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OFFSHORE WIND ENERGY DEVELOPMENT AND HIGHLY MIGRATORY SPECIES: ECOLOGICAL, FISHERY AND MANAGEMENT IMPLICATIONS

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SUMMARY

Little scientific information is available on the potential effects of offshore wind energy (OSW) development on Highly Migratory Species (HMS), including those that inhabit the Atlantic Ocean and connected seas. Here, we draw from recent syntheses and related scientific literature to summarize possible interactions of HMS with OSW infrastructure and development activities. Ecological responses by HMS to OSW may include aggregation around novel structure, altered trophic dynamics, and behavioral responses to physical effects. Concerns surrounding possible changes to HMS fisheries including impacts to fishing grounds, shifts in fishing practices, safety, dockage and socioeconomic aspects. Implications of OSW on HMS population assessments and fisheries management include likely impacts on fishery-dependent and fishery-independent monitoring programs. Warranted is early investment in research and monitoring activities that aim to quantify species, ecosystem and fisheries responses to OSW development and how those changes affect management strategies. Sound science applied at appropriate spatial, temporal and taxonomic levels will provide the means by which negative impacts can be identified and mitigated to the greatest extent possible.

RÉSUMÉ

Peu d'informations scientifiques sont disponibles sur les effets potentiels du développement de l'énergie éolienne en mer (OSW) sur les espèces de grands migrateurs (HMS), notamment celles qui vivent dans l'océan Atlantique et les mers adjacentes. Nous nous appuyons ici sur des synthèses récentes et sur la littérature scientifique correspondante pour résumer les interactions possibles entre les HMS et les infrastructures et activités de développement de l'énergie éolienne en mer. Les réponses écologiques des espèces de grands migrateurs à l'énergie éolienne en mer pourraient inclure l'agrégation autour d'une nouvelle structure, la modification de la dynamique trophique et les réponses comportementales aux effets physiques. Des préoccupations existent concernant les changements possibles dans les pêcheries d'espèces de grands migrateurs, y compris les impacts sur les zones de pêche, les changements dans les pratiques de pêche, la sécurité, les impuretés et les aspects socio-économiques. Les implications de l'énergie éolienne en mer sur l'évaluation des populations d'espèces de grands migrateurs et la gestion des pêcheries comprennent les impacts probables sur les programmes de surveillance dépendants des pêcheries et indépendants des pêcheries. Il convient d'investir rapidement dans des activités de recherche et de surveillance visant à quantifier les réactions des espèces, des écosystèmes et des pêcheries au développement de l'énergie éolienne en mer et la manière dont ces changements affectent les stratégies de gestion. Des connaissances scientifiques solides appliquées aux niveaux spatial, temporel et taxonomique appropriés permettront d'identifier les impacts négatifs et de les atténuer dans toute la mesure du possible.

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RESUMEN

Se dispone de poca información científica sobre los posibles efectos del desarrollo de la energía eólica marina (OSW) en las especies altamente migratorias (HMS), incluidas las que habitan en el océano Atlántico y mares adyacentes. Este documento se basa en síntesis recientes y en la bibliografía científica relacionada para resumir las posibles interacciones de las HMS con la infraestructura y las actividades de desarrollo de la OSW. Las respuestas ecológicas de las HMS a la OSW pueden incluir la agregación en torno a nuevas estructuras, la alteración de la dinámica trófica y las respuestas de comportamiento a los efectos físicos. Preocupaciones en torno a los posibles cambios en las pesquerías de HMS, incluidos los impactos en los caladeros, los cambios en las prácticas pesqueras, la seguridad, el atraque y los aspectos socioeconómicos. Las implicaciones de la OSW en las evaluaciones de stocks de HMS y en la ordenación de las pesquerías incluyen probables impactos en los programas de seguimiento dependientes e independientes de las pesquerías. Se justifica una pronta inversión en actividades de investigación y seguimiento destinadas a cuantificar las respuestas de las especies, los ecosistemas y las pesquerías al desarrollo de la OSW y la forma en que esos cambios afectan a las estrategias de ordenación. Una ciencia bien fundamentada aplicada a niveles espaciales, temporales y taxonómicos adecuados proporcionará los medios para identificar y mitigar en la mayor medida posible los impactos negativos.

KEYWORDS

Offshore wind, large pelagics, artificial reef effects, fishery impacts

1. Introduction

Renewable energy production such as offshore wind (OSW) continues to intensify around the world as nations aim for clean, sustainable energy sources. Denmark was the first nation to harness OSW as an energy source in 1991, and operational OSW energy production now exists in Europe (United Kingdom, Germany, Denmark, Belgium, Netherlands, Sweden, Norway, Finland, France, Ireland, Portugal, Spain, and Italy), Asia (China, Japan, South Korea, Vietnam and Taiwan), and North America (United States) (Diaz & Soares, 2020; Zhang *et al.*, 2021). Globally, infrastructure associated with OSW energy is surpassing that for oil/gas production, which collectively account for more than 86% of artificial structures in the marine environment (Paolo *et al*., 2024). Offshore wind capacity is projected to grow at a rapid rate, reaching 382 gigawatts by 2030 and 2,002 gigawatts by 2050 (Bilgili & Alphan, 2022). Floating OSW technology development - which is not limited by water depths, as is the case with fixed turbine technologies - is expected to see a 68-fold increase in growth, with 8,362 megawatts of capacity anticipated by 2027 (NREL, 2022).

Concerns regarding ecological effects accompany the commencement and expansion of most maritime activities, as is the case currently for OSW energy development. In their literature review of 867 findings pertaining to the ecological impacts of OSW development, Galparsoro *et al*., (2022) noted the prevalence of negative (72%) over positive (13%) effects. Watson *et al.* (2024) found similar, albeit less negative, results in a review of ecological and socio-economic effects of OSW areas. They found negative impacts on biodiversity and ecosystem services were predominant (36%), but positive (28%) or no effects (27%) were also common. In addition, the authors revealed approximately 200 data gaps (or unknown relationships) in existing primary literature; no studies they referenced specifically considered Highly Migratory Species (HMS), which are of primary interest here.

With regard to fisheries in general, Gill *et al.* (2020) identified four potential broad effects in their review of OSW interactions with fish and fisheries: (a) artificial reef effects, (b) fisheries exclusion, (c) fisheries displacement, and (d) sensory and physical energy effects. They noted that effects may be positive (e.g., fish attraction/production) or negative (e.g., exclusion of trawl fishing), and some may be positively viewed by one sector but negatively by another (ten Brink & Dalton, 2018). Ecological effects of such man-made structures and the related management measures will have immediate effects on socio-ecological systems that are dependent on the use of fisheries resources (Kruse *et al*., 2024), but the direct and indirect socio-economic effects on fisheries sectors are yet to be predicted (Stelzenmüller *et al*., 2022). At present, research is lacking on the effects of OSW development on HMS and associated fisheries (McCandless *et al*., 2023; Hogan *et al*., 2023), although similar effects as those noted by Gill *et al.* (2020) would be expected for these pelagic species and their user groups. Additionally, given the broad geographic range of HMS, alteration of migratory patterns resulting from the introduction of OSW structures is a key consideration (Davis & Kneebone, 2023).

