The Environmental Effects of Offshore Wind: Literature Review

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November 27, 2019

ENGS 84: The Environmental Effects of Offshore Wind

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Abstract

Offshore wind energy is a relatively new and extremely promising source of renewable energy, as ocean winds are more abundant, stronger, and blow more consistently than land-based winds. As global energy demand rises and climate change accelerates, it will become increasingly necessary to add offshore wind to our national and global energy mix. At the same time, as more offshore wind farms are proposed around the world, we must work to understand the short- and long-term effects of these developments on aquatic ecosystems. While offshore wind farms are often viewed as a net positive for the environment, we must also consider their potential risks and consequences as well. This paper examines existing literature on the environmental effects of offshore wind farms. As turbines have the potential to affect aerial, pelagic, and benthic ecosystems in a variety of climates, it is very difficult to draw conclusions about the greater effects of turbines on marine ecosystems based on only a few recent studies. For this reason, much more work must be done in this field, and offshore wind farms must be continuously monitored to gain a better understanding of their short-term and long-term effects.

Introduction

Offshore wind farms, as we know them today, have only been in existence since the 1990s (Kaldellis & Zafirakis, 2011). Nevertheless, offshore wind is a very promising form of renewable energy, as ocean winds are more abundant, stronger, and more consistent than land-based winds and, therefore, have the potential to provide more energy. There is currently only one operational wind farm in the United States, but there have been many more proposals for wind farms, especially along the Atlantic coast (see Appendix, Figure 1). While offshore wind energy is likely a necessary part of the solution to the growing demand for renewable energy, it is necessary to understand the potential risks associated with offshore wind as well.

Since the Block Island Wind Farm was built in 2016, the U.S. has not constructed any additional offshore wind farms. However, there is roughly between 18 and 23 GW of potential capacity that has been proposed in the states outlined in Figure 1. Most of this is concentrated in the North Atlantic. As shown in the figure, most of the projects are in the early stages of planning and development, but over the next decade, many will likely move forward.

In addition to more projects being added, wind turbine technology is also changing. Improved technology has led to the construction of larger turbines, which harness more energy. Turbines are now able to be built farther offshore where wind is stronger and more consistent, they are less visible from the shore, and there is less overlap with fishing and recreation. Also, engineers have developed a range of turbine foundations, including floating foundations, to reduce environmental impacts and improve the overall structural integrity of the turbines (Konstantinidis & Botsaris, 2016).

The main components of an offshore wind turbine include the three blades, the nacelle (which typically contains a gearbox), and the turbine shaft. Figure 2 illustrates the different types of turbine foundations. Floating wind turbines are beneficial because they allow for less disruption of benthic environments, and they allow for turbines in deeper waters. There is currently only one floating wind turbine in operation, which was built off the coast of Scotland in 2016, and there is a second being built in Portugal (Konstandinidis & Botsaris, 2016). While offshore wind energy is likely a necessary part of the solution to the growing demand for renewable energy, it is necessary to understand the potential risks associated with offshore wind.

Discussion

Impacts on Humans

Because offshore wind farms are typically between 5 and 15 miles offshore, they do not present the same risks to humans as onshore wind turbines might. With onshore wind farms in close proximity to humans, there are concerns that the shadows caused by the rotating turbine blades have the potential to induce epilepsy in high-risk individuals (Harding et al., 2008). There are also concerns that the noise produced by operating turbines can cause sleep disturbance and psychological distress (Bakker et al., 2012). Neither of these risks are relevant for offshore wind turbines because humans do not spend extended periods of time close enough to offshore turbines to hear the noise or see the blade shadows. As more offshore wind turbines are constructed, more surveys and studies should be conducted to assess the effects on humans.

Impacts on Climate

Some studies have found that offshore wind farms may have effects on local climate. Zhou et al. (2012) found that turbulence generated by rotors can create eddies that enhance vertical mixing of momentum and heat, typically leading to a warming and drying of the surface air. Zhou et al. (2012) observed an area in Texas with four onshore wind farms and recorded a 0.724 degree surface temperature increase from 2003 to 2011. No studies have yet confirmed this local temperature increase at the surface of the ocean surrounding wind farms; however, this warming phenomenon could be a possibility at sea.

