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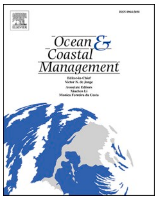

Potential environmental effects of deepwater floating offshore wind energy facilities

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ABSTRACT

Over the last few decades, the offshore wind energy industry has expanded its scope from turbines mounted on foundations driven into the seafloor and standing in less than 60 m of water, to floating turbines moored in 120 m of water, to prospecting the development of floating turbines moored in ~1,000 m of water. Since there are few prototype turbines and mooring systems of these deepwater, floating offshore wind energy facilities (OWFs) currently deployed, their effects on the marine environment are speculative. Using the available scientific literature concerning appropriate analogs, including fixed-bottom OWFs, land-based wind energy facilities, wave and tidal energy devices, and oil and gas platforms, we conducted a qualitative systematic review to estimate the potential environmental effects of deepwater, floating OWFs during operation, as well as potential mitigation measures to address some of the effects. We evaluated six categories of potential effects: changes to atmospheric and oceanic dynamics due to energy removal and modifications, electromagnetic field effects on marine species from power cables, habitat alterations to benthic and pelagic fish and invertebrate communities, underwater noise effects on marine species, structural impediments to wildlife, and changes to water quality. Our synthesis of 89 articles selected for the review suggests that many of these potential effects could be mitigated to pose a low risk to the marine environment if developers adopt appropriate mitigation strategies and best-practice protocols. This review takes the necessary first steps in summarizing the available information on the potential environmental effects of deepwater, floating OWFs and can serve as a reference document for marine scientists and engineers, the energy industry, permitting agencies and regulators of the energy industry, project developers, and concerned stakeholders such as coastal residents, conservationists, and fisheries.

1. Introduction

Increased demand for electrical energy and concerns about the impacts of climate change have prompted many governments at all levels to set aggressive goals to reduce greenhouse gas emissions and increase the proportion of their energy portfolios produced from renewable energy sources such as solar and wind (Graabak and Korpås 2016). One response to these changes is the recent, dramatic increase in the design, development, and deployment of commercial-scale offshore wind energy facilities (OWFs; IRENA, 2016). The total installed offshore wind capacity globally rose over 4 GW in 2017 alone to nearly 19 GW, and is forecasted to reach 120 GW by 2030 (GWEC, 2018).

Over the last few decades, the offshore wind energy industry has expanded its scope from turbines mounted on foundations driven into the seafloor and standing in less than 60 m of water (e.g., Vindeby, Denmark; 4C Offshore 2017), to floating turbines moored in 120 m of water (e.g., Hywind Scotland, Scotland; 4C Offshore 2018), to prospecting the development of floating turbines moored in ~1,000 m of water (e.g., Bureau of Ocean Energy Management [BOEM] wind energy Call Areas and the Castle Winds proposal in California, USA; BOEM, 2018, Trident Winds, 2016). Major incentives to develop deepwater, floating OWFs include reduced impacts on human activities and marine ecosystems, the ability to leverage existing infrastructure and technological advancements from the offshore oil and gas industry, and access to larger and more consistent wind speeds offshore (Musial and Ram 2010, James and Costa Ros 2015; Wang et al. 2019a, 2019b). However,

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technology supporting deepwater, floating OWFs is still in its infancy, with few prototype turbines and mooring systems currently deployed. Thus, the potential effects of these technologies on the marine environment are speculative.

To our knowledge, there is no scientific synthesis to date on the potential environmental effects of deepwater, floating OWFs. We aim to fill this gap by providing a synthesis of the available scientific literature and an assessment of how the operation of such facilities may affect the physical and biological marine environment. Such information will be useful for informing the evaluation and permitting processes of sites for the development of deepwater, floating OWFs, as well as for guiding mitigation strategies of operational facilities. While a robust empirical study and test of such effects is not yet possible due to the lack of deepwater, floating OWFs currently in operation, the plausible types of effects and their potential magnitudes can be estimated and reviewed through a synthesis of the scientific literature on appropriate analogs (e.g., fixed-bottom OWFs, land-based wind energy facilities, marine renewable energy [MRE] devices, oil and gas platforms).

For this review we identified, evaluated, and categorized potential environmental effects of deepwater, floating OWFs. We also identified and discuss potential mitigation strategies that might reduce the magnitude of these effects, thereby providing guidance on which effects may be most problematic, which could be resolved, and which need further study. This synthesis can serve as a reference document on the potential environmental effects of deepwater, floating OWFs—a nascent technology expected to become increasingly employed worldwide. This synthesis is aimed toward marine scientists and engineers, the energy industry, permitting agencies and regulators of the energy industry, project developers, and other stakeholders such as coastal residents, conservationists, and fisheries that could be affected by the development of deepwater, floating OWFs.

2. Methods

We conducted a qualitative systematic review of potential environmental effects of deepwater, floating OWFs. Systematic reviews involve a comprehensive plan and search strategy defined by the research question(s), the search engine(s) used, and *a priori* inclusion/exclusion criteria to identify relevant studies based on keywords, topical relevance, study date and location, and quality and type of study (Uman 2011; Paré et al., 2015). Using standard literature search engines (e.g., Google Scholar,[2] Web of Science[3]), and an online database specifically focused on environmental effects of wind and marine renewable energy (Tethys[4]), we conducted a comprehensive literature search using keyword searches and citation chaining to identify scientific information relevant to the potential environmental effects of deepwater, floating OWFs. Overall, we searched for literature covering, or relevant to, the general topic defined by the keywords “environmental impact/effect” and “offshore renewable energy”.

A synthesis on environmental and ecological effects of ocean renewable energy development by Boehlert and Gill (2010) identified six environmental stressors: energy removal effects, electromagnetic field (EMF) effects, physical presence of devices, dynamic effects of devices, acoustic effects, and chemical effects. A large report on environmental effects of MRE by Copping et al. (2016) discussed these stressors in relation to risks and impacts defined by changes in physical systems due to energy removal and changes in flow, EMF effects on marine animals from cables, changes in benthic habitat and reef fish communities by the energy devices, risks to animals from underwater sound, and collision risk around turbines. We organized the stressors and risks/impacts identified by Boehlert and Gill (2010) and Copping et al. (2016) into six categories of potential environmental effects of deepwater, floating OWFs that are the focus of our synthesis: (1) changes to atmospheric and oceanic dynamics due to energy removal and modifications, (2) EMF effects on marine species from cables, (3) habitat alterations to benthic and pelagic fish and invertebrate communities, (4) underwater noise (acoustic) effects on marine species, (5) structural impediments to wildlife, and (6) changes to water quality (Fig. 1).

To perform an extensive search of the literature on each relevant subtopic, we refined our search with multiple keywords representing each of the six environmental effect categories (e.g., “electromagnetic field”, “electric field”; “noise”, “auditory”), and with keywords describing specific potential effects discussed in the literature and identified from citation chaining, such as “avian collision”, “displacement”, “marine mammal entanglement”, “reef effect”, “wake effect”, and “biofouling”. We also included in our search “mitigation strategies” to identify potential strategies for reducing or regulating effects. We conducted our literature search from 2016 to 2019, and included in our search only peer-reviewed articles and reports published by researchers, project developers, and government agencies, with no restrictions placed on country of origin.

Due to the lack of deepwater, floating OWFs currently in operation, and thus the limited availability of empirical studies and monitoring efforts directly investigating their environmental effects, we expanded our literature review to include other technologies that could, at least in some contexts, serve as analogs for highlighting potential environmental effects of deepwater, floating OWFs. We considered several analogs where appropriate, including fixed-bottom OWFs, land-based wind energy facilities, MRE technologies (such as wave and tidal), offshore oil and gas platforms, ocean vessels, fisheries, subsea cables, and other coastal infrastructure. Thus, phrases describing these analogs (e.g., “wind turbine”, “wave energy converter”) were included with the keywords listed above to identify relevant literature. The literature on environmental effects of these analogs is extensive (e.g., >50,000 articles related to environmental effects of offshore oil and gas platforms), and, in many cases, with a long history (e.g., 100s of articles published prior to 1900 that relate to environmental effects of ocean vessels). Therefore, we used a combination of original research articles and review articles to keep the length (and reference list) of this review manageable. To focus on the most current knowledge and information, we excluded studies whose results were later advanced or superseded by subsequent research. We also excluded review articles published prior to 2000 as well as any studies that were not related to our specific research questions on the environmental effects of deepwater, floating OWFs (Xiao and Watson 2017).

In addition to synthesizing the data and information we obtained from our systematic review, we used our results to generate qualitative inferences on the potential magnitude of the environmental effects of deepwater, floating OWFs. That is, we conducted a qualitative systematic review, as opposed to a quantitative systematic review, such as a meta-analysis, that uses statistical techniques to collectively analyze data from the studies (Paré et al., 2015). We employed the four-level classification scheme—negligible, minor, moderate, and major—used by the Bureau of Ocean Energy Management (BOEM) to characterize impact levels for biological and physical resources (MMS, 2007). The levels are defined by the characteristics of the environmental effect (MMS, 2007): (1) no measurable effects (negligible); (2) effects that could be avoided with proper mitigation, or that would eventually cause no change on the system without any mitigation once the impacting agent is eliminated (minor); (3) effects that are unavoidable and possibly with irreversible outcomes, but that do not threaten the viability of the system, which would fully recover if proper mitigation is applied during the life of the project or proper remedial action is taken once the impacting agent is eliminated (moderate); and (4) effects that are unavoidable and that may threaten the viability of the system, which would not fully recover even if proper mitigation is applied during the life of the project or proper remedial action is taken once the impacting

