Chapter 9
Exploitation of Offshore Wind Energy

Jens Lüdeke

Abstract Offshore wind energy will substantially contribute to future energy generation. However, the use of wind energy in marine areas has implications for marine ecosystems. The results of more than a decade of ecological research concerning offshore wind farms in Germany and abroad have revealed potential negative impacts of offshore wind farms, particularly with regards to seabirds, migrating terrestrial birds, and marine mammals such as harbor porpoises, especially by noise effects during installation of the turbines. Depending on the location of the wind farm, effects on bat populations are also possible. Impact on fish and benthic species are probably less relevant. There are even examples of positive (local) effects on marine biodiversity, for example, due to the introduction of a new hard substrate into ecosystems or the exclusion of fishing from the area of the offshore wind farm. For an overall assessment of the impacts of offshore wind, the effects still have to be investigated on a cumulative and international level over the long term.

A number of measures are necessary to achieve environmentally sound development of the use of offshore wind energy. Marine spatial planning is important for guiding human activities in the marine environment, such as the use of offshore wind energy. Marine protected areas are of high relevance for protecting sensitive habitats and species. State-of-the-art mitigation measures against underwater noise are required to avoid hazards to whales. Finally, marine compensation measures can help to counterbalance adverse impacts of offshore wind farms.

Keywords Offshore wind energy • Offshore wind farms • Underwater noise • Marine spatial planning • Marine compensation measures • Pile driving • Marine mammals • Sea birds protection • Reef effect

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J. Lüdeke, Dr.-Ing.
Environmental Assessment and Planning Research Group,
Technical University of Berlin, Berlin, Germany
e-mail: Jens.luedeke@ile.tu-berlin.de

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9.1 Development of Offshore Wind Energy

Offshore wind energy has many advantages over onshore wind production, most prominently in terms of the higher wind speed offshore: the wind speed in the first offshore wind farms (OWFs) has averaged 10 m/s in recent years, whereas, at onshore locations, the average is often not much higher than 6–8 m/s. Moreover, the wind blows much more regularly offshore (offshore more than 4000 full load hours; onshore only 1300–2000 full load hours, depending on the location of the turbines). OWF can supply electricity at almost every hour of the day and any time of the year. Production is highly predictable, with almost no need for backup capacity from conventional energy producers or greater storage volume. In Germany, OWFs are mostly located far off shore, where they do not create acceptance problems among nearby residents (no "Not in My Back Yard" phenomenon). In other countries, OWFs are sometimes built near the shore and therefore can produce conflicts, e.g., with the tourism sector. Offshore wind industries may also create conflicts with fishermen because commercial fishing is prohibited inside the area of OWFs. Nevertheless, the conflicts connected to OWFs are inferior compared with the problems onshore that wind energy regularly has to face, especially with nearby residents.

In Europe, in pioneer countries, such as the UK, Denmark and Germany, offshore wind energy is now becoming increasingly important for energy transition away from fossil fuels towards renewable energy resources. The first OWFs worldwide were built in Denmark in 1991. In 2016, the capacity of offshore wind energy passed 10,000 MW (UK 6000 MW, Germany 3000 MW, and Denmark 1200 MW). More than 3000 turbines are currently installed and grid-connected in more than 80 OWFs in 11 European countries (see Fig. 9.1). This capacity provides sufficient electricity supply to about ten million households in Europe. The European Commission considers offshore wind energy "the energy of the future." Wind energy is supposed to ensure European energy safety and transition to a low carbon economy. The goal for offshore wind in Europe is over 40,000 MW by 2020 (see Table 9.1) and about 150,000 MW in the long run.

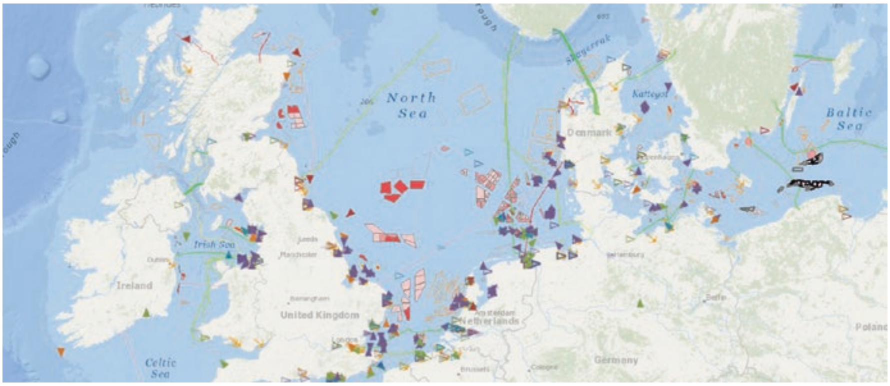

Fig. 9.1 Offshore Wind Projects in selected European Waters (4C Offshore 2016)

Table 9.1 Aims and required marine area for OFW in Europe (Source: adapted from the EU COM 2016, Seaenergy 2020)

Country	2020 Target (MW)	Minimum area for offshore wind farms (≈10 MW per km²) (km²)	Share for offshore wind farms of total EEZ of each country (%)
Belgium	2000	200	5.56
Denmark	1339	140	0.13
Estonia	250	25	0.07
Finland	900	90	0.17
France	6000	600	0.18
Germany	10,000	1000	3.50
Greece	1500	150	0.00
Ireland	550	55	0.01
Italy	680	7	0.00
Latvia	180	18	0.06
Lithuania	100	10	0.16
Netherlands	5978	600	1.02
Poland	500	50	0.15
Portugal	75	7.5	0.00
Spain	3000	300	0.04
Sweden	182	18	0.05
UK	18,000	3300	0.43
Total	≈50,000	≈ 6500 km²	Ø 0.68

