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Section 4

Subchapter 6C

Marine infrastructure outside of coastal areas

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Key points

- Marine infrastructure development beyond coastal areas has intensified pressures on marine ecosystems, including marine noise, seawater quality and changes to hydrodynamic circulation.
- Climate change and adaptation strategies are expected to pose significant risks to marine infrastructure.
- There has been an increasing focus on developing proactive infrastructure strategies to adapt to hazards, including nature-based solutions, buffer zones, physical barriers and systems for early warning and evacuation.
- Over the next 10 to 20 years, marine infrastructure development presents major challenges, especially with respect to climate change, but also offers opportunities for innovation, sustainable growth, enhanced security and greater resilience.

1. Introduction

The ocean offers immense potential for clean energy, resource exploitation and food production, which has led to a surge in marine infrastructure development beyond traditional coastal areas, leading to a significant increase.

Marine infrastructure development offers opportunities to meet societal needs but poses challenges and pressures, such as the potential disruption of marine ecosystems and conflicts with existing maritime activities. Marine infrastructure, including offshore wind and subsea structures, cables, platforms and pipelines, aquaculture facilities and floating islands, exerts extensive and widespread pressures throughout its life cycle, encompassing installation, operation, maintenance and decommissioning (Dannheim and others, 2020; Coolen and others, 2020).

Marine infrastructure development beyond coastal areas has intensified, driven by technological advancements and growing demand for offshore resources (Gill and others, 2020). Marine infrastructure places significant pressure on ocean ecosystems associated with loss or disruption of natural habitats and species, alteration of oceanographic processes and ecological and geomorphic connectivity, noise and vibration generation, decline in marine biodiversity and the introduction of invasive species (Heery and others, 2017; Bishop and others, 2017; Firth and others, 2016; Chapman and Bulleri, 2003; Duarte and others, 2021(a) and (b); Firth and others, 2016; Airoldi and others, 2015).

2. Changes since the publication of the second *World Ocean Assessment*

Multiple factors have contributed to changes in pressures on the open ocean in recent years. While new pressures have emerged, some align with trends previously described in the second *World Ocean Assessment*.

Since the publication of the second *World Ocean Assessment*, offshore wind farms have expanded notably, while oil and gas infrastructure development has accelerated (Jouffray and others, 2020). In addition, substantial developments have occurred in submarine cables and pipelines; there are 550 active or planned cables that span over 1.4 million km worldwide (*The Economist*, 2023). Advancements in robotics, material science and underwater communication have significantly improved the feasibility of deep-sea exploration and resource extraction, which were previously out of reach in some cases.

Meanwhile, climate change impacts have become more pronounced in the past few years. Warming seas and ocean acidification continue to negatively affect marine ecosystems, with cascading effects on human communities that rely on ocean resources (Commission for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Comission), 2024; Short and others, 2021). There is growing recognition that these pressures disproportionately affect vulnerable populations, including marine communities in developing countries and small island nations, especially in polar oceans.

3. Trends in marine infrastructure outside coastal areas

According to Bugnot and others (2021) and global analyses of existing and planned marine construction and its impact on the seascape, the spread of marine infrastructure is among the most significant human alterations to global seascapes. Maps illustrating ocean industrialization at a global scale highlight shifts in some of the largest and most economically significant activities at sea (Paolo and others, 2024). The expansion of marine infrastructure beyond coastal areas represents a dynamic intersection of technological innovation, economic necessity and strategic planning.

There are ongoing efforts to develop comprehensive databases containing information on and maps of marine infrastructure. Existing online maps and databases cover different disciplinary themes, including geology, physics, energy, minerals, biology, seabed habitats, spatial planning and human activities, while also offering data and information on blue economy operations (European Marine Observation and Data Network (EMODnet), 2024; Bureau of Ocean Energy Management (BOEM), 2024; Mid-Atlantic Ocean Data Portal (MARCO), 2024; Open Infrastructure Map, 2024; European Maritime Affairs, 2024)

Marine energy infrastructure

The evolution of the offshore oil and gas sector has been complex, with some regions shifting towards decommissioning while others expand exploration (Shaffer, 2020). Oil and gas platforms are usually located on the continental shelf, but technological advances have enabled drilling in deeper waters, such as those in the Gulf of Mexico, the North Sea and off the coast of Brazil (Zou and others, 2021; Dou and others, 2022; Wen and others, 2023) and other operations in more challenging environments. The oil and gas industry has the potential to play a significant role in the sustainable energy transition.

