climate change, and sustainability. As a result, the port sector and shipping industry are pro-actively working to identify appropriate, credible, and practicable managerial procedures and processes to integrate into their business plans so that compliance, environmental protection, and sustainability is delivered – and seen to be delivered. This requires collaboration with an increasing number of stakeholders and a willingness to adopt local, regional, and global perspectives.

Amongst the most proactive ports, the ‘Environmental Report’ is developing into a far more comprehensive document that details not only the mission, vision, and policies adopted for sustainability in its widest context but also the management processes and procedures necessary to provide evidence-based data and information confirming benchmark performance and trends. Environmental, social, and corporate governance (ESG) is a set of aspects considered when investing in companies that recommends taking environmental issues, social issues, and corporate governance issues into account. Since 2020, there have been accelerating incentives from the United Nations (UN) to overlay ESG data with the Sustainable Development Goals (SDGs), based on their work, which began in the 1980s. The environmental, social, and corporate governance (ESG) approach is rapidly becoming the accepted pathway for achieving sustainability in its widest context. Large ports are demonstrably both acknowledging and actively responding to the multifactorial challenges of climate energy as demonstrated by the management options adopted and applied, and the examples of implementation with the results achieved.

4 Port management options for the greenhouse gases mitigation

4.1 Current emission landscape and greenhouse gases reduction strategies in ports

Ports are dynamic centers of commerce, characterized by a continuous influx, mooring, and departure of vessels. As of 2018, maritime operations constituted roughly 2.89 % of global greenhouse gas (GHG) emissions. If left unattended, forecasts indicate a concerning rise of 150–250 % by the year 2050.²⁵ Mega ports’ energy self-sufficiency and security from renewable sustainable sources is increasing nowadays following the ports’ increased share worldwide of GHGs to reach 3 %.²⁶ The ports’ carbon footprint has risen by 4 % in seven years to reach 52 % in 2020 leading to a rise in that issue priority within European ports interest.

All the seaborne trade emissions in equivalent carbon dioxide reached 1076 million tons in 2018.³ However, a study carried out in 2013 on historical data from 2008 in the UK covers all the UK ports linked carbon dioxide emitted with the tonnage of cargo handled and found that 174 199 Kt of cargo handled caused carbon dioxide emissions of 174 330 tons that ended to a simple reasonable ratio of everyone ton of cargo handled will cause about 1 kg of carbon dioxide emission.²⁷

The majority of these emissions are concentrated at a distance of 400 km from land, resulting in adverse effects on coastal ecosystems and communities.²⁸ Within the Europe region, “water transport” is responsible for 14 % of the total continent’s carbon dioxide emissions. Three hundred and 31 European ports are forming the Trans European transport network (TEN-T) handling about 3.5-billion-ton throughput annually 56 ports hosting industrial activities distributed within 19 European Union countries.²⁹

Forecasting for future ports, The DNV Outlook 2020 categorized the mega future ports within the EU to transport, Industrial Port 1, and Industrial Port 2 depending on their capabilities in the following main five sectors. Port operations required fueling, transitional, and new fuel supply infrastructure, electricity generation capabilities even from fossil fuel or renewable sources, hosting industrial activities, and finally hydrogen production by steam methane reforming (SMR) to serve co-located chemical industries (grey hydrogen). Future production methods include SMR and partial oxidation (POX) of natural gas combined with carbon capture and storage (CCS) resulting in blue hydrogen and electrolysis based on renewable electricity (green hydrogen). Industrial ports that have a surplus production may act as energy hubs for export.²⁹ Since one-fifth of all world-discharged wastes to oceans come from ships, it becomes the duty of every Mega port worldwide to provide reception capabilities to relieve such environmental pressures that may present port-visiting ships with the

possibility to ensure recycling and reuse of the received materials.⁴ The adoption of environmentally friendly fuels such as methanol, ammonia, and liquefied natural gas (LNG) has the potential to significantly mitigate emissions. Ports can facilitate this transformation by providing the necessary infrastructure and incentives to promote the adoption of alternative fuels.³⁰

Operational enhancements encompass many strategies aimed at improving efficiency in operations, such as eco-navigation and controlled speeds, which have the potential to yield rapid savings in emissions. The utilization of onshore power supply (OPS) for docked ships can contribute to a further reduction in emissions, particularly when the power source is derived from renewable energy.³¹ Ports possess the capacity to exert influence on shipping corporations through the provision of financial incentives. An example of a measure that can incentivize industry-wide sustainable practices is the implementation of port charge reductions for ecologically efficient ships.³²

The modernization of infrastructure is necessary for ports to adapt to technological changes. The implementation of renewable energy systems, the utilization of electric equipment, and the optimization of cargo-handling mechanisms have the potential to promote sustainability and enhance efficiency (<https://thecommonwealth.org/>). The Port energy management system must cover the power from renewable sources, energy generation/consumption, the vast amount of electricity to be fed in tariff (fit), and secure different fuel bunker supplies from low carbon transition fuel (LNG, liquefied petroleum gas (LPG), biofuel) or contemporary zero carbon fuel like Ammonia and hydrogen.²

4.2 Exemplary practices from leading ports

One notable European example is the Port of Oostende, which distinguishes itself through its offshore wind turbine project. This initiative is a prominent symbol of integrating renewable energy sources. In recent years, the Port of Dunkirk has been actively pursuing sustainability initiatives, particularly emphasizing waste recycling.³³ Also, the Aalborg Port in Denmark was the pioneer in being a CO₂-neutral.³⁴ Moreover, there are several leading examples of generating energy from renewables for wind turbine usage from (onshore or offshore) fields where the cases of Rotterdam, Copenhagen-Malmö port, and Kitakyushu port in Japan are well known. Regarding wave energy, there will be the Kembla Port (Australia) and Mutriku Port (Basque country). Tidal Energy is applied widely at the Dover Port, Digby, and Nova Scotia. But for geothermal, a suitable example will be the Hamburg Port. And for solar, the Tokyo Ohi terminal and San Diego port.²

The authority of mega port Hamburg (Germany) gave special attention to electrifying port activities from sustainable renewable sources due to the high sensitivity of the surrounding ecosystem through a combination of offshore farms of wind turbines, photovoltaic installations (PV), solar heat systems, geothermal heating systems, and biomass from solid waste. That annually generates, respectively, an approximate capacity of 26 MW from wind, half a million KW-h from PV, 56 000 KW-h solar thermal, heating switches only by geothermal, 160 GW h from biomass, and burning municipal solid wastes.²

Port of Volos (Greece) took a unique initiative to implement Local Traffic Management, implementation of Intelligent Transport Systems for traffic management and control, such as intervening in the timing of intersection signals; this leads to optimizing the acceleration and deceleration maneuvers for heavy goods vehicles (HGVs), increases the percentage of the electrical 2 %, and natural gas trucks 3 %, and reduces the diesel-powered by 5 % in 2018.³

In 2020, the Barcelona (Spain) port authority's efforts were outstanding since they invested more in the alternative fuel supply infrastructure, secured Cold Ironing service, renewed land vehicles that work on diesel oil with either electrical or natural gas-powered vehicles, promoted sustainable mobility with stakeholders, and rail use improvements in 2020. While the Rotterdam Port (Netherlands) is in action to reduce CO₂ emissions to half by 2025, the Guangdong Port in China and San Pedro Bay in California Port have successfully implemented hydrogen bunkering.³