Impacts on Aerial Ecosystems

One of the most highly-publicized concerns associated with wind turbines in general are their effects on bird populations. In a study of 35 seabird species at a German wind farm, Dierschke et al. (2016) found that 6 of those species strongly avoided the wind farm, 1 species saw a population decrease, 7 species showed no changes, and 3 gull species actually increased in population. The effects on the remaining 18 species were unknown. Some migratory species have been found to take detours around wind farms, which, if flown regularly, can increase the energy expenditure of seabirds. Wind farms obstructing migratory paths may have negative impacts on the reproduction rate, breeding success, and overall health of some seabird species (Drewitt & Langston, 2006).

Deaths caused by collisions with turbine blades are another concern for flying birds. It has been estimated that there were as many as 573,000 bird deaths from collisions with onshore turbine blades in 2012 in North America, and this number is presumably increasing (Smallwood, 2013). Compared to the impacts of land based wind turbines, the direct impacts of offshore wind farms on birds are much harder to track. At the Block Island Wind Farm in the U.S., there is currently no empirical data on fatalities due to collisions; however, researchers are experimenting with sensors and drones to better monitor bird collisions with turbine blades (Berwyn, 2017).

Impacts on Pelagic Ecosystems

There are three main impact categories for pelagic ecosystems: sediment disturbance, electromagnetic fields, and noise and vibration. Sediment disturbance mostly arises during the construction phase of offshore wind turbines. Aside from floating turbine foundations, all other turbines require some form of pile driving during construction, which entails embedding the turbine foundation into the sediment by hitting the tops of the piles with a hydraulic hammer (Ingebrigtsen, 2018). This can be extremely disruptive to local flora and fauna and can suspend sediment into the water column. Too much sediment in the water column can be extremely detrimental for animals with gills, as sediment can clog gills and prevent respiration (Zucco et al., 2006).

Electromagnetic fields are produced by the undersea cables that connect the turbines to the power grid (see Appendix, Figures 3 and 4, Tricas & Gill, 2011). The concern with this is that some electro-sensitive species use electric fields for prey detection, spatial orientation, and navigation. Additionally, some fish use magnetic field detection for migration (see Appendix, Tables 1 and 2 for specific species). Studies conducted thus far have not yet revealed any behavioral changes in fish due to the electromagnetic fields from wind turbines, but more studies are necessary (Zucco et al. 2006).

Arguably the most pressing issue associated with wind turbines and pelagic ecosystems is noise. Background noise in the ocean consists mainly of noise from shipping (which produces sounds under 200 Hz) and noise from sea surface effects (which produces sound between 200 Hz and 10 kHz). Typically, fish hear frequencies from 30 Hz to 1 kHz at a threshold between 63 and 103 dB. Small to medium sized operating wind turbines produce sound between 20 Hz and 1 kHz at 102 and 125 dB, which overlaps almost directly with frequencies fish can hear (Kikuchi, 2010). The greatest noise risk to fish, however, is not from operating turbines, but from wind farm construction. Few studies have investigated the direct impact of offshore piling noise on fish, but using past knowledge of seismic shooting and other similar processes, it is assumed that mortality risk due to construction noise is low, and injuries, deafness, behavioral changes, increased stress, and masking of communication are possible (Zucco et al. 2006). Much more research is needed on this topic.