Investigations of the interactions between HMS and platforms associated with oil and gas development provide insight into how billfishes, tunas, swordfish and elasmobranchs may be influenced by OSW physical infrastructure. In their review of the function of oil and gas platforms as fish aggregating devices (FADs) for HMS, Snodgrass *et al.* (2020) summarized five potential influencing factors for pelagic fishes to associate with structure in the marine environment: (1) refuge from predators, (2) concentrated prey, (3) spatial orientation, (4) indicator of environmentally beneficial conditions (e.g., floating object at oceanic frontal zone), and (5) increased encounter potential (for feeding or mating). Price *et al*. (2022) similarly found that yellowfin tuna (*Thunnus albacares*) interacted with deepwater oil/gas platforms in the northern Gulf of Mexico as they tended to with FADs and conspicuous geological features. They surmised that increased energy infrastructure in the offshore marine environment could affect distributions and migrations of the species. The five factors above would presumably apply for OSW infrastructure located in offshore waters in which HMS occur, recognizing the disparity in the extent of areal footprints between large OSW areas (multiple structures interconnected by energized cables within a broader area) and the typical oil/gas platform (single, solitary structures) may lead to very different responses.

The jurisdictional scope of the International Commission for the Conservation of Atlantic Tunas (ICCAT), which directs the management of tunas, swordfish, billfish, and pelagic sharks, includes the Atlantic Ocean and adjacent seas (**Figure 1**). ICCAT also prioritizes reducing fishery interactions with marine mammals, sea turtles, seabirds and other taxa. Water depth is presently a key consideration in OSW siting, as construction and operation costs increase with depth, and the current footprint of OSW energy development is therefore concentrated primarily, but not exclusively, on the continental shelf (Paolo *et al*., 2024), depending on geographic region. While OSW areas are presently extremely limited in spatial scope relative to the overall geographic extent of the ICCAT Convention Area, direct OSW impacts on HMS and their associated fisheries will likely occur in continental shelf waters and offshore areas of Europe, North America and Africa and will differ by season and life stage. In assessing the depth distributions of existing OSW structures, primarily in Europe and Asia, Jung & Schindler (2023) found that most turbines are located in relatively shallow water, with a median depth of 17 m and range of 0 m to 50 m. However, ongoing projects include floating OSW structures that can be deployed in substantially deeper environments, and as technology improves the cost effectiveness of these floating structures is also likely to increase. While some ICCAT-managed HMS may spend minimal time this close to shore, continental shelf waters of the U.S. are, for example, important year-round and include Essential Fish Habitat for many species and life stages (NMFS, 2017), as is also the case in some Mediterranean areas. Some HMS and their fisheries (e.g., hand gear, bottom longline) are also heavily reliant on shallow shelf waters and thus will likely have overlap with OSW development (NMFS, 2017). Additionally, analyses of angler surveys and fishery-dependent data by Kneebone & Capizzano (2020) found wind leases off southern New England (U.S.) overlap areas of HMS-focused recreational fishing. Placement of OSW infrastructure in the vicinity of established fish migration routes and/or routes taken by fishing fleets may also have greater impacts than their individual areal footprints. Certainly, future expansion of OSW energy development farther offshore (Musial *et al*., 2023; USDOE, 2022) will increase interactions with HMS (e.g., U.S. Gulf of Maine; Davis & Kneebone, 2023), as will OSW development in new regions, particularly those with relatively narrow shelf areas (e.g., Caribbean Island nations and Sardinia in Italy).

Given the lack of studies on HMS-OSW interactions and the anticipated expansion of OSW into deeper waters, this paper draws from recent synthesis efforts to summarize potential effects of OSW development on HMS, with consideration of ecological responses by ICCAT priority species, potential changes in HMS fisheries, and implications for management. While most literature on OSW energy development has focused on regional science and management considerations (Methratta *et al.*, 2020), here we evaluate implications for HMS throughout their entire distributional ranges in the Atlantic Ocean and adjacent seas, which extend across multiple jurisdictional boundaries.

2. Materials and Methods

We drew primarily from two recent syntheses produced by the U.S. NOAA Fisheries' Northeast Fisheries Science Center (Hogan *et al.*, 2023) and Southeast Fisheries Science Center (Klajbor *et al*., in review). These syntheses inventory potential causative factors and identify areas requiring additional monitoring, research and data to gauge OSW development effects on HMS biology, ecology, fisheries, assessments and management. Of note, both documents involved subject matter experts on a wide variety of fisheries, wildlife and marine ecosystem topics, and Klajbor *et al*. (in review) also referenced products of the *Synthesis of Environmental*

Effects Research (SEER; https://tethys.pnnl.gov/us-offshore-wind-synthesis-environmental-effects-research-seer). Because of the paucity of literature available on interactions between HMS and OSW infrastructure and operations, we also drew from primary literature sources focused on HMS associations with oil production platforms and FADs (e.g., Snodgrass *et al*., 2020) which also serve as vertical structure in the open ocean environment. Research recommendations were based on these primary sources, as well as Methratta *et al*. (2023a).

3. Results and Discussion

3.1 Spatial Extent and Planning Considerations for Offshore Wind Energy Development

Understanding potential impacts of OSW on ICCAT species and fisheries, and developing related mitigation strategies, will greatly benefit from evaluating the locations, scale, and timelines of OSW development. To place this in context, we briefly and generally describe the spatial scale of existing and planned/potential OSW development throughout the ICCAT regional domain. The pace of planning and implementation of OSW development is rapid, thus generating an accurate inventory of existing development activities is challenging. Presently, OSW development is active off western Europe, in the Mediterranean Sea and off the United States, with potential for near-term expansion off Canada, Morocco and South America and potentially in the Caribbean Sea (**Figure 2**). Development in other areas is likely in the future, as global-scale analyses (e.g., Global Wind Atlas, https://globalwindatlas.info/en) continue to identify areas with favorable wind resources around the globe (**Figure 3**).

Planning for OSW development and establishment of territorial regulations for construction, operation and decommissioning are not consistent across the ICCAT domain, and many such considerations are in their preliminary stages. In North America, the U.S. has enacted region-specific marine spatial planning to identify optimal areas for OSW development by deconflicting siting among user groups and in accordance with management protections (see https://coastalscience.noaa.gov/science-areas/offshore-wind-energy/spatial-planning/). Similarly, Canada has identified potential OSW areas based on sensitive and critical habitats, fishing effort, vessel traffic, existing energy infrastructure (oil/gas) and aquaculture lease areas. In Europe, member states have different approaches to OSW planning and siting, but they generally account for the ecological importance of and human activity in/around potential locations, although considerations for HMS migratory pathways appear to be lacking.