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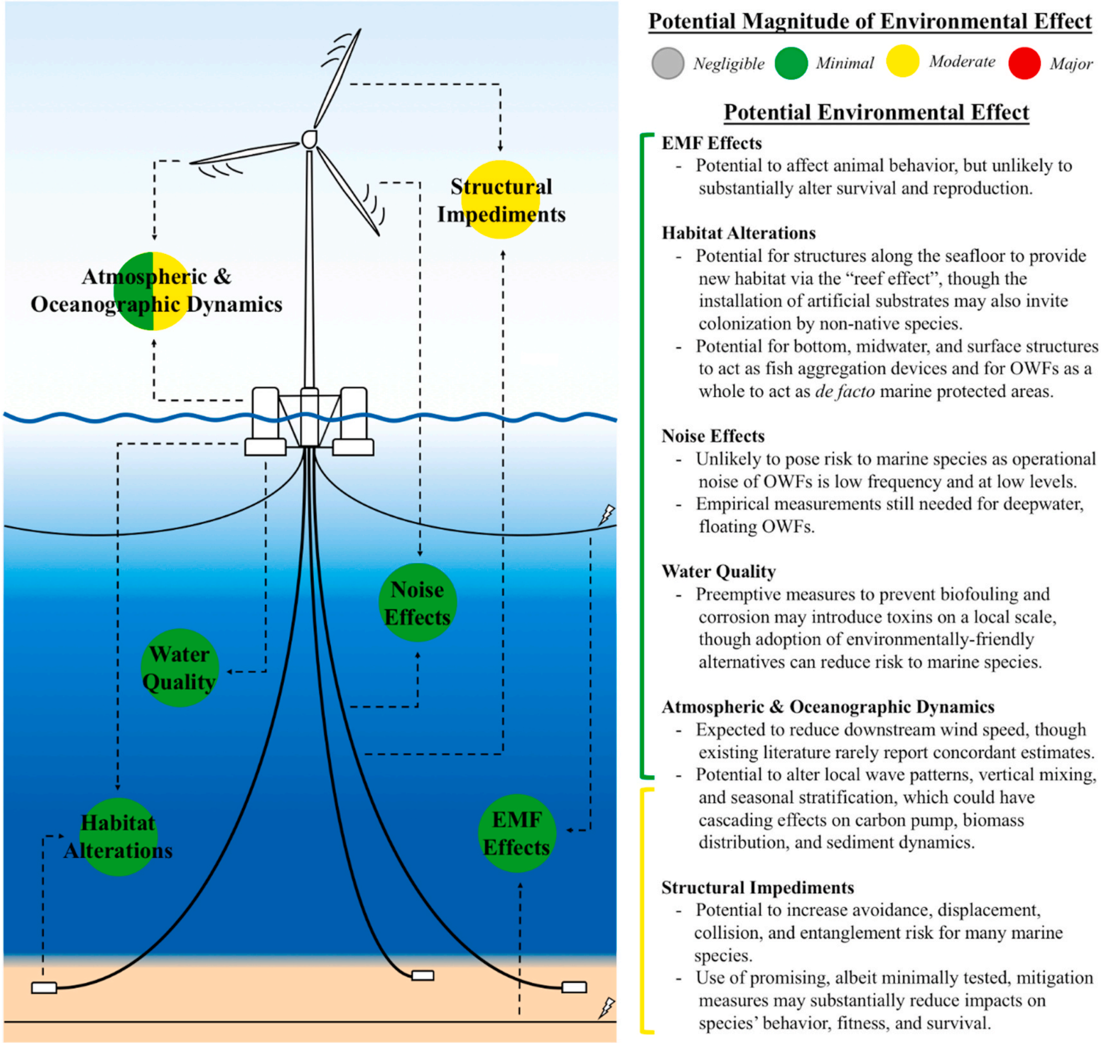
[2] https://scholar.google.com.

[3] http://login.webofknowledge.com.

[4] https://tethys.pnnl.gov.



Potential Magnitude of Environmental Effect

⚪ *Negligible* 🟢 *Minimal* 🟡 *Moderate* 🔴 *Major*

Potential Environmental Effect

EMF Effects
- Potential to affect animal behavior, but unlikely to substantially alter survival and reproduction.

Habitat Alterations
- Potential for structures along the seafloor to provide new habitat via the "reef effect", though the installation of artificial substrates may also invite colonization by non-native species.
- Potential for bottom, midwater, and surface structures to act as fish aggregation devices and for OWFs as a whole to act as *de facto* marine protected areas.

Noise Effects
- Unlikely to pose risk to marine species as operational noise of OWFs is low frequency and at low levels.
- Empirical measurements still needed for deepwater, floating OWFs.

Water Quality
- Preemptive measures to prevent biofouling and corrosion may introduce toxins on a local scale, though adoption of environmentally-friendly alternatives can reduce risk to marine species.

Atmospheric & Oceanographic Dynamics
- Expected to reduce downstream wind speed, though existing literature rarely report concordant estimates.
- Potential to alter local wave patterns, vertical mixing, and seasonal stratification, which could have cascading effects on carbon pump, biomass distribution, and sediment dynamics.

Structural Impediments
- Potential to increase avoidance, displacement, collision, and entanglement risk for many marine species.
- Use of promising, albeit minimally tested, mitigation measures may substantially reduce impacts on species' behavior, fitness, and survival.

Fig. 1. Type and magnitude of potential environmental effects of deepwater, floating offshore wind energy facilities. Effect magnitudes were determined using the four-level classification scheme (negligible, minor, moderate, and major) used to characterize impact levels for biological and physical resources defined in MMS (2007).

agent is eliminated (major). Following convention for conducting a qualitative review, we attempted to make our conclusions as transparent as possible, and to explain conflicting results (Templier and Paré 2015).

3. Results

A total of 89 articles were ultimately included in this review, 16 for describing changes to atmospheric and oceanic dynamics (Table 1), 8 for describing electromagnetic field (EMF) effects (Table 2), 14 for describing habitat alterations (Table 3), 11 for describing noise effects (Table 4), 28 for describing structural impediments (Table 5), and 14 for describing changes to water quality (Table 6). None of the articles focused on environmental effects of deepwater, floating OWFs specifically, which is not surprising given that the technology is still in its infancy, with few prototype turbines and floating systems currently deployed in relatively shallow waters (e.g., Hywind, Scotland in 120 m depth; 4C Offshore 2018). Fifty-eight (65.2%) of the 89 articles contained original research, the remainder were literature review and synthesis articles and reports. While the articles cover the full range of analogs considered, much of the referenced literature focuses on particular regions, species, and/or technologies. For example, 12 (43%) of the articles on structural impediments focus specifically on Europe (Table 5), as that region has far outpaced North America and other regions of the world in the development of fixed-bottom OWFs. Likely for similar reasons, many studies examine potential effects on harbor porpoises (*Phocoena phocoena*), since they are a protected species in much of Europe and there is concern about how they may interact with European fixed-bottom OWFs. The limited availability of research and data on OWF's effects on different species and different regions is discussed further in Section 4.

Numerous potential effects of deepwater, floating OWFs were identified across all six categories of environmental effects (Fig. 1, Tables 1–6). For each category, the magnitudes of the environmental effects therein were inferred to be either minor or moderate (Fig. 1). In the below sections, and in Tables 1–6, we describe in detail the potential environmental effects, their magnitude, and possible strategies for mitigating the effects.

3.1. Changes to atmospheric and oceanic dynamics

Researchers have examined several potential consequences of wind energy extraction on local and regional climate (Table 1). The most widely documented consequence is the wake effect, or the reduction in wind speed and kinetic energy downstream of a wind energy facility (Ludewig 2015). Predominantly modulated by wind speed and direction, wind wakes may also impact local weather, ocean, and sediment

Table 1
Changes to Atmospheric and Oceanic Dynamics literature summary table.

