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Potential impacts of floating wind turbine technology for marine species and habitats

Sara M. Maxwell[a,*], Francine Kershaw[b], Cameron C. Locke[a], Melinda G. Conners[c], Cyndi Dawson[d], Sandy Aylesworth[e], Rebecca Loomis[b], Andrew F. Johnson[f,g]

[a] School of Interdisciplinary Arts and Sciences, University of Washington, Bothell, Bothell, WA, USA
[b] Natural Resources Defense Council, 40 West 20th Street, New York, NY, USA
[c] School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, NY, USA
[d] Castalia Environmental, Hanover St, Santa Cruz, CA, USA
[e] Natural Resources Defense Council, 111 Sutter St, San Francisco, CA, USA
[f] MarFishEco Fisheries Consultants, 67/6 Brunswick Street, Edinburgh, EH7 5HT, Scotland, UK
[g] Marine Sustainability, Policy & Conservation Evidence (Marine SPACE) Group, The Lyell Centre, Institute of Life and Earth Sciences, School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University, Edinburgh, EH14 4AS, Scotland, UK

A R T I C L E I N F O

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A B S T R A C T

Offshore wind energy is expanding globally and new floating wind turbine technology now allows wind energy developments in areas previously too deep for fixed-platform turbines. Floating offshore wind has the potential to greatly expand our renewable energy portfolio, but with rapid expansion planned globally, concerns exist regarding impacts to marine species and habitats. Floating turbines currently exist in three countries but large-scale and rapid expansion is planned in over a dozen. This technology comes with unique potential ecological impacts. Here, we outline the various floating wind turbine configurations, and consider the potential impacts on marine mammals, seabirds, fishes and benthic ecosystems. We focus on the unique risks floating turbines may pose with respect to: primary and secondary entanglement of marine life in debris ensnared on mooring lines used to stabilize floating turbines or dynamic inter-array cables; behavioral modification and displacement, such as seabird attraction to perching opportunities; turbine and vessel collision; and benthic habitat degradation from turbine infrastructure, for example from scour from anchors and inter-array cables. We highlight mitigation techniques that can be applied by managers or mandated through policy, such as entanglement deterrents or the use of cable and mooring line monitoring technologies to monitor for and reduce entanglement potential, or smart siting to reduce impacts to critical habitats. We recommend turbine configurations that are likely to have the lower ecological impacts, particularly taut or semi-taut mooring configurations, and we recommend studies and technologies still needed that will allow for floating turbines to be applied with limited ecological impacts, for example entanglement monitoring and deterrent technologies. Our review underscores additional research and mitigation techniques are required for floating technology, beyond those needed for pile-driven offshore or inshore turbines, and that understanding and mitigating the unique impacts from this technology is critical to sustainability of marine ecosystems.

1. Introduction

There is scientific consensus that decarbonization of the world's energy system is imperative, if humans are to avoid catastrophic climate change (IPCC, 2014). With projected, and in some cases already observed, changes in marine ecosystems due to ocean warming from climate change (Bryndum-Buchholz et al., 2019; Descamps et al., 2017; Henson et al., 2017; Rogers et al., 2020), there is global support for sustainable energy development, and the marine environment holds significant promise for renewables, particularly offshore wind energy. Wind energy is slowly becoming a more cost-competitive and cost-effective renewable energy resource (Bogmans, 2019). Offshore wind energy deployment has increased around the world, because winds at sea are much stronger and much more consistent than terrestrial

* Corresponding author.
E-mail address: smmax@uw.edu (S.M. Maxwell).

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wind, and they allow for a higher production of electricity at a more reliable rate in comparison to their land-based counterparts (Kaldellis and Kapsali, 2013; Possner and Caldeira, 2017). Offshore wind energy generation profiles are complementary to solar energy; solar energy peaks during the day and tapers in the evening, just as offshore winds begin to pick up (Tambke et al., 2005). Further, offshore wind energy is more powerful during winter months when solar power decreases but indoor heating and light demands increase (Kaldellis and Kapsali, 2013; Possner and Caldeira, 2017). Additionally, offshore wind infrastructure is rapidly declining in cost. For example, offshore wind is now considerably cheaper than nuclear energy, with projected global expenditures of over USD 263 million in the next 10 years.[1] If paired with the right policies, offshore wind power could also offer significant socioeconomic benefits in the form of job opportunities (Speer et al., 2016).

A major limitation of offshore wind is that traditional fixed-foundation, static turbines can only be installed in waters less than approximately 60 m in depth (James and Costa Ros, 2015; Speer et al., 2016). Many regions of the world, such as much of the west coast of North America, have steep continental shelves where depths shallow enough for fixed-foundation turbines only occur close to shore (Musial et al., 2016). This raises more marine spatial planning and resource use conflicts relative to deeper waters further offshore. However, some recently developed floating offshore wind turbines (FOWT) can be placed in deeper waters anywhere from approximately 60-1000 m (Musial et al., 2016), creating the potential for expansion of offshore wind energy development in many regions. Scotland, for example, has recently demonstrated the efficacy of this technology by installing five 6 MW (MW) turbines which have performed well (Coren, 2019). A number of other countries have created demonstration sites or are exploring the possibility of installing similar FOWT, including China, Taiwan, Republic of Korea, Spain, France, Japan and the US (Table 1, Fig. 1).

Despite the promise of offshore wind in producing sources of clean, renewable energy that will help mitigate climate change impacts, the installation and infrastructure associated with offshore wind development has the potential to pose significant risks for marine habitats and wildlife if projects occur without due environmental assessment and planning. Potential impacts can occur during site assessment, construction, or regular operation and maintenance, regardless of turbine configuration (Bailey et al., 2014; Bergström et al., 2014; Furness et al., 2013; Schuster et al., 2015). Risks include collision with turbines and vessels associated with the wind project, increased energetic expenditure and habitat loss through avoidance and displacement, noise disturbance during site assessment, construction, and operation and maintenance, and impacts from electromagnetic fields produced by turbine or cable components. There is a robust body of literature detailing these potential impacts, largely focused on fixed-foundation turbines (for example, see (Bailey et al., 2014; Cook et al., 2018; Furness et al., 2013; Schuster et al., 2015), as well as best practices for effective design and operation for the protection of marine species and habitats to reduce these risks (Gartman et al., 2016a, 2016b). However, in comparison to fixed-foundation turbines, little is known about the potential risks of FOWT, though there may be benefits of FOWT over fixed turbines.

While both fixed and floating turbine types are useful in different contexts, there are a number of potential benefits that floating wind turbines may have over fixed-foundation turbines. Pile-driving base components for any marine structure, including fixed turbine foundations, results in significant noise levels harmful to marine life (Madsen et al., 2006; Schuster et al., 2015). In most instances, FOWT does not require pile driving (though see Section 2.3 for discussion on anchor piles), thus removing that impact entirely. Additionally, unlike pile-driving which generally requires assembly *in situ,* assembly of many floating turbine components can be undertaken on land, and shipped to lease areas (James and Costa Ros, 2015). Reduced assembly at-sea means a significant reduction in noise generation from construction. Also, floating turbines can be moved for economic, technical, or environmental reasons, and while relocation (or removal) of floating infrastructure is difficult, it can be done with more ease than fixed-foundation turbines.

While these potential benefits exist, there may also be additional risks. Thus, the objective of this study is to provide a comprehensive review of the potential impacts of FOWT and potential data needs and mitigation techniques, particularly in comparison to fixed-foundation turbine technology. We reviewed peer-reviewed literature, government reports and other documents relevant to FOWT. Specifically, we describe FOWT technology in comparison to fixed-foundation turbines, and then review the suite of potential impacts of FOWT including: entanglement risks; turbine collision; vessel collision; displacement or behavioral modifications; and habitat destruction or disturbance from mooring systems, cables or anchors. We consider these the potential impacts as they may apply to seabirds, marine mammals, fishes and benthic ecosystems. We further consider potential techniques to mitigate impacts on these species and habitats and the data needs that must be addressed to allow for the comprehensive mitigation of impacts.

2. Description of floating technology

FOWT differs from fixed-foundation turbines primarily in the type of platform and anchoring system used to support the turbine. FOWT employs buoyant 'floating substructures,' which are comprised of submerged or semi-submerged platforms that are anchored to the seabed by mooring lines and a variety of anchor types. Inter-array power cables that are suspended in the water column and move with the floating platform are used to transport the energy generated by each of the turbines to an offshore electrical substation, that subsequently connects to a static power cable and, ultimately, the landing site and electrical grid (Fig. 2).