Genoa (Italy) has a port energy environmental plan (PEEP) indicating that 7 terminals and other energy consumers with an annual energy consumption of 96 800 000 KW-h; the port authority has worked mainly on

energy efficiency improvement to reduce emissions, created two berths equipped with Onshore Power Supply (OPS) and developed photovoltaic installations on buildings' roofs,² besides, using new pieces of equipment and implementing new technologies (more electric cars, forklifts, and cranes) or new practices like cold ironing, and the suitability of the existing tool's efficiency through implementing the port's energy management plan.²⁶

Asian ports are also establishing benchmarks in their endeavors. The Green Initiative implemented by the Singapore Port encompasses the integration of green technology and the shift to sustainable fuels, thereby demonstrating a proactive approach toward environmental conservation. The thorough management method of the Taichung Port in addressing greenhouse gas emissions highlights the potential effectiveness of comprehensive environmental planning.³⁵ Again terminal electrification is a benchmark action when it comes to implementing the green port concept and cutting down emissions from mega port terminals like Hong Kong's modern terminal.³⁴ Automated Mooring Systems reduce mooring time and engine operation on part load.²⁷

4.3 Forward outlook

The convergence of the marine industry with worldwide trade situates ports as agents that both shape and mirror wider economic, environmental, and sociological patterns. The pressing nature of the worldwide climate issue necessitates that ports transcend their conventional role as mere facilitators of trade and instead become agents that stimulate sustainable transformation.

To begin with, it is evident that there exists a compelling ethical and ecological necessity for taking action. Ports, being located in coastal areas, are immediately impacted by the consequences of increasing sea levels and other climate disturbances. The adoption of greenhouse gas (GHG) mitigation techniques includes global responsibility and operational sustainability protection. Ports have the potential to serve as catalysts for promoting

Table 8: Relationship between environmental key performance indicators (KPIs) according to ISO14031, divided into environmental management indicators and environmental monitoring indicators, and the top 10 environmental priorities according to European Sea Ports Organization (ESPO).⁴³

Environmental management indicators			
Existence of an environmental monitoring programme	If Y =>	Environmental monitoring indicators	Unit Top ten environmental priorities of European ports for 2022 (rank nr in brackets)
Existence of a certified environmental management system	Y/N	Port waste	Ship waste (7) Garbage/port waste (8)
Existence of an environmental policy	Y/N	Energy efficiency	Energy efficiency (3)
Environmental policy makes reference to ESPO's guideline documents	Y/N	Air quality	Air quality (2)
Existence of an inventory of relevant environmental legislation	Y/N	Water consumption	
Existence of an inventory of significant environmental aspects	Y/N	Noise	Noise (4)
Definition of objectives and targets for environmental improvement	Y/N	Sediment quality	Dredging operations (10)
Existence of an environmental training programme for port employees	Y/N	Carbon footprint	Climate change (1)
Environmental responsibilities of key personnel are documented	Y/N	Marine ecosystems	Water quality (5)
Publication of a publicly available environmental report	Y/N	Terrestrial habitats	
		Soil quality	
			Relationship with the local community (6) Port development (land related) (9)

sustainability within the marine and logistics industries, hence encouraging the adoption of environmentally friendly practices by other stakeholders.³⁶

Moreover, customers, who are being increasingly swayed by a growing awareness of environmental issues, are progressively associating themselves with companies and behaviors that prioritize ecological sustainability. Ports that place a high emphasis on sustainability are meeting their ecological responsibilities and strategically positioning themselves to accommodate the growing demand from environmentally concerned businesses and customers. The alignment mentioned above can lead to concrete economic advantages as green practices increasingly become associated with preparedness for the future and exceptional operational performance.³⁷

Ultimately, achieving sustainability necessitates collective efforts rather than individual endeavors. Effective collaboration is crucial for success. Ports are required to actively interact with a diverse range of stakeholders, encompassing shipping firms, governmental entities, local populations, and international organizations. The shift toward sustainable port operations can be accelerated through the dissemination of knowledge, the establishment of collaborative partnerships focused on environmental preservation, and the joint investment in cutting-edge green technologies.³⁸

5 Identification, selection, and monitoring of significant chemistry-based EPIs directly linked to the top-10 priority issues for ports

5.1 Environmental performance indicators

The ISO 14031 is an international standard for environmental performance evaluation. It provides a set of tools to identify, measure, assess, and communicate environmental performance using key performance indicators (KPIs), based on reliable and verifiable information. Environmental indicators support policy making and priority setting, allow the comparison of environmental performance over time and the identification of optimization potential, and offer a communicational tool for environmental reports.^{39,40} Environmental KPIs can include both environmental management and environmental monitoring. Environmental management indicators comprise 10 indicators for the measurement of a Port Authority's capability to provide environmental protection and sustainability. These indicators are as follows: Existence of a certified Environmental Management System, Existence of an Environmental Policy, Environmental Policy makes reference to ESPO's guideline documents, Existence of an inventory of relevant environmental legislation, Existence of an inventory of Significant Environmental Aspects, Definition of objectives and targets for environmental improvement, Existence of an environmental training program for port employees, Existence of an environmental monitoring program, Environmental responsibilities of key personnel are documented, and Publication of a publicly available environmental report.⁴¹ The category of Environmental monitoring indicators delivers evidence on the present environmental status. This consists of the following indicators: Port waste, Energy efficiency, Air quality, Water consumption, Noise, Sediment quality, Carbon footprint, Marine ecosystems, Terrestrial habitats, and Soil quality⁴² (Table 8).

The European Commission has adopted a set of proposals for reducing net GHGs emissions by at least 55 % by 2030, compared to 1990 levels.⁴⁴ European seaports want to have an active role toward the green transition. The European Sea Ports Organization has published ESPO Environmental Report 2022⁴³ that lists the top 10 environmental priorities of European ports for 2022. These are as follows, in descending order: climate change, air quality, energy efficiency, noise, water quality, relationship with the local community, ship waste, garbage/port waste, port development (land related), and dredging operations.⁴³ This result is the first time that climate change enters the top priority since it entered the top 10 list in 2017. From 2013 to 2021, Air quality, held the top position, while Energy efficiency (previously labeled Energy consumption) has steadily occurred in top three since 2013.⁴³ Notably, these top three priorities over the last decade are rather closely related. Furthermore, ports focusing on green shipping provide on-shore power supply (by replacing onboard-generated power from diesel auxiliary

Table 9: National Ambient Air Quality Standards (NAAQS, according to US EPA.⁶² Units of measure for the standards are volume fraction (ϕ) micromole per mole ($\mu\text{mol/mol}$), nanomole per mole (nmol/mol), and micrograms per cubic meter of air ($\mu\text{g/m}^3$).