The predicted minimum area necessary to achieve the 2020 target is based upon a reference density for offshore wind farms of 10 MW/km² (Seaenergy 2020)

Germany’s energy approach—the *Energiewende*—aims to fundamentally restructure the country’s energy supply with 80% of electricity renewable by 2050. Offshore wind will play an important role, with the German government having established plans for using 6500 MW offshore wind energy by 2020 and 15,000 MW by 2030 (Federal Ministry for Economic Affairs and Energy 2015).

As required by Article 4 of Directive 2009/28/EC on the promotion of the use of energy from renewable sources (Renewables Directive), EU Member States have defined their legally binding 2020 target for the share of renewable energy in their respective National Renewable Energy Action Plans. The 17 European Coastal States of the North Sea, Baltic Sea, Mediterranean Sea, and Atlantic Coast have announced quantitative objectives for offshore renewable energies by 2020. In order to achieve the goals of the National Renewable Energy Action Plans (EU COM 2016), substantial geographical areas of the Exclusive Economic Zone (EEZ) will be occupied (Table 9.1).

Non-European countries have also started developing OWFs. For example, China already built its first OWF in 2010 and South Korea is preparing to build its first OWF. India is currently working on the legal and policy frameworks to formulate its entrance into the offshore market. There are also plans for OWF in the U.S., although offshore wind is yet in the early stage of development: America’s first OWF has been under construction since 2015 and several other projects will be implemented in the next several years (Kota et al. 2015).

9.2 Environmental Impacts of OWF

In the 1990s, prior to the use of offshore wind energy, there was almost no data regarding its potential environmental impacts. Thus, ecological research on the development of OWFs took the highest priority from the outset. Indeed, this is why the Federal Ministry of Environment in Germany provided more than 50 million euros of funding for research. The first German offshore test field—Alpha Ventus—which was completed in the North Sea in 2010, therefore sought to resolve technical and environmental uncertainties. The impact of OWFs on the marine environment has been intensively investigated, as have ways to reduce this impact (Otto et al. 2014). Knowledge concerning the effects of OWFs on the marine environment has been considerably advanced by data gathered in Germany over recent decades. Since the German body of research is comprehensive and unique, this chapter focuses on its research outcomes, evaluated, however, in the context of numerous studies from other countries (Lüdeke 2015).

From the outset, environmental problems presented a major obstacle for the approval of OWFs in Germany, as well as other European countries. One focus of the German research was to compare actual construction and operational effects on the marine environment with the (theoretical) forecasts. Investigations in Germany followed the Before-After-Control-Impact (BACI) design, with comparative investigations in the area of the OWFs (especially in the first OWF Alpha Ventus) and in selected reference areas without turbines, before and during the construction period, as well as in the first years of operation of the wind farm (Beiersdorf 2014).

9.2.1 Impacts of OWFs on Benthos

The impacts of OWFs on benthos (communities of organisms that live in, on or nearby the seabed) are exceptional because they can be assessed as positive in the context of an increase in number of species and biomass. Surveys have demonstrated an increase of endobenthos after OWF construction, although the species composition changed, owing to the new habitats. The results show that OWFs have a substantial effect on the marine benthos. Variations of the benthic in- and epifauna of the sedimentary seafloor indicate an influence on the part of the wind turbines and the associated activities on population dynamics of benthic species. However, the duration of the investigation period still is too short to draw conclusions on the long-term development of the infauna (Gutow et al. 2014). Nevertheless, it was discovered that the cessation of fishing activities in wind farm areas has a positive effect on benthic biodiverstity after several years (Bergman et al. 2015). Even so, according to Gutow et al. (2014), no clear signs of recovery from bottom trawling manifested in the short term. Beyond this, Mesel et al. (2015) note that the community of endobenthos soon became dominated by only a few species, and even non-indigenous, invasive species were found.

The hard bottom associated benthos communities are more likely found around the underground parts of turbines. Although the seafloor changes substantially around the turbine foundations, a great number of species usually inhabiting the original soft bottom fauna is still found in these modified sediments. Turbine foundations serve as artificial reefs, being broadly populated and offering habitats for faunal diversity. This leads to an increase in the number of aquatic animals. At Alpha Ventus, it was not possible to clearly distinguish between the impacts of the turbine foundations (e.g., an increase of biomass caused by the new turbines serving as artificial reefs) and processes associated with their operation (e.g., the recovery of benthic communities after the cessation of bottom trawling).

Five years after the construction of Alpha Ventus and the introduction of new habitats for hard bottom associated mobile demersal megafauna, the fouling assemblage has increased enormously. The new artificial reefs in the marine environment have a substantial influence on nearby sediment and benthic community inhabitants. The species richness and biomass of the fouling assemblage have steadily increased, reaching a biomass of more than 20 kg/m^2 of foundation in the shallow, subtidal mussel accumulation. Shortly after construction, up to 100 times more hard-bottom species were present at the foundations than in the previous soft sediments. Furthermore, the foundation structures have served as nursery grounds, e.g., for the brown crab (*Cancer pagurus*), the Atlantic horse mackerel (*Trachurus trachurus*), and the pouting (*Trisopterus luscus*) (Krone and Krägefsky 2012). Moreover, a large number of mussels (*Mytilus edulis*), which had not formerly been abundant in this location, were observed.