2.1. Types of platforms

There are four main archetypes of floating platform: barge, spar, tension leg platform (TLP), and semi-submersible (see Fig. 3; Salic et al., 2019). The barge represents one of the earliest design concepts and comprises a large flotation system that provides good stability. Despite this, the forces generated by the motion of the turbine combined with that of the barge platform result in significant stress on the turbine tower and blades, and the barge is also susceptible to excessive pitching in extreme wave conditions (Vijay et al., 2016). The design of the spar archetype – a cylindrical vertical platform with large draft – improves upon the stability of the barge concept by increasing ballast in the lower part of the platform and thus lowering the center of gravity (Salic et al., 2019; e.g. 30 MW Hywind-2 project operational in 2017). The deep draft, however, can limit access to shallow-water ports, which is necessary to transport the assembled platform out to the offshore installation site (Barter et al., 2020). The TLP achieves static stability through tension in the stiff mooring lines and a submerged buoyancy tank. The TLP can be unstable during assembly, however, and experiences high vertical load (i.e. perpendicular force) due to the high tension of the mooring lines (Barter et al., 2020). Finally, semi-submersible platforms combine elements of the other archetypes to achieve static stability by distributing buoyancy widely at the water plane, however, a larger relative proportion of the platform's surface occurs above the sea surface resulting in greater vulnerability to waves (Salic et al., 2019; e.g. 25 MW Windfloat Atlantic project operational in 2019). There is also a wide array of new and hybrid floating substructure designs in development (e.g., variation in platform shape, the number of ballasts, columns, and turbines supported, the location of the turbine on the platform) as the industry continues to work to overcome the challenges

[1] https://www.gov.scot/policies/renewable-and-low-carbon-energy/offshore-wind/.

Table 1
Existing or decommissioned floating wind turbines.

Country (Project Name)	Status	Year installed (year decommissioned)	# turbines	Total capacity (MW)	Depth at installation (m)	Citation
Italy	Decommissioned	2007 (2008)	1	80 kW	113	Pool (2010)
Norway	Decommissioned	2009 (2019)	1	2.3	220	Taylor (2019)
Portugal	Decommissioned	2011 (2016)	1	2		Patel (2019)
USA-Maine (VolturnUS demonstration)	Decommissioned	2013 (2013)	1	20 kW		University of Maine Advanced Structures & Composites Center (2020)
France (Floatgen)	Existing	2019	1	2	33	GWEC (2020)
Japan	Existing	2013	5	19	100–120	GWEC (2020)
Scotland (Hywind)	Existing	2017	5	30	130	Hockenos (2020)
Portugal (WindFloat Atlantic)	Under construction	2020	3	25	100	Hockenos (2020)

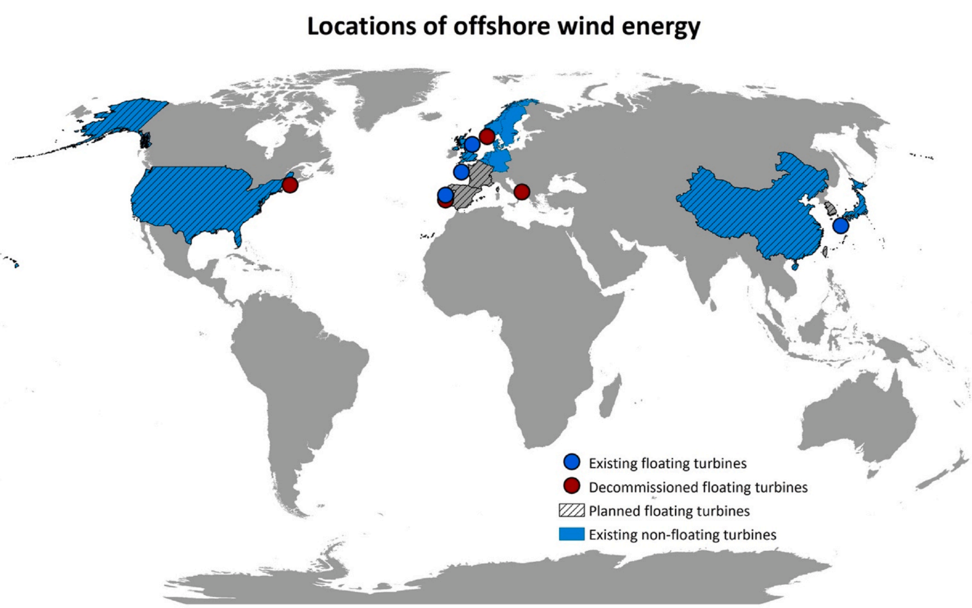

Fig. 1. Distribution of floating wind energy around the world. The locations of existing (blue dots) and decommissioned (red dots) turbines are shown, as well as countries currently using non-floating offshore wind turbines (blue). Countries with plans to install FOWTs are hashed. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

of the four archetypal designs and optimize for integrity, stability, and total cost of the wind project over its lifecycle.

2.2. Types of mooring systems

Each floating platform is stabilized by at least three mooring lines anchored to the seabed (Fig. 3). For a number of mooring configurations, the mooring lines will experience some drift, leading each turbine to also drift within a certain radius of its station (Simos et al., 2018). The different mooring systems leave different sized physical footprints (i.e., the geographic space that the system occupies) and ecological footprints (i.e., the system's impact in the water column and on the seabed) both during and post-installation (James and Costa Ros, 2015). Currently, the three primary types of mooring systems are catenary, taut, and semi-taut, and the materials most commonly used for mooring lines are steel chain, steel wires, and synthetic rope (Monfort, 2017).

Catenary mooring is most commonly used with the spar, semi-submersible, and barge platforms (e.g., Hywind floating wind project; Lin et al., 2019). In this configuration, the mooring lines form a catenary or curve shape. Each line may be divided into an upper segment of lighter and more flexible line (such as large-diameter synthetic rope) that connects to the floating substructure and is suspended in the water column, and a lower segment of heavy chain that weighs down the mooring line along the seabed (Monfort, 2017). Catenary mooring lines are designed to be four times longer than the depth of the water column to account for wave action (Barter et al., 2020). A significant proportion of chain therefore rests on the seabed and may be lifted up and down off the seafloor through surface wave action moving a turbine, particularly where the chain touches the seabed, causing abrasion and trenching (Low et al., 2018; Thethi and Moros, 2001). The catenary mooring system has the largest relative physical and ecological footprint of the three systems (James and Costa Ros, 2015).

The taut-leg mooring system is most commonly used with the TLP. This system has taut mooring lines that are typically at a 45-degree angle to the seabed (Monfort, 2017). As the name suggests, the taut-leg system does not allow for much vertical movement, meaning that these systems will experience huge amounts of force acting on the anchors due to any wave action that the turbine experiences. Thus, the optimal line types for taut-leg systems are synthetic or wire ropes that have higher elasticity (Monfort, 2017). The taut-leg mooring system likely induces the smallest physical footprint and smallest ecological footprint, but the tradeoff is a more challenging installation process (James and Costa Ros, 2015).

Semi-taut mooring systems are also used on some semi-submersible platforms and represent a "compromise" between the taut-leg and catenary systems in terms of stability and forcing. The most common materials for semi-taut systems consist of synthetic fibers, chains, or wire moorings (Lin et al., 2019). The footprint of the semi-taut mooring