Pollutant	Primary/secondary	Averaging time	Level	Form	
Carbon monoxide	Primary	8 h	9 $\mu\text{mol/mol}$	Not to be exceeded more than once per year.	
		1 h	35 $\mu\text{mol/mol}$		
Nitrogen dioxide	Primary	1 h	100 nmol/mol	98th percentile of 1-hour daily maximum concentrations, averaged over 3 years.	
	Primary and secondary	1 year	53 nmol/mol	Annual mean.	
Trioxigen (ozone)	Primary and secondary	8 h	0.070 $\mu\text{mol/mol}$	Annual fourth-highest daily maximum 8-hour concentration, averaged over 3 years.	
Sulfur dioxide	Primary	1 h	75 nmol/mol	99th percentile of 1-hour daily maximum concentrations, averaged over 3 years.	
	Secondary	3 h	0.5 $\mu\text{mol/mol}$	Not to be exceeded more than once per year.	
Particle matter	PM _{2.5}	Primary	1 year	12.0 $\mu\text{g/m}^3$	Annual mean, averaged over 3 years.
		Secondary	1 year	15.0 $\mu\text{g/m}^3$	Annual mean, averaged over 3 years.
		Primary and secondary	24 h	35 $\mu\text{g/m}^3$	98th percentile, averaged over three years.
	PM ₁₀	Primary and secondary	24 h	150 $\mu\text{g/m}^3$	Not to be exceeded more than once per year on average over 3 years.

engines with electricity generated onshore), differentiated fees for clean shipping (financial incentives to encourage shipping companies to reduce their carbon footprint), and LNG bunkering.^{45,46}

It should be further noted that large ports (i.e., Port of Antwerp) often have major, chemical industry sites established within their boundaries or in proximity. By the same token, many smaller operators have processes involving the handling, processing, and storage of chemicals that should also be fundamental components of the combined Safety, Health, Environment, and Security (SHES) approach of the Port Authority.⁴⁷ Ports recognize their role as coordinating agencies and the chemical community of the integrated port/city/hinterland complex would benefit from a focused, yet generic list of chemical EPIs along with practicable, time, and cost-effective monitoring programs.

5.2 Chemistry-based environmental performance indicators

Chemistry-based environmental performance indicators focus on assessing chemical substances and contaminants that can potentially be released into air, water, and soil. These indicators are based on chemical analyses, and the results can be used to evaluate the chemical aspects of environmental performance. A critical step is to identify the most significant activities giving rise to pressures affecting the environmental status in ports. These activities and pressures can vary depending on the location and context of the port. Key activities and pressures include air and water pollution, greenhouse gas emissions, waste management, ballast water treatment, hazardous materials handling, oil spills, noise pollution, energy consumption, and protection of biodiversity and fragile ecosystems. For each activity and pressure, the most pertinent chemistry-based EPIs should be chosen based on several factors, including their ability to accurately assess the issue, the data availability, their scientific validity, the regulations' requirements, and the expectations of the relevant stakeholders. The measurement of the selected EPIs should follow a scientifically robust, consistent, and reliable methodological approach, involving laboratory testing, data collection through sensors or monitoring equipment or calculations based on available data sources.

5.3 Air quality

Air pollution is one of the greatest environmental threats to human health. Commonly used air quality indicators are the measurement of the amount of contaminants released into the air and the monitoring of the concentration of contaminants in the air surrounding the port. Air pollutants with the strongest proof for adverse health issue impacts include particulate matter (PM_{2.5} and PM₁₀), trioxygen (ozone), nitrogen dioxide, sulfur dioxide, and carbon monoxide.⁴⁸ There are several ways to measure air pollutants, but most of them involve taking a sample of the air and analyzing it to determine the pollutant content in the air.⁴⁹

Fine particles as PM_{2.5} are harmful affecting the respiratory and cardiovascular systems, while there is a positive correlation between PM_{2.5} levels and mortality. The ground-level PM_{2.5} is linked to asthma, chronic obstructive pulmonary disease, lung cancer, and cardiovascular mortality.⁵⁰ Fine particles as PM_{2.5} in ambient air can be determined using a Beta Attenuation Monitor (AS/NZS 3580.9.12:2022)⁵¹ and by a gravimetric method utilizing low volume sequential and non-sequential samplers equipped with size selective inlets (AS 3580.9.10:2017). Coarse particles as PM₁₀ can affect the heart and lungs with severe health effects.⁵² Coarse particles PM₁₀ are measured by Tapered Element Oscillating Microbalance (TEOM).⁵³ A Tapered Element Oscillating Microbalance – Filter Dynamic Measurement System (TEOM-FDMS) is used for the continuous simultaneous monitoring of PM_{2.5} and PM₁₀.⁵⁴

Ground-level trioxygen (ozone) is a pulmonary irritant causing asthma worsening, lung inflammation, loss of lung function, and cystic fibrosis; also, it affects the immune system.⁵⁵ Trioxygen (ozone) is measured by ultra-violet technology.⁵⁶

Nitrogen oxide can worsen respiratory diseases and may contribute to the development of asthma; it reacts with air pollutants forming PM and ozone; it leads to the formation of acid rain.⁵⁷ Nitrogen oxide is determined by chemiluminescence.⁵⁸

Sulfur dioxide may cause respiratory irritation, bronchitis, mucus production, bronchospasm, skin redness, damage to the eyes, and worsening of pre-existing cardiovascular disease.⁵⁹ Sulfur dioxide may also lead to acid rain, soil acidification, and ocean acidification (not to be confused with carbon dioxide related ocean acidification, which does not consume alkalinity). Sulfur dioxide is determined by pulsed fluorescent spectrophotometry.⁶⁰

Carbon monoxide is a poisonous gas causing headache, dizziness, nausea, and loss of consciousness. It may also cause cardiovascular disease.⁵⁹ Carbon monoxide is determined by infrared spectrometry.⁶¹

Ports can employ various strategies, such as establishing air quality monitoring stations, to continuously measure emissions of several pollutants and ensure compliance with air quality standards. Continuous monitoring of air quality indicators provides valuable data for evaluating the effectiveness of pollution control strategies and implementing targeted measures to improve air quality in and around megaports.

According to the Clean Air Act, US EPA has set National Ambient Air Quality Standards (NAAQS) to protect human health and welfare and to limit hazardous air pollutant emissions. The Clean Air Act distinguishes between two kinds of national ambient air quality criteria. Primary standards promote public health by preserving the health of “sensitive” populations like asthmatics, children, and the elderly. Secondary standards promote public welfare by protecting against reduced visibility and damage to animals, crops, vegetation, and structures⁶² (Table 9).

5.4 Climate change

Climate change is easily detected in seawater by chemical indicators of acidification and deoxygenation. Extreme weather and climate-related events have many negative effects on ecosystems, various socio-economic sectors, and human health. Therefore, climate change adaptation becomes a top priority issue. Climate short-term risks influencing ports include mainly high tides and storm surges causing increased sea level and high winds, long-term risks include general sea level rise.^{63,64} A Climate Change Risk Indicator (CCRI) framework for climate risk assessment of seaports has been developed.⁶⁴ It was constructed based on the most influential climate indicators

which are warming trend/extreme temperature/drying trend, extreme precipitation, snow cover, damaging cyclone, and sea-level rise. The climate vulnerability was assessed using monthly climate data.

Climate changes impose pressure on the ecological ecosystem biodiversity. Bioindicators are used to assess the quality of the environment and how it changes over time. The European Commission staff working document⁶⁵ emphasizes the responsibility of the port sector for biodiversity issues and its commitment to Natura 2000. Monitoring of marine biodiversity changes and plankton ecosystems disruption indicates the effects of multiple stressors, such as ocean warming and acidification. It is important, yet challenging, to select the most appropriate species considering their climate sensitivity and local environmental parameters. Monthly observations of the hard-bottom epifauna biodiversity of inner, middle, and outer port areas will show differences in species diversity and abundance.⁶⁶

Biodiversity is strongly correlated with chemical indicators; inversely correlated with certain chemical indicators of pollution and positively correlated with chemical indicators of a healthy, functional ecosystem.