Three years after completion of the OWF, the growth was noticeable: mussels, amphipods, crabs, and sea anemones had all settled within the OWF in large numbers. A cover of mussel shells was established around the foundations. The biomass on the turbine foundation attracted predators and scavengers. The fouling biomass now descends to the seafloor when the organisms die. There, it provides food for scavengers. The change in species composition and increased vegetation has attracted larger animals, which find new food sources around the foundations (Gutow et al. 2014).

Similar results have been obtained in studies outside Germany, in other sea regions. It has been demonstrated that OWFs—including both the wind turbines and associated activities (e.g., cessation of fishing)—have affected the population dynamics of benthic species. Another notable result from investigations at European wind farms is the lack of short-term effects on marine soft-bottom benthos. An increase of benthos is predicted over the long term (Lindeboom et al. 2011).

In conclusion, a number of investigations have proven that OWFs can lead to an increase in abundance and number of hard bottom associated benthic species especially within the wind park area (Andersson et al. 2009; Punt et al. 2009; Wilson et al. 2010; Wilhelmsson et al. 2010; Lindeboom et al. 2011; Coates et al. 2012; van Polanen et al. 2012; Gutow et al. 2013; Krone et al. 2013; Schmidt et al. 2013; Ashley et al. 2014; Bergman et al. 2015; Coates et al. 2014; Dannheim et al. 2014; Hooper and Austen 2014; Krägefsky 2014; Vaissière et al. 2014; Wilding 2014; Lüdeke 2015; Hammar et al. 2016). Thus, the introduction of an artificial substratum allows species which are naturally not occurring at these sites to establish themselves. Consequently, especially the benthos species, which depend on hard substratum, benefits from OWFs. However, an assessment of the implications for the ecosystem in a long-term investigation is still lacking.

9.2.2 Impacts of OFWs on Fish

Fish could be affected by pile driving and other construction activities. Injuries from pile driving sounds have been found to cause injuries to several fish species in a laboratory study. The recovery of the fish occured within 10 days and is unlikely to have affected their survival (Bailey et al. 2014). Beyond this, deleterious effects on fish have been documented. For example, intense construction activities, which involve not only pile driving, but also ship traffic, photo pollution, seafloor disturbance has resulted a 40–50% decrease in the abundance of pelagic fish (primarily mackerel, horse mackerel, herring, and sprats) compared to surrounding areas. Construction activities like pile driving, ship traffic or seafloor turbulence disturb fish (Reichert et al. 2012).

After construction, the abundance of fish species was higher at the wind turbine foundations than in areas outside the wind parks. Overall, there was an increase in the number and biomass of fish. The catches were more than twice as large as those before construction, with larger fish being caught (Reichert et al. 2012). The new artificial reef community included fish such as mackerel, striped dragonets, French cod, and flatfish, as well as predatory fish that are rare on pure sand surfaces. Most experts evaluate this artificial effect as positive, as it increases biodiversity. A recovery of fish populations and benthic communities has been noted to date. Again, two factors are responsible for these occurrences, namely the new artificial reef and the prohibition against trawling within OWFs.

Findings from German studies are supported by those in other sea areas (Leitao et al. 2007; Andersson et al. 2009; Langhamer et al. 2009; Punt et al. 2009; Wilhelmsson et al. 2010; Reubens et al. 2011; De Troch et al. 2013; Reubens et al. 2013a, b; Ashley et al. 2014; Lüdeke 2015; Hammar et al. 2016).

9.2.3 Impacts of OWFs on Birds

Impacts on seabirds and migrating terrestrial birds have been at the center of several studies in Germany and other nations. Seabirds can be affected by OWFs in various ways, including collisions with turbines, barrier effects, habitat loss, and attraction (Dierschke and Garthe 2006). Garthe et al. (2013) published a comprehensive study on resting seabirds, clearly showing that seabird distribution changes substantially as a result of OWFs.

9.2.3.1 Seabirds

A decline in the overall abundance of most seabird species was noted on Germany's first OWF, although bird behaviors varied depending on the species (Mendel et al. 2014). A review of the international research confirmed the data from Germany in showing habitat loss for some seabirds, whereby some seabirds were attracted to OWFs, while others ignored their presence (Dierschke and Garthe 2006; Petersen et al. 2006; Schwemmer et al. 2011; Plonczkier and Simms 2012; Furness et al. 2013; Haelters and Vanermen 2013; Petersen 2013; Bradbury et al. 2014; Mendel et al. 2014; Hammar et al. 2016).

Several species completely avoided the OWF (e.g., red-throated divers (*Gavia stellata*) and black-throated divers (*Gavia arctica*)), whereas others (e.g., long-tailed ducks (*Clangula hyemalis*)) only partly stayed away from the OWF area and its direct vicinity. Furthermore, herring gulls, gannets (*Genus: Morus*), guillemots (*Genus: Cepphus*), razorbills (*Genus: Alca*), and divers (*Genus: Gavia*) more or less avoided the area around the OWF. The two most numerous species occurred in lower numbers after construction, as did the blacklegged kittiwake (*Rissa tridactyla*) and northern gannet (*Morus bassanus*). As a result, it can be noted that these species lost a part of their habitat to the OWF (Mendel et al. 2014). Guillemots and razorbills were only seldom observed in the wind farm; thus, the area surrounding the wind farm no longer seems to be suited as a habitat for these species. The shy divers avoid OWF areas as well; therefore, the area available for these species to rest and feed in the North Sea has decreased (Garthe et al. 2013). Nonetheless, thus far there is no evidence indicating whether habitat loss affects the population of certain species.