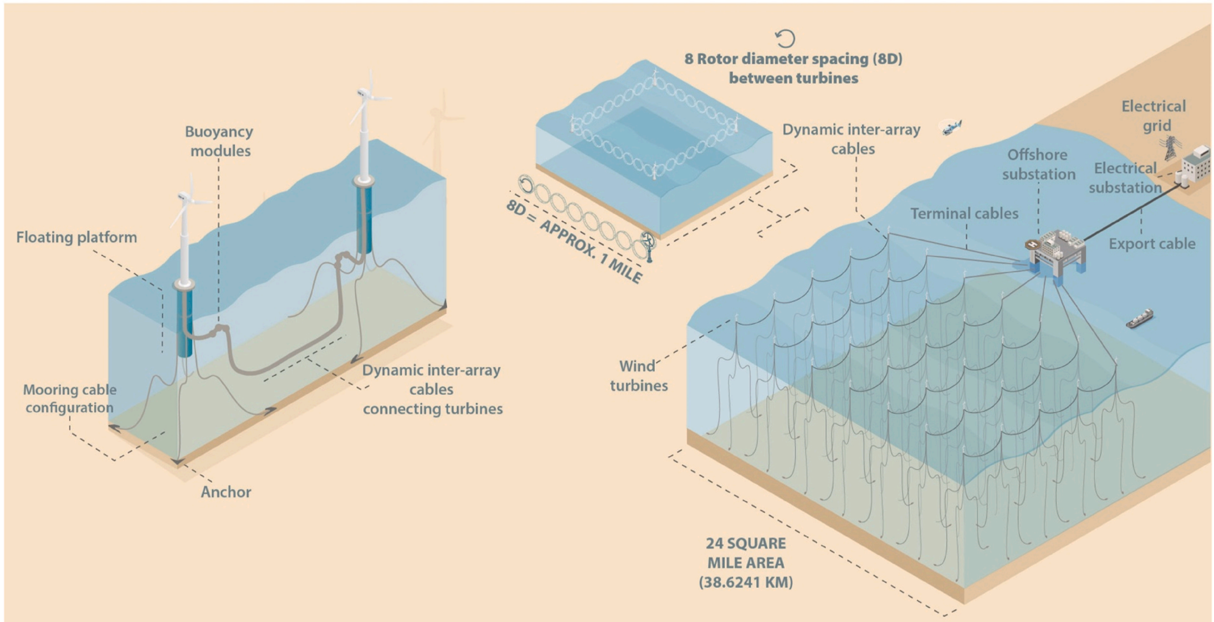

Fig. 2. Schematic of a full-scale floating wind energy development. Floating offshore wind turbines (FOWT) differ from fixed-foundation turbines primarily in the types of platform and anchoring system used to support the turbine. FOWT employs buoyant ‘floating substructures’ which are submerged or semi-submerged platforms anchored to the seabed by mooring lines and a variety of anchor types, and connected to one another by dynamic inter-array cables.

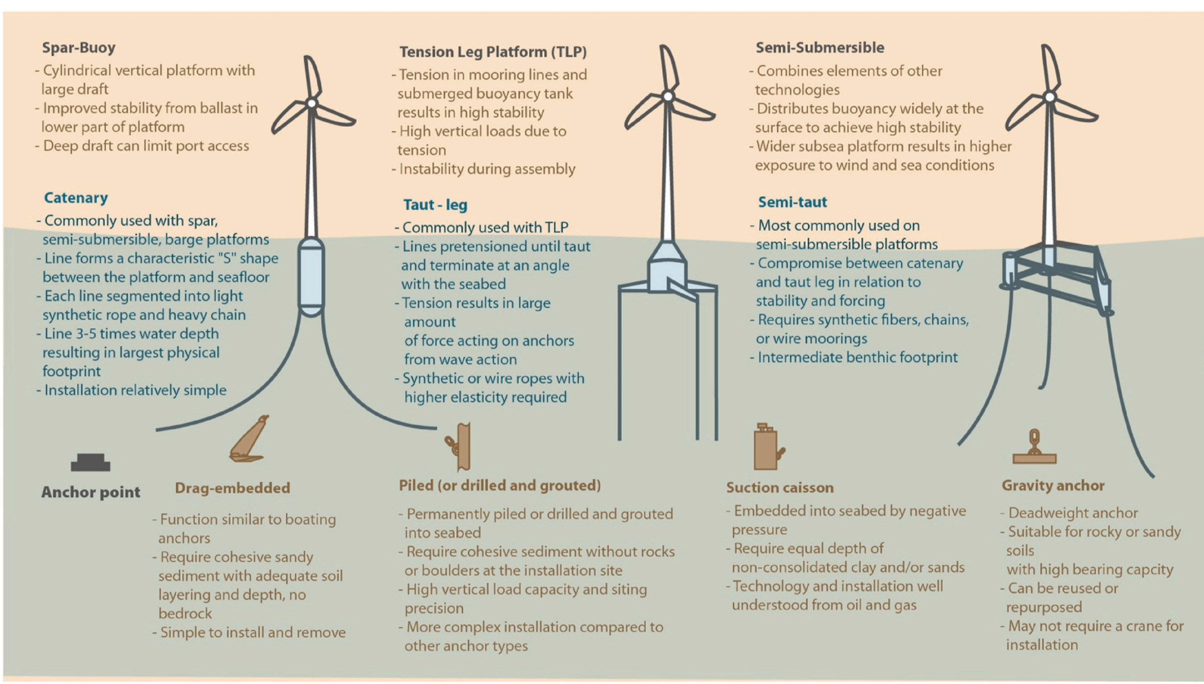

Fig. 3. Representation of some of the current existing cable tie, cover designs and anchor types.

system is considered to be “medium” and it is flexible enough to accommodate for wave action without the added disruption of mooring chains resting on the seabed that occur with catenary systems (James and Costa Ros, 2015). However, trenching where the chains reach the seabed and in the vicinity of the anchors remains a concern for impacts to benthic habitat (Sun et al., 2020).

2.3. Types of anchors

The optimal anchor technology for securing the mooring lines to the seabed depends on the composition of the sediment. Irrespective of the anchor design used, the environmental consequences of their implementation must also be considered. At the site of anchorage, every anchor type will have some degree of direct impact on the seabed and benthic ecosystem (e.g., from installation, trenching, or drift) as well as indirect impacts in some cases (i.e., noise emissions during installation of pile driven anchors).

The four primary anchor types for floating offshore wind platforms are drag-embedment, suction caissons, gravity anchor, and anchor piles (steel-driven or drilled and grouted) (Fig. 3). There are myriad other anchor types, and many others are in development (e.g., drop anchor/ torpedo pile, vertical load anchor, suction embedded plate anchor, multi-line anchors) driven by the challenges of anchoring in rocky, irregular seabeds in deeper waters (Golightly, 2017). Drag-embedment anchors (e.g., Windfloat Atlantic) function similarly to boating anchors and are best suited to cohesive sandy sediment of adequate soil layering and depth and no bedrock. Drag-embedded anchors are simple to install and can be recovered during decommissioning (James and Costa Ros, 2015). Suction caisson anchors resemble an upturned bucket that is embedded into the seabed by negative pressure inside the caisson. Suction caissons require at least an equal depth of non-consolidated clay and/or sands. The technology and its installation and decommissioning processes are well defined from oil and gas platforms, and anchors can be recovered during decommissioning (Golightly, 2017). Gravity anchors use the same principle as a deadweight anchor where the ability to hold the turbine in place is proportional to the anchor's weight. Gravity anchors are suitable for rocky or sandy soils that are stable enough to support the heavy anchor. Gravity anchors have the potential to be repurposed following decommissioning and newer designs do not require a crane for installation, meaning less equipment and installation time is required (Esteban et al., 2019). Anchor piles are permanently driven or drilled and grouted vertically into the seabed. They can achieve a very high vertical load capacity and can be precisely located. They require cohesive sediment without rocks or boulders at the anchoring site and cannot be removed during decommissioning.

2.4. Cable arrays

In addition to the mooring lines, an array of dynamic array power (electrical) cables connect each of the turbines and transmit the generated electricity to shore (also known as "inter-array cables") (Fig. 2). The dynamic array cables extend between multiple floating platforms and subsequently connect with terminal cables that lead to an offshore electrical substation (Rentschler et al., 2020). The dynamic array cables are suspended freely in the water column and are designed to compensate for the movement of the floating platform and the forces of the water column by using bend stiffeners, intermediate buoys, sinkers, touchdown protection or other devices or configurations to stabilize (Taninoki et al., 2017). The depth of the dynamic array cable in the water column is a function of the specific design of an offshore wind project and, in some cases, the cables may be buried or weighted to the seabed between the floating substructures they connect. When buried or weighted, the dynamic array cable may be free-hanging, extending to the seafloor under its own weight. It may also be a "lazy wave" shape with buoyancy elements added to the intermediate part of the cable such that the cables do not touch the seafloor, which is better suited to deeper water (Rentschler et al., 2020). The distance between floating turbines is a trade-off between lower wake losses (i.e., the reduction of wind speeds at downwind turbines due to wakes caused by upwind turbines) and increased array cable cost. Typical spacing varies between 6x and 8x the diameter of the rotor. For example, a GE 12-MW Haliade-X turbine array with spacing 8x the diameter of the rotor would lead to turbines being spaced over 1 mile apart. The dynamic array cables between the turbines therefore represent a sizable physical and ecological footprint, particularly for a utility-scale project.

3. Potential impacts of FOWT

Floating and fixed-foundation turbines are likely to have many impacts in common, particularly those associated with turbine blades. However, there are potentially different impacts for FOWT and these are far less established than fixed-foundation turbines given their relative newness. Here we review how FOWT may result in differing types or severity of impacts compared to fixed-foundation turbines. We loosely follow the framework for evaluating environmental effects of marine renewable energy outlined in Boehlert and Gill (2010) for each marine species group or habitat (referred to as a 'receptor' in Boehlert and Gill (2010)). We describe the FOWT stage (i.e., construction, operation) during which a stressor resulting from FOWT activities (i.e., anchor movement, presence of cables) may result in an effect (i.e., habitat disturbance, entanglement in cables) on a marine species or habitat. If possible, we describe the impact this stressor is likely to have on the population or ecosystem, particularly in terms of severity, the spatial or temporal scale of impacts, and if it is particularly important to consider in concert with other human activities (i.e., if it may contribute to cumulative impacts).