Biodiversity can be estimated using a suitable index, as follows:

- Biotic Index (BENTIX) based on soft bottom benthic indicator species and related habitat types.⁶⁷
- Benthic Quality Index (BQI) based on combination of the species tolerance values, abundance, and diversity.⁶⁸
- Benthic Habitat Quality (BHQ) based on the ecosystem structure.⁶⁹
- City Biodiversity Index (CBI) known also as the Singapore Index on Cities' Biodiversity (SI) evaluating and monitoring the progress of biodiversity conservation efforts and assisting cities in implementing the post-2020 global biodiversity framework.⁷⁰
- Biopollution Level Index (BLI) based on the abundance and distribution of NonIndigenous Species.⁶⁹ The evaluation of nNIS indicator measures the effectiveness of legal and administrative instruments aimed at prevention of NIS species introductions.⁷¹
- Natural Capital Index (NCI) as the product of the size of the remaining area and its quality.⁷² Natural Capital Index considers biodiversity as natural capital that contains all species with their corresponding abundance.

5.5 Water quality

The amount and kind of chemical pollutants discharged into the seawater act as an indicator of the seawater quality; the hydrography and water exchange that occurs in the area will also control the quality.

Nitrogen is a major limiting nutrient in coastal ecosystems which controls the growth of marine flora. Its excess may lead to eutrophication, i.e., increased algal growth causing environmental harm as intense and sometime toxic algal blooms. This extreme production of organic matter then sinks to the seafloor and the increased oxygen demand during degradation cause anoxic zones to spread.⁷³ Beside nitrogen, phosphorus is often the major limiting nutrient of freshwater ecosystems, why both nutrients should be monitored.⁷⁴ Nutrient detection in the water is developing from laboratory analysis to *in situ* automatic monitoring. Spectrophotometry, colorimetry, fluorimetry, and electrochemistry are the most widely used detection methods for nutrients.⁷⁵

Potentially hazardous chemical elements can affect marine species. They are persistent, not biodegradable; they can be bioaccumulated and some of them have high toxicity.⁷⁶ The potential ecological impacts of potentially hazardous chemical elements require their systematic detection. This includes the use of highly sensitive spectroscopic methods, i.e., atomic absorption (AAS), X-ray fluorescence (XRF), inductively coupled plasma mass (ICP-MS), inductively coupled plasma optical emission (ICP-OES) spectroscopies, neutron activation analysis, inductively coupled plasma atomic emission (ICP-AES), ion chromatography ultraviolet–visible (IC-UV Vis), total reflection X-ray fluorescence (TXRF), laser-induced breakdown (LIBS) and atomic fluorescence (AFS) spectroscopies, capillary electrophoresis (CE), and microprobes (MP).⁷⁷

Dissolved oxygen concentration (DO) is the amount, mass/volume, of dioxygen dissolved in a certain volume/mass of water. It represents the level of free dioxygen present in water and is vital to many forms of life. Both the nutrients excess at coastal marine areas and the Earth's warming cause reduction of the DO. The nutrients excess leads to eutrophic conditions increasing the microbial consumption of dioxygen. More than 93 % of the planet's

warming is absorbed into the ocean increasing the temperature of seawater. As the solubility of dioxygen decreases in higher temperature, warm seawater masses contain less dioxygen.

Main DO measurements methods in seawater are iodometric titration,⁷⁸ electrochemical method, and optical method.⁷⁹ Iodometric titration is a purely analytical process, suitable only for laboratory analysis. Dissolved oxygen can be measured *in situ* using an electrochemical DO sensor or an optical DO sensor. The electrochemical DO sensors are divided into polarographic, galvanic cell-type, conductance-type, potentiometric-type, and all-solid DO sensors.⁸⁰ Various optical DO sensors have been developed with different optical principles. Most of them are based on the fluorescence quenching principle.⁸⁰

The biochemical oxygen demand (BOD) measures the concentration of dioxygen consumed by aerobic microorganisms in decomposing the biodegradable organic matter present in a water sample. Biochemical oxygen demand determination requires two measurements at each site, one immediately and another after incubation in the dark at 20 °C for 5 days. The difference in DO levels between the first and second measurement gives the BOD.⁸¹

Floating litter and debris affect water quality and marine life. Based on the material they are made of, they can be classified in chemicals, textiles, food waste, glass/ceramics, artificial polymers, paper/cardboard, rubber, and wood.⁸² They can be collected by using specialized vessels. The type and amount of floating litter and debris is assessed and compared on a seasonal basis.

5.5.1 pH

Major changes in pH can have severe negative environmental impacts, e.g., acidification may hamper calcifying organisms to build their shells, as carbon carbonate saturation states are lowered. In addition, seawater chemical speciation is altered, which may increase toxicity of metals and affect biogeochemical cycling of many elements and compounds.⁸³

It is crucial to note that pH measurements in seawater are affected by the high ionic strength of the salts. In the marine environment, we accurately measure and quantify changes in seawater acidity by using a pH expressed on a total scale, pH_T .⁸⁴ This scale is based on the measurement of free hydrogen ions and hydrogen ions combined with sulfate ions.

Sensors for *in situ* pH measurement apply potentiometric or spectrophotometric methods, but the uncertainties of historic pH determinations are large as they fail to handle salinity and dissolved organic matter gradients.^{85,86}

A commonly used sensor is the one that uses a potentiometric glass electrode. Newer autonomous pH-sensing technologies, include potentiometry with ion sensitive field effect transistors (ISFETs) and spectrophotometry with pH-sensitive indicator dyes.⁸⁷ The measurements of pH_T can be done spectrophotometrically⁸⁸ and is applicable also for situations with wide varieties in salinity and pH, such as the Baltic Sea.⁸⁵

5.5.2 Temperature

Sea surface temperature measurements are crucial in weather prediction, atmospheric model simulations, and marine ecosystems studies. Sea surface temperature is measured using thermistors. The remotely sensed measurements of sea surface temperature can be obtained from satellite infrared radiometers and satellite microwave radiometers.⁸⁹

5.5.3 Salinity

Salinity is the dissolved salt content of a waterbody. Fluctuating levels of salinity can affect species which are adapted to prevailing salinity concentrations. However, many ports are in estuarine environments where marine water meets freshwater. In the case of microtidal conditions, the water can be strongly stratified with a saltwater wedge closest to the seafloor.⁹⁰ Salinity is measured using a conductivity sensor. The conductivity-temperature-depth (CTD) probe, which incorporates a cluster of sensors, can be used for the *in situ* measurement of the three variables salinity, temperature, and water depth.

Table 10: Environmental quality standards (EQS) for metals in surface waters (other than inland).⁹⁸

Name of substance	AA-EQS (µg/l)	MAC-EQS (µg/l)	EQS biota (µg/kg)
Cadmium and its compounds	0.2	1.5	
Lead and its compounds	1.3	14	
Mercury and its compounds		0.07	20
Nickel and its compounds	8.6	34	

Table 11: Environmental Protection Agency of United States of America (U.S. EPA) recommended water quality criteria for aquatic life and the conversion factors for dissolved metals.⁹⁹

Metal	Saltwater CMC ^a (acute) µg/L	Saltwater CCC ^b (Chronic) µg/L	Conversion factors for dissolved metals saltwater CMC	Conversion factors for dissolved metals saltwater CCC
Arsenic	69	36	1.000	1.000
Cadmium	33	7.9	0.994	0.994
Chromium III	–	–	–	–
Chromium VI	1100	50	0.993	0.993
Copper	4.8	3.1	0.83	0.83
Lead	210	8.1	0.951	0.951
Mercury	1.8	0.94	0.85	0.85
Nickel	74	8.2	0.990	0.990
Selenium	290	71	0.998	0.998
Silver	1.9	–	0.85	–
Zinc	90	81	0.946	0.946

^aCMC, criterion maximum concentration; ^bcriterion continuous concentration.

