
JENS LÜDEKE
PhD Student
Environmental Assessment and Planning Research Group
Technical University of Berlin
Straße des 17.Juni 145, Sekr. EB-5, 10623 Berlin,
GERMANY
Jens.luedeke@ile.tu-berlin.de

Abstract: This paper presents a synopsis of the effects of offshore wind farms (OWFs) on benthos, fish, resting birds, migratory birds, and marine mammals based on published data collected in Germany during the past 10 years. German data was obtained from the StUKplus project at the Alpha Ventus wind farm and the first 13 OWFs in Germany. These data were validated against international data via a literature search. The results indicate the following effects of OWFs: (1) no negative effects on benthos or fish could be confirmed; (2) some species of birds avoid OWFs, whereas others ignore them or are attracted to them, and significant effects on migratory birds could not be proven; and (3) harbor porpoises were shown to be impacted during construction, although no long-term impacts to porpoises from the operation of OWFs have been proven.

Key-Words: Offshore Wind Energy, StUK, Ecological Impacts

1. Introduction

Offshore wind energy will play an important role in Germany’s future energy supply. There are plans for 15,000 MW of offshore wind energy by 2030. Therefore, 33 offshore wind farms (OWFs) have been permitted in the German Exclusive Economic Zone (EEZ) and more than 2,300 MW of offshore wind energy is already installed.

Few years ago, little was known about the possible impacts of offshore wind energy on the marine environment. However, in the last 10 years, the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety has made efforts to understand such impacts. The ministry invested more than €50 million to establish the first offshore test field (Alpha Ventus) and launch the research initiative at Alpha Ventus (RAVE). The ministry’s current highest priority is to minimize the impact of OWFs on the natural environment by developing mitigation measures against noise emissions.

2. Methods

The first aim of this study was to prepare a synopsis of the effects of OWFs on benthos, fish, resting birds, migratory birds, and marine mammals. The synopsis is based on published data and research. The first source was published data that were collected in Germany during the past 10 years in connection with Alpha Ventus and the first 13 OWFs in Germany. The second source was international published data.

2.1 Data from German Wind Farms

In Germany, wind farm developers have to extensively investigate and predict the impact of a proposed wind farm on the marine environment. The standards for environmental impact assessments (StUK) address monitoring those impacts on benthos, fish, resting birds, migratory birds, marine mammals, bats, and the landscape. Moreover, StUK specifies the methodology for investigating and monitoring impacts on the species of conservation interest. The study design framework for the
environment impact statement (EIS) is a before–after, control–impact (BACI) design. Data sampling is conducted three years before, during, and three years after construction. Monitoring is performed in the affected area as well as in a reference area [1]. Use of the StUK methodology ensures that the quality of an EIS can be proven and that EISs are comparable.

At Alpha Ventus and the first OWFs in Germany, the StUK-mandated ecological monitoring and mitigation measures were supplemented by a large-scale ecological research program, called StUKplus (2008–2014). It covered a larger area at a higher intensity than StUK and incorporated new investigation methods. Furthermore, long-term studies were performed during the OWF operations. In aggregate, RAVE included more than 30 projects conducted by over 50 universities, research organizations, and private companies. It is the world’s largest and most comprehensive OWF-measurement program and has delivered unprecedented, industrial-scale in situ data. Approximately 500 scientific papers, posters, and talks have resulted from RAVE data.

2.2 International Data

To validate the StUK plus results from Germany, the most important international studies were examined, including the results of the metastudy by Schuster et al. [2]. Sources were located using Google Scholar and ScienceDirect. The search terms offshore wind, energy, ecology, and impact were combined with the text searches of keywords for marine and animal life of interest (e.g., (increase) benthos, (increase) fish, migrating/resting bird, and harbor porpoise). International results were compared with the most relevant German results to validate or invalidate the German findings.