Reference	Study Area	Object(s)	Methodology	Relevant Significant Findings
Carpenter et al. (2016)	German Bight, North Sea	Oceanic dynamics	Idealized models and field measurements were used to assess OWFs effects on large-scale stratification.	The mixing induced by an OWFs' foundations generate significant impact on large-scale stratification.
Cazenave et al. (2016)	South-western UK shelf	Oceanic dynamics	A 3D unstructured hydrodynamic model was used to model the impact of wind farm turbine monopiles in a seasonally stratified shelf sea.	Model simulations indicated that the introduction of turbine monopiles induced changes in velocity fields, tidal harmonics, vertical mixing, and seasonal stratification.
Christensen et al. (2013)	Horns Rev OWF, North Sea	Atmospheric and oceanic dynamics	A parametric study was conducted to examine the influence of three processes (energy dissipation due to drag resistance, wave reflection/diffraction, and a modified wind field) on the wave field in and around an OWF.	Results indicated that OWFs in shallow waters may result in the modification of wave propagation shoreward due in part to the reflection and/or diffraction of wave energy by the turbines' substructures and in part to the extraction of wind energy and reduced wind velocity shear.
Christiansen and Hasager (2005)	Horns Rev OWF, North Sea and Nysted OWF, Baltic Sea	Atmospheric dynamics	Satellite synthetic aperture radar-derived wind speed images were used to quantify wake velocity deficits downstream from two OWFs.	An average deficit of 8–9% in mean wind speed immediately downstream of the OWFs, and recovery to within 2% of the free stream velocity within 5–20 km downstream, were observed.
Clark et al. (2014)	Global	Atmospheric and oceanic dynamics	Literature review and synthesis.	Potential impacts of OWFs on turbulence and mixing, surface wave energy, sediment dynamics, biogeochemistry, mesoscale flows, upwelling and downwelling, and meteorology are highlighted.
Copping et al. (2013)	Global	Atmospheric and oceanic dynamics	Literature review and synthesis.	Several possible environmental concerns associated with the presence of, and removal of energy by, MRE devices, including changes in water movement, vertical mixing, and water column stratification, are highlighted.
Fiedler and Bukovsky (2011)	Central US	Atmospheric dynamics	A regional climate model and 62 years of reanalysis data were used to investigate the effect of a wind farm on precipitation.	A statistically significant increase in average precipitation was observed.
Floeter et al. (2017)	Global Tech I OWF and BARD Offshore 1 OWF, North Sea	Oceanic dynamics; plankton and fish communities	Satellite measurements and field measurements taken by a remotely operated towed vehicle were used to assess the effects of non-operating OWFs' foundations on ambient hydrography, local nutrient concentrations, plankton densities, and fish distribution.	Data indicated that the presence of OWF foundations increased vertical mixing and enhanced local upwelling; however, the changes may still fall under natural variability.
Keith et al. (2004)	Global	Atmospheric dynamics	Two circulation models were used to assess the influence of large-scale wind power on climate at both regional and global scales.	Model simulations indicated that while large-scale use of wind energy can alter turbulent transport in the atmospheric boundary layer, its climatic impact relative to other anthropogenic climate forcing, such as greenhouse gas emissions, is likely to be negligible.
Li et al. (2018)	Sahara and Sahel regions, Africa	Atmospheric dynamics; vegetation	Climate models were used to investigate the effect of large-scale wind farms on regional climate and vegetation.	Model simulations showed that large-scale wind farms led to local temperature and precipitation increases in the two desert regions.
Ludewig (2015)	German Bight, North Sea	Atmospheric and oceanic dynamics	Model simulations and climatological and reanalysis data were used to analyze the impact of an OWF's wind wake on the ocean.	Wind speeds were reduced up to 70% downstream from the OWF for an area 100 times larger than the OWF. The OWF induced numerous changes in ocean dynamics and hydrographic conditions, including changes in vertical mixing and an excursion of the thermocline.
Maria and Jacobson (2009)	Global	Atmospheric dynamics	A Blade Element Momentum model was used to examine the effect of large wind farms on energy in the atmosphere.	When averaged over large geographic regions, energy loss in the lowest 1 km of the atmosphere was estimated to be only 0.007%, even if wind energy was scaled to supply the energy needs of the entire world.
Nagel et al. (2018)	N/A	Atmospheric and oceanic dynamics	An idealized numerical model of the ocean and sediment layers was used to investigate the effect of an offshore wind turbine wake on the coupled atmosphere-ocean-sediment system.	The turbine wake impacted both the ocean and sediment bed layers, and in some cases, generated large-scale eddies.
Porté-Agel et al. (2013)	Horns Rev OWF, North Sea	Atmospheric and oceanic dynamics	Large-eddy simulations were performed to investigate the effect of wind direction on turbine wakes and power losses.	Numerous simulations showed that wind direction can strongly affect the velocity deficit and turbulence intensity of turbine wakes, as well as total power output.
Possner and Caldeira (2017)	Global	Atmospheric dynamics	Model simulations were used to identify areas of open ocean where the large-scale downward transport of kinetic energy may sustain greater wind energy extraction rates than on land.	Results suggested that over some open ocean areas, the downward transport of kinetic energy from the free troposphere is enough to replenish the energy removed by large OWFs.
Vautard et al. (2014)	Europe	Atmospheric dynamics	A regional climate model was used to investigate the effects of current and future European wind farms on regional climate.	Results indicated a limited impact of wind farms on regional climate, with the only statistically significant change in temperature and precipitation found in winter.

dynamics (e.g., Porté-Agel et al., 2013; Clark et al., 2014; Ludewig 2015; Nagel et al., 2018). For example, several studies using climate models suggest that the installation of large-scale wind facilities can drive increases in local precipitation (e.g., Fiedler and Bukovsky 2011; Li et al., 2018). When modeling the interactions between wind facilities and the atmosphere, Vautard et al. (2014) found changes within ±0.3 °C and 0–5% for precipitation during winter months, making it difficult to discern such effects from those of natural variability. Using wind models, Ludewig (2015) and Christensen et al. (2013) estimated wind speed reductions downstream of fixed-bottom OWFs of up to 70–90%. However, the actual wake effect may be less severe; satellite synthetic aperture radar (SAR) data used to quantify wind velocity deficits near Horns Rev in the North Sea and Nysted in the Baltic Sea revealed an average deficit of only 8–9% immediately downstream of the OWFs, and recovery to within 2% of the free stream velocity within 5–20 km downstream (Christiansen and Hasager 2005). The substantial differences between these modeled and remotely sensed effects underscore the uncertainty in the current understanding of the impact of OWFs on atmospheric dynamics.

Nonetheless, the overall effect of deepwater, floating OWFs on regional climate is likely minor to moderate. When averaged over large geographic regions, energy loss in the lowest 1 km of the atmosphere is estimated to be only 0.007%, even if wind energy is scaled to supply the energy needs of the entire world (Maria and Jacobson 2009). Moreover, while large-scale use of wind energy can alter turbulent transport in the atmospheric boundary layer, its climatic impact relative to other anthropogenic climate forcing, such as greenhouse gas emissions, is likely to be negligible (Keith et al., 2004). Recent research even suggests that over some open ocean areas, the downward transport of kinetic energy from the free troposphere is enough to replenish the energy removed by large OWFs (Possner and Caldeira 2017).

Our current understanding of the effects of deepwater, floating OWFs on oceanic dynamics is similarly limited and uncertain. However, Copping et al. (2013) highlighted several possible environmental concerns associated with the presence of, and removal of energy by, MRE devices, including changes in water movement, vertical mixing, and water column stratification. Similarly, several modeling analyses and empirical research of fixed-bottom OWFs indicate that the mere presence of turbines' fixed substructures can enhance localized vertical mixing across isopycnals and alter seasonal stratification and nutrient transport (e.g., Carpenter et al., 2016; Cazenave et al., 2016; Floeter et al., 2017). Deployment of fixed-bottom OWFs in shallow waters may result in the modification of wave propagation shoreward due in part to the reflection and/or diffraction of wave energy by the turbines' substructures and in part to the extraction of wind energy and reduced wind shear (Christensen et al., 2013). If the operation of deepwater, floating OWFs similarly induces localized changes to surface waves, vertical mixing, or water column stratification, cascading effects to the biological (carbon) pump (process by which inorganic carbon is fixed into organic matter via photosynthesis at the surface and the subsequent sinking and sequestration at depth; Geider 2001), biomass distribution, sediment dynamics, and other processes that scale with the OWF's footprint may result. Though deepwater, floating OWFs' substructures and mooring systems are expected to be less disruptive to ocean currents and waves (and hence sediment dynamics) than those with fixed foundations in shallow waters, such effects may still result from potential changes to local weather and wind forcing, and should be explored in future work.

3.2. *Electromagnetic field (EMF) effects*

As deepwater, floating OWFs expand in size and increase in distance from shore, additional, longer, and higher capacity subsea cables will be required to interconnect facility components to each other, to the seafloor, and to shore. For example, floating OWFs' use of inter-array cables suspended within the water column, rather than solely along the seafloor as is often the case with fixed-bottom OWFs, may increase the scope of anthropogenic EMFs in the water column and potentially interact with a greater diversity and abundance of marine organisms. However, EMFs from inter-array cables may be less than those from export cables because of the lower amount of power being transmitted (Thomsen et al., 2015). Additional factors that may influence the strength of EMFs generated from subsea cables include the distance between conductors, balance of the load, and the type of cable (Copping et al., 2016). Three-phase alternating current (AC) cables, which produce both electric and magnetic fields, are the most commonly employed cables in MRE arrays and OWFs (Gill et al., 2014; Copping et al., 2016). Though magnetic fields emitted from AC cables are typically low (i.e., in the μT to pT range within several meters from the cables), deepwater, floating OWFs' longer transport distances may necessitate the use of high voltage direct current (HVDC) cables, which typically emit higher intensity magnetic fields over a greater spatial scale (Gill et al., 2014).

Several taxonomic groups of species, including elasmobranchs, crustacea, cetacea, bony fish, and marine turtles, are sensitive to electric and/or magnetic fields (Gill et al., 2014; Copping et al., 2016). The most likely effects of anthropogenic electric and magnetic field emissions include physiological impacts, such as altered development, and behavioral effects, such as attraction, avoidance, and impaired navigation and/or orientation (Gill et al., 2014; Thomsen et al., 2015; Copping et al., 2016) (Table 2). However, the research to date is limited and observed responses are often species-specific or even individual-dependent (Gill et al., 2014; Copping et al., 2016). For example, Hutchison et al. (2018) found the Little skate (*Leucoraja erinacea*) exhibited a strong behavioral response to the EMFs while the American lobster (*Homarus americanus*) exhibited only a subtle change in behavioral activity. A study in California, United States (U.S.) found no significant difference between the response of caged rock crabs (*Metacarcinus anthonyi* and *Cancer productus*) placed along unenergized and energized subsea cables (Love et al., 2015). While the swimming speed of European eels (*Anguilla anguilla*) in the Baltic Sea was significantly lower near a subsea transmission cable, Westerberg and Lagenfelt (2008) noted that the delay would likely have negligible effects on the eels' fitness and that there was no evidence that the cable acted as an obstruction to migration. Moreover, a study of nearshore and offshore fishes in the North American Great Lakes found no detectable effects of high voltage transmission cables on species' spatial patterns and composition (Dunlop et al., 2016). In the San Francisco Estuary, Kimley et al. (2017) found that distortions in the Earth's main geomagnetic field produced by bridges were an order of magnitude greater than those from a transmission cable on the estuary seafloor. Using an array of acoustic tag-detecting monitors, they found significant numbers of Chinook salmon (*Oncorhynchus tshawytscha*) migrating past the bridges, as well as adult green sturgeon (*Acipenser medirostris*) successfully swimming through the estuary on their way to and from their spawning grounds, indicating that magnetic anomalies produced by bridges and subsea transmission cables do not present a strong barrier to the natural seasonal movement patterns of these fishes (Kimley et al., 2017). Overall, the research to date has demonstrated that the effect of anthropogenic EMFs on receptor species appears to be minor, but there are still large gaps in our understanding, particularly on the interaction of pelagic, demersal, and benthic species with subsea cables (Copping et al., 2016).

