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Offshore Wind Farms in the Adriatic Sea: Bathymetric, Meteorological, Navigational and Environmental Constraints

Abstract

The development of offshore wind farms has become an important component of the energy transition in European maritime regions, particularly in the North Sea, where favorable natural conditions and a long tradition of industrial use of maritime space have enabled large-scale deployment [1,2]. In this context, increasing attention has been given to the potential development of offshore wind farms in the Adriatic Sea, including the Croatian maritime area. However, the Adriatic Sea represents a specific spatial, environmental and economic system that differs significantly from the North Sea [13].

This paper examines the justification for offshore wind farm development in the Croatian part of the Adriatic Sea through a comparative analysis with experiences from the North Sea and the western Mediterranean. Particular attention is given to bathymetric and meteorological characteristics, navigation safety, the legal regime of the maritime domain, environmental impacts and socio-economic effects on tourism, yacht charter and fisheries. The application of floating offshore wind technology is also analyzed as a potential technical solution for deeper waters, with reference to French pilot projects [9,10].

The analysis indicates that greater water depths, pronounced spatial constraints, seasonal wind variability and high maritime traffic density in the Adriatic Sea significantly reduce the technical and economic feasibility of offshore wind farms compared to the North Sea. At the same time, the construction of such installations has a considerable impact on navigation safety, limits the general use of the maritime domain and poses potential cumulative risks to the marine environment and established economic activities.

This paper provides a qualitative and comparative assessment of structural constraints and does not represent a site-specific or quantitative techno-economic feasibility study.

It is concluded that, although offshore wind energy represents an important renewable energy source in certain European seas, under the specific conditions of the Croatian Adriatic Sea its potential benefits are not proportionate to the associated safety, environmental and socio-economic impacts. Therefore, offshore wind development in this area should be approached with caution, supported by comprehensive expert analyses and consideration of alternative energy solutions better suited to the characteristics of the Adriatic region.

Keywords: offshore wind farms, Adriatic Sea, navigation safety, maritime domain, environmental impacts, spatial constraints

1. Introduction

The development of offshore wind farms has become an integral part of European energy and climate policies, particularly in regions with extensive maritime areas and long-standing industrial use of the sea [1,2]. The North Sea is widely recognized as the most prominent example of successful integration of offshore wind energy into a broader economic and infrastructural framework, supported by favorable natural conditions and strong institutional coordination [2,3].

In contrast, the Adriatic Sea represents a fundamentally different maritime environment. It is a semi-enclosed basin with limited spatial capacity, complex coastal morphology and intensive maritime traffic, particularly along the eastern Adriatic coast [13]. These characteristics significantly influence the feasibility of offshore energy development and distinguish the Adriatic from northern European maritime regions.

Unlike the North Sea, where industrial maritime activities have coexisted with offshore energy infrastructure for decades, the Adriatic Sea is primarily oriented towards navigation safety, tourism and fisheries, all of which depend on unrestricted access to maritime space [21,17]. Consequently, offshore wind development cannot be assessed solely from the perspective of energy production but must also account for navigational safety, environmental protection and the legal regime governing maritime space.

An additional challenge arises from the fact that the Croatian part of the Adriatic Sea is, on average, significantly deeper than the shallow shelf areas where most fixed-bottom offshore wind farms have been constructed in northern Europe [4,9]. Greater water depths directly affect technical feasibility and economic viability, leading to increased interest in floating wind technologies, particularly those developed in the western Mediterranean [5–7].

The purpose of this paper is to critically assess the justification for offshore wind farm development in the Croatian Adriatic through comparison with the North Sea and selected Mediterranean experiences. Particular attention is given to bathymetric and meteorological conditions, navigation safety, the legal regime of the maritime domain, and the environmental and socio-economic impacts associated with offshore wind development.

In this paper, the analysis primarily focuses on the Croatian territorial sea, while potential implications for the Exclusive Economic Zone are acknowledged but not examined in detail due to ongoing regulatory developments.

2. Methodology

This paper applies a qualitative and analytical research methodology aimed at assessing the feasibility and implications of offshore wind farm development in the Croatian part of the Adriatic Sea [1–3]. The methodological approach is based on an interdisciplinary framework combining maritime safety analysis, spatial planning principles, environmental assessment and comparative policy analysis [13,21].

The research is primarily founded on a systematic review of relevant scientific literature, professional studies and strategic policy documents related to offshore wind energy, maritime spatial planning and navigation safety [1–4,14]. Particular attention is given to peer-reviewed scientific publications and reports issued by recognized institutions such as the European Commission, the International Energy Agency, the European Maritime Safety Agency and the International Maritime Organization [1,3,15,18].

In addition to international sources, the analysis places strong emphasis on the Croatian regulatory and institutional context. National strategic documents, maritime spatial planning instruments and legal acts governing the maritime domain, navigation safety and environmental protection are examined in order to assess the compatibility of offshore wind development with the existing legal framework and operational practices in the Adriatic Sea [19,20].

A comparative analytical approach is applied by contrasting the physical, spatial and operational characteristics of the Adriatic Sea with those of the North Sea, which represents the most developed reference area for offshore wind energy in Europe [2,3]. This comparison focuses on key parameters such as bathymetry, wind regimes, maritime traffic density, spatial availability and the maturity of supporting infrastructure [4,9].

The assessment of navigational safety is based on an evaluation of traffic density, typical navigation patterns, meteorological conditions and the potential interaction between offshore installations and existing maritime routes [21,22]. Particular consideration is given to confined sea areas, emergency maneuverability, and the operational requirements of commercial shipping, passenger transport and search and rescue activities [21,22].

Environmental considerations are addressed through a qualitative synthesis of existing research on marine ecosystems, seabed disturbance, underwater noise, avifauna interactions and cumulative environmental effects [8–12]. Rather than providing a site-specific environmental impact assessment, the paper evaluates systemic risks and sensitivities characteristic of the Adriatic Sea as a semi-enclosed and ecologically sensitive basin.

Socio-economic impacts are examined through the lens of spatial competition between offshore energy development and established maritime activities, particularly tourism and fisheries [17]. The analysis considers how spatial restrictions, visual impacts and changes in navigational patterns may influence economic activities that are central to coastal communities.

Overall, the methodology follows an integrative and precautionary approach, combining technical, environmental, legal and socio-economic perspectives. This approach allows for a comprehensive assessment of offshore wind development in the Adriatic Sea, recognizing the interdependence of maritime safety, environmental protection and sustainable use of marine space [21].