3.1. Entanglement

Entanglement risk exists during the operation stage of FOWT and is one of the key potential risk differences between fixed-foundation and floating turbines. The risks result from the presence of lines and cables needed to operate FOWT such as mooring lines that attach to anchors, cables that connect multiple turbines together (inter-array cables), and cables that connect turbines to land-based power grids (Table 2, Fig. 4). Entanglement risk may include *primary entanglement*, where animals are entangled in the lines or cables themselves, or *secondary entanglement* where other materials such as fishing gear become entangled in lines or cables, and this material goes on to entangle animals.

Primary and secondary entanglement risk at floating turbines is likely influenced by a number of factors (reviewed in Benjamins et al., 2014) including:

- The geometry of the mooring lines (i.e., diameter of lines, whether they are taut or draped);
- The depth of the draping of mooring lines, if they are draped;
- Animal behavior near turbines;
- Detection of mooring lines by animals, which will be influenced by the configuration and material used for mooring lines, as well as how far mooring lines move in the water column;
- The abundance of derelict fishing gear or other materials in the region, as well as;
- Proximity to fishing grounds.

3.1.1. Primary entanglement

Risk of primary entanglement with FOWT is highest with marine mammals, but the overall risk to this group has been suggested to be low given that the cables and mooring lines are often taut and of a diameter large enough to preclude easily entanglement of even a large whale (Bailey et al., 2014; Benjamins et al., 2014) (see Fig. 4 for relative scale of whales to mooring lines and cables). Additionally, the mooring lines have less curvature and are made of more rigid material than fishing lines making the risk of loop creation and subsequent entanglement relatively low (Benjamins et al., 2014). Furthermore, marine mammal species are likely to be able to detect large-diameter mooring lines, either through echolocation (in the case of odontocetes), vibrations detected through vibrissae (in the case of pinnipeds), or basic acoustic detection (hearing) since ropes produce noise in proportion to current flow (reviewed in Benjamins et al., 2014). Detection may occur at a distance of as little as 10s of meters, and has been shown to occur for odontocetes for much smaller diameter lines than those that would occur with floating wind turbines (Nielsen et al., 2012). Large baleen whales are considered to be of the greatest entanglement risk of all marine mammals because of their large body size and foraging habits (Benjamins et al., 2014). Baleen whales forage by feeding with their mouths open and therefore may be entangled through the mouth, and lines may become lodged behind the jaw or baleen and be difficult to remove without human aid (Sharp et al., 2019). Large whales have also been anecdotally observed using surfaces to rub against to presumably remove parasites or scratch itches (Benjamins et al., 2014).

Catenary moorings have the most slack in mooring lines and thus

Table 2
Summary of impacts from floating offshore wind energy.

Impact	Stressor	Description	Current scientific knowledge around risk	Potential for impact	Potential Solutions	Key references
Primary entanglement	Presence of cables or mooring lines	Entanglement of animals in cables or mooring lines	Low	Entanglement potential greatest for marine mammals, particularly large whales, though potential is likely low due to size and structure of cables and lines	Bury cables when possible	Benjamins et al. (2014)
Secondary entanglement	Presence of ensnared debris on mooring lines or cables	Entanglement in fishing gear or other marine debris caught on mooring lines or cables	Low	Greatest for species with large appendages or diving species	Monitor and clean cables and lines regularly	(Benjamins et al., 2014; Harnois et al., 2015)
Habitat displacement	Presence of FOWT structures	Displacement from key foraging or breeding habitats	Moderate for offshore wind broadly; low for FOWT, particularly some species	Displacement from habitats further offshore may have differing impacts from nearshore	Avoid important habitats	(Bailey et al., 2014; Bradbury et al., 2017; Cook et al., 2018; Dierschke et al., 2016; Peschko et al., 2020; Russell et al., 2014)
Habitat destruction or disturbance	Presence of FOWT structures, dynamic movement of components such as anchors, lines and cables	Destruction of habitat, scouring and sediment resuspension where anchors, cables and lines are placed	Moderate	Impacts largely dependent on habitat type and configuration of turbines; footprint of individual turbines may be small but overall large for industrial scale arrays	Bury cables if possible; use low footprint configurations (taut/semi-taut moorings)	(Davis et al., 2016; Harris, 2014; Hutchison et al., 2020a; James and Costa Ros, 2015; Miller et al., 2013)
Vessel collision	Presence of vessels required to construct or maintain FOWT	Collision of marine species (particularly whales and sea turtles) with vessels associated with FOWT construction and maintenance	High	Potentially less for FOWT construction because less construction at sea required	Reduce number of vessels as possible; reduce vessel speed; train vessel crew as lookouts; use dynamic management techniques	(Banister, 2017; Conn and Silber, 2013; Hazen et al., 2016; Maxwell et al., 2015)
Turbine collision (seabirds)	Rotation of turbines	Collision with turbine blades by seabirds resulting in injury or death	Moderate	Because FOWT provides structure for birds to perch, turbines may serve as a greater attractant increasing collision potential for some species	Use of deterrent devices and monitoring	(Ainley et al., 2015; May et al., 2020; Musial, 2020)
Behavioral modification from electromagnetic fields (EMF) from cables	EMF emissions from cables associated with turbines and connection to power grids	Can alter the ability to detect or respond to natural magnetic signatures, potentially altering fish survival, reproductive success, or migratory patterns	Moderate	FOWT will require cables being run across the seafloor as well as suspended in the water column, increasing the potential of impacts over pile-driven turbines	Research impacts of EMF; monitor cables for wear and tear; bury cables	(Bennun et al., 2021; Gill and Desender, 2020; Hutchison et al., 2020b; Normandeau et al., 2011; Taormina et al., 2018)

pose the greatest potential risk of entanglement, but entanglement has not been reported for oil platforms with similar configurations (Harnois et al., 2015). No primary entanglement in mooring lines, cables or related gear has been reported for floating turbines in Scotland since operation began in October of 2017 (the largest FOWT array currently in operation).[2] Killer (*Orcinus orca*), long-finned pilot (*Globicephala melas*), sperm (*Physeter macrocephalus*), fin (*Balaenoptera physalus*), and minke whales (*Balaenoptera acutorostrata*) as well as pinnipeds occur in Scottish waters in high densities so potential for entanglement exists (Gillham and Baxter, 2009). However, large populations of baleen whales are not present in the North Sea, so results cannot be generalized to all other regions where baleen whales occur in high densities.

3.1.2. Secondary entanglement

Secondary entanglement, or entanglement in fishing gear or other marine debris caught on mooring lines, may represent the greater risk. However, little is known about the likelihood of this occurring. Species with large appendages such as humpback whales (*Megaptera novaeangliae*) or leatherback sea turtles (*Dermochelys coriacea*) also have a greater propensity for entanglement with ropes, lines or cables such as those used in fishing gear (Benjamins et al., 2014). In addition, underwater mooring lines pose an entanglement risk for diving seabirds, sea turtles, elasmobranchs, and fishes if the underwater infrastructure accumulates derelict gear, such as nets and hooks/lines, or plastic pollution. In turn, fish and other animals caught in the abandoned gear can serve as bait for larger predators bringing them closer to debris and increasing entanglement risk. It is likely that with increased biofouling around turbine platforms and mooring lines, there will be an increased risk of snagging fishing gear as the windfarm structures become increasingly textured. Thus, there is a need for planners to evaluate 'snagging risk' of derelict fishing gear on cables within the mooring system of floating turbines (Benjamins et al., 2014). There is also a tradeoff between the use of biocides to keep the mooring lines and platforms free from biofouling to decrease the risk of gear entanglement, and increasing pollutants locally present in lease areas from biocides.

Secondary entanglement could pose a significant risk and have population-level impacts, particularly if highly endangered species occur in the areas around FOWT. Entanglement, particularly in derelict fishing gear, represents one of the greatest threats to cetaceans worldwide (Baulch and Perry, 2014). Annual reported humpback whale entanglements have significantly increased on the U.S. West Coast between 1984-2012 and 2014–2017, with 71 cases of reported entanglements in 2016 (Lebon and Kelly, 2019). Additionally, entanglement from fishing

[2] Personal communication, Caroline Carter, Scottish National Heritage.