3.3. *Habitat alterations*

The deployment of any novel, offshore structure (e.g., OWFs, MRE devices, oil and gas platforms) may induce physical changes in habitats that have the potential to alter species composition and abundance at localized scales or provide opportunities for colonization by new species (Table 3). At the seafloor, the mooring anchors and subsea cables associated with deepwater, floating OWFs, if not entirely buried, may function as artificial reefs by introducing hard substrate that can become

Table 2
Electromagnetic Field (EMF) Effects literature summary table.

Reference	Study Area	Object(s)	Methodology	Relevant Significant Findings
Copping et al. (2016)	Global	EMF-sensitive marine animals	Literature review and synthesis.	Several taxonomic groups of species can detect and respond to the electric and magnetic fields from MRE devices, but there was no evidence that such species are negatively affected.
Dunlop et al. (2016)	Wolfe Island Submarine Cable, Lake Ontario, Canada	Laurentian Great Lakes fish community	Nearshore electrofishing and offshore fisheries acoustic surveys were conducted to investigate whether the presence of a HVAC cable affected the spatial pattern and composition of fish communities.	No detectable effects of the cable on the fish community were found.
Gill et al. (2014)	Global	EMF-sensitive marine animals	Literature review and synthesis.	The properties, sources, and detection of anthropogenic EMFs, as well as the evidence base regarding marine animals' interactions with EMFs, are highlighted.
Hutchison et al. (2018)	Cross Sound Cable, Connecticut, US	American lobster (*Homarus americanus*) and Little skate (*Leucoraja erinacea*)	Field-deployed enclosures and acoustic telemetry were used to assess the effect of exposure to EMF from a buried HVDC cable on lobster and skate behavior.	The Little skate exhibited a strong behavioral response to the EMFs from the energized subsea cable, while the American lobster exhibited only a subtle change in behavioral activity. For either species, the cable did not constitute a barrier to movement.
Kimley et al. (2017)	Trans Bay Cable, San Francisco, California, US	Chinook salmon (*Oncorhynchus tshawytscha*) and green sturgeon (*Acipenser medirostris*)	Magnetic field surveys were conducted and an array of acoustic biotelemetry receivers were used to examine the effect of magnetic anomalies on fish movement patterns.	Distortions in the Earth's main geomagnetic field produced by bridges were an order of magnitude greater than those from the Trans Bay Cable. Magnetic anomalies produced by bridges and subsea transmission cables do not present a strong barrier to the natural seasonal movement patterns of Chinook salmon or green sturgeon.
Love et al. (2015)	Las Flores Canyon, California, US	Rock crabs (*Metacarcinus anthonyi* and *Cancer productus*)	Individual rock crabs were placed in boxes along either an energized or unenergized cable to investigate potential behavioral responses.	No significant difference was detected between response of crabs placed along energized and unenergized cables.
Thomsen et al. (2015)	Thorntonbank OWF and Northwind OWF, Belgium	EMF emissions	Electric and magnetic fields from industry standard inter-array and export cables (AC) were measured during operation using The Swedish Electromagnetic Low-Noise Apparatus.	EMFs emitted from the turbines were considerably weaker than those from the export and inter-array cables. EMFs emitted from the export cables were higher than those from the inter-array cables. E-fields measured were within the range of known detection by sensitive receptor species, while the B-fields were at the lower range of detection.
Westerberg and Lagenfelt (2008)	Kalmar Strait, Baltic Sea	European eel (*Anguilla anguilla*)	Sixty tagged eels' migration speeds were recorded during transit through a strait with a 130 kV AC power cable to investigate potential changes to movement or migration.	Eel swimming speed was significantly lower around the cable, though there was no evidence that the cable acted as an obstruction to migration.

colonized by invertebrates and reef-associated fishes (Langhamer 2012). Often regarded as a valuable conservation tool, this "reef effect" of anthropogenic structures on the benthos serving as artificial reefs is well-documented at OWFs, oil and gas platforms, and subsea pipelines (e.g., Love and York 2005; Krone et al., 2013; Claisse et al., 2014; Reubens et al., 2014). Off the coast of Sweden, Wilhelmsson et al. (2006) found evidence to suggest that OWFs can function as both artificial reefs and fish aggregation devices for demersal fish. However, the installation of artificial hard substrates may also invite colonization by non-native (invasive) species, whose threat to marine biodiversity can have far-reaching ecological and economic consequences (Molnar et al., 2008). For example, Bulleri and Airoldi (2005) found that the proliferation of artificial marine structures in nearshore areas facilitated the spread of a non-indigenous green algae (*Codium fragile* ssp. *tomentosoides*) along the coasts of the north Adriatic Sea. However, no OWF studies to date have demonstrated significant deleterious effects on reef fish or benthic communities (Copping et al., 2016) and the offshore locations of deepwater, floating OWFs make these pathways less likely than those nearshore.

Midwater and surface structures, namely mooring lines and floating substructures, may similarly act as fish aggregation devices (Kramer et al., 2015), as well as settlement surfaces for invertebrates and algae. Hundreds of different fish species from dozens of taxonomic families aggregate around floating structures (Castro et al., 2002), suggesting that floating OWFs may attract a variety of species and potentially alter species composition in midwater and surface ecological communities. In instances where fishing activity is restricted within and around OWFs, they may act as *de facto* marine protected areas, creating refuges for some marine species, increasing local species abundances, and generating spillover effects to adjacent areas (White et al., 2012; Wilhelmsson and Langhamer 2014; Hammar et al., 2016). Overall, any habitat alterations that may result from the operation of deepwater, floating OWFs are likely to have minor impacts on local marine organisms and are unlikely to present many novel challenges that have yet to be observed and addressed with the deployment of other marine structures.

3.4. Noise effects

Anthropogenic noise sources have the potential to displace, physically injure, and/or affect many marine organisms' ability to communicate, forage, and otherwise interact with their environment (Götz et al., 2009) (Table 4). However, operational noise from existing, fixed-bottom OWFs typically occurs within regulatory thresholds, is low in frequency and level, and is likely to pose low risk (Madsen et al., 2006; Thomsen et al., 2015; NYSERDA 2017). Research indicates that while OWF operational noise, which would be continuous, may be detectable to some marine mammals and fishes, it is unlikely that these noise levels would result in physiological damage (Wahlberg and Westerberg 2005; Madsen et al., 2006; Tougaard et al., 2009; Marmo et al., 2013). However, sounds from turbines also generate particle motion (back-and-forth

Table 3
Habitat Alterations literature summary table.

Reference	Study Area	Object(s)	Methodology	Relevant Significant Findings
Bulleri and Airoldi (2005)	North-east coast of the Adriatic Sea	Green alga (*Codium fragile* ssp. *tomentosoides*)	A field survey was used to investigate the distribution and dynamics of an introduced green alga on breakwaters.	Results indicated that artificial structures can facilitate the spread of non-indigenous species.
Castro et al. (2002)	Global	Fish	Literature review and synthesis.	More than 300 fish species from 96 families were found to be associated at least occasionally with floating objects.
Claisse et al. (2014)	Southern California, US	Fish communities	Data from annual visual surveys were used to calculate and compare secondary fish production, total fish density, and total fish biomass on oil and gas platforms to those on natural reefs and other marine habitats.	Results showed that oil and gas platforms off the southern California coast have the highest secondary fish production per unit area of seafloor of any marine habitat studied due to the amount of hard habitat created and resulting recruitment.
Copping et al. (2016)	Global	Benthic habitats and reefing patterns	Literature review and synthesis.	No studies to date have demonstrated significant deleterious effects of changes in habitat due to OWF development on reef fish or benthic communities.
Hammar et al. (2016)	Global	Seabed habitats and benthos, epifouling benthos, fish, marine mammals, and seabirds	Literature review and synthesis.	With the exception of several seabird species, OWFs may be at least as effective as marine protected areas by creating refuges for and increasing the biodiversity and abundance of benthic organisms, fish, and marine mammals.
Kramer et al. (2015)	US West Coast and Hawaii	Fish	Literature review and synthesis.	MRE devices placed on or near the seabed may act as artificial reefs, while midwater and floating devices in tropical waters may act as a *de facto* fish aggregating device.
Krone et al. (2013)	Southern German Bight, North Sea	Mobile demersal megafauna communities	Diving censuses were used to assess the mobile demersal megafauna communities associated with soft bottom habitats, several shipwrecks, and an offshore research platform.	The megafaunal communities found at the research platform foundations were similar to those found at wrecks, though its upper regions were more scarcely colonized.
Langhamer (2012)	Global	Fish and invertebrates	Literature review and synthesis.	Offshore renewable energy structures on the seafloor may function as artificial reefs by introducing hard substrate that can become colonized by invertebrates and reef-associated fishes.
Love and York (2005)	Santa Barbara Channel, California, US	Fish communities	A manned research submersible was used to survey for fishes along part of an oil pipeline and the surrounding seafloor in shallow and deep waters.	Fish densities along the pipeline were six to seven times greater than those on the adjacent seafloor habitats.
Molnar et al. (2008)	Global	Invasive (non-native) marine species	A quantitative global assessment of invasive species' distributions, their impacts on biodiversity, and invasive species introduction pathways was conducted.	Invasive species' threat to marine biodiversity can have far-reaching ecological and economic consequences, and only 16% of marine ecoregions have no reported marine invasions.
Reubens et al. (2014)	C-Power OWF, North Sea	Atlantic cod (*Gadus morhua*)	Catch statistics, telemetry, stomach content analysis, and visual observations were used to assess the impact of OWFs on the ecology of benthopelagic fish.	Specific age groups of Atlantic cod were seasonally attracted to the OWF, but no evidence of an ecological trap was observed.
White et al. (2012)	Massachusetts Bay, Massachusetts, US	American lobster (*Homarus americanus*) and flounder fisheries, and whale-watching tourism	A spatially explicit, tradeoff analysis, involving a coupled biological–economic model, was used to evaluate the potential impacts of OWF installations on commercial fisheries and whale-watching tourism and conservation.	Marine spatial planning provided added value over single sector management, and has the potential to prevent losses in value by fisheries and whale-watching sectors at no cost to the OWF sector.
Wilhelmsson and Langhamer (2014)	Global	Fish and crustaceans	Literature review and synthesis.	OWFs may act as *de facto* marine protected areas, creating refuges for some marine species, increasing local species abundances, and generating spillover effects to adjacent areas.
Wilhelmsson (2006)	Strait of Kalmar, Baltic Sea	Fish and invertebrates	Visual transect surveys were conducted at two OWFs to investigate the potential for wind turbines to alter fish densities and assemblages.	OWFs can function as both artificial reefs and fish aggregation devices for demersal fish.