Despite these proactive planning measures, all potential effects of OSW on marine biota, including HMS, have not been considered nor appropriately addressed, and it remains to be seen how these projects will fit within international sustainability objectives (e.g., UN Sustainable Development Goal 14). Factors such as underwater noise, vibrations and light alterations associated with OSW have been evaluated for marine mammals and other protected species, but considerations for finfish are largely absent (Popper *et al.*, 2022). Additionally, regulatory conditions will vary across jurisdictions, so a one-size-fits-all approach to understanding and mitigating effects to HMS and its fisheries will not be possible across the ICCAT domain. For instance, it is expected that OSW lease areas of the U.S. will not be expressly prohibited to fishing (although operational limitations may prevent some commercial fisheries from operating safely in/around lease areas during construction and/or operation). Meanwhile, some authorities in Europe are planning to declare OSW zones as Marine Protected Areas, wherein any fishing or human activity will be banned (except for OSW maintenance efforts). Consequently, scientists and managers will need to assess region-specific factors of OSW development and how regulatory restrictions and anticipated effects of development will alter HMS behaviors, populations and fisheries.

A listing of potential factors associated with OSW leading to possible effects on HMS is presented in **Tables 1, 2 and 3** for ecological, fishery and management considerations, respectively. Factors and effects presented are broad and general, given the lack of published studies on HMS and OSW, and ecological and fishery responses to OSW energy development may vary across regions within the ICCAT jurisdiction. For instance, effects of additional structure introduced into the offshore marine environment in the U.S. Gulf of Mexico, where oil and gas infrastructure has existed for decades, may be less pronounced on the biology and ecology of HMS than in Mediterranean, Caribbean or Atlantic waters, which have historically not had a high volume of offshore industrial infrastructure.

3.2 Ecological Considerations

Artificial Reef Effects - Broadly applicable to virtually all ecosystem levels are artificial reef effects resulting from the introduction of OSW-related structures into the marine environment (Degraer *et al*., 2020). While physical (e.g., electromagnetic fields, heat and sound pressure) and anthropogenic (e.g., increased vessel traffic) effects of OSW operations may deter some species or individuals from OSW areas, the introduction of OSW structures is likely to have an attractant effect for many others. Ecological consequences may include, among other things, alterations in habitat use, shifts in migratory patterns, changes in trophic dynamics, and altered individual fitness (including spawning) (**Table 1**). Most research on artificial reef effects on fishery species has focused, with some exceptions, on reef fishes and reef-associated invertebrates, as these taxa are more likely to establish residency on artificial structure and therefore be subject to more immediate and long-term effects. Recent studies from the southern North Sea showed empirical evidence for the attraction of benthopelagic species such as Atlantic cod, *Gadus morhua*, (Gimpel *et al.* 2023; Werner *et al.* 2024) and flatfish species including European plaice, *Pleuronectes platessa*, (Buyse *et al*. 2023) to OSW development areas. While artificial reef effects may be more expected for fixed structures, floating OSW turbines may have similar effects and will likely function as massive FADs concentrating HMS predators, prey and fishers.

Given the extensive geographic ranges within the vast open-ocean environment associated with HMS species, artificial reef effects on HMS have garnered less attention than on demersal species (in the form of offshore oil and gas platforms; Haugen & Papastamatiou, 2019; Snodgrass *et al.*, 2020; Price *et al.*, 2022). Research on FADs, however, may also provide some degree of insight into possible responses of HMS to OSW structures, recognizing that the surficial area and spatial extent of FADs do not compare to the scales of OSW zones; OSW areas will include structures positioned in arrays, have turbines and/or mooring systems extending from below the seafloor through the water column and into air spaces, and introduce hard substrates for infrastructure protection throughout the footprint of turbines and cable corridors which will represent new habitat. Girard *et al*. (2003) found that yellowfin tuna in the Indian and Pacific Oceans were attracted to FADs but did not aggregate at those structures (based on relatively short periods of occurrence), and Véras *gvf* (2020) noted similarly short periods of presence of electronically tagged yellowfin tuna at anchored FADs deployed off northeastern Brazil. Of 45 yellowfin tuna and 12 bigeye tuna (*Thunnus obesus*) acoustically tagged at 13 FADs off Oahu, Hawaii (U.S.), only eight and one fish, respectively, were detected at a FAD subsequent to release, but yellowfin tuna were present within the array for up to 150 days (Dagorn *et al*., 2007). Hallier & Gaertner (2008) reported that migratory directions of yellowfin and skipjack tuna (*Katsuwonus pelamis*) in the Atlantic and Indian Oceans were altered in the presence of drifting FADs and that FAD-associated individuals were slimmer (girth relative to length) and had less full stomachs than free-schooling conspecifics. These researchers recommended additional studies to better define the effects of structure on HMS, including potential shifts in migratory habits as also noted by Davis & Kneebone (2023).

The debate as to whether artificial reefs/structures simply attract and aggregate fish versus increase production (Bohnsack, 1989) persists, with numerous publications focused on this question primarily for reef fishes (Lindberg, 1997; Pickering & Whitmarsh, 1997; Powers *et al.*, 2003; Smith *et al.*, 2016). Whether production is affected, either positively or negatively, is species-specific (Cresson *et al*., 2019) and is likely to vary among structure types and among geographic locations. Determining attraction versus production effects of OSW infrastructure for HMS remains a critical - but unresolved - need from an ecological perspective and in terms of consequences for HMS fisheries and management. Well-crafted studies focused on individual species and life stages specific to regional OSW areas, with considerations for broader ecosystem effects, are necessary to provide defensible answers to this extremely difficult question, especially for HMS.

Physical Effects - Behavioral and physiological responses by HMS may be expected from electromagnetic fields (EMF), heat, light and altered hydrodynamics produced during OSW operations, with sound pressure being potentially influential during construction, operation (particularly for floating OSW) and decommissioning phases (**Table 1**). Shifts in habitat use, feeding activities, individual growth and reproduction could be primary or secondary effects from such physical stimuli. McCandless *et al*. (2023) summarized existing studies on these potential OSW-related factors and noted that EMF effects (electro- and magnetoreception) were primarily specific to elasmobranch species, with yellowfin tuna also exhibiting some degree of magnetoreception. Turbines in general and mooring cables for floating OSW structures are sources of novel sound and vibration, which may have attraction, repelling or communication masking effects on HMS, as sound effects have been documented for elasmobranchs and for bluefin tuna (*Thunnus thynnus*), the latter of which altered behavior in the presence of OSW-generated noise (Puig-Pons *et al*., 2021). Underwater noise and vibrations associated with floating OSW may interfere with the communication systems of HMS and affect their feeding strategies, including prey detection. Upwelling caused by turbine wakes are known to vertically mix normally stratified water columns in and around OSW wind structures resulting in redistribution of prey, potential changes in primary and secondary productivity and increased turbidity, each of which would alter local trophic dynamics (Paskyabim, 2015; Floeter *et al.*, 2022). Lighting associated with OSW infrastructure may also influence the behavior of animals across a wide spectrum of sizes and trophic levels, particularly those with positive phototaxic behaviors. As with artificial reef effects, there is limited literature on physical effects of OSW on the ecology of HMS, therefore extensive research is needed to identify responses to allow for quantification of negative effects and assessment of potential mitigation measures (Klimley *et al.*, 2021; McCandless *et al*., 2023).