3. Results and Discussion

3.1 Impacts of OWFs on Benthos and Mobile Megafauna

Benthos-related research at Alpha Ventus surveyed the benthic fauna in the wind farm and a reference area for three years using a beam trawl and a Van Veen bottom grab sampler. Scientific divers sampled the assemblages of fouling organisms, such as mussels and sea anemones that were colonizing the turbine foundations, and of mobile demersal megafauna. Mobile demersal megafauna were also visually surveyed using belt transects that ranged on the seafloor away from the turbine foundations [1]. The survey showed an increase in endobenthos after construction. The mean species richness did not vary in the reference area but increased in impact locations. These results suggest significant temporal and spatial variation in the benthic community and sediment parameters five years after construction [3].

The OWF created new habitats for hard-bottom-associated mobile demersal megafauna and increased the population. Artificial hard substrata in the marine environment have substantial influence on nearby sediment and inhabiting benthic communities. After construction of the turbine foundations, species richness and biomass of the fouling assemblage increased steadily, reaching a biomass of over 20 kg/m² in the shallow subtidal mussel accumulation. Two years after construction, 100 times more hard-bottom species were present at the foundations than at former soft sediments. The foundation structures were densely and exclusively colonized by young brown crabs, in excess of 2300 individuals inside the OWF in comparison to 29 individuals in the reference areas. Evidently, the foundation structures served as nursery grounds [4]. Extrapolations of the observed densities of the mobile demersal megafauna predict an increase in population size of several hundred percent for some species [5,6].

Divers observed a large number of shells that were not present before the establishment of wind turbines. Moreover, atypically elevated populations for several species were recorded in areas of soft ground without reefs. Three years after the completion of construction, the growth was pronounced; mussels, fleas, crabs, and sea anemone settled in the wind farm. Massive mussel cover was observed around the foundations. Changes in the soil led to changes in species composition, and
increased vegetation attracted larger animals that found new food sources around the foundations.

At Alpha Ventus, it was not possible to clearly distinguish between the impacts of turbine foundations (e.g., import of biomass into the sediment) and processes associated with operation (e.g., recovery of benthic communities after cessation of bottom trawling).

These results from German studies were mirrored in the international research, which showed OWFs, including both the wind turbines and associated activities (e.g., fishery cessation), impacted the population dynamics of benthic species. Another notable result from other European wind farms was a lack of short-term effects on marine soft-bottom benthos and an increase in benthos in the long term [7]. In the Thorntonbank wind farm in Belgium, structural changes in benthic communities were evident six years after construction [8].

In summary, StUKplus researchers concluded that OWFs increase the abundances of benthos inside OWFs [3,5,6]. This hypothesis was supported by international research reviewed in the present study [2, 7–22].

3.2 Impacts of OWFs on Fish

In StUKplus, fish were investigated before and during construction, and during operation of the OWF (inside and outside the wind farm area). All investigations were combined into a multiday, ship-based hydroacoustic survey conducted in an area of 200 km², with Alpha Ventus at its center. The survey was conducted along transects or with a stationary echosounder, and measurements were supplemented by a stationary long-term hydroacoustic measurement system. Net catches with a pelagic trawl showed species composition and size distribution. A statistical model was used to validate the comparison of composition and distribution inside and outside Alpha Ventus. The stomach contents of mackerel were investigated to understand the influence of the wind farm on the feeding behavior of pelagic fish [1].

Pile driving and other construction activities caused construction scaring effects on fish. A relative decline in the abundance of pelagic fish (primarily mackerel, horse mackerel, herring, and sprat) was observed inside Alpha Ventus during construction. Before construction, the hydroacoustic survey showed equal distribution of pelagic fish inside and outside the Alpha Ventus area. During construction, a 40–50% decrease in abundance of pelagic fish was observed in the Alpha Ventus area, compared with the surrounding area. The change was ascribed by Krägefsky [23] to the known sensitive hearing of these species. After construction, abundances of fish and crab were higher at wind turbine foundations than in open areas. Overall, there was an increase in the number and weight of fish after construction. The catches in 2011 were more than twice as productive as those in 2010, and larger fish were caught [24].