As for marine mammals, sound measurements and models suggest that the impact range of operational noise emissions on marine mammals is relatively small; however, scientists predict that as wind turbine sizes increase and as the sheer number wind turbines in the oceans increases, operational noise may have negative effects on marine life. Studies conducted thus far have revealed that the construction of wind turbines has an immediate negative effect on the abundance of some species, such as harbor porpoises (Kastelein et al. 2005). While pile driving may inhibit hearing for some animals because of neural/muscular accommodation or distraction by the high sound pressures, Madsen et al. (2006) conclude that due to the short duration and low duty cycle of pile-driving sounds, they are not likely to mask marine mammal communication. The use of explosives to decommission turbines generates intense acoustic impulses that are likely to cause injury and/or hearing impairment to marine mammals at a close range if done with no precautionary measures (Zucco et al. 2006).

Impacts on Benthic Ecosystems

Similar to pelagic ecosystems, the main impact categories for benthic ecosystems are noise and vibration, temperature, and electromagnetic fields. Three separate studies have found that animals such as shrimp, lobsters, and squid have exhibited behavioral changes at 25-400 Hz, 30dB, 10-75 Hz, and 100 Hz, respectively (Lagardere, 1982, Offut, 1970, Packard et al. 1990). At the same time, however, researchers have found that benthic organisms, such as barnacles, mussels, and kelps colonize wind turbines, suggesting that the noise and vibrations from the turbines have no significant effects on the attached fauna (Vella et al. 2001). Krone et al. (2017) examined the mobile demersal megafauna associated with different types of turbine foundations in the North Sea. The study revealed strong evidence that all three observed foundation types (jacket, tripod, and monopile with scour protection) function as aggregation sites and nursery grounds for the edible crab *Cancer pagurus*, which attracts other fish and crustaceans. Researchers and turbine developers are experimenting with designs featuring increased horizontal surface area in order to support the reef effect and increase productivity (see Appendix, Figure 5, Lacroix & Pioch, 2011).

Temperature is a concern specifically when it comes to heat emissions from power cables, which are typically buried under the seafloor. Based on theoretical models, it is predicted that, for a cable buried at 3m below the sea floor, the temperature at 0.3 cm deep would increase by about 0.37 degrees C, but at greater depths closer to the cable, the temperature increase will be much higher (Zucco et al. 2008). Permanent temperature rise potentially leads to changes of physicochemical conditions of sedimentary substrates, by altering, oxygen levels, sulphide profiles, nutrient profiles and bacterial activity (Zucco et al. 2008).

As with pelagic ecosystems, there is a concern that electromagnetic fields from undersea power cables will affect benthic ecosystems as well. While much more research is needed in this field, Tricas and Gill (2011) conclude it is likely that elasmobranchs (including sharks and rays) and decapod crustaceans with high electro-sensitivity can detect electromagnetic fields from AC and DC cables, with a higher sensitivity to DC cables (see Appendix, Tables 1 and 2, Tricas & Gill, 2011). Some decapod crustaceans with high magneto-sensitivity are more likely to detect electromagnetic fields from DC cables. Models of electromagnetic fields from power cables reveal that these fields are limited both vertically and horizontally, thus benthic species are at a greater risk of exposure to these EMFs compared to pelagic species (Tricas & Gill, 2011).

Conclusion

Although offshore wind farms have become widespread in Europe, offshore wind is still a relatively new field, and there is much more research to be done to understand the impacts of offshore wind turbines. After reviewing offshore wind literature, the following areas seem to be the least well understood: seabird collision patterns, the long-term effects of noise pollution on fish and marine mammals, and the effects of artificial reefs on ecosystems.

Based on existing research, noise appears to be one of the highest priority issues with offshore wind, as it has the potential to affect many different species in ways scientists struggle to predict. One mitigation strategy for construction noise is to use bubble curtains, which consist of a wall of bubbles around the pile driving zone to reduce noise levels by up to 30 dB (see

Appendix, Figure 6). Of course, eliminating pile driving altogether is the most effective strategy for reducing construction noise. Engineers are currently experimenting with and improving upon floating wind turbine designs that require no pile driving (see Appendix, Figure 2).