For foraging, areas both within and outside the OWF appeared suitable for some species. The proportion of lesser black-backed gulls (*Larus fuscus*) searching for food was relatively similar within and outside the OWF area. Actively feeding birds were observed more often within the OWF. A part of the lesser blackbacked gulls fed within Alpha Ventus. This might be a result of the new hard substrate or small-scale turbulence around the wind turbines providing an increased food supply. In the reference area, only a few actively feeding gulls were observed. Overall, foraging appeared to be more common inside rather than outside the wind farm (Garthe et al. 2013).

Some seabird species were even attracted to OWFs. For example, the number of little gulls (*Hydrocoloeus minutus*) increased after OWF construction, and some species (e.g., gulls and tern species) did not hesitate flying into wind farms to forage. Cormorants even used the structures for resting (Dierschke and Garthe 2006). Also little gulls and herring gulls are numerous inside OWFs. Data have shown that approximately 80% of the seabirds in the wind farm are herring gulls (Mendel et al. 2014). The occurrence of the birds is certainly correlated with an increase in the benthic structural diversity and fish as prey (see Sects. 9.2.1 and 9.2.2).

Flight height measurements suggest some overlap between the flight heights of seabirds and the operational height of Alpha Ventus. The animals exhibited different behaviors, from resting within the OWF to flying through it. They were often observed searching for food inside Alpha Ventus. In most cases, their flight altitude was so low that they could not collide with the rotor blades. Only some of the birds flew in the height range of the rotors. Large gulls were exposed to high collision risks (Mendel et al. 2014). At present, it seems difficult to set thresholds for the impairment of the habitats of seabirds by OWFs. Busch and Garthe (2016) therefore present a new approach for assessing displacement impacts of OWFs on seabirds by making the best use of limited data, which is called potential biological removal assessment (PBR).

9.2.3.2 Migratory Birds (Seabirds and Terrestrial Birds)

Millions of migratory birds pass the North Sea area, especially during the autumn and spring. Research was conducted in Germany on how birds are affected during the daytime and at night, when the OWF is brightly illuminated. Migration mainly occurs over the sea at night and partly at rotor height. Coppack et al. (2013) attempted to quantify the collision risk within the rotor-swept zone in relation to overall migration rates. Some birds were measured at the lowest at 200 m, suggesting that a part of migration over the sea occurred at an altitude that would bring birds within reach of the wind turbines (Hill et al. 2014).

Fijn et al. (2015) showed the magnitude and variation of low-altitude flight activity across the North Sea. More than a million radar echoes, representing individual birds or flocks, were recorded crossing a Dutch wind farm annually at altitudes between 25 and 115 m (the rotor-swept zone). The majority of the birds flying in the daytime consisted of gull species, while at night the mayority were migrating passerines. The results of Fijn et al. (2015) are be useful for assessing the consequences of offshore wind farms for birds.

Although there are very few cases of observed collisions with turbines on OWFs, this does not mean that none have occurred. It was not possible to record collisions or count their number; rather, the probability of collision had to be inferred from the frequency of birds recorded in close proximity to wind turbines. The animals took notice of the turbines and avoided the rotating rotors during the daytime and at night.

Forecast models for possible collisions of migratory birds offshore initially lacked an empirical basis. At the beginning of research conducted on the effects of OWFs, the prognosis models were quite mechanical. The calculation of the probability for collisions was primarily based upon the rotor surface and the existence of birds in the vicinity of moving rotors. At that time, little was known about birds' avoidance behavior of the wind turbines. Consequently, it was not easy to predict the risk of collision. Through extensive research in Germany, it was discovered that in daytime migratory birds have a low risk of collision, given that a large proportion of birds avoid the rotating rotor blades. A number of studies support the observation of (species-specific) avoidance behavior with regards to OWFs, especially in the daytime (Diederichs et al. 2008; Grünkorn et al. 2009; Masden et al. 2009; Aumüller et al. 2011; Kahlert et al. 2011; Reichenbach and Grünkorn 2011; Mateos et al. 2011; Plonczkier and Simms 2012; Cook et al. 2012; Coppack et al. 2013; Furness et al. 2013; Hill et al. 2014; Lüdeke 2015; Schuster et al. 2015).

Nevertheless, OWFs also have an attraction effect, especially when they are illuminated at night. Since a significant proportion of migratory birds fly at night, the research concentrated on this issue. The investigations demonstrated that the risk of collision is strongly related to weather conditions, whereby the highest danger exists during times of fog, and poor and abruptly changing weather conditions. This is a result of the fact that migratory birds tend to fly especially low when weather conditions are poor (and therefore at the height of the rotors), while they are simultaneously attracted to the brightly illuminated wind turbines (Hill et al. 2014).