5.5.4 Fecal bacteria

Fecal bacteria indicate possible sewage contamination. Their presence may indicate pathogenic bacteria and viruses. *Enterococci* are the best bacterial indicators for marine waters. Climate change enhances the content of fecal bacteria in seawater by increasing rainfall, leading to sewage spills from overloaded systems, and elevating seawater temperature, which help bacteria endure longer and possibly multiply. Fecal bacteria are determined following a laboratory analysis.⁹¹

5.5.5 Metals

Metal contamination has become a significant concern due to its toxicity, abundance, and persistence in the environment, and its subsequent accumulation in aquatic habitats. Because sediments can record and incorporate environmental events, they are being used to assess the condition of aquatic environments.⁹²

Port sediments often have high concentrations of metals, e.g., due to leakage from antifouling coatings and scrubber water discharge.⁹³ Recent research even suggests metal extraction from dredged sediments to be economically and environmentally beneficial.⁹⁴

Each metal has a different level of toxicity. Because there is no general toxicity threshold, each metal must be examined individually. When metals are evaluated separately, the effect of cumulative toxicity is ignored. Some metals' toxicity varies with water chemistry.

Environmental risk assessment of port areas is often carried out using the hydrodynamic and chemical fate model MAMPEC, but cumulative risk of elements and compounds are rarely made. Lunde Hermansson *et al.*⁹³ showed that cumulative risk assessment leads to three out of four modeled ports to have unacceptable risk due to metal and

PAH contamination. In addition, ports can act as contamination hotspots, leading to pollution of surrounding areas, i.e., potentially impacting biodiversity negatively and thereby aggravating climate change related effects.

Metals are studied following a laboratory analysis and their content is determined by AAS, GFAA, ICP-AES, or ICP-MS.⁹⁵ The *in situ* metal determination uses a portable spectrophotometer.

In the European Union, since 2000, the Water Framework Directive⁹⁶ has been the main law for water protection. It concerns inland, transitional, and coastal surface waters plus groundwaters. It guarantees a comprehensive strategy for managing water resources while upholding the integrity of entire ecosystems through the regulation of specific contaminants and the establishment of appropriate regulatory standards. All surface water bodies are to attain good chemical and ecological state, according to the EU policy. To qualify for the former, surface waters need to include a minimum amount of quality elements, including biological, hydro-morphological, and physico-chemical ones. Surface waterways must minimize or phase out the emissions of specific pollutants into the water, as well as fulfill minimum quality standards for those pollutants, to maintain a good chemical status.

On June 17, 2008, the European Parliament adopted the Marine Strategy Framework Directive (MSFD).⁹⁷ Its primary goal is the effective protection of the marine environment throughout Europe and the achievement of good environmental status of marine waters by 2020. According to the MSFD, Member States should elaborate marine strategies as well as develop and implement monitoring programs and measures to achieve or maintain good environmental status of marine waters. Thus, the primary concern of countries is to ensure that levels of certain chemical substances that pose a potential risk to the environment or human health do not cause pollution effects in coastal waters. Metals of a specific environmental interest include Hg, Cu, Cd, Cr, Sn, Zn, and Pb.

On August 24, 2013, Directive 2013/39/EU⁹⁸ of the European Parliament and of the Council amended Directives 2000/60/EC and 2008/105/EC as regards priority substances in the field of water policy. It provides environmental quality standards for priority substances and certain other pollutants. Referring to metals, those included are shown in the following table (Table 10).

The maximum tolerable concentration limits for metals in seawater depend on its use. The following table lists the U.S. EPA recommended water quality criteria for aquatic life and the conversion factors for dissolved metals. Note that water quality criteria refer to the highest contaminant concentration in seawater that is not expected to pose a significant risk to most species in each environment (Table 11).

5.5.6 Bioindicators

Apart from chemical indicators, bioindicators are also used for environmental assessments. The former measure the concentration of a specific contaminant at a given moment, while the latter focuses on the biological responses to environmental stressors. Changes in their composition is a tool to measure the environmental impact of anthropogenic activities. In the Mediterranean Sea, invertebrate such as mussels are commonly used as bioindicators for quality assessments of the marine environment.¹⁰⁰ The mollusk sea hare *Aplysia fasciata* is a potentially hazardous metals bioaccumulator and it has been suggested to be used as a bioindicator of marine pollution in harbors and bays.¹⁰¹ Oysters are also a candidate species for biomonitoring contaminant exposure. Sydney rock oyster (*S. glomerata*) which is widely grown in the Pacific coastal areas was used as a bioindicator to assess the distribution and levels of trace element accumulation in ports.¹⁰² Bioindicators can record the cumulative impact of various contaminants and habitat changes, in an early stage and over time.¹⁰³

6 Supporting stakeholder participation in sustainable port planning: a review of tools and methods

6.1 Seaports, managers, and stakeholders

Marine ports at national and global level are considered as a key industry and pillars of the countries' economy. Although, on the one hand, ports play an important role in the development of national and international trade, transport, and economies, on the other hand, they can have a strong impact on neighboring communities and the environment. Ports can also be seen as a critical hub in supply chain networks as they link global supply chain networks and regional production and consumption markets.¹⁰⁴ Since seaports are complex environments and key hubs of supply chains involving various interested parties and activities with often conflicting goals and interests (e.g., environmental, social, and economic), exploring the contribution of stakeholder relationships to ports sustainability has been proved to be an important issue.

Nowadays, a new activity environment has been created in port areas. The phenomenon of globalization of production and consumption, the development of international trade and transport, the global trend toward sustainability, the growing public awareness of possible effects on human health and climate change from exposure to air emissions and the need to comply with the legal requirements have led to substantial changes in the inter-port/intra-port relations.^{105–108} The success of a port depends, to a large extent, on the port managers and how they can successfully manage the various stakeholders and the interactions among them, balancing conflicting interests through open dialogue, mediation, and involvement of all interested parties from the beginning of the planning process.^{106,109} Careful procedures and right skills are required for a successful port planning. In recent years, there has been a significant evolution in port planning, from a top-down approach, in which only the judgments and/or intentions of the port authorities were taken into consideration, to a bottom-up approach, in which the judgments and/or intentions of different stakeholders are equally taken into consideration. Therefore, the participation of all stakeholders, from the beginning of the process, with different levels of involvement, is considered essential.¹⁰⁶ The well-known participatory concept, which is very common in spatial planning, has been used in recent years also in transport planning.¹¹⁰ In this direction, the EU urges the Member States to adopt Sustainable Urban Mobility Plans, enhancing cooperation opportunities among various policy areas and sectors, with various levels of governance and management and in cooperation with civil society and other interested parties. In the port community, port planning should be based on urban planning and vice versa, to promote a common sustainable development.