Currently, proposed wind farms in the United States, such as Vineyard Wind off the coast of Martha's Vineyard, are undergoing significant environmental impact assessments to identify and better understand the potential consequences to the surrounding area. While tests like these will reveal important ecological risks, conducting more of these tests is not necessarily the single best solution. More environmental testing means potentially putting offshore wind projects on hold for months or years, which we may not necessarily be able to afford. As climate change is moving at an alarming rate, not incorporating offshore wind farms into our energy grid may be the worst risk of all to the animals and habitats discussed previously. Instead of implementing additional regulations and screenings, we should instead work to create a comprehensive database of marine habitat information that can allow developers, scientists, and policymakers to make quicker, accurate decisions regarding new offshore wind sites. In this way, we can continue moving forward with offshore wind while also protecting marine life.

Appendix

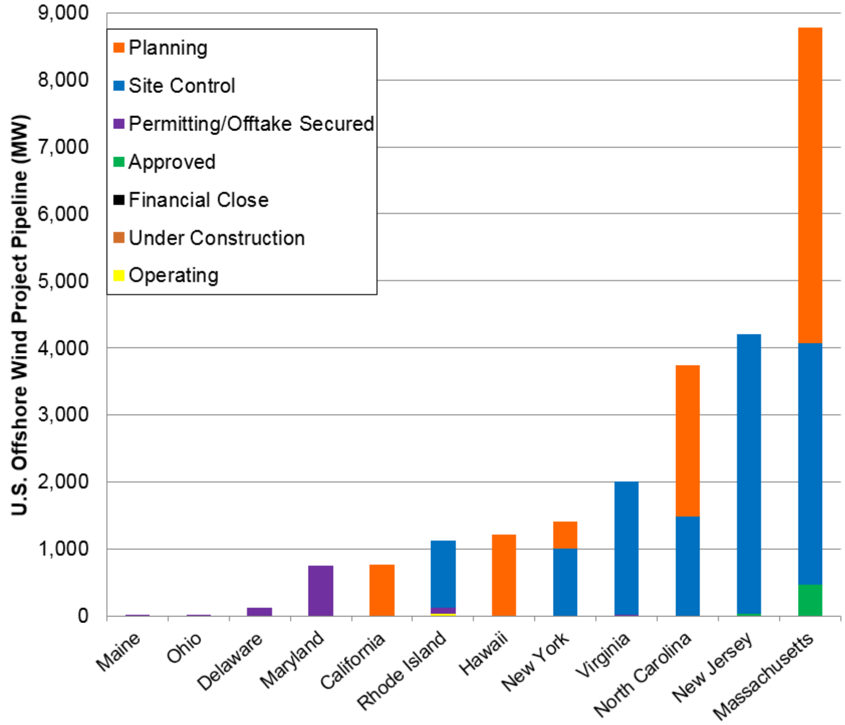

Figure 1: Offshore wind project pipeline in the United States (energy.gov).