Radar and night-vision cameras proved that the illuminated OWF attracted nocturnal migrating birds, leading to a greater risk of collision. However, such attraction effects might be offset by micro-avoidance in response to rotor movements at some OWFs (Coppack et al. 2013). Birds that migrate nocturnally might be more affected by OWFs. Nocturnal migration is dominated by passerine species (e.g., such as thrushes). Circling flights around illuminated OWFs were observed by radar, thermal imaging, and video cameras. Several technical methods for monitoring were employed, although collisions were only very occasionally detected.

Studies from other sea areas also indicated that the construction of OWFs led to changes in the number and composition of species, as well as migration volumes and flight altitudes (Wendeln et al. 2013). Some studies found that OWFs are barriers in the daytime and that lethal collisions predominately occur at night or during poor weather, while some observed that collisions were more common when good migration weather changed to fog, drizzle or tailwinds. Namely, at night and during poor weather, birds are attracted to lit structures (Hüppop et al. 2006, 2016; Ballasus et al. 2009). Hüppop et al. (2016) estimated that the mortality rate at more than 1000 human structures in the North Sea could reach hundreds of thousands of birds that had collided with turbines. Nevertheless, Schuster et al. (2015) concluded that the fatality rate of migrating birds offshore is lower than expected, due to species-specific avoidance behavior. However, with the current state of knowledge, an exact quantification of the mortality rate of migrating birds colliding with OWFs seems to be not yet possible.

9.2.4 Impacts of OWFs on Bats

Bats are primarily species that inhabit terrestrial environments. Thus, only lately has attention been drawn to the potential effects of OWFs on bats. Only a few species are known to forage and migrate offshore. The investigation of Ahlén et al. (2009) observed the migration behavior of bats offshore, up to 14 km off the coastline, reporting that not only migrants, but also residents had been foraging in the offshore area. Most bats migrate lower than 10 m above the water surface (Ahlén et al. 2009), which is below the rotor swept area. But some bats increased their flight elevation because of an accumulation of insects at the level of the turbines.

Hatch et al. (2013) observed bats flying more than 40 km off the coastline and at relatively high altitudes of over 100 m and sometimes even higher than 200 m above sea level. Migration behavior took place during daylight as well. Bat activity peaked in the month of September and when there were strong tailwinds (Hatch et al. 2013). Sjollema et al. (2014) recorded bats at up to 22 km off the coastline with a mean distance of about 8 km. In two Dutch OWFs, bats of the species *Nathusius pipistrelle* and *Noctule spec* have been detected on autumn nights when there were low wind speeds (Jonge Poerink et al. 2013).

Ahlén et al. (2009) concluded that the risk of collision during migration offshore is likely to be low. During foraging, the risk increased for migrating and resident species, especially close to departure points near the coast and under weather conditions that attract insects. By contrast, Sjollema et al. (2014) declare that OWFs might produce similar collision rates as onshore wind farms. Since 2014, in the German Baltic Sea, which is known for its bat migrating routes (Rydell et al. 2014), bats have been taken into consideration as part of the environmental impact assessment (BSH 2013).

9.2.5 Impacts of OWFs on Harbor Porpoises

In addition to birds, the discussion concerning the environmental impact of OWFs in Germany (in the North Sea) has particularly focused on harbor porpoises (*Phocoena phocoena*). Other mammals, like seals, (at least in Germany) do not yet seem susceptible to the risk of injury or disturbances by OWFs.

The current practice for constructing OWF foundations is pile driving, which is associated with strong impulse noise emissions. Given the sensitive hearing of harbor porpoises, they are at the center of research related to the ecological effects of OWFs and possible mitigation measures (see Sect. 9.3.2).

In German investigations, a greater number of harbor porpoises were detected at distances >10 km from the OWFs than at shorter distances from the installations. Porpoises were displaced by construction at least in the zone of 8–10 km from the wind farms (Gilles et al. 2014). Wahl et al. (2013) also observed that harbor porpoises left the vicinity of winds farm during pile driving. The porpoises' acoustic activity was reduced by almost 100%. After construction, their acoustic activity remained below normal levels for up to 20 h. The displacement time widely varied, from <1.5 h to more than 140 h, with an average of approximately 17 h (Gilles et al. 2014).

An aerial survey by Dähne et al. (2014) showed that ramming without mitigation had effects at up to 20 km from OWF sites. Data from Horns Rev 2 in Denmark revealed the existence of spatial displacement effects up to 18 km from the construction site (without noise mitigation). Using technical mitigation measures, Nehls et al. (2016) studied the effects of OWF construction on harbor porpoises in an area up to 10 km from the sites.

Operation of OWFs has no proven effect on harbor porpoises. Noise effects were validated, although they did not prove to have an effect on the number of harbor porpoises in the vicinity of the OWFs (Gilles et al. 2014). A study by van Radecke and Benesch (2012) describes the operational noise of the OWF as akin to "background noise" at a distance of 100 m from the site. No effect was observed on animals at that distance.

Furthermore, it seems that the operation of OWFs does not appear to affect harbor porpoise density in the long term. Harbor porpoise density in the southern German Bight—with more ten OWFs already installed—increased from 3000 in 2004, when the first OWF was constructed, to 15,000 (Gilles et al. 2009; Gilles et al. 2011; Dähne et al. 2013). Similar increases were observed in neighboring countries (Scheidat et al. 2012; Hammond et al. 2013). The population of harbor porpoises in the entire North Sea is estimated to be >200,000.