6.2 Overview of methods and tools

The concept of stakeholder was originally proposed by R. E. Freeman¹¹¹ and can be defined as “*any group or individual who can affect or is affected by the achievement of the organization's objectives*”.¹¹¹ Individuals and organizations can be considered as the main stakeholders in the transport sector who, although they have a stake

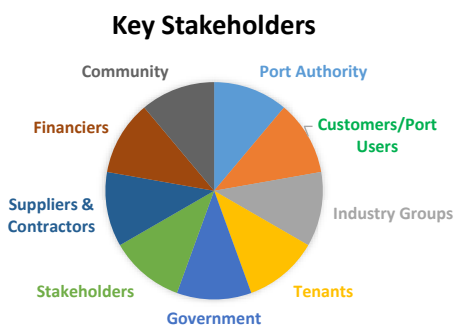


Fig. 2: Key stakeholders: port of Melbourne (Australia).¹¹⁸

Table 12: Stakeholders' engagement in the port of Melbourne (Australia).¹¹⁸

Inform	Consult	Involve	Collaborate	Empower
Provide insights to stakeholders to understand issues, opportunities and solutions.	Ask feedback from stakeholders and inform them about outcome of their feedback.	Work closely with stakeholders to ensure their needs and expectations are understood, and provide feedback.	Collaborate with stakeholders about development of alternative plans, decision-making, and preferred solutions.	Collaborate with stakeholders to build networks, develop opportunities, and empower teams to lead the development of initiatives.
Tools/methods				
Website	Contributions to studies	Workshops	Involvement in tasks and advisory panels	Working groups
Social media	Calls for comment or submission	Public/industry meetings	Advisory committees	Joint ventures
Publications	Surveys	Webinars	Technical advisory groups	Sponsorship
Presentation/Events	Focus groups	Education sessions	Roundtables	Provision of data
Press releases	E-mail	Stakeholder workshops	Expert panels	
Fact sheets		Roadshows and briefings		

and/or interest in a specific issue, do not have an official role in the decision-making process.^{106,112} Public participation is the official process that aims to engage civil society and stakeholders in the decision-making process.¹¹³

Identifying all relevant interested parties is not a trivial matter. The decision-making context can support in this direction by framing the key players. According to the literature review, a typical stakeholder classification is the following:¹¹⁴

- Internal stakeholders: parties within port authorities, such as managers, board members, employees, etc.
- External stakeholders: terminal operators, shipping and industrial companies, supporting industries, port customers, trading companies, etc.
- Public policy stakeholders: ministries or government departments responsible for shipping, transport, international trade, environment, spatial planning, etc.
- Community stakeholders: non-market actors, the general public, civil society organizations, etc.

These four categories can be further merged into two (2) main categories: internal stakeholders and the remaining three categories as external stakeholders. They can also be divided into three classes: experts who are the main source of information for a port, general stakeholders, including institutions, transport companies, environmental organizations, etc., and citizens or civil society, who can be individuals or groups.¹¹⁵ Usually, experts are characterized by high skills but low share. On the contrary, stakeholders have skills and high share. Citizens or civil society have low share but act in the public interest.¹⁰⁶

Determining the desired level of involvement of each actor, also known as the “ladder of citizen participation”, can be considered as one of the main initial steps of the participation process. Four levels can be identified in transport planning, according to the phases of the planning process: a) identification of the actors involved (usually at the beginning of the decision-making process), b) analysis of current state and identification of plan objectives, c) consultation and provision of information, and d) involvement in the final choice.¹¹⁶ Public participation should be included in all the above phases.

Today, various tools and practical methods are used to support the participation process, such as focus groups, workshops, interviews, public meetings, consensus meetings, scenario analysis, use of Multi-Criteria Decision Analysis (MCDA) techniques, etc. Multi-Criteria Decision Analysis techniques combined with scenario analysis are used to extract the preferences of different stakeholders (e.g., development of alternative and sustainable projects) according to multiple criteria and expert judgments. Workshops and one-on-one interviews are considered appropriate for listening and information purposes. In contrast, focus groups, involving small

groups of stakeholders, are more suitable for consultative purposes. Consensus meetings are also essential tools for converging opinions toward a common plan.

Furthermore, more science-oriented tools, such as desk analysis, are used, to support the management of the participation process.¹⁰⁶ In this direction, key stakeholder mapping is considered an easy way to group the different parties involved. Social Network Analysis can also be used to explore social structures and to shorten the process of analyzing stakeholders.¹⁰⁶ Both techniques can be used in the initial stages, e.g., stakeholder identification, in order to understand the actors involved and their role in the decision-making process. The port community can be regarded as a highly complex environment, consisting of multiple decision-makers and different types of stakeholders, where the relationship among them can be characterized as competitive, cooperative, or informative. The influence of stakeholders can be analyzed through centrality indices, based on their position and role in the wider network. Furthermore, a variety of simulation models, such as Agent-Based Models (ABM) has been developed in the field of transportation planning (e.g., reproduction of port terminal container management, simulation of stakeholder relationships toward a more sustainable port and terminal management, etc.), permitting the exploration of the role of network topology and other factors in reaching a shared decision.^{106,113,117}

An actual example of key stakeholders and the methods used to engage them in port-related decisions is shown in Fig. 2 and Table 12.

The optimal goal of a port is to satisfy the needs of its customers and neighboring communities, while preserving the environment. In this direction, the European Seaports Organization (ESPO) is already urging European ports to adopt Environmental Management Systems (EMS), based on, e.g., the Port Environmental Review System (PERS) and the Eco-Management and Audit Scheme (EMAS), as one of the prominent tools for a more sustainable port planning.¹⁰⁸ Implementing sustainable and environmental port planning can ensure responsible use of resources, promote economic development, and improve quality of life of neighboring communities.

The motivation for a more sustainable approach can be the objectives shared by all parties involved. Meeting these objectives can be seen as a significant way to ensure the viability of long term port development plans, supporting the development of a collaborative environment and contributing to a more sustainable development.¹¹⁴

6.3 Collaborative innovation in ports

The ability to innovate can be seen as a prerequisite for the sustainable development and the competitiveness of ports in a rapidly changing world. In the context of a globalized, integrated, and digital society and economy, all economic sectors and activities face strong competition that changes the current situation. The adaptability of ports to this new era and the adoption of innovation as a part of their own transformation can be seen as key tools to deal with this changing situation.

The port industry can be considered as a conservative sector, often focusing on cargo traffic and supply chain, applying port-to-port approaches. In light of this changing world, ports need to adapt to new national and international regulatory requirements, intense competition, digitalization, and climate and environmental challenges, exploring new emerging opportunities beyond cargo traffic and supply chain. Traditional strategies based on cost optimization, investment planning, and other related techniques are no longer suitable. Instead, an innovation strategy is more appropriate, as it gives ports the opportunity to adapt and reinvent themselves in the context of the new economic environment. The port sector can be characterized as an ideal place to implement collaborative innovation. Ports are made up of various public and private interested parties. This group of stakeholders could work together to address the upcoming challenges of globalization and related issues in terms of safety, quality of services, performance and sustainable development, etc. In this context, a real example comes from the port of Hamburg (Germany). The port of Hamburg has implemented the home PORT as a test space within the port, operating as a real laboratory. For example, the Hamburg Port Authority is one of the main partners of the EU-funded research project SeaClear, which will develop autonomous underwater robots to detect

Table 13: List of best practices of ports at a global scale, including the measures taken and the subsequent results.