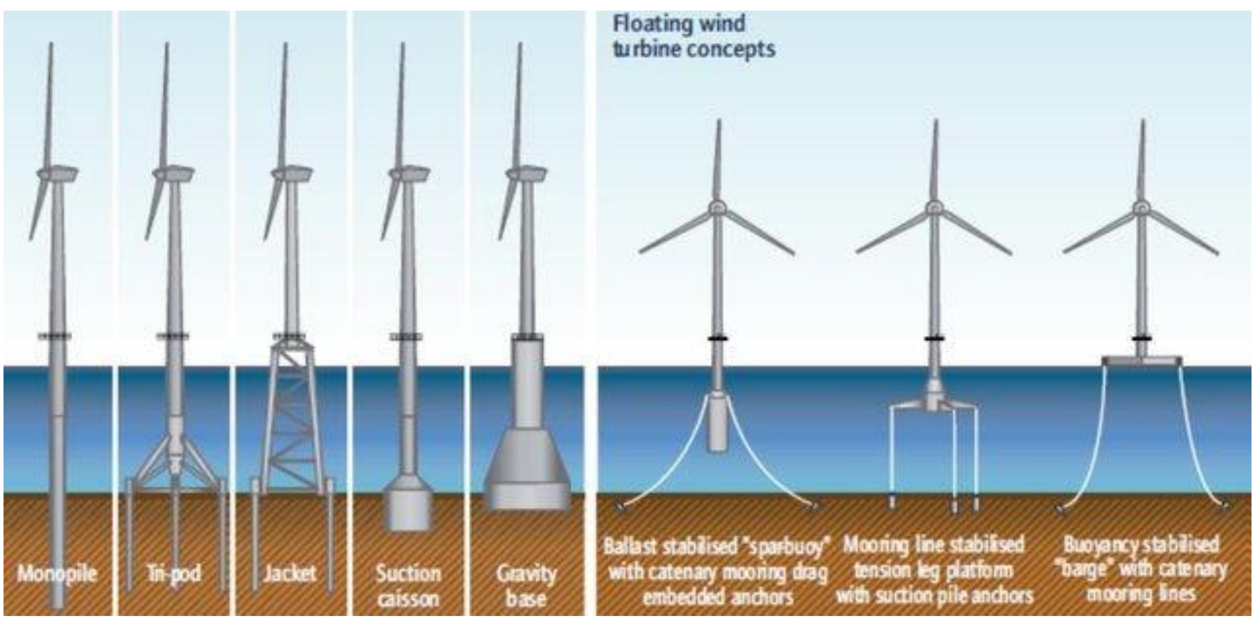

Figure 2: Offshore wind foundation designs (Konstantinidis & Botsaris, 2016).

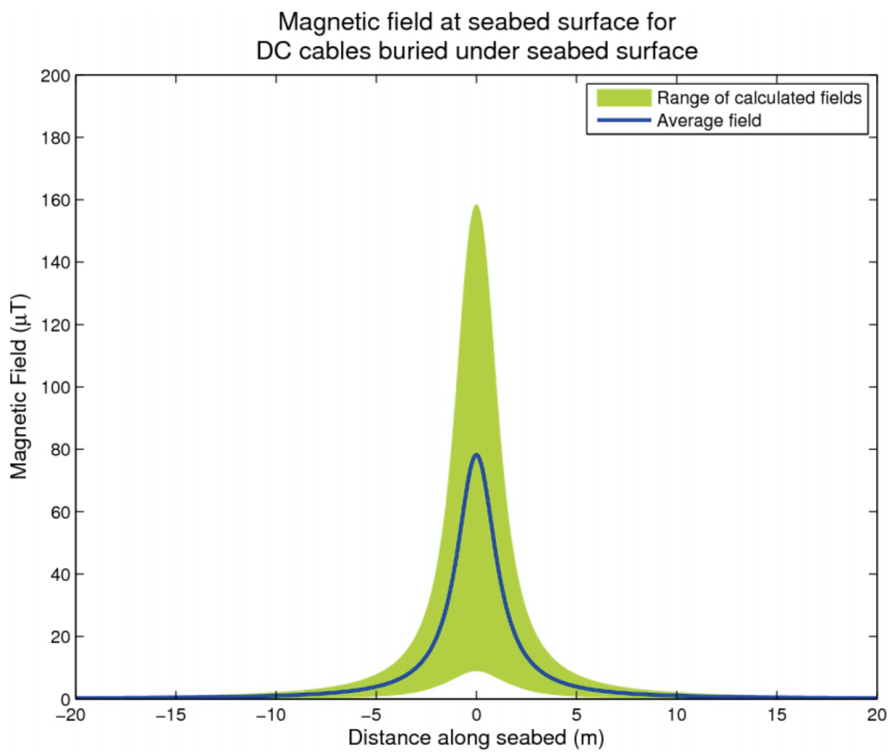

Figure 3: Modeled averaged and range of magnetic field strength at the seabed surface over nine DC cables (Tricas & Gill, 2011).