Limitations of the analysis. This study is based on a qualitative and comparative approach and does not aim to provide a detailed site-specific or quantitative techno-economic feasibility assessment. Regional differences within the Adriatic Sea are addressed at a conceptual level, while detailed local variations require further dedicated studies. The analysis primarily focuses on the Croatian territorial sea; potential implications for the Exclusive Economic Zone are acknowledged but not examined in detail due to ongoing regulatory developments.

3. The North Sea as a reference model for offshore wind development

The North Sea is widely regarded as the benchmark area for the development of offshore wind farms in Europe. This status is not the result of technological advancement alone, but rather of a combination of favorable natural conditions, long-standing industrial use of maritime space and a well-established institutional and regulatory framework [1,2].

One of the key characteristics of the North Sea is its relatively shallow continental shelf, with average water depths across large areas ranging between 20 and 40 meters. Such conditions have enabled the extensive use of fixed-bottom foundations, primarily monopile and jacket structures, which have proven to be technically reliable and economically viable at scale [4,9]. The relatively uniform seabed morphology has further simplified design, installation and long-term maintenance, reducing construction risks and operational uncertainty.

In addition to bathymetric advantages, offshore wind development in the North Sea has taken place in a maritime space that had already been intensively industrialized. Oil and gas exploration and production activities have been present for decades, resulting in developed port infrastructure, specialized installation vessels, experienced offshore service fleets and a regulatory culture accustomed to managing large-scale offshore installations [2,20].

Spatial availability has also played an important role. The North Sea is characterized by vast open sea areas, where shipping lanes, although busy, are well defined and separated from zones designated for industrial use [3]. This has allowed the allocation of large offshore areas for wind farms with comparatively limited conflict with tourism and recreational activities, which do not represent a dominant economic sector in this region to the same extent as in the Mediterranean.

Institutional coordination further supported this development. North Sea states recognized offshore wind energy early as a strategic component of their energy transition and established long-term policy frameworks, incentive mechanisms and cross-border cooperation models [1,2]. In parallel, maritime traffic management systems, safety zones around offshore installations and environmental protection standards were progressively developed and refined [20].

For these reasons, the North Sea model of offshore wind development rests on a unique combination of shallow waters, spatial capacity and institutional maturity. While it provides valuable technical and organizational experience, it cannot be considered a universally applicable template. When transferred without sufficient adaptation to different maritime environments, such as the Adriatic Sea, this model risks overlooking fundamental spatial, safety and socio-economic constraints that define those regions [13,21] (Figure 1).

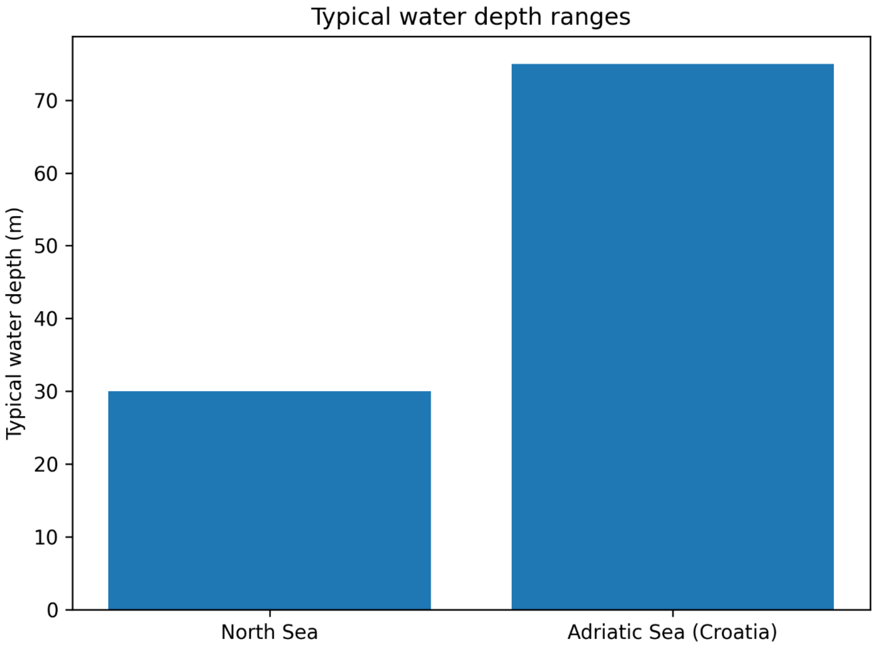

Figure 1. Typical water depth ranges in the North Sea and the Adriatic Sea. Source: Author's elaboration based on [4,13].

4. Bathymetric and spatial constraints of the Adriatic Sea

Bathymetric characteristics represent one of the fundamental constraints when considering offshore wind development in the Adriatic Sea, particularly within the Croatian maritime zone [13]. Unlike the North Sea, where extensive areas of shallow continental shelf are available, the eastern Adriatic coast is characterized by a steep bathymetric gradient. Water depths exceeding 30 meters occur relatively close to the shoreline, while depths of 50, 80 or even more than 100 meters are common in the central and southern Adriatic [13].

It should be noted that bathymetric conditions within the Adriatic Sea are not uniform. While the northern Adriatic is predominantly shallow, with extensive areas of relatively low depths, the central and southern Adriatic are characterized by rapidly increasing depths close to the coastline. Consequently, the technical and spatial constraints for offshore wind development differ substantially between these sub-regions, particularly regarding the feasibility of fixed-bottom foundations and the likely reliance on floating solutions.

This bathymetric profile has direct technical and economic implications. Conventional offshore wind farms based on fixed-bottom foundations are generally designed for moderate water depths, where monopile or jacket structures can be installed efficiently [4,9]. In deeper waters, the size, mass and complexity of such foundations increase significantly, resulting in higher construction risks, greater material requirements and substantially increased costs. Under these conditions, the economic competitiveness of offshore wind energy becomes questionable, particularly when compared to other renewable energy options [9,10].

Beyond water depth, the spatial configuration of the Adriatic Sea presents an additional layer of complexity. The coastline is highly indented, with numerous islands, islets and reefs, creating a network of narrow channels that serve as primary navigation routes [21,22]. These routes are not only of local importance but form part of regional and international maritime traffic patterns, as well as seasonal corridors for recreational and charter navigation [17,21].

In such a constrained spatial environment, the allocation of large offshore areas for wind farms inevitably interferes with existing uses of the sea. Unlike the North Sea, where offshore wind farms are often located tens of kilometers from the coast, potential sites in the Adriatic would in many cases be situated much closer to land [3,13]. This proximity amplifies spatial conflicts, increases visual impacts and further limits maneuvering space for navigation.