motion of the medium), which is the primary acoustic stimulus for all fishes; the impact of increased particle motion on the hearing of marine species has received little research attention and remains uncertain (Popper and Hawkins 2019). Furthermore, differential effects of operational noise on fish with and without a swim bladder, which is used in sound frequency detection (Blaxter 1981), is unknown. Nonetheless, behavioral responses by marine species to operational wind turbine noise appears to be minimal; modeled scenarios presented in Marmo et al. (2013) predicted that only a small proportion (<10%) of minke whales (*Balaenoptera acutorostrata*) and harbor porpoises (*Phocoena phocoena*) would exhibit behavioral responses up to ~18 km away from an OWF, while the majority of animals studied would not show a behavioral response, indicating low potential for displacement. Monitoring at Horns Rev in the North Sea revealed that the OWF's operational noise had no detectable effect on harbor porpoise abundance (Tougaard et al., 2006). Further, analysis of noise measurements from two Danish (Middelgrunden and Vindeby) and one Swedish (Bockstigen-Valar) fixed-bottom OWFs concluded that operational noise levels are unlikely to harm or mask acoustic communication in harbor seals (*Phoca vitulina*) and harbor porpoises (Tougaard et al., 2009).

However, field measurements and modelling efforts to estimate operational noise levels have predominantly focused on fixed-bottom OWFs in shallow, nearshore environments (<100 m depth; e.g., Tougaard et al., 2009; Marmo et al., 2013; Thomsen et al., 2015). Though measurements of and research on OWFs' operational noise remain a low priority in comparison to that of construction noise (Popper and

Table 4
Noise Effects literature summary table.

Reference	Study Area	Object(s)	Methodology	Relevant Significant Findings
Brandt et al. (2011)	Horns Rev II OWF, North Sea	Harbor porpoises (*Phocoena phocoena*)	Passive acoustic monitoring was used to investigate the behavioral responses of harbor porpoises to OWF construction and pile driving.	Harbor porpoise acoustic activity significantly decreased during construction (by 100% during the first hour and stayed below normal levels for 24–72 h at a distance of 2.6 km). The duration of the effect declined with increasing distance, and no negative effect was found at a mean distance of 22 km.
Götz et al. (2009)	Global	Marine animals	Literature review and synthesis.	Anthropogenic noise sources have the potential to displace, physically injure, and/or affect many marine organisms' ability to communicate, forage, and otherwise interact with their environment.
Madsen et al. (2006)	Global	Noise emissions and marine mammals	Literature review and synthesis.	Operational noise from existing, fixed-bottom OWFs is low, does not exceed ambient noise levels, and is unlikely to impair hearing in marine mammals.
Marmo et al. (2013)	N/A	Several marine mammal and fish species	Acoustic modelling was used to assess the acoustic output of an operational wind turbine on three different foundation types and marine species' responses.	Foundation type influenced sound pressure level and sound field. Results indicated that the modeled noise levels may be audible to some marine mammals and fishes. Modeled scenarios predicted that only a small proportion (<10%) of minke whales (*Balaenoptera acutorostrata*; low-frequency specialists) and harbor porpoises (*Phocoena phocoena*) would exhibit behavioral responses up to ~18 km away from an OWF, while the majority of animals studied would not show a behavioral response, indicating low potential for displacement
NYSERDA (2017)	Global	Marine mammals and sea turtles	Literature review and synthesis.	Noise from operational OWFs is likely to pose low risk to marine mammals and sea turtles.
Popper and Hawkins (2019)	Global	Fishes	Literature review and synthesis.	The impact of increased particle motion, in general and from OWFs, on the hearing of marine fishes has received little research attention and remains uncertain.
Russel et al. (2016)	Inner Dowsing OWF, Lynn OWF, Sheringham Shoal OWF, and Lincs OWF, The Wash, North Sea	Harbour seals (*Phoca vitulina*)	Telemetry data from animal-borne tags were used to compare the abundance of harbor seals during the pile driving, construction, and operation of several OWFs.	Seal abundance was significantly reduced during pile driving, but no significant displacement was observed during OWF construction or operation.
Thomsen et al. (2015)	Global	Marine animals	Literature review and synthesis.	Operation noise of OWFs occurs within regulatory thresholds, making these noise sources less of a concern than those by OWF construction, which have the greatest potential for conflict with marine organisms. Some fish and marine mammals may be capable of detecting operational noise from OWFs at distances of several kilometers.
	Thorntonbank OWF and Northwind OWF, Belgium	Noise emissions	Underwater sound pressure measurements were recorded using a drifting platform and an acoustic hydrophone suspended below a vessel.	Monopiles emitted higher sound levels than jacket foundation turbines.
Tougaard et al. (2006)	Horns Rev OWF, North Sea	Harbor porpoises (*Phocoena phocoena*)	A long-term monitoring program involving seven years of field surveys and five years of acoustic recordings was conducted.	The harbor porpoises exhibited a weak negative reaction during construction and semi-operation, and no effects were observed during operation.
Tougaard et al. (2009)	Middelgrunden OWF and Vindeby OWF, North Sea and Bockstigen-Valar OWF, Baltic Sea	Harbor porpoises (*Phocoena phocoena*) and harbor seals (*Phoca vitulina*)	Underwater noise measurements were recorded at three OWFs during normal operation to assess potential effects on hearing.	Analysis of noise measurements concluded that noise from the OWFs was unlikely to harm or mask acoustic communication in harbor seals and harbor porpoises.
Wahlberg and Westerberg (2005)	Global	Fish	Literature review and synthesis.	Noise from operational OWFs may mask communication and orientation signals in fish, but is unlikely to cause physiological damage or consistent avoidance.

Hawkins 2019; Thomsen et al., 2015), an in-depth examination of the acoustic propagation characteristics of floating substructures and their associated moorings, as well as the overall noise levels of operational floating, deepwater OWFs would enhance the current understanding of the interactions of these facilities and marine organisms. Because sensitivity to acoustic frequencies differs among species (Popper and Hawkins 2019; Southall et al., 2019), a thorough investigation of the topic will need to cover a broad range of taxonomic diversity of marine organisms. Additionally, as larger turbines are deployed, evaluation of the noise levels from these turbines will be needed to assess their potential effects. Nevertheless, the ocean soundscape is complex and discerning effects from natural variability in ambient noise levels, including those from commercial vessel traffic, may prove difficult without further long-term studies.

3.5. *Structural impediments*

The physical presence of offshore structures, whether dynamic or static, may present both novel obstacles and benefits to marine organisms, and deepwater, floating OWFs are likely no exception (Table 5). The deployment of such facilities, for example, may result in displacement of individuals from key habitats such as foraging and breeding grounds. Russell et al. (2016), however, found no evidence of harbor seal (*Phoca vitulina*) displacement during the operation of several OWFs in the United Kingdom (U.K.). Russel et al. (2014) even demonstrated two seal species' (*Phoca vitulina* and *Halichoerus grypus*) ability to maneuver between OWF components unharmed and inferred that these animals were using the structures to forage. Similarly, Scheidat et al. (2011) presented evidence of a substantial increase in acoustic activity of harbor porpoises within the Dutch OWF Egmond aan Zee, and posited that an increase in food availability and/or an absence of vessels may explain the apparent preference.

Deepwater, floating OWFs may, however, exhibit barrier effects on migrating birds, bats, marine mammals, and fishes. Avoidance of OWFs may cause migrating bird species to use more circuitous routes and expend more energy (Fox et al., 2006). Though the consequences of such barrier effects on flight energetics remain largely unknown (Hüppop et al., 2006), comparison of pre- and post-construction data from Nysted in the North Sea suggests that, while birds exhibit avoidance responses, the energetic cost of the additional distance travelled to circumvent the OWF is insignificant (Masden et al., 2009). Monitoring of bird behavior at the Thanet OWF in Kent, U.K. found that 96.8% of recorded seabirds avoided turbines by flying between turbine rows while the remaining 3.2% adjusted their flight height to fly below the rotor-swept zone (Skov et al., 2018), again suggesting that avoidance responses may not require more circuitous routes and increased energy expenditure. Conversely, the percentage of flocks of ducks and geese entering the Nysted area decreased by a factor of 4.5 between pre-construction and initial operation periods, signifying a substantial, and possibly a species-specific, avoidance response (Desholm and Kahlert 2005). Even so, less than 1% of the migrants that entered the facility flew close enough to turbines to risk collision (Desholm and Kahlert 2005).

Avian collision risk remains among the most publicized concerns regarding wind energy facilities, despite the estimate that mortality from these facilities are substantially lower than from other anthropogenic sources. Buildings, powerlines, and cats comprise approximately 82% of annual avian mortality from anthropogenic sources, while land-based wind turbines comprise only 0.003% (Erickson et al., 2005). Avian collision mortality at land-based wind energy facilities, estimated at 250,000–500,000 birds annually in the U.S. (Johnson et al., 2016), is a function of spatial, temporal, and species-specific factors (Barrios and Rodríguez 2004). Similarly, patterns of bat collision mortality at land-based facilities in North America reveal that weather, season, and habitat type are key factors influencing collision risk, as well as a predominance of migratory, foliage-, and tree-roosting lasiurine species colliding with turbines (Arnett et al., 2008; Thompson et al., 2017). For offshore locations, a vulnerability assessment examining avian species in the California Current System found that pelicans, terns, gulls, and cormorants are at the greatest risk of collision, and alcids, terns, and loons are at the greatest risk of displacement (Adams et al., 2016). In the North Sea, seabird vulnerability is similarly species-specific and decreases with distance from shore (Garthe and Hüppop 2004). Wind speed and direction also have an important effect on seabird flight height, behavior, and relative vulnerability to collision with OWFs; Ainley et al. (2015) found that species that exhibit a prevalence of gliding versus flapping behavior are more vulnerable to OWFs because they often increase their flight height to within the blade-swept zone when winds are strong and are generally less maneuverable.