3.3 Fisheries Considerations

Nearshore OSW energy development will have obvious implications for a variety of fisheries (**Table 2**), and effects on HMS will, initially, be commensurate with each species' and fishery's use of more nearshore continental shelf waters where most OSW infrastructure is currently planned (Jung & Schindler, 2023; McCandless *et al*., 2023). The expansion of these novel habitats into deeper, offshore waters (Musial *et al.*, 2023), which will include floating OSW turbines, will also overlap with habitats, migratory corridors and fishing grounds for HMS (Kneebone & Capizzano, 2020; Davis & Kneebone, 2023; McCandless *et al.*, 2023; Kneebone *et al.*, in review). Syntheses by Hogan *et al.* (2023) and Klajbor *et al*. (in review) identify two primary causative factors of OSW that may have HMS fishery implications: (a) introduction of novel structure and (b) marine industry expansion.

Introduction of Novel Structure - New structure from OSW development, again, has the potential to introduce artificial reef effects, which will likely increase fishing effort and/or efficiency in lease areas for some fisheries while excluding or displacing others (Gill *et al.*, 2020). For instance, for OSW leases within which fishing is allowed, recreational and charter fishing is likely to increase in the OSW infrastructure area. Not only would many target species be expected to aggregate around new OSW turbines, but those structures will be highly visible and readily located by anglers and captains. Unrestricted, this concentration of effort will likely lead to increases in catch and bycatch, change the overall spatial footprint of recreational fishing effort, and may elevate space conflicts within and among user groups leading to potential maritime safety concerns.

Conversely, authorities may wholly prohibit fishing and boating activities within OSW areas, as is expected for some European nations, thereby preventing access to fishery resources that aggregate around the novel structures. Some commercial fisheries, even if not explicitly prohibited from accessing lease areas, may not be able to effectively and/or safely fish among the expanse of OSW turbines, which present entanglement hazards, or where scour protection and distribution powerline infrastructure may snag or entangle subsurface gear. For example, pelagic longline gear targeting HMS is typically deployed in lengths exceeding 30 km and is transported by ocean currents as it fishes over the course of many hours. The length of gear and the distance it can move between deployment and retrieval locations would preclude fishing in close proximity to OSW lease areas due to risk of entanglement with turbine structures and associated operations; entangled gear would then present secondary entanglement risks to biota in the area. This fishery would therefore avoid (i.e., be excluded from) OSW development areas and shift effort elsewhere, potentially to less productive fishing grounds. As an alternative, some commercial HMS fishers may switch to a different gear/tactic, such as 'greenstick' trolling (Snodgrass *et al*., 2020) or buoy gear (Sepulveda *et al*., 2014), which would allow for targeting HMS in closer proximity to OSW structures; however, it is not known if such alternative fishing tactics would ultimately be cost-feasible. The possible impact of OSW development along migratory courses of HMS and in the vicinity of traditional tuna traps (i.e., bluefin tuna) is another source of uncertainty and concern.

For all sectors, modifications to fishing activities, in terms of areas fished and gear utilized, has secondary consequences. Changes in catch-per-unit-effort (CPUE), catch size and species composition, and bycatch (including regulatory discards) will alter the dynamics of fisheries. Ecosystem shifts of predators (e.g., sharks and piscivorous marine mammals) may also increase depredation in/around structured OSW areas for both recreational and commercial fisheries (Streich *et al.*, 2018). Fishing mortality will undoubtedly increase within OSW leases (with unrestricted access) for one or more sectors and have implications for stock assessments and subsequent management measures. Consequences of elevated fishing mortality may be exacerbated if OSW structures simply attract HMS without increasing production.

Finally, fishery-based revenue may increase for some user groups while decreasing for others. For example, charter operators may realize a direct increase in revenue from more charter trips if catch of target species increases in nearby OSW areas or if there is a reduction in the operating costs associated with finding free schooling fish; however, that profit may only be short-term if attraction prevails over production. Conversely, some commercial fishers may face cost increases resulting from greater transit times around OSW areas in which they cannot effectively fish or safely transit through, from increased fuel usage and/or lost revenue from transitioning to new gear. Increased insurance premiums may also result, depending on the operational changes each fishery is compelled to make. Resultant changes in seafood supply may have broader socio-economic ramifications, and decreases in domestic catches may elevate seafood security concerns at the national level. Incorporating human dimensions into fisheries assessments and analyses will be key to understanding the scope and scale of social, economic and cultural effects of OSW development.

Marine Industry Expansion - Expansion of OSW production will require considerable maritime and infrastructural support for construction and operations. Shore-based space will be needed for construction staging, material storage and vessel dockage, and power substations along coastlines will serve as primary hubs for terminating distribution lines from OSW production areas. That infrastructure will require development of new coastal areas or a shift in use of existing spaces, which may impact fisheries infrastructure (e.g., harbors and processing facilities) as well as coastal residential areas. Industrial expansion also has the potential to increase demand for labor, fuel, housing and amenities, subsequently increasing costs and/or reducing supply for other sectors. Labor shifts from fisheries to OSW production support would directly impact the former, possibly requiring vessels to reduce fishing days or fish with fewer or less experienced crew members (thereby increasing safety concerns). These effects would have additional consequences for seafood supply and cost. Closure of OSW lease areas to fishing during construction phases, or permanently as is expected for some areas of Europe, will also have direct fishery effects, and increased vessel traffic for maintenance and operations has the potential to elevate user conflicts and safety issues within/around lease areas post-construction. For example, OSW development along narrow passages such as the Strait of Sicily will potentially increase risk of collisions and decrease opportunities for fishing fleets.

3.4 Assessment and Management Considerations

Shifts in fisheries summarized above will have implications for fisheries assessments and management (**Table 3A**). The ability to minimize uncertainties in related fishery metrics will depend on the degree to which those changes can be tracked and quantified over time, which will subsequently impact stock assessments and resultant catch limits and management targets. Exclusion of historical sampling (as part of routine monitoring programs) within and around lease areas may also limit the application of fishery-independent indices historically used in assessments. New or modified strategies in those areas will likely be required to maintain the integrity of scientific surveys. Just as important will be the commencement of spatially-focused and temporally-appropriate sampling in/around OSW areas to allow for detecting impacts and quantifying fishery and ecosystem changes which may be attributable to OSW effects. For areas that do not have a history of effective fishery monitoring, tracking catches and effort around newly-installed OSW infrastructure could represent an opportunity to begin a fishery time series that will have management utility in the future.