Floating offshore wind technologies are frequently proposed as a solution to bathymetric limitations. While floating platforms indeed allow installation in deeper waters without massive seabed foundations, they do not eliminate spatial constraints. Mooring systems and dynamic cables associated with floating turbines occupy a significantly larger horizontal area than the platform itself, effectively expanding the functional footprint of the installation [9,10]. As a result, the overall spatial impact of floating wind farms may be greater than initially perceived.

Taken together, bathymetric conditions and spatial limitations of the Adriatic Sea do not merely represent technical challenges to be overcome through engineering solutions. Rather, they constitute structural constraints that fundamentally differentiate the Adriatic from the North Sea and require a cautious and context-specific approach to offshore wind planning [13,21].

5. Meteorological conditions and wind regime of the Adriatic Sea

Meteorological conditions in the Adriatic Sea differ substantially from those prevailing in northern European offshore wind regions, not only in terms of average wind speeds but also in the temporal distribution, spatial variability and operational characteristics of dominant winds [16,22]. These factors have a direct influence on energy yield, structural design requirements, installation feasibility and long-term operational reliability of offshore wind farms [1,3].

The wind regime of the Adriatic Sea is primarily governed by three dominant winds: bora, sirocco (jugo) and maestral. Each of these winds exhibits distinct characteristics that carry specific implications for offshore wind development [16,22] (Figure 2).

Bora is a cold, dry and highly gusty downslope wind blowing from the northeast. It is characterized by sudden and extreme wind gusts, rapid changes in wind direction and pronounced spatial variability, particularly along the eastern Adriatic coast and within island channels [16,19]. From an engineering perspective, bora represents a critical design condition due to the high dynamic loads it imposes on turbine structures, towers, rotors and mooring systems. For floating wind platforms in particular, the combination of strong gusts and short-period waves increases fatigue loading and requires conservative design assumptions [9,10]. The localized nature of bora further complicates wind resource assessment, as measurements taken at one location may not be representative of nearby areas [16].

Sirocco is a warm, humid and long-lasting wind associated with cyclonic systems over the Mediterranean. Unlike bora, sirocco produces more uniform wind fields but is typically accompanied by increased wave heights and longer wave periods [1,3]. These conditions significantly reduce accessibility to offshore sites, limiting the availability of weather windows for installation, inspection and maintenance activities. In practice, prolonged sirocco events during winter and transitional seasons can lead to extended operational downtime, directly affecting capacity factors and increasing operational expenditure [3].

Maestral is a thermally driven, diurnal wind that develops predominantly during the summer months. It is generally more stable and predictable than bora and sirocco, which is favorable from an operational standpoint [22]. However, its average wind speeds are moderate and insufficient to compensate for reduced production during periods dominated by less favorable wind conditions. Moreover, the peak occurrence of maestral coincides with the height of the tourist season, when maritime traffic density is at its maximum, further complicating offshore operations [21].

The combined effect of these wind systems results in pronounced seasonal variability and reduced predictability of energy production when compared to offshore wind farms in the North Sea, where strong and relatively consistent winds prevail throughout much of the year [1,2]. In the Adriatic, higher energy yields during certain periods are offset by extended intervals of unfavorable meteorological conditions that constrain both production and maintenance (Figure 3).

In addition to wind characteristics, other meteorological and oceanographic factors must be considered, including wave climate, sea currents and the frequency of suitable weather windows for offshore operations [16,19]. In the Adriatic Sea, favorable operational conditions are often limited in duration and strongly seasonal, which increases construction timelines and lifecycle costs.

Overall, while the Adriatic Sea does possess exploitable wind resources, its meteorological regime introduces a level of operational uncertainty that differs fundamentally from that of the North Sea. These conditions necessitate careful long-term measurements, conservative design approaches and realistic assessments of operational availability, all of which further influence the economic and technical feasibility of offshore wind development in this region [13,21].

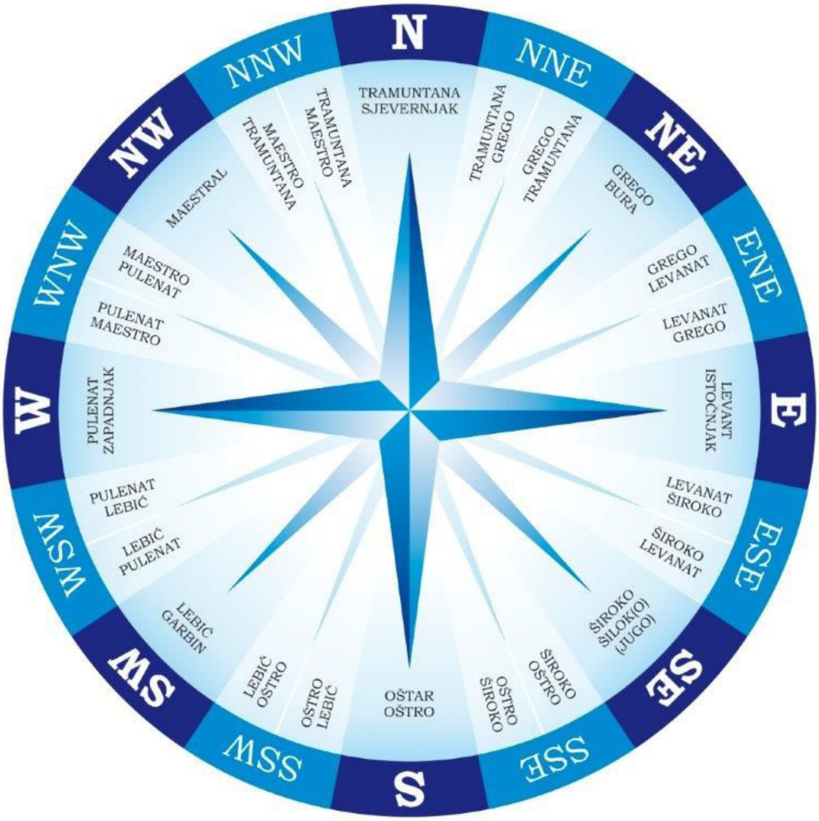

Figure 2. Dominant wind systems in the Adriatic Sea: bora, sirocco (jugo) and maestral. Source: Author's elaboration based on [16].