After construction, the artificial reef community included fish such as mackerel, striped dragonets, French cod or flatfish, and predatory fish that are rare on pure sand surfaces. Most experts evaluate this artificial effect as positive, as it increases biodiversity. However, some fear the impacts of a change in the benthic and fish communities on a habitat with predominantly sandy soil.

The true impact of an OWF on marine life can only be assessed after several years of operation. The recovery of fish stocks and benthic communities has been recognized so far. This is because of two reasons—the new artificial reef and trawling is prohibited inside OWFs.

As in the case of benthos, StUKplus researchers concluded that OWFs increase abundances of fish inside OWFs [23], and this conclusion was supported by the international research comparison in the present study [15, 21, 22, 25–30].

3.3 Impacts of OWFs on Resting Birds

The North Sea is an area of worldwide importance for seabirds breeding along coasts and for birds that are migrating and wintering. Seabirds can be affected by OWFs in different ways, such as collision, barrier effects, habitat loss, and attraction [31].
Comprehensive studies on resting birds were conducted by Garthe et al. [32]. The methods used were multiple-day, ship-based surveys and aerial surveys in Alpha Ventus and a reference area. Data were collected on seabird distribution, habitat, behavior, and flight heights for species that were abundant or of particular interest. Data from EIA studies of other OWFs were integrated. Flight heights were measured by a rangefinder using a laser, and behavior was observed by boat. Digital aerial surveys used high-definition technology [1]. Red-throated and black-throated divers were selected as species of interest. The most numerous species (lesser black-backed gulls and common guillemots) were also investigated before and after construction to show impacts on abundance.

The results indicated that seabird distribution changed substantially as a result of OWFs. A decline in the overall abundances of most seabird species was noted, but bird behaviors varied.

Several species completely (e.g., red-throated and black-throated divers) or partly (e.g., long-tailed ducks) avoided the wind farm and its direct vicinity. These birds may have lost part of their habitat to the OWF. However, there was no evidence indicating whether lost habitat affected population numbers [33]. The two most numerous species occurred in lower numbers after construction, as did the black-legged kittiwake and northern gannet.

Other seabirds were attracted to the OWF. Little gulls were numerous after construction, and some species did not hesitate to fly into wind farms to forage (particularly gull and tern species) or even to use the structures for resting (cormorant) [31]. For foraging, areas inside and outside the OWF both appeared suitable. For example, the proportion of black-backed gulls searching for food was relatively similar inside and outside the OWF. Actively feeding birds were observed proportionally more often in the OWF area. Half of the lesser black-backed 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 than outside the wind farm [32].

Flight height measurements suggest some overlap between flight heights of seabirds and the operational height of Alpha Ventus. Large gulls were exposed to high collision risks [33]. Avoidances were observed among guillemots, razorbills, and loons. Such information may become relevant for collision risk models [33].

In recent years, guillemots and razorbills were sighted only sporadically in the wind farm; thus, the area of the wind farm is no longer considered a habitat of these species. The shy loons avoid Alpha Ventus; therefore, the resting ground has slightly decreased [32]. Dwarf and herring gulls are numerous inside Alpha Ventus. Data showed that approximately 80% of the seabirds in the wind farm are herring gulls [33]. The occurrence of the birds is surely correlated with the increase of the benthic structural diversity (and of fish as prey) as shown by Gutow et al [34].

Data from OWFs in the Netherland and Denmark confirmed data from Germany in showing habitat loss for some seabirds. In the Dutch wind farm Egmond aan Zee, eiders and cormorants used OWF areas and offshore platforms for hunting fish [8]. Furthermore, monitoring showed that some seabirds were attracted to OWFs and others ignored their presence [35]. Petersen [36] observed attraction to OWFs by gull species and avoidance reactions by divers and, to some extent, guillemots. The avoidance behavior seemed to be dependent on wind farm design elements, such as size and configuration of turbines.

The issue of potential habituation of resting birds cannot yet be answered. At the Horns Rev 1 wind farm in Denmark, no habituation was observed in divers after five or six years. The birds still avoid the area [37]. The effects of ship and helicopter traffic must also be studied more intensively, as these cause disturbances and temporary habitat loss [38]. Species such as divers and sea ducks respond negatively to ship traffic.