Wind facility-specific factors, including turbine features, blade height and visibility, and lighting, also influence avian collision risk (Marques et al., 2014). For example, facility configuration, turbine row spacing, and column number influence the number of birds entering wind farms and thus being at risk of collision (Masden et al., 2012). OWFs' artificial lighting may also attract bird and bat species, thus increasing the potential for collision. Vessels, lighthouses, light-induced fisheries (e.g., harvesting squid), and oil and gas platforms are all sources of artificial light in marine environments that may have significant influences on the reproductive physiology, migration, and foraging habits of many marine species, as well as avian collision risk (Montevecchi 2006). Although OWFs will undoubtedly contribute to the presence of artificial light in the marine environment, the use of blue and green lighting may reduce disorientation in nocturnally migrating birds more than red and white lighting (an industry standard), thus reducing avian collision risk at offshore facilities (Poot et al., 2008). Other viable collision mitigation strategies may include the use of auditory deterrents and restricting turbine operation at certain times, seasons, or during specific weather conditions (Marques et al., 2014). However, preventative initiatives, such as careful siting of OWFs to ensure minimal overlap with important habitats, migration corridors, and large populations of high risk species, may be the most effective method to minimize risk to marine species (White et al., 2012).

Additional concerns regarding deepwater, floating OWFs are the potential for marine mammal collision and entanglement, or the inadvertent restraint of marine animals by anthropogenic materials, such as fishing nets and lines (Benjamins et al., 2014). Since floating OWFs require mooring systems to keep their substructures stationary, marine mammal entanglement risk will likely be influenced by the type of mooring system employed (slack or taut-moored systems), mooring characteristics, and turbine array configuration. Benjamins et al. (2014) provided an in-depth qualitative assessment of relative entanglement risk, taking into consideration both biological risk parameters (e.g., body size, flexibility, and ability to detect moorings) and physical risk parameters of mooring elements (e.g., tension characteristics, swept volume, and mooring curvature). They found that due to their large size and foraging habits (i.e., rapidly engulfing dense prey aggregations), baleen whales incur the greatest risk of entanglement among cetaceans while small, toothed whales incur the least risk (Benjamins et al., 2014). Additionally, catenary moorings present the greatest risk while taut systems present the lowest relative risk due to their lower swept volume ratios, reduced curvatures, and stiffer behavior (Benjamins et al., 2014). Still, given the size and physical characteristics of the mooring systems required for deepwater, floating OWFs, it is unlikely that upon encountering such facilities, a marine mammal of any size would become directly entangled in the moorings themselves. Mooring systems in the offshore renewables industry typically employ high modulus polyethylene ropes and chains averaging between ~100 and 240 mm in diameter (Benjamins et al., 2014), while fishing gear, which has been identified as a major entanglement risk for whales (NOAA 2018), is typically ~1–7 mm in diameter (Wilcox et al., 2014). Thus, marine mammals are more likely to be at risk from secondary entanglement, in which an organism becomes entangled in derelict fishing gear that has accumulated on a facility component, and tertiary entanglement, in which an organism already entangled in gear swims through a floating OWF and the gear becomes entangled with a facility component. Whether direct, secondary, or tertiary, entanglement may result in severe injury or mortality via tissue damage, starvation, or drowning (Cassoff et al., 2011); however, the actual risks posed by floating OWFs' mooring lines are not yet known.

Similar risks may be associated with OWFs' subsea transmission cables, which interconnect components of OWFs and export energy to onshore electricity grids. However, as a result of advances in cable deployment techniques, such as cable burial procedures, no entanglements with telecommunication cables have been reported since 1959 (Wood and Carter 2008), suggesting that entanglement with subsea cables poses less of a risk to marine mammals than secondary or tertiary entanglement with mooring systems. Though cable burial in depths of up to 1,500 m are common (Carter et al., 2009), developers may deem routing the cables that interconnect facility components to the seafloor impractical and may instead seek to employ subsurface buoys to submerge cables to depths within the water column (e.g., Trident Trident

Table 5
Structural Impediments literature summary table.

Reference	Study Area	Object(s)	Methodology	Relevant Significant Findings
Adams et al. (2016)	California Current System, California and Oregon, US [and Baja California, Mexico]	81 marine bird species	A vulnerability assessment was used to examine avian species' risk of collision and displacement at the population level.	Results showed that pelicans, terns, gulls, and cormorants are at the greatest risk of collision, and alcids, terns, and loons are at the greatest risk of displacement.
Ainley et al. (2015)	Southern Ocean, Peru Current, California Current, and Equatorial Pacific	Birds	Strip survey data from 114 cruises were used to evaluate seabird flight height and behavior in response to altered wind speeds and direction.	Wind speed and direction have an important effect on seabird flight height and behavior. Species that exhibit a prevalence of gliding versus flapping behavior are more vulnerable to OWFs because they often increase their flight height to within the blade-swept zone when winds are strong and are generally less maneuverable.
Arnett et al. (2008)	US and Canada	Bats	Literature review and synthesis.	Patterns of bat collision mortality at land-based wind energy facilities reveal that weather, season, and habitat type are key factors influencing collision risk. Results show a predominance of migratory, foliage-, and tree-roosting lasiurine species colliding with turbines.
Barlow and Cameron (2003)	California and Oregon coasts, US	Marine mammals	A field experiment was carried out to investigate the effectiveness of pingers to reduce marine mammal mortality in a drift gill net fishery.	The use of acoustic deterrent devices reduced cetacean and pinniped entanglement rates in the gill net fishery by two-thirds.
Barrios and Rodríguez (2004)	E3 and PESUR wind farms, Tarifa, Spain	Birds	Carcass surveys, behavioral observations, and generalized linear modeling were used to assess the influence of various factors on bird mortality.	Results indicated that avian collision mortality at wind energy facilities were a function of spatial, temporal, and species-specific factors.
Benjamins et al. (2014)	N/A	Marine megafauna	In addition to literature review and synthesis, a qualitative assessment of relative entanglement risk was conducted based on both biological risk parameters and physical risk parameters of mooring elements.	Results suggested that while MRE device moorings are unlikely to pose a major threat to most marine megafauna groups, baleen whales incurred the greatest risk of entanglement among cetaceans and small, toothed whales incurred the least risk. Results indicated that catenary moorings presented the greatest risk of entanglement while taut systems presented the lowest relative risk due to their lower swept volume ratios, reduced curvatures, and stiffer behavior.
Carlström et al. (2009)	Bloody Bay and Lagabay, Scotland, UK	Harbor porpoises (*Phocoena phocoena*)	Shore-based observations and porpoise click train detectors were used to investigate the spatial and temporal responses of harbor porpoises to pingers on a bottom-set gill net.	Results showed that pingers could reduce harbor porpoise abundance at greater distances than previously observed, potentially resulting in local habitat exclusion.
Cassoff et al. (2011)	Atlantic waters of US and Canada	Minke whale (*Balaenoptera acutorostrata*), Bryde's whale (*B. brydei*), North Atlantic right whale (*Eubalaena glacialis*), and humpback whale (*Megaptera novaeanglia)*	The available sighting history, necropsy observations, and subsequent data analyses for 21 cases of baleen whale entanglement were reviewed and analyzed.	Acute drowning, impaired foraging and starvation, infection, and/or severe tissue damage were identified as major causes of mortality in entangled baleen whales.
Cox et al. (2001)	Bay of Fundy	Harbor porpoises (*Phocoena phocoena*)	A field experiment involving a moored pinger was conducted to determine whether harbor porpoises habituate to pingers.	Results showed that initial displacement decreased over time and that the harbor porpoises habituated to the presence of the pinger.
Desholm and Kahlert (2005)	Nysted OWF, Baltic Sea	Ducks, mainly common eider (*Somateria mollissima*), and geese	Flight trajectories were collected using surveillance radar during pre-construction and initial operation to investigate avoidance response and collision risk.	The percentage of flocks of ducks and geese entering the OWF area decreased by a factor of 4.5 between pre-construction and initial operation periods. Less than 1% of the migrants that entered the facility flew close enough to turbines to risk collision.
Erickson et al. (2005)	US	Birds	Literature review and synthesis.	Buildings, powerlines, and cats comprise approximately 82% of annual avian mortality from anthropogenic sources, while land-based wind turbines comprise only 0.003%.
Fox et al. (2006)	Denmark	Birds	Literature review and synthesis.	Avoidance of OWFs may cause migrating bird species to use more circuitous routes and expend more energy.
Garthe and Hüppop (2004)	Exclusive Economic Zone and national waters of Germany, North Sea	Seabirds	A wind farm sensitivity index for seabirds was developed and applied to estimate vulnerability to collision with OWFs.	Results indicated that seabird vulnerability decreases with distance from shore and was species-specific, with black- and red-throated divers at the greatest risk.