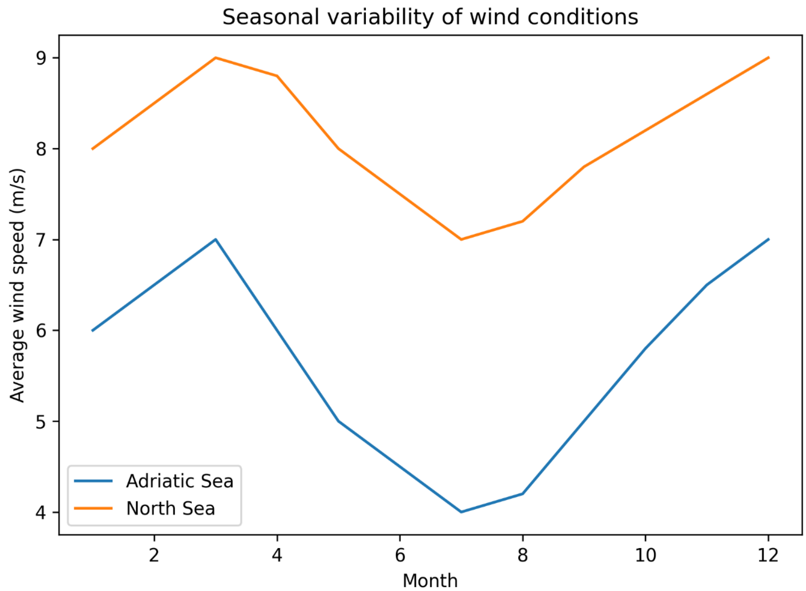

Figure 3. Seasonal variability of wind conditions in the Adriatic Sea compared to the North Sea. Source: Author's elaboration based on [1,2,16].

6. Navigation safety and restriction of the maritime domain

The introduction of offshore wind farms into a maritime area represents not only an energy infrastructure project but also a direct intervention in existing navigation systems and patterns of sea use [19,22]. In the Adriatic Sea, where maritime space is limited and intensively utilized, such interventions have pronounced and long-lasting implications for navigation safety and the regime governing the use of the maritime domain [19].

Offshore wind installations introduce permanent physical obstacles in the form of turbine towers, floating platforms, mooring systems and associated safety zones. These elements alter established navigation routes, require rerouting of traffic and reduce available maneuvering space [21,22]. In the Adriatic Sea, where a significant proportion of maritime traffic passes through narrow channels, straits and port approaches, the reduction of navigable space has a greater safety impact than in wide, open sea areas [21].

Navigation risks become particularly pronounced under adverse meteorological conditions, such as strong bora or prolonged sirocco events. In such circumstances, vessel controllability is already reduced, and the presence of fixed or semi-fixed obstacles further limits options for evasive maneuvers or emergency responses [16,21]. This is especially relevant for large commercial vessels, passenger ships and vessels carrying hazardous cargo, for which navigational margins are already constrained (Figure 4).

Floating offshore wind farms introduce additional safety considerations. Although floating platforms avoid the need for massive seabed foundations, their mooring systems extend over a considerably wider horizontal area than the visible structure itself. These mooring lines and anchor points are generally not visible from the surface, creating hazards for fishing vessels, small craft and emergency anchoring [9,10]. As a result, the effective spatial footprint of a floating wind farm is substantially larger than its apparent surface layout.

Offshore wind installations also affect emergency response operations. Search and rescue (SAR) missions, firefighting assistance and medical evacuations rely on rapid access and sufficient maneuvering space. The presence of wind farms and associated exclusion zones can delay response times and complicate coordination between maritime authorities, rescue units and airborne assets such as helicopters [21,22].

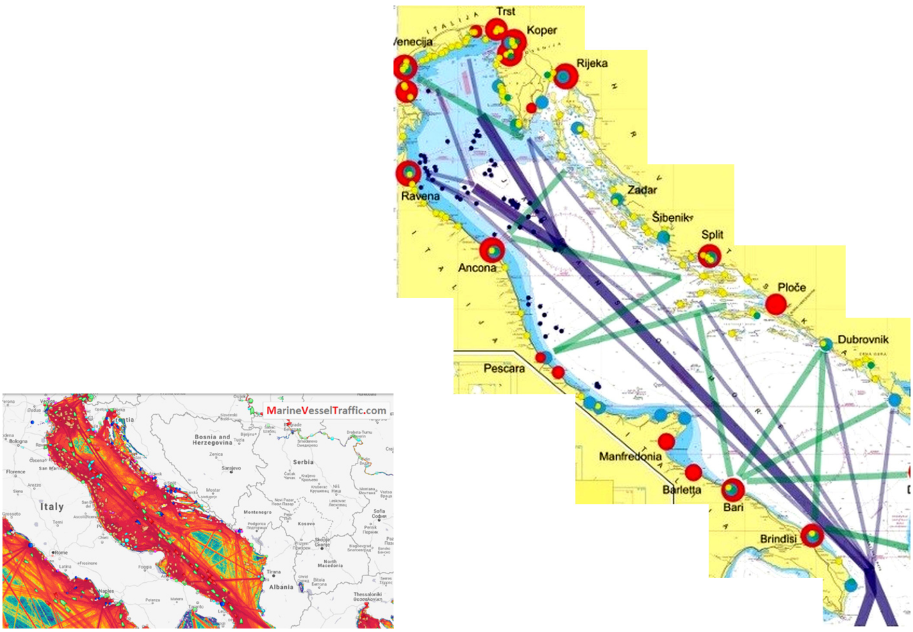

Figure 4. High-density navigation routes in the Adriatic Sea and their spatial constraints. Source: Author's elaboration based on [13,21,22].

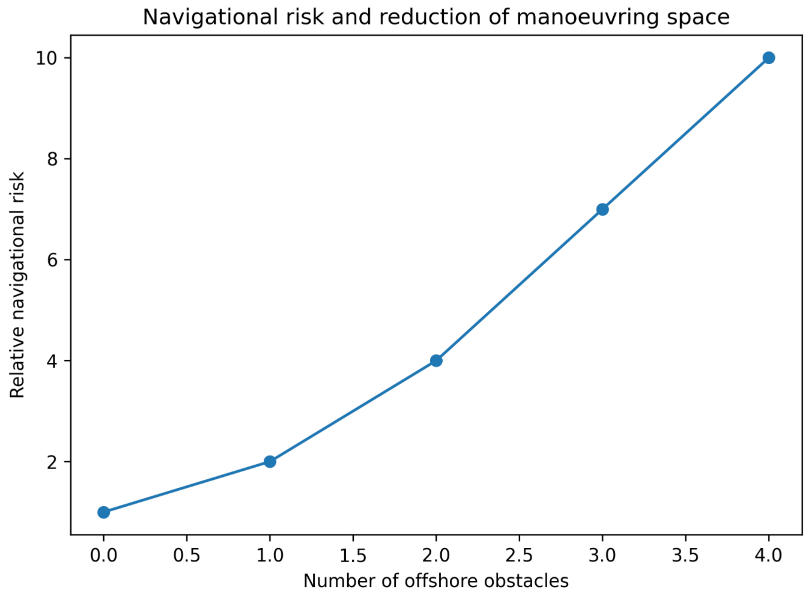

Figure 5. Conceptual increase of navigational risk with reduced maneuvering space. Source: Author's elaboration.