Country	Port/terminal	Action taken	Results	References
Belgium	Antwerp Port	The world's first H ₂ dual fuel straddle carrier, running on a mixture of H ₂ and diesel.	Dual-fuel technology can replace 70 % of diesel consumption with H ₂ on new straddle carriers	https://safety4sea.com/worlds-first-hydrogen-dual-fuel-straddle-carrier-launches-in-port-of-antwerp/#:~:text=Antwerp%20Terminal%20Services%20(ATI)%2C,developed%20by%20cleantech%20company%20CMB. https://www.globalpsa.com/wp-content/uploads/nr230315.pdf
Canada	Halifax Port	Transformation of the terminal into an all-electric Rubber Tyred Gantry operating environment.	Reduction of CO ₂ by half by 2030 compared with 2019 and achievement of net zero CO ₂ emissions by 2050.	https://news.gov.bc.ca/releases/2023EMLI0034-000881
Canada	Vancouver Port	Financial support for a project to help port industries use H ₂ fuel-cell powered trucks.	Reduction of CO ₂ emissions by 110 tons/year.	
China	Guangzhou Container Terminal	Project to replace all 40 existing dPM with electric ones over the course of 5 years.	Cut of CO ₂ emissions by about 52 % compared to using dPMs.	https://sustainableworldports.org/project/guangzhou-container-terminal-electric-prime-movers/
China	Ningbo Zhoushan Port	Replacement of the boilers and portions of electricity with renewable sources of energy (wind and solar sources).	Incremental annual energy savings. An estimated 14 % reduction in total CO ₂ emission was achieved based on the 2013 account.	120
China	Qingdao Port	Alternative fuels used in place of diesel oil are LNG, electricity and batteries. Development of a hydrogen energy-driven solution for the fueling of equipment needed for the operation of the port.	The world's first 'hydrogen + 5G' smart ecological terminal, pioneering hydrogen-powered crane technology and systems. Reduction of CO ₂ emissions by some 3.5 kg and SO ₂ emissions by 0.11 kg per twenty-foot equivalent unit (TEU). Annual cut of 21 000 tons of CO ₂ and 640 tons of SO ₂	https://www.porttechnology.org/news/qingdao-port-becomes-the-worlds-first-hydrogen-powered-and-5g-intelligent-port/
China	Shanghai Port	Maersk signed memorandum of understanding (MOU) with Shanghai International Port Group on green methanol fuel vessel-to-vessel bunkering operation, after the delivery and operation of 19 container vessels with dual-fuel engines able to operate on green methanol. High loading and unloading efficiency, short berthed time. Use of electric RTG crane only. Cold chain logistics in the western port area.	Acceleration of the evolution of climate neutral shipping.	https://www.maersk.com/news/articles/2023/03/24/maersk-signs-mou-with-shanghai-international-port-group-on-green-methanol-bunkering
China	Shenzhen Port		Less carbon emissions from ships at berth. Little carbon emissions from rubber-tired gantry (RTG) crane.	120

Table 13: (continued)

Country	Port/terminal	Action taken	Results	References
Egypt	Damietta Terminal	Establishment of a multi-purpose terminal including 630 m long, 17 m deep berth.	OPS available for the berthing ships in addition to oil and waste reception facility	https://www.dpa.gov.eg/?p=4922
Egypt	East Portsaid Port	Creation of a consortium between EPS Port, COWI Belgium, Project Planning and Management Ltd Bulgaria, The Technical Assistance of the EIB in the Mediterranean region.	Creation of the first Green Added Value Logistics Center in the region (VALC) in the east of Portsaid integrated zone. In August 2023, the first green fuel ship bunkering	https://sczone.eg/services/east-portsaid-port/ https://egyptoil-gas.com/news/east-port-said-receives-worlds-first-green-fuel-ship/
France	HAROPA-Port	Financial incentives	Air quality improvement	https://www.haropaport.com/en/havre/air
France	Sète Port	Two offshore floating solar units in the Mediterranean Sea providing clean electricity.	Estimated production of 400 MWh/ year, transported by a submarine cable to supply renewable electricity to the infrastructures of the port.	https://www.offshore-energy.biz/france-gets-its-first-offshore-solar-farm/
Finland	Turku Port	Support the use of electric cars within the port to reduce carbon footprint.	Emission reduction 40 % by 2025 and became a carbon neutral port by 2029.	https://aboard.portofurku.fi/en/category/environment-and-safety/ https://aboard.portofurku.fi/en/2022/11/disposal-site-for-dredging-masses-completed/ https://aboard.portofurku.fi/en/2022/11/new-innovation-removes-microplastics-from-the-sea/ https://www.railtech.com/rolling-stock/2023/03/06/bremerhaven-shunting-locomotives-switched-over-to-hvo/?gclid=accept
Germany	Bremerhaven Port	Use of Hydro-treated Vegetable Oil instead of diesel for the shunt trains being used in the port.	Reduction of GHG emissions by around 90 %/year.	https://www.duisport.de/unternehmen/unser-verantwortung/ressourcen-umwelt/?lang=en https://www.sustainable-ships.org/rules-regulations/port-hamburg
Germany	Duisburg Port	Use of a highly transportation network	Contribution to environmental protection	
Germany	Hamburg Port	Shore power use.	CO ₂ emissions will be reduced by 50 % by 2025 and cut by 100 % by 2040.	
Hong Kong	Hong Kong Container Terminal 9	Launch of new rubber-tyred gantry cranes and an automated container stacking system.	Increasing efficiency, productivity, occupational safety and working conditions of the site's crane operators. Port's carbon emissions reduction.	https://www.hutchisonports.com/en/media/news/hits-container-terminal-9-north-launches-remote-controlled-operations/
India	Mumbai Port	Development of a 6.25 MW solar farm, which will power the PSA's Bharat Mumbai Container Terminal with renewable energy.	When completed, it will provide nearly 70 % of PSA Mumbai's power, reducing the terminal's CO ₂ emissions by 10 000 tons/year.	https://indiashippingnews.com/psa-mumbai-announces-partnership-to-develop-6-25-mw-solar-farm-with-o2-power/
Italy	Genoa Port	Shore power supply from renewable energy sources Port Environmental Energy Plan that ensures energy saving and efficiency optimization.	Emission reduction and air quality improvement.	https://inea.ec.europa.eu/featured-projects/greener-port-genoa_en

Table 13: (continued)

Country	Port/terminal	Action taken	Results	References
Netherlands	Rotterdam Port	Development of an 11-ha site suitable for a green hydrogen plant.	2–2.5 GW of electrolysis by 2030.	https://www.portofrotterdam.com/en/news-and-press-releases/port-of-rotterdam-authority-site-green-hydrogen-plant-1GW
Nigeria	Lagos Port	Implementation of a smart traffic planning and optimization transport system, aiming at addressing truck congestion.	Substantial reduction of CO ₂ emissions from trucks and rubber tyred gantry cranes.	https://issuu.com/mercatormedia/docs/greenport_36_pages_summer_2021_programme/s/12644939
Singapore	Singapore Port	First marine biofuel bunkering trial in an ocean-going vessel.	The use of advanced biofuel reduces CO ₂ emissions by 80–90 % well-to-exhaust compared with Heavy Fuel Oil (HFO)/Very Low Sulfur Fuel Oil (VLSFO).	https://www.bhp.com/news/media-centre/releases/2021/04/bhp-olderdorff-and-goodfuels-successfully-complete-first-trial-with-sustainable-biofuel-supplied-in-singapore
Spain	Valencia Port	Agreement signed between the Port Authority and the city council for the installation of a device for the generation of electrical energy from waves in the Marina of Valencia.	Generation of about 130 MW per year, reducing the city's annual CO ₂ production by 16 tons.	https://www.valenciaport.com/en/the-pav-and-the-valencia-city-council-collaborate-in-the-installation-of-a-pilot-device-for-generating-electricity-from-waves/
Sweden	Malmö Port	Onshore power supply for cruise ships at Ocean Quay in the North Harbor.	reduction of the emissions from cruise ships.	https://stateofgreen.com/en/news/reducing-air-pollution-from-cruise-ships-in-the-port-of-copenhagen/
Sweden	Gothenburg Port	M/S Hamnen converted to run on electrical power.	Emissions reduction.	https://www.vesselfinder.com/news/25640-The-Port-of-Gothenburgs-inspection-vessel-to-be-electrified
USA	Los Angeles Port	A reduction in ships at anchor. Port's ongoing environmental initiatives.	Significant clear air progress in 2022. DPM, NO _x , and SO _x emissions are down 88 %, 62 %, and 97 %, respectively, since 2005.	https://www.portoflosangeles.org/references/2023-news-releases/news_090723_air_emissions

and clear marine litters. Similar initiatives are observed in many European countries. Furthermore, many ports around the world have already developed digital platforms, bringing together all interested parties involved in the supply chain and ensuring optimal coordination and real-time information exchange. A representative example of collaborative innovation is Port Community Systems (PCSs).¹¹⁹

An innovation approach must be implemented to all available products and services, procedures, organizational structures as well as business models in a port. It is important to note that technology facilitates innovation, rather than being a solution in itself. Ports must focus on products, services, procedures, etc., understanding that technology is the driving force behind innovation, but not all innovation is based on technology.