StUKplus researchers concluded that OWFs can be positive, neutral, or negative for the abundance of seabirds, depending on the species [33]. This conclusion was supported by the comparison with international research undertaken in this study. International data indicated that some species avoided OWFs, some were attracted, and some were unaffected [39–47].
3.4 Impacts of OWFs on Migratory Birds

Millions of migratory birds pass through the Alpha Ventus area in autumn and spring. Studies investigated how the birds are affected during the day and at night (the OWF is lit). Automated techniques such as radar, camera systems, and recording of species-specific flight calls were used. Some studies used video and heat imaging, as well as various radar systems, to monitor birds that encountered the rotor-swept zone and to record evasive bird movements. The sensors could monitor birds from a fair distance [1].

Migration occurs mainly over the sea at night and partly at rotor height. Coppack et al. [48] attempted to quantify the collision risk within the rotor-swept zone in relation to overall migration rates. Some birds were measured in the lowest 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 [49]. In unfavorable weather conditions (e.g., fog), there is a possibility of collision.

The animals showed different behaviors, from resting inside 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 the birds could not collide with the rotor blades. Only a few of the birds flew partly in the height range of the rotors [33]. No collisions were observed in Alpha Ventus; however, this does not mean that none occurred. It was not possible to count the number of collisions; collision probabilities had to be inferred from the frequency of birds recorded in close proximity to wind turbines. The animals seemed to notice and avoid the rotating rotors during the day and night. The recorded results suggest that Alpha Ventus is not a barrier to large-scale bird migration [33].

Radar and night-vision cameras proved that the illuminated OWF attracted migrating birds, leading to a greater risk of collision for nocturnal migrants. However, such attraction effects might be offset by micro-avoidance in response to rotor movements at some OWFs [48].

Thus, species that migrate nocturnally might be slightly more affected by OWFs. Nocturnal migration is dominated by passerine species (e.g., thrushes). Circling flights were observed around illuminated OWFs by radar, thermal imaging, and video. No collisions could be detected. The total number of observed collisions at Germany’s FINO1 platform (which is of a very different structure than a turbine) was approximately 1000 between 2003 and 2014, with four mass-collision events that caused between 88 and 199 casualties in total (mainly thrushes at night). The number of casualties caused by storms or being eaten by gulls is unknown.

Results from the international literature indicated that the construction of OWFs resulted in changes in the number and composition of species as well as migration volumes and flight altitudes [50]. Some studies found that OWFs are barriers in the daytime and that lethal collisions predominately occur at night or during bad weather, and some observed that collisions were more common when good migration weather changed to fog, drizzle, or tailwinds. At night and during bad weather, birds seem to be attracted by light sources on platforms or wind turbines [51].

Like Alpha Ventus data, international data indicated that different species generally have different reactions to OWFs. International studies showed ducks, geese, swans, waders, auks, fulmars, gannets, little gulls, and kittiwakes or sandwich terns with avoidance reactions. Large gulls of the genus Larus, black-headed gulls, and common gulls were shown to be unaffected by wind farms. Other species (passarine species) are attracted. Some research showed wind-farm-induced deviations in route under daylight conditions, and there was no evidence of attraction during daylight. The 50% reduction in the diversity of migrating birds at Alpha Ventus indicates the dominance of avoidance behavior across species [49].

International data do not allow quantification of the mortality rate of migrating birds that is associated with OWFs.

StUKplus researchers concluded that the fatality rate of migratory species offshore could be lower than expected, due to species-specific avoidance behavior [49]. The international comparison in the present study supports a theory of species-specific avoidance behavior [2, 42, 43, 46, 47, 52–63].
3.5 Impacts of OWFs on Harbor Porpoises and Other Marine Mammals

The current practice for constructing OWF foundations is impact pile driving, which produces strong impulse noise. Thus, given the sensitive hearing of this species, the harbor porpoise is at the center of research related to the ecological effects of OWFs. Limited data is available for impacts on other marine mammals around OWFs, and so the present study focuses on data related to porpoises.