Studies have shown that animals return to area around the wind farm within hours or days after pile driving has ceased. The impacts of OWF operation on marine mammals indicated by international research have varied. Increased porpoise detection rates were observed at the first OWF in the Netherlands, probably due to the artificial reef effect (Scheidat et al. 2012) and the absence of ship traffic and fishing (Dähne et al. 2014). Moreover, other studies have shown that operational wind farms are regularly frequented by porpoises, presumably attracted by the increased number of fish around the structures (Reichert et al. 2012). Data from another OWF in the Dutch North Sea, however, did not indicate increased rates of porpoises after the wind farm was built (van Polanen et al. 2012).

Overall, the noise of pile driving has a strong displacement effect on harbor porpoises. This displacement effect was temporary and no long-term impacts on the numbers of porpoises around OWFs could be found (Brandt et al. 2011; Nehls and Betke 2011; Scheidat et al. 2011; Haelters et al. 2012; Haelters and Vanermen 2013; Wahl et al. 2013; Lüdeke 2015; Schuster et al. 2015). Around operating OWFs, the abundance of harbor porpoises was similar to or higher than it was prior to construction of the wind parks (Diederichs et al. 2008; Scheidat et al. 2011; Scheidat et al. 2012; Dähne et al. 2014).

9.3 Strategies for an Environmentally Sound Development of Offshore Wind Energy

Marine Protected Areas (MPA) and marine spatial planning are important management instruments for protecting ecological sensitive sea areas from the construction of OWFs. The abundance of species under special protection (such as rare seabirds and marine mammals) should thus be monitored and special sensitive sea areas need to be identified. Another possibility for protecting marine biodiversity from the construction of OWFs is through alternative foundation methods (like gravity foundations) or technical mitigation measures against underwater noise (like bubble curtains). A measure for minimizing collision risk could be a requirement that lighting is used only when necessary. At present, this seems compatible with existing shipping and aviation security requirements (Hill et al. 2014). Finally, potential impairments or injuries to species that cannot be avoided or mitigated can be offset by marine compensation measures.

9.3.1 Exclusion of OWFs in Areas of High Ecological Priority

The environmentally sound development of offshore wind power should start already in the planning stage of the installations. Inappropriate sites from the ecological perspective should be excluded. One must define the area of the potential effects, as well as the scale and significance of the impacts of construction on population levels (Bailey et al. 2014; Federal Ministry of Environment, Nature Protection and Nuclear Safety 2014). In Germany, large parts of marine areas are already protected. Approximately 30% of the German EEZ is under special protection (see von Nordheim Chap. 46). No feed in tariffs for renewable electricity production are paid for OWFs in these marine protected areas (MPAs). Since 2011 the installations of OWFs is excluded in these MPAs (BSH 2011a, b). Moreover, nature conservation, species protection laws, and legally protected biotopes (after § 30 Federal Nature Conservation Act) outside the marine protected areas should be taken into account. Bearing in mind the main results of German ecological research with regards to OWFs, this should be particularly concentrated on the most relevant impacts of OWFs, namely habitat loss for seabirds and marine mammals caused by construction noise and the potential collision risks for migratory birds. Research and monitoring are important for gaining a better understanding of the ways in which this use of the sea affects the marine ecosystem.

Construction of future OWFs should thus be planned outside important seabird habitats (e.g., of loons) to avoid high collision rates and habitat loss. In accordance with the precautionary principle, corridors between seabird habitats should be left free of wind farms so that birds can safely move between sites. At the spatial planning stage, it seems crucial to avoid dead-end corridors between wind farms. Beyond this, the primary migrating routes of seabirds (e.g., through the Baltic Sea) should be kept free of OWFs.

This is also true for sea areas with a high density of whales, such as harbor porpoises. To this end, a sound abatement against ramming noise was established in Germany to protect these animals. The highest abundance of harbor porpoises has been detected in the early summer months at the Sylt Outer Reef, northeast of the German EEZ (Gilles et al. 2009). Thus, this area has special protection status and the construction of OWFs is strictly regulated (Federal Ministry of Environment, Nature Protection and Nuclear Safety 2014).

9.3.2 Technical Mitigation Measures against Ramming Noise

A number of investigations proofed that marine mammals can be injured or disturbed during the period, when turbines are rammed into the seabed. Most OWFs are constructed by impact pile driving, causing highly relevant underwater noise, which can cause harm, particularly to whales such as harbor porpoises (*Phocoena phocoena*) (Gilles et al. 2014).

Pingers can be used to scare porpoises away from the dangerous area around the pile sites. Seal scarers have been used to displace harbor porpoises up to 7.5 km in the North Sea (Brandt et al. 2013). Another possibility is to start pile driving at a low energy level (a so-called soft start) that gradually increases.

Unless alternative foundations without ramming noise are not state-of-the-art, there is a need for mitigation measures to avoid sound injuries or disturbances that could affect marine mammals (e.g., their fecundity) (Gilles et al. 2014). In Germany, the Federal Ministry of Environment has provided more than €25 million to investigate the possibilities of minimizing the impacts of pile driving, with several technical mitigation measures against noise emissions having been developed.

The hydraulic ramming of the OWF leads to dangerous sound pressure. To avoid direct damage to whales, a threshold of 160 dB SEL at 750 m distance from the OWF was established in Germany. Furthermore, noise mitigation measures were implemented to ensure maximum safeguards for harbor porpoises. These set a limit such that at most 10% of the area of the German North Sea may under sound pressure at one time. Moreover, special protection of the species during particularly sensitive months is foreseen. The application of best available practices and techniques is required to avoid underwater noise (Federal Ministry of Environment, Nature Protection and Nuclear Safety 2014). To date, other countries such as the UK and Denmark have not restricted the employment and in particular the sound emissions of offshore ramming in the same way as Germany has (Lüdeke 2012).