Offshore wind energy has grown remarkably, as larger turbines have been deployed further offshore. Wind farms are typically located in shallow waters up to 50 m deep, but their installation has been moved further offshore to capture stronger and more consistent wind resources. Floating wind farms are also being developed for deeper waters, including those in the North Sea (Gușatu and others, 2021) and along the Atlantic coast of the United States (Baker and others, 2024; Shields and others, 2023). However, better planning and optimization of locations are required to induce the modification of atmospheric dynamics and, consequently, wind speed reductions (extending as far as more than 40 km downwind from the farm) (Akhtar and others, 2021). The countries that have the most consistent environmental and regulatory policies and that have a tendency to use renewable energy technologies have been the fastest to implement these wind turbines (Long, 2014). The areas with the greatest potential for offshore wind energy production are located mainly in Asia (on the China Sea) and Europe (on the North Sea, western part of the Baltic Sea and East Atlantic) (Enevoldsen and Jacobson, 2021).

Wave and tidal energy installations are placed in areas with strong tidal currents and significant wave activity, often near the coast but sometimes further out to harness stronger resources (Khojasteh and others, 2023). Progress has been made on tidal energy projects, and several commercial-scale installations are now operational. Wave energy converters represent a promising technology for future deployment (Neill and others, 2017).

Shipping and navigation infrastructure

Deepwater ports are located further offshore to accommodate large vessels that cannot navigate closer due to depth constraints. Transoceanic shipping routes have led to the development of infrastructure supporting shipping lanes that traverse open oceans, including emergency response facilities. Seaports, due to their strategic locations and infrastructure, are emerging as pivotal hubs for the production, storage and distribution of green hydrogen (Notteboom and Haralambides, 2023).

Subsea cables and pipelines

Subsea communication cables are used to respond to the demand for global connectivity, which leads to extensive networks of submarine cables crossing ocean basins. Subsea cable installations have increased significantly, forming a critical part of global communications infrastructure (Submarine Cable Map, 2023). A systematic review of the current security threats to the European Union subsea data cable network (Bueger and others, 2022) contains several recommendations on how to improve the resilience of the network. Oil and gas pipelines connecting offshore platforms to coastal refineries and distribution networks usually follow the most direct and safest route along the seabed. The development of renewable marine infrastructure requires the development of new routes for power transmission cables to connect offshore renewable energy (ORE) sources to onshore grids (Cullinane and others, 2022). Recent incidents involving cable damage and geopolitical tensions have led to a greater emphasis on safeguarding undersea infrastructure. For example, naval exercises have been conducted specifically to protect submarine cables and pipelines (National Oceanic and Atmospheric Administration (NOAA), 2024).

Other technologies

With advancements in underwater technology, there is increasing interest in mining the deep seabed for minerals, including polymetallic nodules, cobalt and rare earth elements, particularly in the Clarion-Clipperton Zone in the Pacific Ocean. Offshore aquaculture has also expanded significantly, with larger fish farms deployed further offshore (Gentry and others, 2017). Combining energy production, food systems and resource extraction within shared offshore spaces is a common future pathway globally (Depellegrin and others, 2019). One growing trend involves the utilization of multi-use platforms combining different industries, such as offshore energy production (wind, solar or tidal) with aquaculture and desalination plants.

4. Interactions with and effects on marine ecosystems and human well-being

Marine infrastructure interacts with ecosystems on multiple temporal scales. Short-term construction activities cause immediate disturbances, while long-term interactions involve changes to ecosystem structure and function (Dannheim and others, 2020). Infrastructure significantly impacts seabed ecosystems but may also increase habitat heterogeneity (Coolen and others, 2020). Increased underwater noise pollution affects marine life behaviour and physiology (Nowacek and others, 2015). Large-scale infrastructure can alter local hydrodynamics, potentially affecting sediment transport and larval dispersal (van Berkel and others, 2020). Socioeconomic impacts include job creation and the potential disruption of traditional maritime activities (Hooper and others, 2015). The expansion of marine infrastructure has implications for human health, both positive and potentially negative (Buonocore and others, 2016).

Far-field marine noise

Ocean noise perturbs the oceanic environment and impacts marine life to an extent that is still not completely understood (Duarte and others, 2021(a)). Some species are more sensitive to short but powerful impulsive bursts, while others are deeply affected by continuous low power disturbances (Merchant and others, 2020). Depending on the power and frequency of noise and the physical properties of the ocean, acoustic waves can propagate rapidly to long distances (Jensen and others 1994; Nieukirk and others 2004). While the noise generated by offshore infrastructure is only one component of overall anthropogenic noise (Sirovic and others, 2021), it is an important one because of its persistence.

The noise generated by offshore infrastructure can be categorized according to three phases of the infrastructure life cycle: installation, operation and decommissioning. Depending on the specific type of infrastructure, installation may involve the bottom fixing or bottom laying of cables or pipes (Jiang, 2021). Preparatory work generally encompasses careful sounding of the bottom and sub-bottom, which often requires extensive light seismic surveys at the site and on the route to the site (Duarte and others, 2017). The sound sources used in such surveys can be very harmful for sensitive species at the local or regional level (Duarte and others, 2021(a); Spadoni and others, 2023). During installation, pile driving and dredging are the most common sources of noise (Amaral and others, 2020).