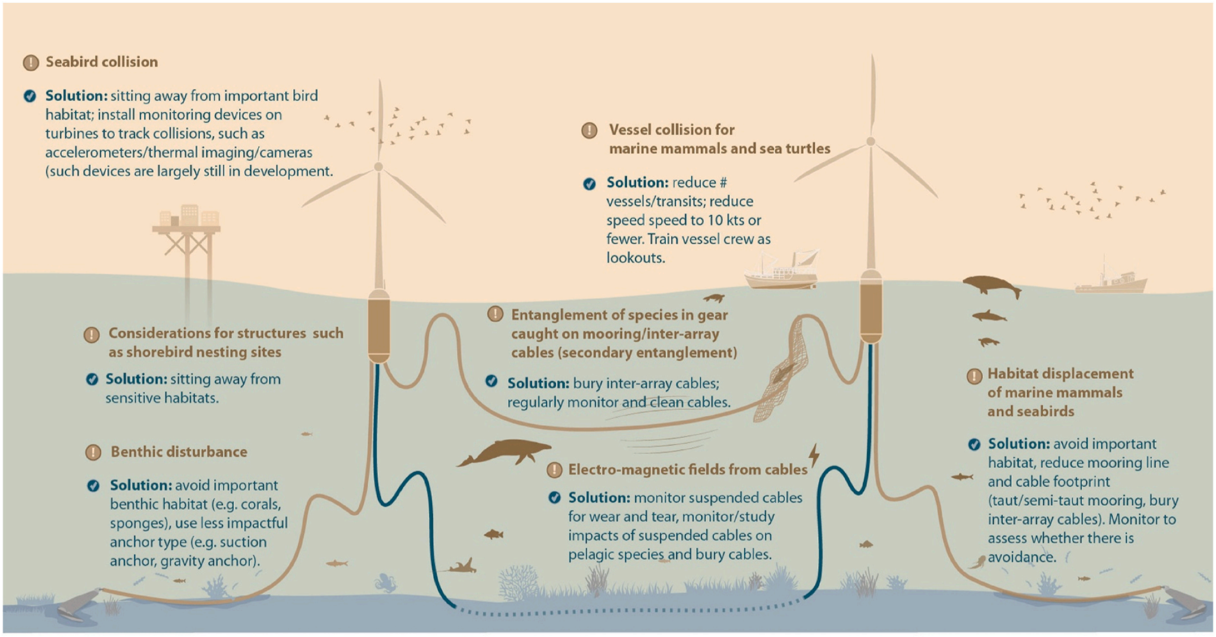

Fig. 4. Illustration of potential impacts of floating offshore wind and associated potential solutions.

gear currently poses a significant threat to the critically endangered North Atlantic right whale (*Eubalaena glacialis*). As of 2009, 83 percent of North Atlantic right whales showed evidence of entanglement; 26 percent showed new entanglement scars every year, and 59 percent had been entangled more than once (Knowlton et al., 2012). Thus, while secondary entanglement risks in FOWT are currently unknown, it is critical to monitor for effects, particularly when sensitive species are present in turbine lease areas.

3.2. Turbine collision

Collision with moving turbines can result in injury or death to seabirds, and can occur during the operational phase of offshore wind development, and depending on the number of individual birds killed or injury, could result in population level impacts. While there has been considerable discussion about collision risks for turbines broadly (e.g., Cook et al., 2018), there are significant gaps in the current understanding of seabird and FOWT turbine collision risk (Table 2, Fig. 4). FOWT is designed for deeper waters than fixed foundation offshore wind (out to 1000 m depth) and will be deployed farther offshore than existing fixed-foundation offshore wind developments. Seabird presence generally decreases offshore, for example on the US West Coast (Leirness et al., 2021), but behaviors also change offshore. Offshore environments have higher wind speeds, and researchers have shown that seabirds change their behavoirs in response to these wind speeds. Of particular concern, seabirds appear to rely more on gliding and flap-gliding movements offshore, while using flapping behavior near shore (Ainley et al., 2015), and seabirds engaged in gliding may have more difficulty avoiding wind turbines (Ainley et al., 2015; H.T. Harvey and Associates, 2020). Furthermore, flight height is a crucial determinant of turbine collision risk, but less is known about the flight heights of many seabirds in the areas where FOWT will be deployed because of the difficulty of observing flight heights further from shore (Borkenhagen et al., 2018). However, one study using boat-based survey observations showed that seabirds have a higher probability of flying higher as wind speed increases (Ainley et al., 2015). Because they are floating, FOWT also have an increased range of both vertical and horizontal motion compared with stationary OWT (Musial, 2020). This motion could potentially increase the risk of seabird turbine collision as it makes collision risk dynamic in space and time near turbines. Increased bird injury and mortality due to turbine collisions require further study, including consideration of flight height, flight behavior, and turbine motion.

3.3. Vessel collision

Collision with vessels can result in serious injury or death to marine mammals, particularly whales (Table 2, Fig. 4), and when combined with impacts from other vessel-based activities in some regions, could contribute to population-level impacts, particularly for whales (Rockwood et al., 2017). Wind energy installations will result in increased vessel presence, during construction, operation and maintenance phases. Vessels must also transit through coastal habitats to reach offshore wind installations, thereby increasing collision risks inshore as well. Many seabird species such as gulls, albatrosses and petrels are considered to be vessel-attracted species as they have learned to forage on fishing discards (Furness, 2003). As a result, vessel collision from FOWT-related vessels with seabirds is possible, though it is not expected to be higher than with other vessel types. Studies that look at collisions specific to offshore wind, however, have not been conducted.

There may be less of a likelihood of collision with FOWT vessels, however, for several reasons. First, much of the construction can be done on land with pre-constructed components towed to the site and installed in relatively short amounts of time compared to the time, number of vessels, and level of construction necessary for fixed-foundation turbines attached to the seabed (Banister, 2017). Second, in some FOWT platform configurations there is a larger surface area where helicopter landing pads can be installed. This means that maintenance can be done by helicopter, reducing transit times to the offshore turbines and also reducing the potential of vessel-cetacean collision, though helicopters would still be a source of disturbance for marine species, including marine mammals, and also pose collision risk for birds (Banister, 2017; Patenaude et al., 2002).

3.4. Displacement and behavioral modification

3.4.1. Seabirds and marine mammals

The net impact of platforms on animal behavior may be positive or negative, will likely be species dependent, and effects may occur during all stages of offshore wind development. Behavioral responses may also vary over different spatial scales, ranging from avoidance on a ‘macro’ scale, where species avoid wind energy area altogether, to micro-avoidance, where species avoid turbines at very close range (Cook et al., 2018) (Table 2, Fig. 4). If turbines are placed in critical habitats for any species, species may be displaced from important areas such as feeding or breeding sites, or they may experience secondary stressors or effects (e.g., noise, collision with vessels in the region) if they continue to use those areas. Similarly, studies have shown that some seabirds avoid offshore wind development areas, and that this may result in loss of resources due to displacement from foraging grounds (Peschko et al., 2020).

In contrast, turbines and other infrastructure may also increase foraging habitat for marine animals, particularly marine mammals and seabirds, in that platforms provide surface area for species to attach. This may aggregate prey species, resulting in localized productivity hotspots (Bailey et al., 2014). Seals in UK waters adjusted their behavior to use wind turbine structures and cables for foraging, with some animals' movements forming a grid-like pattern that mirrored the turbine array (Russell et al., 2014, 2016). Similarly, another study indicated that a large proportion (75%) of GPS-tracked Australian sea lions (*Neophoca cinerea*) use human-made structures such as pipelines and oil platforms to forage, and that distance to human structure was the most important factor in predicting foraging activity for a large portion (26%) of tracked individuals (Arnould et al., 2015). Thus, the structures associated with turbines, cables and other infrastructure may therefore act as attractants for some species.

Similar to offshore oil and gas rigs, many configurations of FOWT have above-water surfaces that are used for turbine stabilization (Fig. 3), and these surfaces may be beneficial to seabirds as they can be used as perches, thereby reducing energy expenditure (Ronconi et al., 2015); this is in contrast to fixed-foundation turbines in which the stem of the turbine is perpendicular to the water surface, and provide little or no area for perching. While some species may be displaced by offshore wind developments through avoidance (e.g. loons [*Gavia* spp.], gannets [*Morus* spp.], fulmars [*Fulmarus* spp.], guillemots), other species may be attracted to FOWT as opportunities for roosting, preening, and socializing (e.g. cormorants, gulls) (Dierschke et al., 2016; Leopold et al., 2011). Some vessel-attracted species (e.g., gulls) may be attracted to FOWT areas due to lighting or increased vessel traffic present for activities like turbine maintenance (Dierschke et al., 2016; Marques et al., 2014). Seabirds have been seen feeding within offshore wind areas, attributed to increased fish stocks as a result of increased structure and habitat (Krijgsveld et al., 2010; Vanermen et al., 2020).