Navigation safety considerations are closely linked to the legal status of the maritime domain. In the Republic of Croatia, the sea is designated as a public good intended for general use, including free navigation [19]. The establishment of offshore wind farms inevitably leads to long-term or permanent restrictions on such use through the designation of safety zones and controlled access areas. These restrictions must therefore be justified by a clearly demonstrated public interest and assessed against their proportional impact on navigation, safety and other legitimate uses of the sea [19,22].

Unlike the North Sea, where offshore energy installations are frequently located in areas already designated for industrial use, the Adriatic Sea lacks extensive zones reserved exclusively for such purposes [3,14]. Consequently, the allocation of maritime space for offshore wind farms directly overlaps with areas of high navigational, economic and social importance. This overlap elevates navigation safety from a secondary technical issue to a primary criterion in the evaluation of offshore wind projects [22,23].

From the perspective of maritime spatial management, the introduction of offshore wind farms in the Adriatic Sea requires an exceptionally cautious approach. Navigation safety and the preservation of the maritime domain's general-use function must be considered fundamental constraints rather than issues to be addressed only in later stages of project development [19,23].

7. Environmental impacts of offshore wind farms in the Adriatic Sea

Any consideration of offshore wind development in the Adriatic Sea necessarily involves an assessment of environmental impacts, given the semi-enclosed nature of the basin and its high ecological sensitivity [11,12]. Unlike large open seas, the Adriatic has a limited capacity for dilution and recovery, meaning that even moderate interventions can lead to long-term environmental consequences if not carefully managed [11,19].

Environmental impacts of offshore wind farms in the Adriatic must therefore be examined holistically, taking into account effects on the marine ecosystem, the seabed and the airspace above the sea, as well as cumulative impacts arising from multiple projects [12,19].

7.1 Impacts on the marine ecosystem

During the construction phase of offshore wind farms, increased underwater noise is generated by installation activities, anchoring operations and cable laying. Such noise can disturb marine organisms, particularly fish and marine mammals, by altering behavior, displacing individuals from preferred habitats and interfering with communication and feeding patterns [11,12]. While these effects are often described as temporary, their repetition across multiple sites may lead to cumulative disturbances in a sensitive marine environment such as the Adriatic [19].

During the operational phase, offshore wind farms introduce continuous low-frequency noise and vibration, as well as electromagnetic fields associated with subsea power cables. The long-term effects of these factors on marine species remain an active area of research, but existing studies suggest that certain species, particularly those sensitive to electromagnetic cues, may be affected in ways that are not yet fully understood [11,13]. In the Adriatic Sea, where biodiversity is relatively high and several species are already under pressure from climate change and other anthropogenic impacts, such uncertainties warrant a precautionary approach [12,19].

7.2 Impacts on the seabed

Physical disturbance of the seabed represents one of the most direct environmental impacts of offshore wind development. Fixed-bottom wind farms require the installation of foundations that permanently occupy sections of the seabed, while floating wind farms, although reducing direct seabed penetration, still rely on anchoring systems and seabed contact points that alter benthic habitats [9,10].

Seabed disturbance may result in the destruction or degradation of benthic communities, resuspension of sediments and increased turbidity, which can negatively affect filter-feeding organisms and photosynthetic species [11,12]. In the Adriatic Sea, where many benthic habitats are characterized by slow-growing and vulnerable species, recovery from such disturbances may be prolonged or incomplete [19].

7.3 Impacts on airspace and avifauna

The Adriatic Sea lies along important migratory routes for birds travelling between northern and southern Europe and Africa. Offshore wind turbines introduce tall vertical structures into these migration corridors, increasing the risk of collision and altering established flight paths [11,12]. Species flying at lower altitudes or using coastal and island corridors are particularly vulnerable.

In addition to avifauna, offshore wind farms affect the use of airspace for low-altitude aviation activities, including search and rescue operations, medical evacuations and maritime surveillance. The presence of turbine towers and rotating blades requires specific marking and coordination measures, potentially complicating aerial operations in emergency situations [21,22].

7.4 Cumulative impacts and environmental monitoring

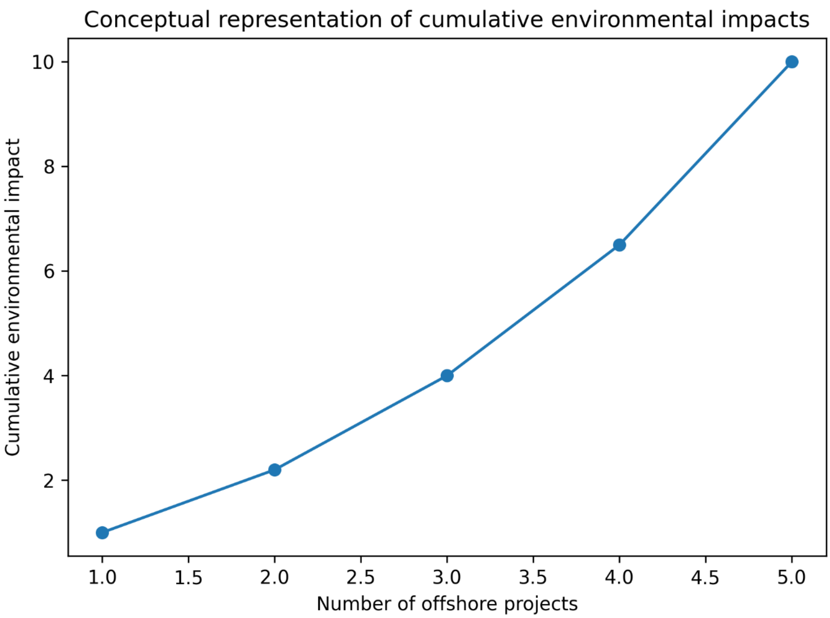

Figure 6. Conceptual representation of cumulative environmental impacts. Source: Author's elaboration based on [11,12,19].