Fishery-Dependent Data - As fisheries adapt to the introduction of OSW infrastructure and operations, changes are likely to occur for a number of factors in and around lease areas, including locations and extent of fishing effort, species-specific catch rates, size composition of catch, discarded catch (bycatch and regulatory discards) and release mortality [which may be exacerbated by shifts in non-targeted predator behavior (i.e., depredation)]. Those shifts are likely to vary among sectors and specific fisheries but will change how fisheries operate. Unlike for many stocks which are tracked via scientific (fishery-independent) surveys, management of most HMS relies upon fishery-dependent CPUE indices (Maunder & Punt, 2004) used either in stock assessments or management procedures. Properly tracking changes in HMS fisheries (e.g., via fishery observer programs) is therefore critical to maintaining effective management.

Table 3B identifies a set of potential impacts, causative mechanisms and possible solutions for fishery-dependent indices when confronted with OSW impacts. Under best-case scenarios, where OSW-related impacts can be predicted and empirically tested, effects can be accounted for in CPUE standardization. Nonetheless, the addition of model parameters usually introduces added uncertainty, which will reduce the precision of the indices, resulting in additional uncertainty in assessment results, if not bias. This added uncertainty would, according to the precautionary approach to fisheries management (de Bruyn *et al.,* 2013), result in lower catches for a similar probability of overfishing. A worst-case scenario of splitting indices would lead to quite substantial uncertainty in stock status and recommended yields. In the case of management procedures, this would most certainly invoke “exceptional circumstances” provisions, as the original tested index would no longer be available. Hence, it is critical to anticipate and take proactive measures to mitigate the impacts of OSW on fishery-dependent indices so as to not jeopardize the assessment and management process. Ultimately, mitigation for fishery-dependent indices for HMS is just as important as mitigation for fishery-independent indices derived from scientific surveys. The continuous collection of precise location data in fishery-dependent data programs from logbooks, vessel monitoring systems, and other sources may provide opportunities to empirically examine these impacts before and after construction of OSW projects.

Fishery-Independent Data - Ecosystem- and population-level data obtained from long-term scientific surveys may be jeopardized as a result of interruption to sampling events or preclusion/exclusion of sampling in and around OSW lease areas. For example, areas may be closed to navigation during construction activities, and vessels may not be able to safely or efficiently sample in lease areas post-construction; similarly, aerial surveys conducted for HMS populations such as bluefin tuna may also require modifications (e.g., higher survey altitude), which will likely decrease detectability of target individuals. The inability to sample in those areas will result in a loss of survey area coverage for monitoring programs. Larval abundance indices are another source of information integrated in the different assessment procedures of Atlantic bluefin tuna in ICCAT (Ingram *et al*., 2010), and the potential displacement of reproductive aggregations that occur in geographically restricted spawning grounds (Muhling *et al*. 2017) may alter larval distributions and the derived indices of abundance, consequently increasing uncertainty for these fishery-independent indices. As such, the few fishery-independent surveys which exist for HMS species, notably aerial (https://www.iccat.int/gbyp/en/), bottom longline (NOAA Fisheries), and larval surveys (Ingram, 2018; Alvarez-Berastegui *et al.*, 2020), could be substantially impacted by OSW development; however, when a scientific survey can be continued within OSW development areas, it may provide a sound basis to assess the effect of OSW structures through spatio-temporal contrasts (before-after-control-impact or gradient studies).

Such survey impacts can be mitigated through planning, design and applying new methods and approaches, and supplemental survey strategies can be developed to address those spatial data gaps (e.g., Hare *et al*., 2022; Kellison *et al.*, in review) and alleviate, or at least minimize, impacts to assessments and management. Directed fishery-independent sampling within OSW development areas, properly calibrated to past surveys, as part of lease-specific monitoring (see below) or survey mitigation requirements, may generate data that has utility for both assessment and management if effectively designed. Fishery-independent data integrity should also be a key consideration in marine spatial planning for region-specific OSW development, and survey mitigation should be coordinated with energy regulatory authorities and OSW developers. In the U.S., where national strategies state that mitigating these impacts is a joint responsibility of government and OSW developers, regulatory requirements have been instituted that require lessees to mitigate the impacts from OSW development due to survey preclusion on U.S. NOAA Fisheries resource surveys (Hare *et al*., 2022).

Lease-Specific Assessments - A critical need for evaluating OSW impacts will be directed monitoring in and around OSW areas, developed and implemented at appropriate scales, to allow for quantifying ecological and fishery changes which may be attributable to OSW development (Methratta, 2024). Science-based surveys applied for stock assessments are typically designed at broader spatial scales than would be required for detecting fishery effects and ecosystem responses in OSW lease areas and surrounding waters. As such, monitoring at the lease area scale can be instituted as a requirement and developed collaboratively to ensure impacts to biota, habitats, migratory courses, fisheries and user groups can be sufficiently quantified (Hare *et al.*, 2022). Such evaluations will be paramount to identifying/refining mitigation measures to reduce negative effects and establishing (or adjusting) compensation to user groups in accordance with findings. Of consideration here, however, is the potential change in spatial distribution of the surveyed species, given the possibility that HMS may become less available and/or generally less detectable in the survey area because of movements or behavioral changes as a result of repulsion from (or attraction to) OSW infrastructure.

Coordination with OSW developers early in the planning process will be the most effective means to address these needs. Coupling lease-specific monitoring with survey mitigation may be possible to leverage resources and more broadly supplement data collection with greater efficiency. Opportunities for incorporating advanced sampling technologies (e.g., optical and/or acoustic fish and marine mammal detection devices, satellite and acoustic telemetry, eDNA) within or adjacent to OSW infrastructure should be explored and is currently being employed in some monitoring plans off the northeastern U.S. (e.g., Bangley *et al*., 2020). As stock assessments and management procedures for HMS will still mostly rely on fishery-dependent indices, a key component of lease-specific activities will be fishery-dependent index mitigation. This could involve working with the fishery to estimate key parameters that would be needed for model-based standardizations to maintain the integrity of the CPUE indices and to inform the change in size-selectivity associated with the changes in fishing gear or practices.

3.5 Conclusion and Recommendations

Potential effects of OSW development on HMS ecology, fisheries and management identified here align with general categories identified by Gill *et al*. (2020) and with general interactions noted by Methratta *et al*. (2020) in their reviews of OSW interactions with fish and fisheries. Whether effects are positive, negative or neutral, and the extent of such effects, remains largely unknown and will likely vary among species, regions and life stages. Additionally, greater uncertainty surrounds environmental, behavioral and fisheries issues with respect to cumulative effects, unintended consequences, and regional ecosystem responses. As such, research, monitoring and targeted data collection will be key to understanding both localized and regional effects of OSW development across all phases (pre-construction, construction, operation, decommissioning) and from ecological, fishery, management and socio-economic perspectives. Such data needs related to HMS are provided in **Table 4** and include fishery-independent and fishery-dependent monitoring, directed research, and modeling. Addressing those needs should include stakeholder engagement, public participation and public-industry-scientist collaboration, to the greatest extent practicable.