FOWT may also serve as an attractant, and increase the risk of collision due to proximity to turbine blades (Benjamins et al., 2020). Recent research on lesser black-backed gulls (*Larus fuscus*) has also shown that there can be variability in avoidance behavior in different parts of the same windfarm with birds avoiding the inner parts of the turbine array, but perching on structures at the edges, adding additional complexity to understanding species responses (Vanermen et al., 2020). As such, behavioral responses of species to windfarms (attraction or avoidance) need to be quantified and used in models to evaluate population impacts of both habitat displacement (avoidance species), increased collision risk (attracted species), and energetic consequences across all species and even within the same wind energy area.

3.4.2. Fish

For fish, changes in assemblages or movements around FOWT are difficult to generalize, will likely be species dependent, and can occur during any stage of development. Similar to seabirds, any significant changes in the behavior of fish as a result of avoidance or displacement due to FOWT may lead to increased energy expenditure from, for example increased search time for conspecifics or prey items. This behavior could cause alterations to aggregations, spawning events and migration patterns and may also influence the ecological community structure if species of ecological importance avoid impacted areas altogether (Malcolm et al., 2010). Connections between species in ecological communities can be highly complex and impacts on one species in a community can often impact more than one species. For example, the importance of apex predators such as sharks in maintaining food web structures across multiple species has been noted in certain systems including coastal and pelagic environments (Bornatowski et al., 2014). As a result, reduced coastal and pelagic species abundance in impacted areas could therefore have impacts on upper trophic level populations, many of which prey heavily on forage fish species (Cury et al., 2011; Smith et al., 2011).

The generation of electromagnetic fields (EMFs) is of concern for fish species in close proximity with wind farms, as the flow of electricity through a conductor produces both an electric and magnetic field around a conductor (Gill et al., 2014) (Table 2, Fig. 4). Studies have shown that some fish species are magneto-sensitive and use geomagnetic field information for orientation purposes (Normandeau et al., 2011; Peters et al., 2007). EMF effects can alter the ability to detect or respond to natural magnetic signatures, potentially altering fish survival, reproductive success, or migratory patterns (Normandeau et al., 2011). Long-lived slow reproducing elasmobranch species (sharks, rays, skates etc.) are of particular concern (Hutchison et al., 2018). EMF deterrents have been successfully tested as depredation-mitigation devices in fisheries to reduce shark bycatch. This highlights the potential EMF has to alter shark behavior in offshore wind developments, however, in some studies results have been mixed or not significant (Mitchell et al., 2018; O'Connell et al., 2014). While field studies have been conducted on the effects of EMF from cables buried in the seabed (e.g., Hutchison et al., 2018), there is a limited understanding of the EMF impacts of cables suspended in the water column as will be the configuration for FOWT inter-array cables (Gill and Desender, 2020; Hutchison et al., 2020b). More work needs to be done to understand attraction or aversion effects of suspended cables, particularly on pelagic species (Taormina et al., 2018).

Noise made by turbines may also be an important stressor during all phases of wind energy generation (surveying, construction, operation and maintenance and decommissioning) (Mooney et al., 2020). Studies concluded that noise produced by floating turbine-bearing structures will mainly be lower-frequency sounds with dominant frequencies of ~1 kHz or less (Madsen et al., 2006; Tougaard et al., 2020). Noise from fixed-platform turbines, however, is highly variable depending on wind speed, the size of the turbine, the type of platform used and other variables related to the ambient environment (Marmo, 2013; Mooney et al., 2020; Tougaard et al., 2020). The distance over which noise from fixed-foundation wind farms extends is only a few kilometers in low ambient noise conditions (Tougaard et al., 2020), however, it is largely unknown how noise levels differ for floating versus fixed-foundation turbines, though it is likely to be highly depending on the type of mooring used, and the size and number of turbines, and local weather and oceanographic conditions among other factors.

3.5. Destruction or disturbance to habitat

3.5.1. Fish

While marine mammals, seabirds or fish may experience displacement from habitat as a result of turbines, fishes and benthic communities may also experience direct habitat disturbance or destruction, and this may occur during turbine construction or operation. However, understanding effects of habitat destruction on highly migratory fish species (HMS) or coastal, pelagic fish species (CPS) is difficult because historic catch records show a wide distribution within and between species that varies temporally. This makes it difficult to specifically demarcate areas of importance at a resolution of the wind lease areas. Habitat for CPS and HMS is largely defined by water temperature and can be highly variable between seasons and years (Morita et al., 2010; Webb et al., 2020). The thermal habitat preferences of CPS and HMS are therefore not likely to be impacted by FOWT as the presence of the floating turbines and moorings will unlikely change local water temperatures significantly, barring some shading effects, though hydrodynamics may be altered in the vicinity of turbines (Schläppy et al., 2014; van Berkel et al., 2020). Benthic habitat, however, is important for some coastal and pelagic species during certain stages of their life cycle (i.e., attachment of egg cases), and FOWT impacts on the benthos may affect these species.

In contrast, groundfish species, which are associated with benthic and demersal habitats during most life stages, are more closely tied to fixed habitat structures and generally experience lower levels of abiotic habitat variability compared to CPS and many HMS (Shepherd and Litvak, 2004). As a result, it is easier to define fixed habitat areas for groundfish species than for CPS and HMS. Thus, potential habitat loss is also more readily predicted. If FOWT are deployed in locations that coincide with important habitats for demersal species, impacts to this habitat would likely occur as a result of FOWT anchors and cables, at least at local levels.

The impacts of the different forms of marine renewable energy developments on benthic habitats have been widely studied, indicating potentially large changes in sedimentation regimes, scouring and resuspension of sediment, and impacts to habitat forming species or structures (Miller et al., 2013). Compared to fixed-platform turbines, FOWT may cause increased sedimentation as a result of scour from anchors and other components as, in contrast to fixed-foundation structures, these components will be impacted by wave action and currents, similar to traditional boat anchors (Davis et al., 2016). Increased sedimentation could impact benthic fish populations associated with the sea bottom. Increased sedimentation may also cause the release of seabed sediment contaminants which could impact the benthic spawning habitat quality of some fish species (Wenger et al., 2017).

3.5.2. *Benthic communities*

The disturbance regime of benthic habitats will be a key factor in determining potential impacts of FOWT on associated faunal communities. Natural disturbance which occurs at regular intervals, such as benthic storms, may be a part of an ecosystem's natural processes; these disturbances may allow for better nutrient accessibility and recycling, and communities are well adapted to natural levels of disturbance (Harris, 2014). FOWT, however, could significantly increase the frequency of disturbance as a result of mooring cables, cable lines or anchors being in contact with the seabed during operation. The benthic footprint and level of impact will depend on the type of turbine system selected, the number of turbines, and the exact location of deployment. A taut-leg mooring system coupled with suction pile anchors would have the smallest benthic footprint if this combination is determined to be appropriate for the conditions in a project area; a catenary mooring system would have the largest benthic footprint (James and Costa Ros, 2015). Additionally, cables must be run from platforms to power plants on land, and cables will disturb sediments wherever they are laid or buried.

The greatest potential FOWT stressor to deep-sea benthic communities may be from anchors because of their weight and direct contact with the seabed. Dragging or 'lock-in' (when the anchor drags across the seafloor until planted into the seabed) is likely to result in the most damage (Milazzo et al., 2004), but once a FOWT anchor is embedded in the sediment, it will remain in place for years. Post lock-in, however, waves, currents and movement of the turbines will result in continued scouring action of the chains or lines attached to the anchor across and above the seabed as the chain lifts and drops from wave action, if excess chain or line is part of the mooring configuration (Davis et al., 2016) (see Section 2.2 *Mooring systems*). The distance over which scour can occur, however, will be limited as turbines will be anchored at multiple locations for stabilization. Anchor setting and potential drag across the seabed can also cause sediment suspension in the water column, obscuring light sources and potentially reducing the already limited capacity of deep-sea organisms to photosynthesize (Davis et al., 2016). The frequency of sediment suspension to be expected from FOWT is unclear, as is whether particles will be resuspended at a rate which obscures light sources for extended periods of time, but this should be considered as a potential stressor for these soft-bottom communities.