One of the key challenges in assessing environmental impacts of offshore wind farms lies in the cumulative effects of multiple installations within the same marine area (Figure 6). While a single project may appear environmentally manageable, the combined impact of several wind farms can significantly alter ecosystem structure and function [11,19].

In the Adriatic Sea, cumulative impacts are of particular concern due to the basin's limited spatial extent and ecological sensitivity. This underscores the necessity for long-term environmental monitoring programs that extend beyond individual project boundaries and encompass broader regional effects [12,19].

Such monitoring increases project complexity, duration and cost, but it is essential to ensure that environmental thresholds are not exceeded. In the absence of comprehensive and long-term data, the environmental risks associated with offshore wind development in the Adriatic remain difficult to quantify and, consequently, difficult to justify [11,12].

8. Socio-economic impacts of offshore wind farms in the Adriatic Sea

The assessment of offshore wind farm development in the Adriatic Sea cannot be limited to technical feasibility and environmental considerations alone. It must also include a careful evaluation of socio-economic impacts, particularly in relation to activities that form the backbone of the coastal economy [18,21]. In the Croatian Adriatic, tourism, especially nautical tourism and yacht charter, and fisheries represent long-established and economically significant uses of maritime space, whose sustainability depends on unrestricted and safe access to the sea [21].

Unlike industrialized maritime regions, where offshore energy infrastructure may coexist with other activities with limited interaction, the Adriatic Sea is characterized by an intensive overlap of uses within a relatively confined space. As a result, even moderate spatial restrictions can have disproportionate economic and social consequences [18,21] (Figure 7).

8.1 Impacts on tourism and yacht charter

Nautical tourism and yacht charter have developed into one of the most dynamic segments of the Croatian tourism sector. Their attractiveness relies on freedom of navigation, access to safe anchorage areas, predictable sailing routes and the preserved visual identity of the seascape [21]. Offshore wind farms, particularly when located near established navigation corridors or popular cruising areas, directly affect these fundamental conditions.

Safety zones around wind turbines and the spatial extent of mooring systems associated with floating platforms reduce the available sea area for recreational navigation. This leads to a concentration of traffic in remaining corridors, increasing congestion and reducing navigational comfort, especially during the peak summer season [21,23]. In practical terms, charter operators may be forced to modify traditional itineraries, shorten routes or avoid certain areas altogether, thereby reducing the perceived value of the sailing experience.

Visual impact constitutes an additional factor of importance in the Adriatic context. The tourism appeal of the region is closely linked to the perception of an open, natural maritime landscape. The presence of large offshore structures within visible range of the coast or islands may alter this perception, with potential long-term effects on destination image [18]. While offshore wind farms have, in some regions, been promoted as points of interest, such approaches are typically associated with areas where industrial maritime use is already well established, a condition that does not generally apply to the Adriatic [21].

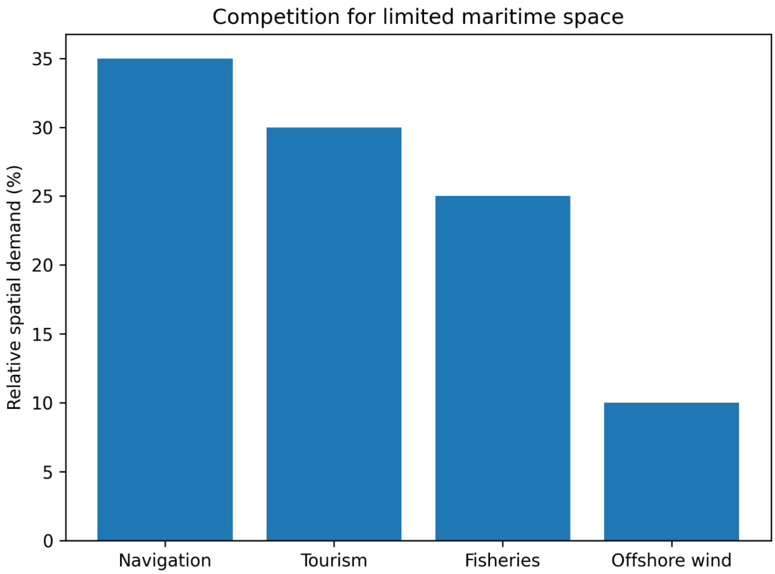

Figure 7. Competition for limited maritime space in the Adriatic Sea. Source: Author's elaboration based on [18,21].

8.2 Impacts on fisheries

Fisheries represent another sector highly sensitive to spatial restrictions and environmental changes. Offshore wind farms impose limitations on fishing activities within safety zones and in the vicinity of turbine foundations and mooring systems. These restrictions may result in the loss of traditional fishing grounds and require fishermen to operate in more distant or less favorable areas, increasing fuel consumption and operational costs [18,21].

In addition to direct spatial exclusion, fisheries may be affected by indirect environmental impacts associated with construction and operation of offshore wind farms. Changes in seabed conditions, underwater noise and electromagnetic fields from subsea cables can influence fish behavior and distribution [11–13]. While some studies suggest the potential for artificial reef effects, such outcomes are neither universal nor guaranteed, and their relevance to traditional fishing practices in the Adriatic remains uncertain [11,19].

Small-scale fisheries, which are common along the Croatian coast, are particularly vulnerable to such changes. Their limited range and dependence on local fishing grounds reduce their capacity to adapt to spatial displacement, making them disproportionately affected by offshore developments [18,21].

8.3 Broader economic and social considerations

The socio-economic impacts of offshore wind farms extend beyond individual sectors. Restrictions on maritime space, changes in navigation patterns and perceived alterations to the seascape can influence local communities' acceptance of offshore projects [21]. In regions where the sea holds strong cultural, social and economic significance, such perceptions play an important role in shaping public attitudes toward new developments.

When considered collectively, the potential losses in tourism and fisheries raise questions regarding the overall economic balance of offshore wind projects in the Adriatic Sea. While the generation of renewable energy provides a public benefit, this benefit must be weighed against the long-term impacts on established economic activities that already contribute substantially to national and local economies [18,21].

In the context of the Croatian Adriatic, where tourism and fisheries are not marginal but central components of economic development, the displacement or degradation of these activities represents a significant cost. Such costs are often difficult to quantify in early planning stages, yet they tend to materialize over time through reduced competitiveness, income loss and structural changes in coastal communities [18,21].