Population and ecosystem monitoring will be required at different scales to effectively assess OSW effects on ICCAT priority resources. Continuation of long-term fishery-independent surveys, with appropriate mitigation for exclusion from lease areas, will allow for an uninterrupted data time series to inform broader, regional assessments; those data will also be useful for determining if population-level effects of OSW are being realized. At the same time, new lease-focused surveys will provide the spatially-distinct data needed to evaluate localized effects in and around OSW lease areas, which may also provide for new time series of data for management purposes in areas that do not have a history of effective fishery monitoring. Directed research should include tagging studies for HMS, using traditional (e.g., angler-based mark-recapture) and advanced technology-based approaches (e.g., satellite tags, passive acoustic telemetry). Field-based (and laboratory-based, where appropriate) assessments of behavioral responses by HMS to physical influences of OSW (i.e., EMF, heat, sound and hydrodynamics) are also needed to determine how individual responses may relate to population-level effects.

Above and beyond lease-specific monitoring, it is vital to consider cumulative effects of OSW at multiple scales. Given the extensive geographic ranges and migratory paths of HMS, the accumulation of interactive effects of individual OSW zones must be evaluated in a broad spatial context, as impacts considered to be localized to a specific lease may, in fact, have broader scale effects for wide-ranging HMS stocks. Biomass changes at the ecosystem level will also have secondary repercussions for both higher and lower trophic levels, which will then likely have tertiary effects (e.g., shifts in fishing effort). Understanding effects among the various OSW-induced pressures is also needed, as those may also be cumulative for some species/groups (e.g., EMF and artificial reef effects for elasmobranchs). Where possible, sampling methodologies, experimental designs and/or calibration approaches should be applied from existing regional surveys to new science programs to allow for comparative analyses.

Understanding, and quantifying, fishery changes associated with OSW development may require expansion of data collection, vessel monitoring and fishery observer programs. Monitoring of commercial effort and catch should be evaluated and adjusted, where needed, to track shifts in fisheries to OSW lease areas (where fishing is possible) or away from those areas (where fishing is displaced). Recreational and charter data collection programs may also need to be modified to adequately quantify increased effort and associated catch and discards in and around OSW lease areas. For all sectors, the composition and fate of discards (regulatory or bycatch) may also change and should be included in considerations for data collection modifications. The implications of potential changes in fishery dynamics should be investigated through exploratory model runs to estimate how those effects may impact stock assessments and resultant management targets, with outputs informing the modifications to data collection programs. While timely and appropriate marine spatial planning has the potential to reduce conflicts among user groups, human dimensions assessments should be integrated during all phases of OSW development to ensure that social, cultural and economic effects (direct and indirect) are recognized and mitigated where possible. The concept of socio-ecological systems (e.g., Woods *et al*., 2022) can be applied not only to describe complex human-nature interactions but also to derive estimates of socio-ecological impacts due to effects of OSW development.

OSW energy will become an increasing part of the renewable energy portfolios of ICCAT member nations. Given the observed and predicted effects of climate change on HMS and fisheries (Crear *et al.*, 2023; Braun *et al*., 2023), there is a need for global expansion of renewable energy production, within the bounds of sustainability (e.g., UN Sustainable Development Goal 14). However, OSW development and its effects on HMS will only be understood with early investment in research and monitoring activities that aim to quantify species, fisheries and ecosystem responses and how those changes affect management strategies. Sound science applied at appropriate spatial, temporal and taxonomic levels will provide the means through which negative impacts can be identified and mitigated to the greatest extent possible, while maximizing positive effects.

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Table 1. Potential causative factors of OSW and likely effects on HMS for ecological considerations. ◍ = at least one related reference; ◐ = no published studies but likely effect; ◎ = unknown status or not applicable.

		Potentially Affected HMS		
		Groups		
Potential Causative Factor	Potential Ecological Effect	Billfishes	Tunas	Elasmobranchs
Introduction of novel structure	Artificial reef effect (+/-)	◍	◍	◍
	– altered habitat use	◍	◍	◍
	– altered migratory patterns	◐	◐	◐
	– altered trophic dynamics	◐	◍	◐
	– altered fitness	◐	◐	◐
	– altered spawning behavior	◐	◐	◐
	– attraction versus production	◎	◎	◎
	Avoidance	◐	◐	◐
	– altered habitat use	◐	◐	◐
	– altered migratory patterns	◐	◐	◐
	– altered fitness	◐	◐	◐
Electromagnetic fields	Behavioral and physiological responses (electroreception)	◐	◐	◍
	Behavioral and physiological responses (magnetoreception)	◐	◐	◍
	Altered migratory patterns	◐	◐	◐
	Ecosystem shifts	◐	◐	◐
Heat	Behavioral and physiological responses	◐	◐	◐
	Altered migratory patterns	◐	◐	◐
	Ecosystem shifts	◐	◐	◐
Sound pressure	Behavioral and physiological responses	◐	◍	◍
	Altered migratory patterns	◐	◐	◐
	Ecosystem shifts	◐	◐	◐
Altered hydrodynamics	Changes in water column stratification	◎	◎	◎
	Altered migratory patterns	◐	◐	◐
	Ecosystem shifts	◐	◐	◐
	Changes in trophic interactions	◐	◐	◐

Table 2. Potential causative factors of OSW and likely effects on HMS for fishery considerations. No published studies specific to HMS fisheries were found, but these potential effects should be considered.

Potential Causative Factor	Potential Fishery Effect
Introduction of novel structure	Increased fishing effort (artificial reef effect)
	Increased vessel traffic
	– safety concerns
	– user conflict
	Decreased fishing effort
	– avoidance
	– exclusion
	– effort shift to non-OSW areas
	Changes in CPUE
	Changes in catch size composition (impact of shift in regulatory discards)
	Changes in bycatch composition
	Changes in fishing gear/tactics
	Depredation effects
	Changes in revenue (+/-)
	– increased landings (potentially short-term)
	– cost increases (e.g., transit time/distance, new gear, insurance)
	Changes in seafood supply
Marine industry expansion	Increased costs (e.g., dockage, fuel, crew wages)
	Limited shore-based infrastructure
	Increased vessel traffic
	Labor displacement
	Changes in seafood supply

Table 3. (A) Potential causative factors of OSW and likely effects on HMS for management considerations. No published studies specific to HMS management were found, but these potential effects should be considered. **(B)** Examples of potential OSW impacts (and causative factors) to fishery-dependent indices, including best-case solution and worst-case scenario for those impacts. * Survey mitigation and regional marine spatial planning are being evaluated as part of ongoing U.S. federal planning activities.