According to precautionary principles for environmental conservation, noise mitigation should be obligatory for pile driving. Noise mitigation techniques like bubble curtains depend on an air barrier or sound-dampening obstacles placed between the pile and the water. The available methods for noise reduction and alternative foundations are as follows (after Lüdeke 2012; Verfuss 2014; Bellmann et al. 2015):

- *Bubble curtains* are the most developed noise mitigation technique, whereby air bubbles are produced over the entire height of the water column by pumping compressed air through a perforated hose (see Fig. 9.2).
- *Large bubble curtains enclose* an entire construction site. Large bubble curtains have proven their efficacy in more than 150 cases, reducing noise by approximately 15 dB up to 750 m. In this way, the sensitive area for a potential injury can be reduced by approximately 98% and the area of disturbance (>145 ΔSEL [dB]) by 90% (Nehls et al. 2016).
- *Small bubble curtains* are used in direct vicinity of a pile. Initial tests of SBCs have shown reductions of up to 14 ΔSEL [dB].
- *Hydro sound damper* is a bubble curtain placed in the vicinity of a pile (within a few meters); air bubbles are replaced by air-filled balloons of different sizes, enabling a possible reduction of up to 13 ΔSEL [dB].
- *Casings* can be made for pile sleeves out of different materials or from hollow steel tubes around the pile. The latter are particularly suited for monopiles. The IHC noise mitigation system is a double-walled steel cylinder with sound-insulated

Fig. 9.2 Bubble curtain against underwater ramming noise at OWF Godewind (© DONG Energy)

connections and an air-filled cavity, allowing a possible reduction of up to 15 ΔSEL [dB].

- *Cofferdams* are based upon the idea of driving the piling in the air rather than in the water (dewatered casing), enabling a possible reduction of up to 20 ΔSEL [dB].
- *Vibratory piling* is a low-noise foundation installation technology limited to the first several meters of the foundation.
- *Offshore foundation drilling* is particularly suited to difficult soil conditions (e.g., rocky seabed) and up to 80 m of water depth. However, in relation to other methods, it is more expensive and requires more time. Several approaches are under development to make offshore foundation drilling more practical.
- *Suction buckets and suction cans* provide an alternative to piles for securing OWFs. The technique is already used by the oil and gas industry. Initial experiences with the erection of wind turbines on bucket foundations already occurred a decade ago. However, the approach has not yet been tested on a full scale and potential risks to the stability of wind turbine substructures have not yet been assessed.

9.3.3 Application of Marine Compensation Measures

9.3.3.1 The Need for Marine Compensation

The Federal Law on Nature Protection in Germany requires that, in cases in which nature is impaired, impact should first and foremost be avoided. If that is not possible, impact to the environment should be reduced or minimized, and lastly compensated measures should be taken. Only if real compensation is not possible, in-lieu fee mitigation in the form of monetary compensation can be granted. However, no compensation is required for offshore wind power until 2017. The model for onshore compensation needs be similarly adopted for marine areas (Lüdeke et al. 2014).

It seems obvious that even with the use of avoidance and mitigation measures, the risk of impact—especially on birds and mammals—will remain. A portion of the remaining impact could be reduced with compensation measures. According to Jacobs et al. (2016), only 7% of the proposed measures in French environmental impact assessments of the effects of OFWs on marine life have the goal of offsetting the predicted degradation of sites containing remarkable biodiversity. The other 93% of proposed measures consist of avoidance, reduction, and monitoring measures.

Compensation measures could perhaps also serve to avoid prohibition pursuant to the European species protection law, for example. For instance, compensation could serve as CEF measures (Measures of Ecological Functionality), thereby functioning as a special form of avoidance. Up until the present, there has been a lack of experiences with marine compensation measures. As compensation measures for OWFs are not yet obligatory, according to national conservation laws, actual marine compensation for OWFs does not yet exist. Nevertheless, many investigations concerning the possibilities for practical implementation of compensation measures have been completed nationally and internationally, with several international agreements (e.g., the Convention on the Protection of the Marine Environment of the Baltic Sea Area (HELCOM), the Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR) and the EU-Habitat Directive) requiring such measures.

9.3.3.2 Real Marine Compensation Measures

Possible approaches to marine compensation exist, which make manifest that marine compensatory mitigation measures are a prerequisite for offshore renewable energy development. In the international context, numerous studies already have been conducted on the creation of marine habitats that have been quite effective. For example, the restoration of sea grass meadows and the creation of artificial reefs have been successfully implemented (Levrel et al. 2012; Hudson et al., 2008; Kilbane et al. 2008; Van Dover et al. 2014). Artificial reefs can be easily created using stones found in the ocean. The turbines of the OWF themselves serve as artificial reefs, thus the OWF represents an in-situ compensation. Experiments with marine compensation measures have therefore already been performed, though most have been realized very close the coast, whereas experiments in deeper water are thus far lacking (Van Dover et al. 2014).

As habitat loss for seabirds and for harbor porpoises are of particular relevance, focus should be concentrated upon compensation measures for these species. A genuine compensation measure was implemented in the German OWF Riffgat with the reintegration of the population of lobsters (Homarus gammarus) on that OWF.