During the operation phase, underwater noise is generated by structural moving parts, turning engines and other specific sound-emitting machinery. Machinery, turbines and other engines above water transmit vibrations through the submerged supporting structure or through the water interface. Although levels are low relative to shipping noise, underwater noise from wind farms can be substantially higher (Tougaard and others, 2020). Offshore infrastructure also generates a significant acoustic particle acceleration signature that is highly disturbing for species living near the ocean bottom, the sea surface and the infrastructure that supports wind turbines (Sigray and Andersson, 2011) and marine energy converters (Popper and others, 2023).

Wave and current circulation patterns

Hydrocarbon extraction platforms and subsea infrastructure can modify local hydrodynamics by creating physical barriers that affect sediment transport and coastal erosion processes (Erikson and others, 2022).

Offshore aquaculture installations similarly affect local water flow and wave patterns, affecting nutrient distribution and sedimentation in the surrounding areas (Wang and others, 2021).

Seawater quality and marine mammals

Hydrocarbon extraction can lead to water pollution through oil spills, drilling muds and produced water discharge, which can contain hydrocarbons and heavy metals, affecting seawater quality and impacting the food-chain (Erikson and others, 2022). Marine renewable energy devices generally have less severe impacts, although they can release antifouling agents and other chemicals used to maintain equipment (International Energy Agency (IEA), 2019). Offshore aquaculture can cause nutrient enrichment and organic matter accumulation, potentially leading to eutrophication and harmful algal blooms, thereby degrading water quality (Wang and others, 2021).

Marine mammals can be affected by offshore activities, primarily through noise pollution, physical barriers and water quality degradation. Noise from hydrocarbons extraction and renewable energy installations can disrupt marine mammal behaviour and communication (Erikson and others, 2022; IEA, 2019). Offshore aquaculture poses entanglement risks and disrupts natural foraging patterns and habitats (Wang and others, 2021). Undersea cables, although less impactful, generate electromagnetic fields that can affect marine mammals, especially when high voltages are involved.

Seabed interaction

Deep seabed mining generates negative impacts to human health through three possible pathways, most importantly through its impacts on fish stocks and fisheries. Semi-permanent ships, support platforms and riser pipes transporting mined minerals may interrupt fish migration due to light and noise pollution. The collective impact on global fisheries has repercussions for food security, especially for Indigenous Peoples and local communities that are highly dependent on the marine ecosystem as their main source of nutrition (Hamley, 2022). Moreover, increased ambient concentrations of metals, such as copper, lead, zinc, cadmium and rare earth metals, in marine ecosystems may accumulate and enter the human food web (Hauton and others, 2017). There is concern that seabed mining will disturb and resuspend seabed sediments, potentially releasing sequestered carbon (Hamley, 2022).

Health and well-being

Marine infrastructure is vital to advancing national economic and security interests. Improving marine infrastructure, such as seaports and shipyards, could improve human well-being by reducing consumer prices, creating new jobs and assisting local communities in marketing their seafood and farming products to other areas. However, marine infrastructure planning and development is often marked by a failure to include Indigenous Peoples and local communities in decision-making processes and to consider the environmental impacts on neighbouring coastal communities and ecosystems (Morgera, 2024; Morgera and Lily, 2022). Environmental impact assessments are undertaken on a project-specific basis, without consideration being given to the dynamic nature of ocean and coastal ecosystems and without an assessment of the cumulative impacts associated with marine infrastructure developments (Sunde, 2022).

5. Conclusion

Marine infrastructure development outside coastal areas has intensified, introducing new pressures on marine ecosystems. While offering economic benefits and potential contributions to sustainable energy and food production, such development presents complex challenges for marine ecosystem health and ocean governance. Primarily, climate change, adaptation strategies and resilience reflected by rising sea levels and more frequent extreme weather events are expected to pose significant risks to marine infrastructure (Talukder and others, 2022).

The advantages of deploying environmentally friendly emerging technologies whose benefits are demonstrated by relevant extensive life-cycle analyses across the entire life cycle of marine infrastructure could contribute significantly to the predicted technological and economic benefits and to sustainable energy. Many Governments are adopting more integrated approaches to marine management, considering the interconnections between land and marine use, development, natural hazards and environmental protection (Eger and others, 2021).

There is an increasing focus on developing proactive infrastructure strategies to adapt to hazards, which may include nature-based solutions, buffer zones, physical barriers like seawalls, retreat and protect approaches, and systems for early warning and evacuations. While developed nations focus on adaptation and resilience, many developing countries may struggle with basic marine infrastructure needs, potentially widening the global infrastructure gap.

Over the next 10 to 20 years, marine infrastructure poses significant challenges, particularly from a climate change perspective, but also presents opportunities for innovation, sustainable development, security and improved resilience. Proactive planning, substantial investment and effective collaboration between government bodies, industries and communities are required to minimize pressures from marine infrastructure.

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