(A)

Potential Causative Factor	Potential Management Effect
Fishery-dependent data limitations	Uncertainty in fishing effort shifts, by sector, in/around OSW areas
	Uncertainty in changes in retained catch, by sector, in/around OSW areas
	Uncertainty in changes in discarded catch, by sector, in/around OSW areas
	Uncertainty in post-release mortality and depredation in/around OSW areas
	Implications for stock assessments
	Marine spatial planning for OSW lease siting*
Fishery-independent data limitations	Uncertainty in individual/population responses to OSW development
	Impacts to existing surveys (exclusion)*
	Implications for stock assessments
	Marine spatial planning for OSW lease siting*

(B)

Impact	Mechanism	Best-Case Solution	Worst-Case Scenario	Example
Preclusion	Fishery is precluded from fishing in certain area(s)	Collect catch/effort information before and after, add additional spatial model parameter and assume that any trends post-development mirror those in the fished areas	Split index	Imposition of closed areas
Change in vulnerability	Fish are attracted to structures (or opposite)	Estimate catchability change and account for in CPUE modeling	Split index	Artificial reef effect (FAD, oil platform)
Change in selectivity	Larger or smaller fish are available to the fishery	Estimate selectivity change, informed by changes in spatial distribution of stock	Split index and split selectivity	Artificial reef effect (FAD, oil platform)
Change in gear or methodology	Fishing tactics must be altered in order to fish in/around OSW areas	Conduct before/after gear testing so as to be able to estimate additional model parameter-related to the gear change	Split index and split selectivity	Shorter sets to avoid entanglement

Table 4. Inventory of monitoring, research and data needs for assessing potential OSW effects on HMS fish, fisheries and management.

Monitoring, Research and Data Needs	Research and Data Components
Long-term population and ecosystem monitoring	– Continue established fishery-independent surveys for population-wide analyses, effectively mitigating impacts to surveys (e.g., Methratta *et al.*, 2023b) – Implement new, site-specific fishery-independent monitoring in/around OSW lease areas to assess localized effects – Consider ecosystem effects (e.g. trophic ecology, competition, spawning, etc.)
Fish movements and migrations	– Continue and expand conventional angler-based tagging programs – Expand satellite and archival tagging research – Implement long-term, field-based telemetry via passive acoustic telemetry (e.g., Gervelis & Kneebone 2022)
Fish behavior	– Assess behavioral and physiological responses to OSW infrastructure and operations (field-based; e.g. noise and vibrations); differentiate potential effects between fixed and floating turbines, where appropriate – Assess sensory physiological mechanisms of behavioral responses using controlled experiments (laboratory- or mesocosm based; e.g., sound, light, electromagnetic fields)
Fishery-dependent data and programs	– Ensure appropriate level of vessel monitoring for commercial fisheries observer operating in/around OSW lease areas – Expand monitoring of recreational effort, catch and discards in/around OSW lease areas – Improve spatial and temporal resolution of existing fishery data – Assess fate of regulatory discards and other bycatch in/around OSW lease areas
Stock assessment	– Conduct exploratory model runs to assess how/if increased uncertainty may affect management outcomes – Forecast how assessment uncertainty may increase with the expansion of OSW lease areas
Marine spatial planning	– Determine and fill primary data gaps to increase the effectiveness of marine spatial planning
Human dimensions	– Understand changes in fishing behavior and tactics, by sector – Quantify economic impacts of fishery shifts, by sector – Assess impacts to local fishing and fishing-related communities – Maintain and communicate transparency about uncertainties

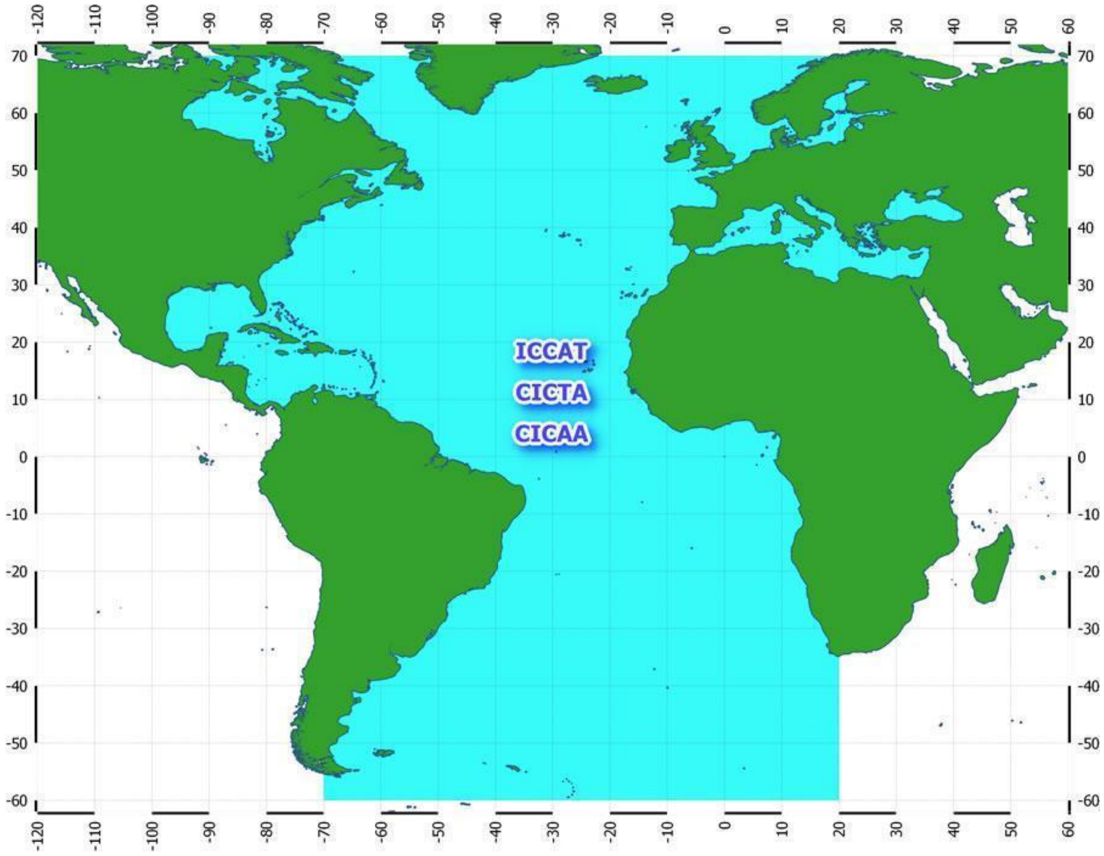

Figure 1. Spatial extent of the ICCAT Convention Area for the management of HMS tuna, swordfish, marlin and shark species. (source: https://www.iccat.int/img/misc/ConvArea.jpg)