3.5.3. *Corals and sponges*

Deep sea corals and sponges are long-lived sessile macroinvertebrates that provide habitat complexity and a range of ecosystem services that create aggregations of biodiversity in the deep sea (Hourigan et al., 2017). Deep sea coral and sponge ecosystems may occur in FOWT project areas. For example, deep sea corals and sponges occur in areas where FOWT are being considered off California.[3] Although there are no studies assessing the impact of FOWT anchors and moorings on these habitats, anchors could do considerable damage to these ecosystems, as has been shown from boat anchors in tropical coral and sponge ecosystems (Harriott and Dinsdale, 2004). Further evidence from Davis et al. (2016) notes that any biota that comes into contact with a dragging anchor or a sweeping anchor chain will sustain some sort of damage, whether being swept from the sea floor, or being crushed altogether. Additionally, there are numerous studies documenting the negative effects of bottom contact fishing gear on deep-sea corals and sponges (Fuller et al., 2008; Lumsden et al., 2007; Salgado et al., 2018). Other studies documenting the impacts on deep sea corals and sponges from derelict fishing gear in Alaska (Rooper et al., 2017) and in the northern Gulf of Mexico (Etnoyer et al., 2016) provide evidence that negative impacts to coral and sponges would likely be expected if anchoring systems from FOWT were located in these habitats. Any level of impact on deep sea benthic communities and hard bottom communities is considered negative because these communities are not adapted to frequent disturbance from human activities (Harris, 2014).

3.6. *Mitigation and data needs*

Here we discuss potential mitigation measures to reduce the impact of FOWTs on biological resources (Table 2, Fig. 4). Placing turbines in low-impact areas, or "smart siting," is the critical first step to mitigate impacts, particularly avoiding areas high in biodiversity including but not limited to Key Biodiversity Areas, Particularly Sensitive Sea Areas, Important Marine Mammal Areas, or other types of designated critical habitats (Bennun et al., 2021). Since the environmental impacts of offshore wind are not yet known, siting initial projects in less environmentally sensitive areas is a strategic way to minimize local environmental impacts, and optimizing avoidance of impacts in the planning stages is critical (IUCN, International Union for Conservation of IUCNInternational Union for Conservation of Nature, 2021).

3.7. *Entanglement*

3.7.1. *Monitoring of lines and cables*

While risk of primary entanglement is thought to be low, until that is proven, it may be useful to monitor tension of lines and cables used in FOWT. This could be used to detect both primary entanglement of large marine species and secondary entanglements if derelict gear or material is entangled. Tension monitors can be connected wirelessly to remotely alert to the presence of a potentially entangled species; this is being undertaken for floating turbines in Scotland.[4] Additionally, autonomous underwater vehicles (AUVs), remotely operated underwater vessels, or wireless video can potentially be used to monitor for primary or secondary entanglement events at key parts of the turbines, such as the cables. These techniques can be used in conjunction with tension monitoring to ground truth potential entanglements remotely. Furthermore, wire-walker devices (such as Wirewalker TM by Del Mar

[3] https://catalog.data.gov/dataset/noaa-national-deep-sea-coral-and-sponge-database-1842-present.

[4] Personal communication, Caroline Carter, Scottish Natural Heritage.

Oceanographic, San Diego CA USA), could be adapted for cables and allow for manual cleaning of turbine bases. Reducing biofouling may also reduce potential for secondary entanglement as there will be less surfaces for additional materials to adhere to. A plan for the frequency and type of monitoring, and how derelict gear would be removed should be included in all environmental assessments.

3.7.2. Materials and configuration of FOWT

To reduce entanglement risk, and also to better understand the factors that result in entanglement, the structure of mooring lines should be included in environmental impact assessments, with particular focus on the number and tautness of lines, and the materials used to construct lines, as these factors are likely to most greatly influence the potential for entanglement. For example, taut mooring configurations are preferable because less slack in lines is likely to reduce entanglement potential (Benjamins et al., 2014). Highest relative risk may occur with catenary moorings given that the lines are not taut. Chains and nylon ropes are thought to have a higher snagging potential is higher, as do accessory buoys (Harnois et al., 2015). Studies have also shown that different species may respond to different color ropes, potentially allowing them to avoid lines (Benjamins et al., 2014; Kot et al., 2012; Kraus et al., 2014; Swimmer and Brill, 2006). Results are thus far, however, are inconclusive and the use of color on mooring and other lines should not yet be considered an appropriate mitigation measure for floating wind impacts, but color should be included in environmental impact assessments. Additionally, significant changes to moorings or buoys during construction or operation that may influence entanglement risk should be reported so that configurations can be assessed if primary or secondary entanglements should occur.

3.7.3. Entanglement deterrent mechanisms

Pingers may be a method of reducing entanglement on moorings and other lines though this technique needs additional research (Benjamins et al., 2014). Pingers have been used to successfully and significantly reduce small cetacean bycatch in some fisheries (Carretta et al., 2008; Carretta and Barlow, 2011), however, habituation to pingers may occur (particularly with pinnipeds (Cox et al., 2001)) and attention must be paid to device durability and maintenance over the long term (Dawson et al., 2013). It is important to consider that the use of acoustic deterrent devices, may result in increased noise pollution and other negative impacts, such as attracting some species to turbine areas (Carretta and Barlow, 2011; Findlay et al., 2018). This may make their use potentially outweigh benefits especially if entanglement risk is low, and they are not likely to work for some priority species such as large whales.

3.7.4. Biological risk and reporting structure for entanglements

Biological risk assessment similar to Benjamins et al. (2014) could be conducted to determine what local species have the greatest probability of entanglement (for example, determining the cetaceans whose dive behaviors and dive depths overlap with depths of inter-array cables) and mitigation responses could be tailored to those species. A reporting structure should be in place to report primary and secondary entanglement of marine species in mooring lines and associated gears, giving relevant agencies the ability to trigger emergency procedures that occur in other industries, such as NOAA's Biological Opinions which are used in the fishing industry in the US.

3.8. Displacement and behavioral modification

3.8.1. Siting in low-impact habitat

It is critical that site planning and development consider site- and species-specific risks, and that mitigation planning and monitoring for wildlife impacts occur before, during and after development. Species- and site-specific risks require knowledge of animal distribution, understanding of the location of important habitats, and migration data for marine mammals, seabirds and fish through satellite tracking, at-sea surveys, acoustic monitoring, and fishery-based data; this kind of information has been critical in determining turbine areas for fixed-foundation platforms (e.g., Bradbury et al., 2017). Placing turbines in low-impact areas will be a critical first step to reducing displacement and behavior impacts on marine species though additional considerations for FOWT (e.g., seabird behavior in higher speed winds further offshore) need to be considered.

Migratory species can be particularly difficult to detect offshore and data are more limited as a result. It will also be necessary to verify the migratory periods and any persistent or seasonally occurring oceanic habitat features associated with marine species of commercial interest and/or ecological importance that may occur within the FOWT lease areas. To determine times of high risk for migratory species, or to detect species expected to be present in the development area year-round, long-term and near real-time passive acoustic monitoring or automated radio telemetry (i.e., the Motus Wildlife Network) should be considered to determine presence of whales or seabirds (Salisbury et al., 2016; Taylor et al., 2017; Williamson et al., 2016). For FOWT, it may be feasible to conduct construction and deployment of turbines during low-impact times of the year when animals are less likely to be present or impacted given that installation of a single platform was identified to be 6–8 weeks (not including pre-laid mooring lines) for the WindFloat demonstration project off Coos Bay, Oregon in the US (Banister, 2017). This is likely to be a relatively accurate estimate of installation, as simulations were performed to determine confidence in the timeline. The construction window will likely be significantly longer for commercial-scale projects, however.

3.8.2. Noise

Baseline data on noise levels is needed in offshore wind areas. Particularly needed are studies that estimate noise at various distances from turbines to determine baseline levels prior to construction, installation and operation of FOWT, with control sites for future monitoring (Bailey et al., 2014). These data can be used in conjunction with animal distribution to identify priority areas for monitoring and mitigation during construction and operation, particularly to determine when construction and maintenance can best occur. It is critical to understand sound propagation at varying distances from lease sites to understand how sound moves in certain areas, and across different frequencies, and this will be different for floating than for static, fixed-foundation turbines, and will vary by location and even across seasons due to environmental conditions. It is also important to understand the impacts of noise on marine mammals and their prey species (krill, small schooling fish), particularly the impact from operational use of turbines, for which data is severely lacking (Bailey et al., 2014).

Noise levels associated with construction of FOWT are likely to be markedly less than with construction of pile-driven, fixed-foundation turbines, but are expected to be similar during operation and maintenance, although no information is available on the latter. There are two primary approaches to reducing potential noise impacts: reducing the noise levels at the source (e.g., operating equipment at the lowest practicable noise level) and spatially and/or temporally separating the noise-producing activity from the sensitive species. For example, for migratory species such as some species of large whales, impacts can be reduced by limiting construction activities to seasons when fewer animals are present or when animals are not engaging in biologically important activities (e.g., foraging, breeding, calving). Furthermore, noise quieting technologies such as bubble nets could be used during construction (Dähne et al., 2017); such technologies should be considered to reduce operation and maintenance noise as well.