9.3.3.3 Alternative forms of Offshore Compensation: Onshore Compensation of Offshore Impacts or Minimization of Other Marine Impacts

Another approach would be to fulfill compensation measures onshore, as these efforts could support affected species through establishing compensation measures for specific species, for example, in the onshore breeding areas of affected birds. Furthermore, species-specific risks, such as collision risks with grid connections or hunting, could be reduced as a form of compensation. For the harbor porpoises the incidental bycatch, prey depletion or the pollution of oceans, could be decreased as compensation from possible OWF impacts (Lüdeke et al. 2014).

To minimize intensive marine use as a form of compensation could, for example, entail fisheries and shipping companies receiving payment not to use specific sensitive areas. However, because of the competency of the EU with regards to fishing grounds, and because of the status of the International Maritime Organization with regards to shipping, there are legal restrictions to compensation payments for less intensive fishing.

9.3.3.4 Monetary Payment as a form of Marine Compensation

As ultima ratio, marine compensation measures could also take the form of monetary payment. Especially in cases where compensation is disproportionate to impairment, in-lieu fees could replace other compensation measures (Lüdeke et al. 2014). Kyriazi et al. (2015) describe how to coordinate a net gain compensation agreement from the OWF developer to the manager of the marine protected area.

However, the methods for assessing amounts of monetary compensation are still underdeveloped, as they have rarely been applied in Germany or in other countries.

9.3.3.5 Compensation Models

To quantify the necessity for marine compensation, Levrel et al. (2012) attempted to assess impacts according to the loss of ecosystem services. Sylvain (2015) suggests assessing the level of marine compensation payment (e.g., for the impact on fish of the creation of new reefs) using the Visual Habitat Equivalency Analysis. Scemama and Levrel (2016), by contrast, use the Habitat Equivalency Analysis to assess the rehabilitation of marshes as a form of marine compensation to mitigate the effects of nitrate loading on the sea.

Marine compensation measures for certain marine biotopes and onshore compensation measures already exist and should be required as part of the approval procedure for new construction of OWFs. Only in cases where compensation is disproportionate to impact could in-lieu fees replace these compensation measures. There is a need for a consistent, international marine compensation model for offshore wind energy (Lüdeke et al. 2014).

9.3.3.6 Disadvantages and Weaknesses of Marine Compensation Measures

Marine compensation measures alone of course cannot fully offset the impairments of the marine environment by offshore wind farms. Ecologic compensation measures (onshore and offshore) currently have some weaknesses, e.g. of the lack of species-specific real compensation measures and of a consistent compensation model, the frequently occurring problem of inadequate implementation of compensation measures or the time lag effect until the compensatory measure reach its ecological effectiveness. Moreover, if compensation is accomplished by monetary payment, it cannot be guaranteed that the current state of the species will be maintained. This is particularly true if payments are not used to implement for species-specific measures. Marine compensation therefore should only be the last step of the mitigation hierarchy.

Aware of the huge plans for offshore wind energy, the possibility for compensation measures could soon reach its spatial boundaries anyway. Next, before a large-scale use of marine compensation measures can be accomplished, further research on the environmental effectiveness of marine compensation measures is needed (including a long term monitoring).

9.3.4 Conclusions and Future Tasks

Data gathered in Germany and other nations over the last decade has significantly advanced knowledge regarding the impacts of OWFs on the marine environment. Sufficient data exists that assesses certain impacts caused by OWFs, such as the change in habitats for benthic organisms and fish close to OWF foundations, the impact on birds caused by rotating and illuminated wind turbines, as well as the impact on the behaviors of harbor porpoises. Although research is ongoing, some conclusions are fairly clear; for instance, negative impacts mainly affect resting birds, migrating birds, and harbor porpoises during the time of construction. However, there is still a lack of data on the longer-term impacts of OWFs, especially with regards to population levels.

The current challenge is to integrate these findings into future planning processes, licensing conditions, and construction processes, as well as to share this knowledge internationally. The Environmental Impact Assessment approval procedure first has to be updated to include more recently acquired knowledge. Thresholds should be established, especially for the relevant negative impacts on birds and harbor porpoises; otherwise, comprehensive environmental assessments cannot be reflected in approval decisions to erect new OWFs. Unless standardized methods and thresholds are established in Europe and internationally, it will remain impossible for agencies to effectively assess and compare impacts.

Marine spatial planning methods are crucial to ecologically steering the development of the use of offshore wind (Schubert, Chap. 54). Areas with a high abundance of rare or sensitive marine organisms, such as divers or harbor porpoises, should be kept free from the installation of OWFs.

Technical mitigation measures are capable of keeping piling noise beneath the level of sound exposure that causes injuries. These measures should continue to be integrated in construction processes, as has already been undertaken in Germany.

In summary, the adverse impacts of OWFs on marine life can be reduced or, at least partially, avoided by careful and well coordinated planning of the times of year and locations chosen for wind farm installation.

Given that the impacts of OWFs cannot always completely be avoided or properly mitigated by spatial planning and technical mitigation measures, compensation measures (offshore and onshore) provide another option.

The review of offshore data from the last decade shows that environmentally sound development of offshore wind energy and even synergies between offshore wind energy and nature protection seem to be possible, e.g., through the localized cessation of fishing and shipping to develop de facto marine reserves or the creation of artificial reefs.

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