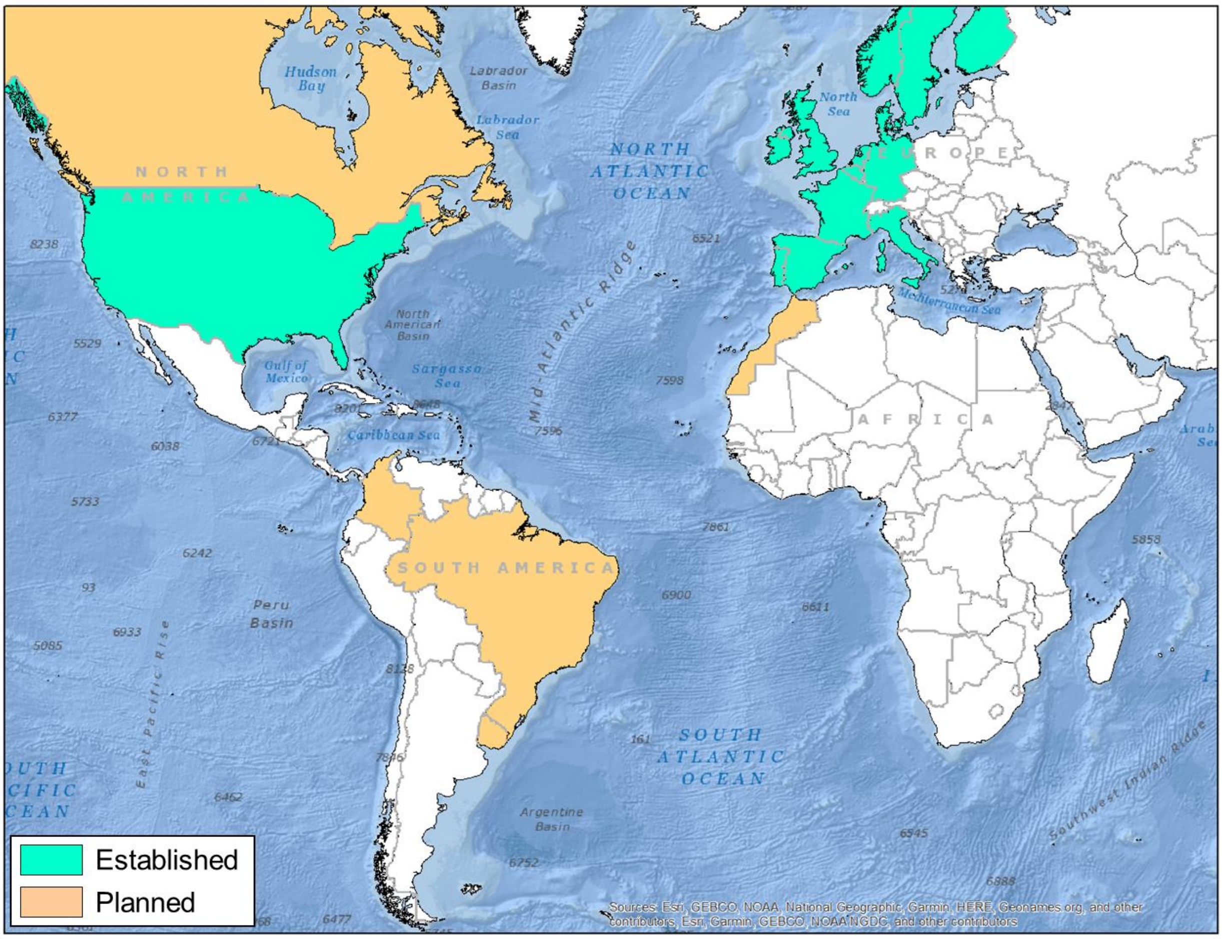

Figure 2. Map of countries within the ICCAT spatial domain with established and planned/future offshore wind operations (as of April 2024).

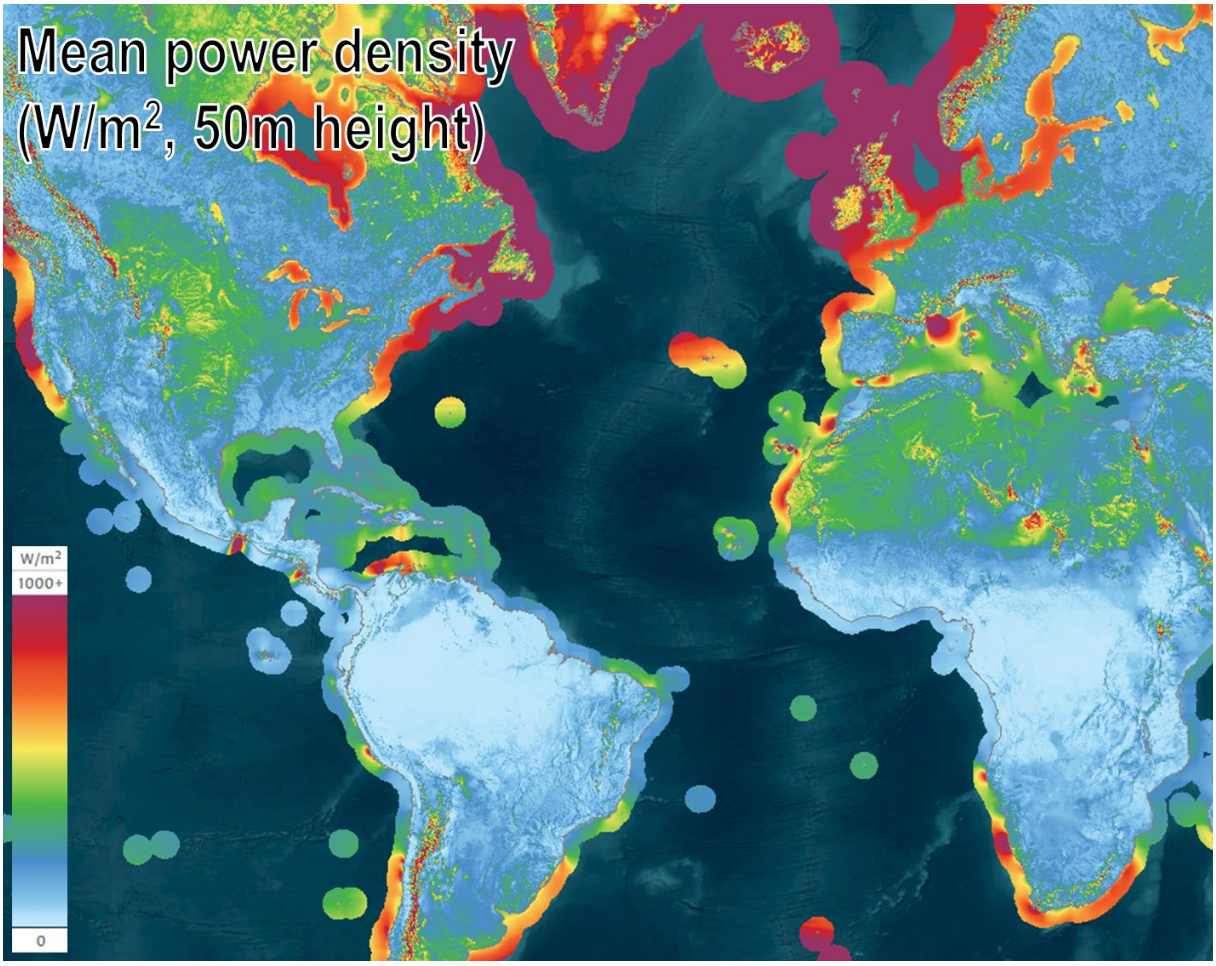

Figure 3. Mean power density for wind resources within the ICCAT regional domain (based on 50m elevation); higher mean density values relate to better available wind resources. (source: Global Wind Atlas, https://globalwindatlas.info/en).