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Table 5 (*continued*)

Reference	Study Area	Object(s)	Methodology	Relevant Significant Findings
Harcourt et al. (2014)	Cape Solander, Sydney, Australia	Humpback whales (*Megaptera novaeangliae*)	Observations of 137 migrating humpback whale pods were made as they passed a moored acoustic alarm.	There was no evidence that the acoustic alarm served as an effective deterrence.
Hüppop et al. (2006)	German Bight, North Sea	Migrating birds	Measurements from radar, thermal imaging, and visual and acoustic observations were compiled to investigate bird migration and potential collision risk. Between October 2003 and December 2004, bird carcasses found at the FINO I offshore research platform were documented, measured, and examined.	Results indicated that large numbers of diurnal and nocturnal birds migrate through the German Bight year-round, and nearly half fly at altitudes considered to increase collision risk. A total of 442 birds of 21 species (predominantly passerines) were found dead, 76.1% of which had outwardly apparent injuries likely due to collision with FINO 1. However, over 50% of the strikes occurred in just two nights, both characterized by poor visibility.
Johnson et al. (2016)	US	Birds	Three publications estimating avian mortality at wind energy facilities were compared and contrasted.	Estimates indicated that roughly 250,000–500,000 birds are killed annually by colliding with wind turbines.
Kot et al. (2012)	Mingan Archipelago, Gulf of St. Lawrence, Canada	Minke whales (*Balaenoptera acutorostrata*)	A series of field experiments were conducted involving both visual and acoustic monitoring of whale behaviors near experimental ropes and buoys of different colors.	Results showed that minke whales were able to detect and avoid some fishing ropes and that use of high contrast, black and white ropes in particular may reduce entanglement risk.
Kraus et al. (2014)	Cape Cod Bay, US	North Atlantic right whale (*Eubalaena glacialis*)	Field trials involving colored rope-mimics were conducted to document changes in behavior and the distance at which a change occurred.	Results indicated that North Atlantic right whales can detect red and orange colored rope mimics at significantly greater distances than green ones.
Marques et al. (2014)	Global	Birds	Literature review and synthesis.	A wide range of factors influencing avian collisions at wind energy facilities, including species-, site-, and facility-specific factors are highlighted. The relationship between turbine size and avian collision rate may be site- or species-dependent.
Masden et al. (2009)	Nysted OWF, Baltic Sea	Common eiders (*Somateria mollissima*) and other migrating waterbirds	Flight trajectories were collected using surveillance radar during pre- and post-construction to assess the OWF's effect on migration distance.	Birds adjusted their flight trajectories to avoid the OWF post-construction, but the energetic cost of the additional distance travelled to circumvent the OWF was insignificant.
Masden et al. (2012)	Nysted OWF, Baltic Sea	Common eiders (*Somateria mollissima*)	Flight trajectory data collected during operation were used to parameterize models of the movements of birds in response to wind turbines and to assess the effects of facility-specific factors on avoidance response.	For species vulnerable to collision, facility configuration, turbine row spacing, and column number were shown to influence the number of birds entering the OWF.
Montevecchi (2006)	Global	Marine species	Literature review and synthesis.	Vessels, lighthouses, light-induced fisheries, and oil and gas platforms are all major sources of artificial light in marine environments, each with significant influences on the reproductive physiology, migration, and foraging habits of many marine species, as well as avian collision risk.
Poot et al. (2008)	Nederlandse Aardolie Maatschappij natural gas production site, Ameland, Netherlands	Birds	An experiment using lamps with red, green, blue, and white filters was conducted to observe the reactions of nocturnally migrating birds to different light conditions.	Results indicated that the use of blue and green lighting disorient nocturnally migrating birds less than red and white lighting.
Russell et al. (2014)	Alpha Ventus OWF, Germany and Sheringham Shoal OWF, UK	Harbor seals (*Phoca vitulina*) and grey seals (*Halichoerus grypus*)	High resolution GPS data and state-space models were used to assess potential associations with anthropogenic structures.	The data suggest that the seals maneuvered between OWF components unharmed and used anthropogenic structures within the OWF for foraging.
Russell et al. (2016)	Inner Dowsing OWF, Lynn OWF, Sheringham Shoal OWF, and Lincs OWF, The Wash, North Sea	Harbor seals (*Phoca vitulina*)	Telemetry data from animal-borne tags were used to compare the abundance of harbor seals during the pile driving, construction as a whole, and operation of several OWFs.	Seal usage was significantly reduced during pile driving, but no significant displacement was observed during OWF construction as a whole or operation.
Scheidat et al. (2011)	Egmond aan Zee OWF, North Sea	Harbor porpoises (*Phocoena phocoena*)	Stationary passive acoustic monitoring was used prior to construction and during operation of an OWF to examine potential effects on harbor porpoise occurrence.	Acoustic activity of harbor porpoises substantially increased from baseline to operation of the OWF, indicating a general increase in occurrence.
Skov et al. (2018)	Thanet OWF, Kent, UK	Northern gannet (*Morus bassanus*), black-legged kittiwake (*Rissa tridactyla*), herring gull (*Larus argentatus*), great black-backed gull (L.	A multi-sensor monitoring system was used to collect avoidance behavior and the Empirical Avoidance Rates (EARs)	96.8% of recorded seabirds avoided turbines by flying between turbine rows while the remaining 3.2% adjusted their

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Table 5 (*continued*)

Reference	Study Area	Object(s)	Methodology	Relevant Significant Findings
		marinus), and lesser black-backed gull (*L. fuscus*)	methodology was developed and used to quantify avoidance rates.	flight height to fly below the rotor-swept zone.
Thompson et al. (2017)	US and Canada	Bats	Literature review and synthesis.	Avian collision mortality at wind energy facilities is greatest for migratory tree-roosting species between July and October.
Wood and Carter (2008)	Global	Whales	Information derived from global cable fault databases were used to identify instances of whale entanglement.	As a result of advances in cable design, marine surveying, and cable laying techniques, no entanglements with telecommunication cables have been reported since 1959.

Winds, 2016), thus creating additional obstacles for marine mammals and, depending on the characteristics of these cables, providing additional avenues for secondary or tertiary entanglement.

Recent work has demonstrated the value of specific collision and entanglement mitigation strategies. Kot et al. (2012) demonstrated that minke whales are able to detect and avoid some fishing ropes and that use of high contrast, black and white ropes in particular may reduce entanglement risk. Similarly, Kraus et al. (2014) found that North Atlantic right whales (*Eubalaena glacialis*) could detect red and orange colored rope mimics at significantly greater distances than green ones. Barlow and Cameron (2003) found that the use of acoustic deterrent devices reduced cetacean and pinniped entanglement rates in a gill net fishery by two-thirds. Conversely, Harcourt et al. (2014) found no discernible response of migrating humpback whales (*Megaptera novaeangliae*) to acoustic alarms, suggesting that responses may be species-specific. Additional challenges regarding the use of acoustic alarms as a means to reduce collision and entanglement include habituation risk (Cox et al., 2001), local habitat exclusion (Carlström et al., 2009), and device durability and regulatory compliance (Dawson et al., 2013). Thus, the most effective way to reduce marine mammal collision and entanglement may be through siting OWFs in areas that reduce overlap with biologically important areas, such as feeding grounds and migration corridors.

3.6. Changes to water quality

Developers of OWFs will almost certainly include preemptive measures to prevent corrosion and biofouling, since seawater is highly corrosive and maintenance of offshore structures, especially those far from shore, is difficult and expensive (Table 6). Corrosion protection measures for OWFs typically involve numerous epoxy-based coatings, a polyurethane topcoat, and cathodic protection (Price and Figueira 2017). These corrosion protection measures are a direct source of chemical emissions, including organic compounds such as bisphenol A, and metals such as aluminum, zinc, and indium (Kirchgeorg et al., 2018). For example, Vermeirssen et al. (2017) demonstrated the release of large amounts of bisphenol A from epoxy resin-based anti-corrosion coatings on onshore infrastructure. Gomiero et al. (2015) analyzed mussels (*Mytilus galloprovincialis*) from offshore gas platforms in the Adriatic Sea and hypothesized that galvanic anodes (a form of cathodic protection) were the potential source of zinc and cadmium accumulation in the mussels. Although the available data from OWFs is scarce, there is currently no clear evidence of a negative impact on the marine environment from these sources (Kirchgeorg et al., 2018).

Prior to the global ban of organotin-based antifouling paints in 2008, biofouling protection measures predominantly involved tributyltin, a highly toxic, broad-spectrum biocide whose prolonged use in the shipping industry has had detrimental effects on non-target species (Bryan et al., 1986; Takahashi et al., 2009; Nurioglu et al., 2015). In response to the ban, biofouling protection throughout many marine industries is now largely achieved through the use of zinc and/or copper based conventional or self-polishing copolymer antifouling paints (Takahashi et al., 2009; Ciriminna et al., 2015). To increase the length and functionality of these coating systems, booster biocides such as zinc pyrithione and copper pyrithione are typically incorporated despite the need for further research into their long-term fate in, and effects on, the marine environment (Konstantinou and Albanis 2004; Chambers et al., 2006). Copper pyrithione, for example, can induce morphological changes and oxidative stress in juvenile brook trout (*Salvelinus fontinalis*) at environmentally relevant doses (Borg and Trombetta 2010). Moreover, dissolved copper concentrations exceeding US federal standards of 3.1 μg/L can affect the development and survival of several fish, mollusk, and echinoderm species (Thomas and Brooks 2010); however, such impacts are typically limited to marinas, harbors, and ports, which can contain elevated copper concentrations due to high boating activity and increased residence times (Takahashi et al., 2009). Thus, continued use of conventional antifouling agents will certainly introduce additional chemicals into the marine environment via passive leaching, but the extent to which the chemicals released from deepwater, floating OWFs may harm sensitive marine species remains unclear.

However, following increased health and environmental concerns regarding heavy metal and booster biocide use in antifouling coatings, stricter regulations have initiated the research and development of alternative approaches to biofouling protection, such as fouling release, biomimetics, acoustic approaches, and more commonly, the use of various non-toxic, non-biocide-release antifouling coatings (Chambers et al., 2006; Ciriminna et al., 2015; Legg et al., 2015; Nurioglu et al., 2015). Ultimately, the magnitude of the water quality effects from deepwater, floating OWFs may depend on whether the offshore wind energy industry adopts (by choice or regulation) such environmentally-friendly alternatives to biofouling protection, but will likely be minor nonetheless. Once again, these challenges are not unique to deepwater, floating OWFs and have been addressed in other marine industries.