Ports as open innovation ecosystems should facilitate the participation of the various stakeholders involved in port community as well as neighboring communities in the port. This may include the development of committees or working groups in which all stakeholders involved in innovation procedures can participate, addressing the upcoming challenges of a port. The choice of the most appropriate innovation tools depends on the available resources as well as the ability of a port to transform scientific breakthroughs into applicable technologies that will have a great economic and social impact. This can simply include a Proof-of-Concept (PoC) request to resolve a business issue, organizing a hackathon to attract new talented scientific workforce and start-ups or even funded pilot projects under the right guidance and mentoring. In this context, the National Ports Agency (NPA) of Morocco in collaboration with Global Alliance for Trade Facilitation of the World Economic Forum successfully organized in 2021 an online hackathon with the participation of more than 500 participants from 30 countries in order to respond to seven challenges facing the port. Thus, in this way, new forms of cooperation were now accessible to those interested in solving complicated challenges that limit further development.¹¹⁹

Ports as innovation hubs should promote innovation through the development of a variety of R&D infrastructure, innovation centers (e.g., exploring new emerging technologies), incubators and accelerators (e.g., developing, testing, and improving innovation), testing facilities (e.g., validating and testing innovations in real world conditions), and training centers (capacity building). An important initiative comes from the Port of Valencia (Spain). The Port of Valencia launched the Fundación Valencia port in 2004 as an Applied Research, Innovation and Training center, providing a wide range of services to the port and the logistic cluster. This initiative brought together notable companies, universities, research centers, and organizations from the port community, developing a strong collaborative innovation ecosystem to create innovative projects. OPENTOP in 2022 launched an innovation hub for the Valencia Port Cluster as a complimentary action, providing a wide range of specialized incubation and acceleration programs for port and logistics, as well as venture capital services to invest in innovative start-ups and develop labs that facilitate trials in the port area.¹¹⁹

Funding is a critical part of an innovation ecosystem. Available sources of funding may come from state public tenders, regional, or national funds, innovation agencies, private investment companies, etc. The adoption of the Corporate Venture Capital (CVC) approach by ports is also seen as the best option, promoting innovation, increasing revenue, as well as attractiveness of working with a port. A representative example is the Port of Ashdod (Israel), which had launched three innovation models: a) a PoC program, b) an accelerator, bringing together almost 500 start-ups, and c) corporate venture capital (CVC) services. The program focuses on various areas such as port operations, logistics, security, cybersecurity, etc. Any start-up that intends to work with the port must apply for a PoC program. Successful submission of a PoC provides the option for further collaboration as part of the CVC services offered by the port.¹¹⁹

7 Conclusions

Ports, situated at the intersection of international trade, have a distinct obligation and capacity to transform the discourse on the environment, gradually implementing sustainable practices. The increasing global awareness of climate change is actively acknowledged by the port sector. Port environmental management is well-aware of the contributions to climate change arising from port and shipping operations, and the sector is actively involved and

interested in options for mitigation (Table 13). Mega ports address not only environmental liabilities and responsibilities but also opportunities to be pro-active in achieving the delicate balance between the potential competing demands of economic vitality, social demands, and environmental quality and protection. The adaptability of ports to this new era and the adoption of innovation as a part of their own transformation can be seen as key tools to deal with this changing situation. The identification, selection, and monitoring of significant chemistry-based environmental performance indicators (EPis) add to the tools and methodologies available to assist ports to control related impacts.

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Acknowledgement: Grateful thanks that permission has been granted by European Sea Ports Organization (ESPO) and Eco Sustainable Logistic Chain (EcoSLC) to analyze, interpret, and report the baseline and benchmark performance of the sector as a global profile.

Research ethics: Not applicable.

Informed consent: Not applicable.

Author contributions: All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Use of Large Language Models, AI and Machine Learning Tools: None declared.

Conflict of interest: The authors state no conflict of interest.

Research funding: IUPAC, Div. VI, Project #2021-026-3-600.

Data availability: Not applicable.

List of acronyms

AAPA	American Association of Port Authorities
AAS	Atomic Absorption Spectrometry
ABM	Agent-Based Models
BENTIX	Biotic Index
BHQ	Benthic Habitat Quality
BLI	Biopollution Level Index
BOD	Biochemical oxygen demand
BQI	Benthic Quality Index
CAC	Common Air Contaminants
CBI	City Biodiversity Index
CCC	Criterion Continuous Concentration
CCRI	Climate Change Risk Indicator
CCS	Carbon Capture and Storage
CMC	Criterion Maximum Concentration
CVC	Corporate Venture Capital
DO	Dissolved Oxygen
ECOSLC	Eco Sustainable Logistics Chain Foundation
EM	Environmental Management
EMAS	Eco-Management and Audit Scheme
EMS	Environmental Management Systems
EPIs	Environmental Performance Indicators
EQS	Environmental Quality Standards
ESG	Environmental, Social, and Governance
ESPO	European Sea Ports Organization
FSB	Financial Stability Board
G20	Group of 20
GFAA	Graphite furnace atomic absorption
GHGs	greenhouse gases
HGV	Heavy Goods Vehicle
IAPH	International Association of Ports and Harbors
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ISO	International Organisation for Standardisation
ISP-AES	Inductively Coupled Plasma Atomic Emission Spectrometry
LPG	liquefied petroleum gas
MAC	Maximum Allowable Concentration
MCDA	Multi-Criteria Decision Analysis
NCI	Natural Capital Index
NDCs	Nationally Determined Contributions
LNG	Liquified Natural Gas
NGOs	Non-Governmental Organizations
nNIS	Non-Indigenous Species
NPA	National Ports Agency
OPS	Onshore Power Supplies
PEEP	Port Energy Environmental Plan
PERS	Port Environmental Review System
PM	Particulate matter
PoC	Proof-of-Concept
POX	Partial Oxidation
SDGs	Sustainable Development Goals
SDM	Self-Diagnosis Methodology
SEAs	Significant Environmental Aspects
SI	Singapore Index on Cities' Biodiversity
SHES	Safety, Health, Environment, and Security
SMR	Steam Methane Reforming
TCFD	Task Force on Climate Related Financial Disclosures
T&E	Transport & Environment
TEN-T	Trans European transport network
TPIC	Taiwan Ports International Corporation
US EPA	Environmental Protection Agency of United States of America

WPCI World Port Climate Initiative
 WPSP World Port Sustainability Program

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