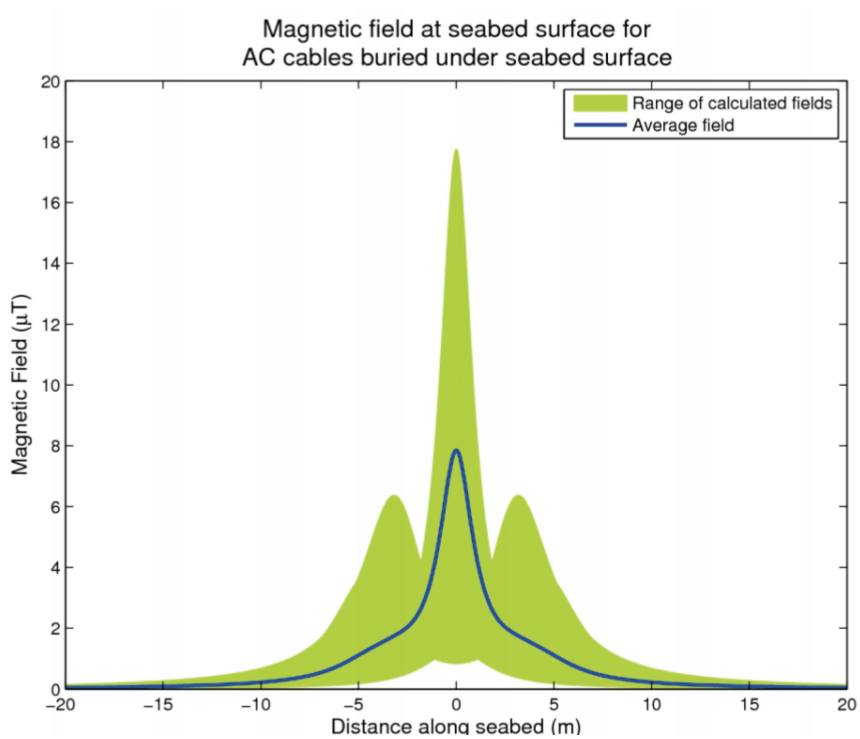

Figure 4: Modeled average and range of magnetic field strength at the seabed surface over 10 AC cables (Tricas & Gill, 2011).

Species	Species Groups	Type of Sensitivity (No. of studies)	Evidence Basis[a]	Life Functions Potentially Affected
Elasmobranchs	Dogfish	None (1)	B	None?
	Nurse sharks	E (1)	B	Feeding, predator or conspecific detection
	Mackerel sharks	E/M? (2)	B, A	Feeding, predator or conspecific detection, navigation
	Cat sharks	E (4)	B, P	Feeding, predator or conspecific detection
	Hound sharks	E (3)	B	
	Requiem sharks	E (4)	B	
		E/M? (1)	B, A	Feeding, predator or conspecific detection, navigation
		None (1)	B	None?
	Hammerhead sharks	E/M (1)	B, A	Feeding, predator or conspecific detection, navigation
		E (1)	B, A	Feeding, predator or conspecific detection
	Torpedo rays	E (1)	B	
	Thornback rays	E (1)	P	
	Skates	E (4)	A, T, P	Feeding, predator or conspecific detection
		E/M? (2)	B, A	Feeding, predator or conspecific detection, navigation
	Stingrays	E (4)	B, T	Feeding, predator or conspecific detection
		E/M (1)	B, P	Feeding, predator or conspecific detection, navigation
		M? (1)	T	Navigation
Other Fishes	Lampreys	E (3)	P	Feeding, predator or conspecific detection
	Ratfishes	E (1)	P	
	Sturgeons	E (2)	B, P	
		E/M (1)	B	Feeding, predator or conspecific detection, navigation
	Eels	E/M (2)	P, B, A	
		M (1)	P	Navigation
	Sea catfishes	E (1)	P, A	Feeding, predator or conspecific detection
	Salmonids	M (5)	B, A	Navigation
		M/E? (1)	P, B, A	Navigation, feeding, predator or conspecific detection
	Cods	E (1)	B	Feeding, predator or conspecific detection
	Scorpionfishes	M (1)	P	Navigation
	Grunts	M? (1)	B	
	Mackerels	M (1)	B, A	
	Righteye flounders	None (1)	No toxicity (M)	
		M? (1)	B	Navigation

Table 1: B = behavioral, A = anatomical, P = physiological, T = theoretical (Tricas & Gill, 2011).