3.8.3. EMF

Acoustic and electromagnetic frequency (EMF) effects, and thresholds for fish, crustaceans and other species of concern will also need to be established. Some of these studies may be completed before FOWT developments are built by running laboratory-based experiments. If time and or budgets are limited, an effective approach to understand these impacts would be to group functionally or biologically similar species and test individuals from each group. Suspended cables are more vulnerable to wear through hydrodynamic stress (fatiguing pressure and twist) and biofouling, and increased wear can cause technical problems, as well as increase EMF impacts. Thus, cables should be monitored regularly for wear and tear (Taormina et al., 2018). Burying cables may reduce impacts of EMF on fish and other species, however some cables will need to be suspended in the water column in order to connect floating turbine cables to the seafloor, and the effectiveness of cable burying is unclear in reducing EMF impacts (Bennun et al., 2021).

3.9. Turbine collision

There are a number of land-based systems to mitigate impacts of turbines on birds, and they are thoroughly reviewed elsewhere (May et al., 2015). New potential techniques continue to emerge to prevent birds from colliding with turbines (e.g., making the blades more distinguishable to birds when in motion (May et al., 2020)), however more research and validation of these approaches are needed (Bennun et al., 2021). Additionally, avoidance and detection systems such as DTBird® can auto-detect species of special concern (e.g. eagles, condors) in turbine areas and subsequently communicate a signal to deter birds, or to indicate the need for temporary cessation of turbines (Desholm et al., 2006; McClure et al., 2021). Techniques that use artificial intelligence and machine learning are also being used to detect birds (Niemi and Tanttu, 2020).

The ability to detect collisions when they occur is critical to accounting for FOWT impacts on seabird populations and mitigating long-term impacts. Technology exists for land-based systems that could be adapted to offshore wind infrastructure if funding is available to support research and development. For example, Suryan et al. (2016) describe a proof of concept systems for continual monitoring of bird collisions using a multi-sensor array and central on-board processing systems integrated into the turbines themselves. This integrated monitoring system was designed to observe injury and mortality events by using three sensor modalities: 1) accelerometers and microphones to detect impact, 2) optical sensors (including infrared) to track moving objects and calculate distance and size, and 3) bioacoustics recorders to store vocalizations to be used in species identification. Not only is it important to design continuous impact detection systems, but FOWT design should also include additional safeguards, such as deterrence systems, and/or detection systems (e.g., thermal cameras, radar, artificial intelligence software for identifying species), many of which already exist for land-based systems. To reduce the ability for seabirds to perch on turbine structures, bird scaring devices can be used. These may include noise deterrents or physical deterrents such as spikes on structures to reduce perching areas, similar to those used on buildings and structures on land.

3.10. Vessel collision

Understanding co-occurrence of transit routes with whale habitat and subsequently limiting the number of vessels and reducing vessel speeds should be considered as a means to reduce potential impacts. Reducing vessel speeds has been shown to reduce collision-related mortality for whales (Conn and Silber, 2013; Vanderlaan and Taggart, 2007); however, stationing trained marine mammal lookouts on vessels is an important complementary risk-reduction measure (Kelley et al., 2021). Vessel collisions with wildlife may be reduced by including a helipad on turbine platforms for helicopter access. Helicopters can be used for operations and maintenance in order to reduce vessel traffic in the area though helicopters pose a risk for collisions with birds (Banister, 2017) (Table 2, Fig. 4). Dynamic management approaches can also be used to determine when it is safe to engage in construction and/or maintenance using near real-time data (Maxwell et al., 2015). In the case of FOWT, construction could be paused or vessels could be slowed or restricted from the FOWT area when sensitive species are determined or likely to be present. To reduce the potential for collision with whales, acoustic monitoring and/or aerial surveys could be used to determine presence, or modeling techniques could determine the likelihood of presence based on environmental conditions, and vessels could be restricted or slowed during those times. Near real-time dynamic management tools such as Whale Alert (Wiley et al., 2013), WhaleWatch (Hazen et al., 2016) and EcoCast (Hazen et al., 2018) are already in use to reduce impacts on sensitive species in shipping and fishing industries, and a similar system could potentially be designed to meet the specific needs of the offshore wind sector.

3.11. Destruction or disturbance to habitat

One of the best ways to reduce the impacts on benthic habitat is to reduce the overall area or footprint of the turbine matrix and cable array, as well place anchors and mooring cables in areas of lower ecological importance (Table 2, Fig. 4). Identifying these areas of relatively lower ecological importance will require a thorough assessment of the benthic habitats in potential lease areas. Fine-scale spatial analysis of benthic habitat is critical and may be done using: surveys of habitat structure to understand the location of sensitive benthic habitat; detailed ground truthing of modeled habitat maps; mapping in areas where the substrate and biological communities are unknown; and updating biological surveys where they have been previously done. These studies will be required to ensure FOWT sites are selected to minimize impact to benthic communities, and areas with structure-forming organisms such as corals and sponges should be avoided. New technologies such as rapid deploy landers, AUVs and improvements to towed camera sleds make this work both highly feasible and affordable. It is critical that comprehensive pre-installation and ongoing-monitoring are implemented.

To further reduce the impact of anchors on benthic species of importance, it is possible to use designated or directed anchoring (Davis et al., 2016) to reduce anchor or mooring line scouring. This technique entails using a submersible or other device to guide the anchor during anchor fall to direct exactly where the anchor will land on the seabed. Directed anchoring considers the impact site and the area around the impact site to determine whether or not the area may potentially encounter damage via anchor drag. Reducing the length of the mooring chain may also reduce dragging and scouring, ensuring that any excess length of chain that is needed to adjust for drift does not rest on the seabed, though there will need to be some extra length to account for wave or tidal action (James and Costa Ros, 2015). Additionally, it may be possible to use wave dampening technologies to reduce turbine movement and subsequent sea bottom scour (Jang et al., 2019; Park et al., 2019).

'Nature inclusive design' options, such as the use of reef balls, can also be used to create habitat, particularly in areas where habitat has been degraded by wind infrastructure (Hermans et al., 2020). Nature inclusive designs would involve, for example, the use of additional rocks or boulders around FOWT components to reduce scour from mooring lines or cables. Furthermore, comprehensive analysis of the route of the grid connection will be required to minimize impacts, particularly if cables connecting turbines to onshore power are to be buried. Burying cables could potentially reduce impacts such as primary or secondary entanglement or EMF impacts, but would result in impacts to benthic ecosystems.

Finally, we recommend the application of a two-tiered monitoring approach that uses both basic and targeted monitoring to understand impacts of FOWT structures such as anchors and cables on benthic habitats (Hutchison et al., 2020a; Lindeboom et al., 2015). Basic monitoring is often a requirement of permitting, and is used to observe and quantify impacts of human activities, whereas target monitoring focuses on understanding the cause and effect relationships of impacts, and bases this understanding in ecological processes. As a result, targeted monitoring can be particularly useful for designing mitigation approaches to reduce future impacts. This approach to monitoring has been adopted at fixed-foundation wind areas, including in Belgium (Hutchison et al., 2020a).

4. Conclusion

Empirical assessments of the impacts of offshore floating wind turbines are lacking given the newness of the technology. Though there are pilot projects in locations across Europe, the results from environmental monitoring are not yet publicly available. Regardless of turbine configuration, it is critical that site selection decisions are based off empirical biological data collected at appropriate spatial and temporal scales in order to accurately and robustly understand the baseline marine environment and risks of development (Furness et al., 2013).

Understanding population level risks of wind energy, including FOWT, are critical across all types of potential impacts. Additional understanding of population level impacts of turbine collisions need to be developed (Horswill et al., 2017). While population consequences are possible due to displacement and avoidance, there remains a need for robust quantitative methods to measure impacts from both direct and indirect effects of FOWT on wildlife populations, not to mention cumulative effects of FOWT and other disturbances on species of concern (Maxwell et al., 2013; Ronconi et al., 2015). Additional studies similar to those suggested by Cook and Robinson (2017) are needed that link behavioral responses through lost energy from disturbance or avoidance all the way to population-level impacts, specifically in the context of noise and other non-lethal impacts from wind energy. Studies such as these are being completed to understand consequences of noise such as that from military operations; frameworks for these studies (i.e., Population Consequences of Disturbance or PCoD (King et al., 2015; Pirotta et al., 2018)) are rapidly emerging and include analyses for species such as gray whales (*Eschrichtius robustus*) (Villegas-Amtmann et al., 2015) which are of concern to wind energy development. Further development of such models should be applied to offshore wind energy, however in the interim, other mitigation measures discussed herein should be implemented to the degree feasible.

Author contributions

SMM led the writing of the manuscript. All authors conceived the ideas, contributed critically to the drafts and gave final approval for publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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