4. Discussion

This study provides the first synthesis of the potential environmental effects of deepwater, floating OWFs during operation, as well as potential mitigation strategies to some of the effects. Using the available scientific literature concerning appropriate analogs (e.g., fixed-bottom OWFs, land-based wind energy facilities, MRE devices), we evaluated six major categories of potential effects (cf. Boehlert and Gill 2010; Copping et al., 2016). If mitigation strategies and best-practice protocols are properly adopted, our research suggests that the effects associated with EMFs, noise, habitat alterations, and changes to water quality are likely to have minor impacts on marine organisms. Similarly, preventative initiatives such as the careful siting of deepwater, floating OWFs outside of important habitats, may reduce otherwise moderate impacts of displacement, avian collision, and marine mammal collision and entanglement (e.g., White et al., 2012). Lastly, deepwater, floating OWFs' overall effect on atmospheric and oceanic dynamics is likely minor to moderate, but given the potential for such technologies to have cascading effects on large-scale atmospheric and oceanic processes, future work on the underlying uncertainties of this impact is needed. Additionally, it is important to note that the magnitude of each potential

Table 6
Water Quality literature summary table.

Reference	Study Area	Object(s)	Methodology	Relevant Significant Findings
Bejarano et al. (2013)	Atlantic Outer Continental Shelf	Chemical releases	In addition to a literature review and synthesis, a consequence analysis was conducted to assess the potential environmental effects of chemical releases from OWFs.	Oil and chemical releases associated with the routine maintenance of OWFs, or in the unlikely event of catastrophic facility failure (e.g., toppling of a turbine or electrical service platform), may result in low to moderate adverse impacts to marine resources. Depending on the volume of the release, highly viscous oils (e.g., biodiesel and dielectric insulating fluids) may pose moderate fouling risks to marine mammals and birds.
Borg and Trombetta (2010)	Laboratory study	Brook trout (*Salvelinus fontinalis*)	Electron microscopy and histological analysis were used to investigate the acute effects of copper pyrithione on juvenile brook trout.	Results indicated that copper pyrithione is potentially harmful to nontarget marine organisms at environmentally relevant doses.
Bryan et al. (1986)	South-west England	Common dogwhelk (*Nucella lapillus*)	A survey of dogwhelks at several sites and an experimental tank test were used to assess the effect of tributyltin on penis development in females.	Concentrations as low as 20 ng/L caused imposex in female dogwhelk.
Chambers et al. (2006)	Global	Marine antifouling coatings	Literature review and synthesis.	Modern approaches to environmentally effective antifouling systems, such as those using tin-free self-polishing copolymers and foul release technologies, and their performance are highlighted.
Ciriminna et al. (2015)	Global	Marine antifouling coatings	Literature review and synthesis.	Biofouling protection throughout marine industries is largely achieved through the use of zinc and/or copper based conventional or self-polishing copolymer antifouling paints. Recent advances in nanochemistry have led to the development of several non-toxic alternatives to biocidal antifouling paints, including silicon-based and sol-gel coatings.
Gomiero et al. (2015)	Central Adriatic Sea	Mediterranean mussel (*Mytilus galloprovincialis*)	Biological and chemical data were used to investigate the biological effects of offshore gas platforms on mussels.	Higher levels of zinc and cadmium in the tissues of mussels sampled near offshore gas platforms suggested that galvanic anode corrosion might be the source of metal accumulation.
Kirchgeorg et al. (2018)	Global	Corrosion protection systems	Literature review and synthesis.	Cathodic protection systems using galvanic anodes or impressed current cathodic protection systems, corrosion allowances, and coatings and their potential for chemical emission from OWFs are presented. Corrosion protection measures are a direct source of chemical emissions, but the available data from OWFs is scarce and there is currently no clear evidence of a negative impact on the marine environment.
Konstantinou and Albanis (2004)	Global	Booster biocides	Literature review and synthesis.	The occurrence and effects of the most commonly used booster biocides in marine antifouling coatings are highlighted.
Legg et al. (2015)	Global	Acoustic methods for biofouling control	Literature review and synthesis.	Acoustic techniques for biofouling control and their potential impacts on marine life are highlighted.
Nurioglu et al. (2015)	Global	Marine antifouling coatings	Literature review and synthesis.	Non-toxic, non-biocide-release antifouling coating strategies are highlighted, with an emphasis on the chemical and physical aspects of their antifouling mechanisms.
Price and Figueira (2017)	Global	Corrosion protection systems	Literature review and synthesis.	Corrosion protection measures for OWFs typically involve numerous epoxy-based coatings, a polyurethane topcoat, and cathodic protection.
Takahashi et al. (2009)	Global	Antifouling coating biocides	Literature review and synthesis.	Recent advances in the understanding of antifouling biocides in the marine environment, including their behavior, toxicity, biological impacts, and regulation are presented.
Thomas and Brooks (2010)	Global	Antifouling coating biocides	Literature review and synthesis.	The environmental fate and occurrence of antifouling paint biocides, including their effects on non-target species, are highlighted.
Vermeirssen et al. (2017)	Laboratory study	Corrosion protection coatings	Two experiments were conducted using a series of bioassays to investigate the release of toxicity from four epoxy based anti-corrosion coatings.	Bioassay results indicated that one of four tested products released large amounts of bisphenol A.

effect will likely scale, either linearly or nonlinearly, with the size and configuration of an OWF. Monitoring of pilot and future deepwater, floating OWFs will help to calibrate these findings.

Although the scope of this work does not encompass potential environmental effects of deepwater, floating OWFs outside of the operational stage, there are likely effects associated with other stages of an OWF's life cycle that warrant mention. For example, oil and chemical releases (e.g., fuel spills) associated with the routine maintenance of OWFs, or in the unlikely event of catastrophic facility failure (e.g., toppling of a turbine or electrical service platform), may result in minor to moderate adverse impacts to marine resources (Bejarano et al., 2013). Depending on the volume of the release, highly viscous oils (e.g., biodiesel and dielectric insulating fluids) may, for example, pose moderate fouling risks to marine mammals and birds (Bejarano et al., 2013). Implementation of oil/chemical transfer spill prevention measures and best-practice protocols, however, may reduce the likelihood and extent of both accidental and intentional releases from OWFs' components and support vessels. Additionally, the majority of greenhouse gas emissions from renewable energy technologies likely occur prior to and after facility operation. Raw material extraction, component manufacturing, transportation to the offshore site, installation, and decommissioning will all have air quality effects. A recent life cycle analysis of floating offshore wind projected greenhouse gas emissions of ~15.35 kg CO_2-eq/MWh, with manufacturing as the major contributor. However, even with an uncertainty range of 8.58–30.17 kg CO_2-eq/MWh, the maximum emissions estimate for floating offshore wind was still less than 1/10th and 1/20th the minimum emission estimates for natural gas and coal, respectively (Bang et al., 2019). Furthermore, since deepwater, floating OWFs lack fixed foundations, they do not require pile driving. Pile driving is among the most environmentally impactful practices associated with the construction of fixed-bottom OWFs, since it typically emits relatively high noise levels that cause displacement and injury of marine mammals and changes to fish behavior (Brandt et al., 2011; Thomsen et al., 2015; Russell et al., 2016). Also, deepwater, floating OWFs can be constructed onshore prior to transportation to the offshore site, which further reduces both the amount and duration of anthropogenic noise emissions (e.g., vessel noise) and other construction-related impacts in marine habitats. These factors suggest that a deepwater, floating OWF will have relatively minor effects during non-operational stages of its life cycle; nonetheless, research on OWFs during their construction and decommission stages is required to generate more accurate estimate of their effects.

Much of the referenced literature in this review is based on research focused on specific regions, species, and/or technologies, and the conclusions drawn therein may be as well. Given the limited availability of information specifically on deepwater, floating OWFs, we have extrapolated, when appropriate, from research on fixed-bottom OWFs, MRE, and other appropriate analogs. Development of fixed-bottom OWFs in northern Europe has far outpaced that in North America, Asia, and other regions of the world. Therefore, much of the available literature is geographically-biased towards northern Europe, which has had such technologies in operation for some time. Further, the species within these regions, as well as those afforded various protections or that are considered commercially valuable, tend to be the focus of many studies, such as harbor porpoises in northern Europe. However, the findings of such studies are not necessarily specific to harbor porpoises, and may be applicable to other marine mammals as well as seabirds. Likewise, much can be learned from research on OWFs in northern Europe, and from research on analogous industries, and applied to inform our understanding of the nature and magnitude of the potential effects deepwater, floating OFWs may have around the world. There also may be environmental effects, not identified by this review, that are outside the six categories of effects that we considered based on the stressors and risks/impacts identified by Boehlert and Gill (2010) and Copping et al. (2016). Finally, this synthesis is based on a literature review up through 2019, and since then more information has been learned about potential environmental effects of deepwater floating OWFs (e.g., ICF 2020). Thus, this synthesis should be considered as a benchmark for the state of knowledge that can be improved upon through an updated synthesis covering the most recent scientific literature. Ultimately, the conclusions drawn in this study are not meant to preclude future empirical studies and monitoring of the environmental impacts of deepwater, floating OWFs in specific regions and on specific species. Rather, the aim of this literature review is to synthesize the available literature to better estimate how the operation of deepwater, floating OWFs may affect the physical and biological marine environment.

Knowledge of deepwater, floating OWFs' potential effects on the marine environment remains limited due to the lack of these facilities in operation at this time. Thus, this synthesis takes the necessary first steps in summarizing the available information on the potential environmental effects of deepwater, floating OWFs and some associated mitigation strategies, and can serve as a reference document for marine scientists and engineers, the energy industry, permitting agencies and regulators of the energy industry, project developers, and concerned stakeholders such as coastal residents, conservationists, and fisheries. Given the likely integration of deepwater, floating OWFs into an increasingly crowded seascape, it is vital that the drive to reduce greenhouse gas emissions, diversify energy portfolios, and combat climate change account for the proper assessment and mitigation of these facilities' potential environmental effects.

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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