9. Floating offshore wind farms and the French approach

The development of floating offshore wind technology has gained momentum as a response to the limitations of conventional fixed-bottom foundations in deep-water environments. This technological pathway has been particularly advanced in the western Mediterranean, where bathymetric conditions resemble those of the Adriatic Sea more closely than those of the North Sea [9,10]. In this context, French floating offshore wind projects are often cited as a relevant technical reference for regions characterized by greater water depths.

France has faced challenges similar to those encountered in the Adriatic, including a narrow continental shelf and rapidly increasing depths close to the coast. These conditions have constrained the applicability of monopile and jacket foundations and prompted a strategic shift toward floating solutions. As a result, several pilot and precommercial projects have been developed, employing different floating concepts such as spar-buoy, semi-submersible and tension-leg platforms [9,10].

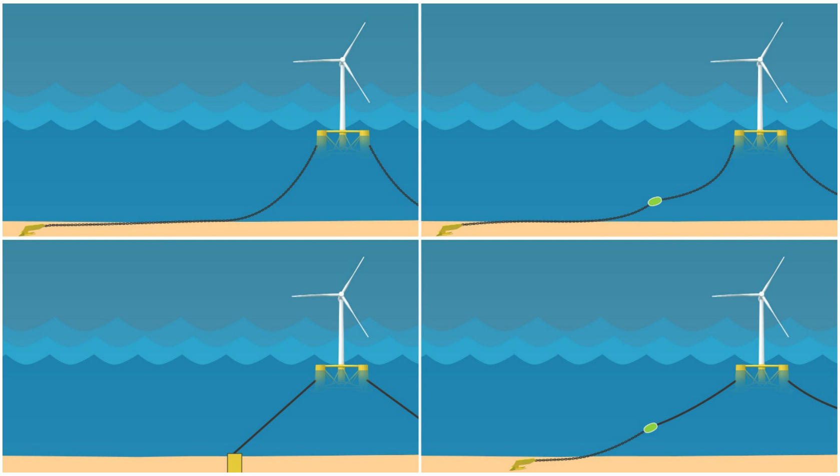

Figure 8. Floating offshore wind turbine concept and mooring system. Source: Author's elaboration based on [9,10].

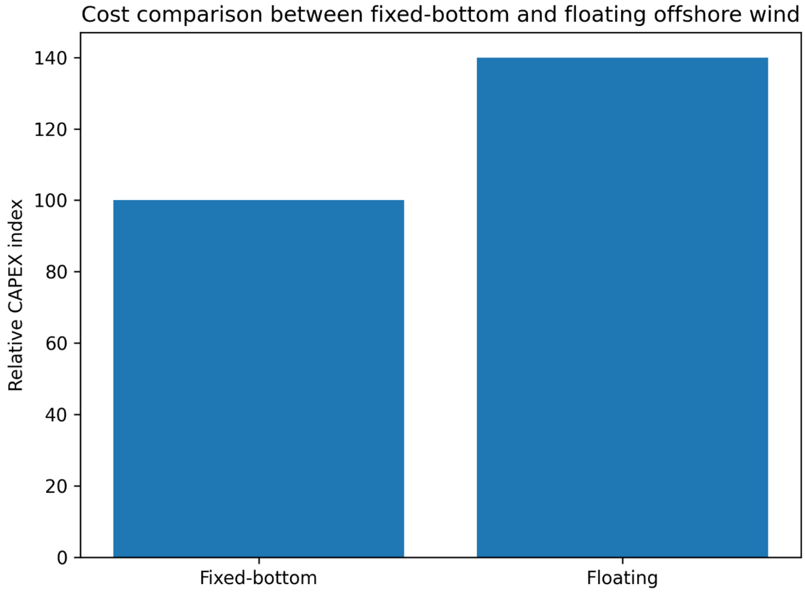

Figure 9. Indicative cost comparison between fixed-bottom and floating offshore wind farms. Source: Author's elaboration based on [4,9,10].

Projects including *Floatgen*, *Provence Grand Large* and *EolMed* have demonstrated the technical feasibility of floating wind turbines under real offshore conditions [9,10]. These projects have contributed valuable experience to platform stability, mooring system design and integration with onshore power grids. However, they have also highlighted the complexity inherent in floating systems, particularly with respect to installation procedures, dynamic cable management and long-term maintenance [10].

From a navigational safety perspective, floating offshore wind farms introduce challenges distinct from those associated with fixed-bottom installations. Mooring systems typically extend far beyond the visible footprint of the platform, occupying a larger horizontal area on and below the sea surface [9,10]. These submerged elements are not readily detectable by mariners and may pose hazards to fishing activities, anchoring in emergency situations and small craft navigation [21].

Economic considerations further complicate the assessment. Floating offshore wind farms generally involve higher capital and operational expenditures due to more complex structures, specialized installation vessels and increased maintenance requirements [9,10]. While cost reductions are anticipated as the technology matures and scales up, current experience suggests that floating solutions remain significantly more expensive than fixed-bottom wind farms developed in shallow waters [1,3] (Figure 8).

In the Adriatic context, the French approach illustrates that technological adaptation to deep-water conditions is possible, but it does not resolve the fundamental spatial, safety and socio-economic constraints inherent to the region [13,21]. Although floating platforms reduce direct seabed disturbance compared to fixed foundations, they do not eliminate conflicts related to limited maritime space, navigation safety, environmental sensitivity and competing sea uses [11,12].

Accordingly, the French experience should be viewed primarily as a demonstration of technical capability rather than as a comprehensive solution applicable without modification. In the Adriatic Sea, floating offshore wind technology may address certain bathymetric challenges, yet it simultaneously introduces new layers of complexity that must be carefully evaluated against the broader constraints of the maritime environment [21].