At Alpha Ventus, aerial surveys, static acoustic monitoring, and shipboard line transect sampling were performed to study impacts of OWF construction on marine mammals [64]. The ship survey was accompanied by a towed hydrophone system capable of detecting porpoise echolocation clicks. Investigations were conducted during construction and operation in a sea area of thousands of square kilometers. A habitat modeling project was also conducted, which evaluated the distribution and abundance of harbor porpoises not only in the Alpha Ventus area but around other OWFs in Germany [1].

During construction, more porpoises were detected at distances greater than 10 km from Alpha Ventus than were detected near the OWF, which suggests that porpoises were displaced by construction in the zone within 8–10 km of the wind farm [64]. Wahl et al. [65] observed that harbor porpoises left the vicinity of the wind farm during pile driving, as porpoise acoustical activity was reduced by almost 100%. After construction, the acoustical activity stayed below normal levels for up to 20 h. The displacement time varied widely, from less than 1.5 h to more than 140 h; the average was approximately 17 h [64].

During operation of Alpha Ventus, no effect on harbor porpoises has been proven. Noise effects were validated but did not prove an effect on harbor porpoise abundance around the OWF [64]. A study by von Radecke described 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 [66]. Furthermore, studies showed that the operation of OWFs does not appear to impact harbor porpoise density in the long term. Harbor porpoise density in the southern German Bight increased from 2004 (when the first OWF was constructed) onward from 3000 to 15000 in Germany [67–70]. Similar increases were observed in neighboring countries [71, 72]. The population of harbor porpoises in the entire North Sea is estimated to be higher than 200,000.

Findings of international research on the effects of construction noise on marine mammals are as follows. An aerial survey by Dähne et al. [73] showed ramming without mitigation had effects at up to 20 km. Diederichs [74] showed the effects of OWF construction on harbor porpoises in an area up to 8 km (with the use of technical mitigation measures). The effect gradually decreased with increasing distance. In the area between 5 and 8 km, nearly no effect was observed, and beyond 8 km no consistent pattern could be noted. Data from Horns Rev 2, in Denmark, showed spatial displacement effects up to 18 km from the construction site. Horns Rev 2 did not employ any noise mitigation [46]. This effect had a clear gradient, with more animals being affected with decreasing distance. One study showed the animals returning to the wind farm hours or days after pile driving ceased [3].

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 [75] and the absence of ship traffic and fisheries [73]. Some other studies showed that operational wind farms are regularly frequented by porpoises, presumably in search of the increased fish stocks at the structures [24]. However, data for another OWF in the Dutch North Sea did not indicate increased detection rates of porpoises after the wind farm was built [76].

StUKplus researchers concluded that harbor porpoises leave the area during pile driving (displacement effect) due to the noise, but that this displacement effect was temporary, and there were no long-term impacts on the numbers of porpoises around OWFs. The comparison with international data confirmed the displacement effect of pile driving [2, 70, 77–88] and confirmed that it is temporary [2, 75, 77, 84, 86, 88–90]. International data also showed the abundance of harbor porpoises
to be similar or higher around operating OWFs than before their construction [73, 75, 83, 91, 93].

3.6 Summary of the Relevant Ecological Effects of OWF

As shown above, only parts of the ecological effects seem to be relevant negative impacts. The summary of the results found in the StUKplus research and confirmed by the international research are shown in Table 1.

Knowledge of the effects of OWFs on the marine environment has been considerably advanced by data gathered in Germany over the past decade. Sufficient data exists to assess some impacts, 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, and the impact on the behavior of harbor porpoises. Although some unknowns exist, some findings are fairly clear.

Now, the tasks are to integrate these findings into future planning processes, licensing conditions, and construction processes and to share this knowledge internationally, as has been attempted by Lüdeke 2015 [94]. This review of the past 10 years of research into the impacts of OWFs in Germany and internationally provides strong evidence that sustainable development of offshore wind is possible.

References:


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Tab. 1 Summary on the main results of impacts by OWF

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<th>Migrating Birds</th>
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