10. Assessment of the balance between benefits and impacts

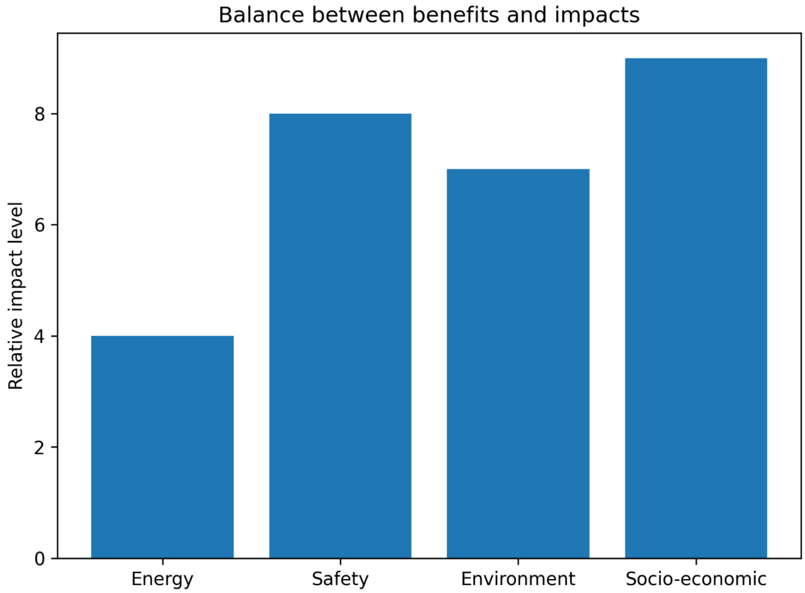

Figure 10. Comparative balance of benefits and impacts of offshore wind development in the Adriatic Sea. Source: Author's elaboration.

Assessing the justification for offshore wind development in the Adriatic Sea requires a balanced consideration of anticipated benefits against the range of impacts identified in the preceding chapters [1,2] (Figure 10). In maritime areas characterized by extensive space, stable wind regimes and long-standing industrial use, such assessments often yield favorable outcomes. In the Adriatic Sea, however, the balance is more complex and context-dependent [14,21].

From an energy perspective, offshore wind farms offer a contribution to the diversification of electricity supply and to decarbonization objectives [1,3]. Nevertheless, in the Adriatic context this contribution is constrained by several structural factors. Wind resources are characterized by pronounced seasonal variability, while construction and operational costs are significantly higher due to greater water depths, complex meteorological conditions and the need for floating technologies [9,10]. As a result, the energy output achieved per unit of investment remains lower and less predictable than in the established offshore wind regions such as the North Sea [2,3].

Against these limited benefits stand a series of long-term impacts. Navigation safety considerations are particularly prominent. The introduction of permanent obstacles and restricted zones in a maritime space already subject to dense traffic patterns alters navigational behavior and reduces available safety margins [22,23]. These effects are amplified during adverse weather conditions and peak seasonal traffic, increasing the demands placed on vessel operators and maritime safety authorities [17,23].

Environmental impacts further affect the overall balance. While offshore wind energy is often described as environmentally benign during operation, the ecological sensitivity of the Adriatic Sea requires a more cautious interpretation [11,12]. Disturbance of marine ecosystems, seabed alteration, potential impacts on migratory birds and cumulative effects of multiple installations introduce uncertainties that are difficult to mitigate fully, even with comprehensive monitoring programs [11,19].

Socio-economic impacts reinforce these concerns. Tourism, particularly nautical tourism and yacht charter, as well as fisheries, are not peripheral activities in the Adriatic but core components of coastal economies [18,21]. Spatial restrictions, changes in navigation routes and perceived alterations to the seascape may erode the competitiveness of these sectors over time [21]. Such losses, although not always immediately quantifiable, tend to materialize gradually and can outweigh the local economic benefits associated with offshore wind projects [18].

When these factors are considered together, the balance between benefits and impacts in the Adriatic Sea differs markedly from that observed in regions where offshore wind has been successfully deployed at scale [2,3]. The cumulative effect of higher costs, spatial constraints, safety considerations and socio-economic impacts suggests that the net benefit of offshore wind development in the Croatian part of the Adriatic remains limited under current conditions [14,21].

11. Conclusion

The analysis presented in this paper demonstrates that offshore wind development in the Croatian part of the Adriatic Sea cannot be approached through simplified analogies with other European maritime regions [1,2]. The Adriatic Sea represents a specific spatial, environmental and functional system in which natural characteristics, navigation safety, economic activities and the legal regime of the maritime domain are closely intertwined within a relatively limited area [21].

A comparison with the North Sea clearly illustrates that the key preconditions enabling large-scale offshore wind deployment there, e.g. extensive shallow waters, wide open sea areas and a long tradition of industrial maritime use, are not present to the same extent in the Adriatic [2,3]. Greater water depths, a highly indented coastline and dense maritime traffic significantly constrain the applicability of conventional offshore wind models, particularly within the Croatian territorial sea [14].

Bathymetric and meteorological analyses indicate that offshore wind projects in the Adriatic require more complex and costly technical solutions, including floating wind technologies [9,10]. While such solutions demonstrate technical feasibility, they simultaneously introduce additional spatial, safety and environmental challenges, particularly in relation to mooring systems, dynamic cables and expanded exclusion zones [9,10].

Navigation safety emerges as a critical limiting factor. The introduction of permanent structures and restricted areas in a maritime space already characterized by intensive commercial, passenger and recreational navigation reduces maneuvering margins and increases operational risk [22,23]. These effects are especially pronounced under adverse weather conditions and during emergency situations, where unrestricted access and navigational flexibility are essential [23].

Environmental considerations further complicate the assessment. As a semi-enclosed and ecologically sensitive basin, the Adriatic Sea is less resilient to cumulative impacts than larger open seas [11,12]. Disturbance of marine ecosystems, seabed alteration and potential effects on migratory bird routes necessitate extensive and long-term environmental studies, adding uncertainty and complexity to offshore wind development [11,19].

Socio-economic impacts also play a decisive role. Tourism, particularly nautical tourism and yacht charter, along with fisheries, constitute central pillars of the Adriatic coastal economy [18,21]. Any long-term restriction of maritime space or alteration of the seascape has implications that extend beyond immediate project boundaries and affect the broader economic and social fabric of coastal communities [18,21].

The legal status of the maritime domain in the Republic of Croatia reinforces these considerations. As a public good intended for general use, the sea requires careful management to ensure proportionality between public interest objectives and restrictions imposed on existing uses [21]. Long-term allocation of maritime space for offshore wind installations therefore raises fundamental questions regarding the balance between energy policy goals and the preservation of navigation safety and common maritime use.

The findings presented here should be interpreted as a qualitative, comparative assessment of structural constraints rather than as a site-specific feasibility determination.

In conclusion, while offshore wind energy represents an important component of the energy transition in certain maritime regions, the specific conditions of the Croatian Adriatic Sea indicate that its development entails more limitations than advantages. The anticipated energy benefits are not proportionate to the cumulative safety, environmental and socio-economic impacts identified in this study. Consequently, offshore wind development in the Adriatic should be approached with considerable caution, prioritizing alternative renewable energy solutions better aligned with the spatial, economic and functional characteristics of the region [14,21].

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