Species	Species Groups	Type of Sensitivity (No. of studies)	Evidence Basis[a]	Life Functions Potentially Affected
Marine Mammals	Baleen whales	M (2)	T	Navigation
	Toothed whales	M (13)	T, B, A	Navigation
		None (3)	T	None
Sea Turtles		M (4)	B, T	Navigation
Invertebrates				
Mollusks	Snails	M(1)	B	Orientation
	Bivalves	None (1)	No toxicity (M)	
		M (1)	P	Uncertain
Arthropods	Isopod	None (1)	No toxicity (M)	
		M (1)	B	Orientation
	Amphipod	M(1)	B	Orientation
	Shrimp	None (1)	No toxicity (M)	
	Lobster	None (1)	P	
	Crayfish	M (1)	P	Orientation
		E (2)	B	Feeding, predator detection,
	Spiny lobster	M (1)	B, A	Navigation
	Crab	None (1)	No toxicity (M)	
Echinoderms	Sea urchin	M (2)	P, embryonic development	Reproduction

Table 2: B = behavioral, A = anatomical, P = physiological, T = theoretical (Tricas & Gill, 2011).

Figure 5: Example of design with increased surface area to promote the reef effect (Lacroix & Pioch, 2011).

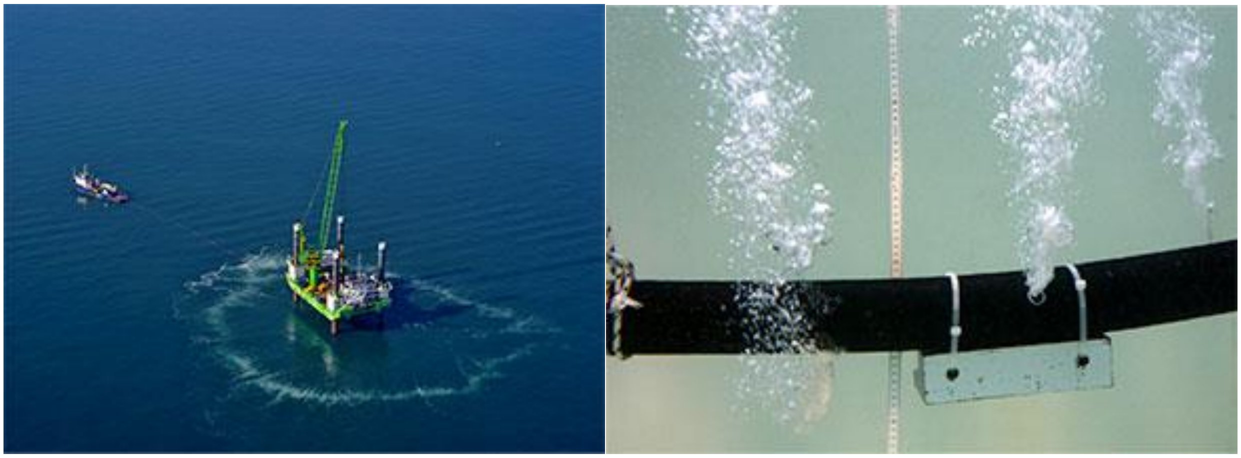

Figure 6: Active bubble curtain around a pile driving installation (left), close-up view of bubble curtain (right) (University of Rhode Island, 2018).

Works Cited

Bakker, R. H., Pedersen, E., van den Berg, G. P., Stewart, R. E., Lok, W., & Bouma, J. (2012). Impact of wind turbine sound on annoyance, self-reported sleep disturbance and psychological distress. Science of the Total Environment, 425, 42-51.

Berwyn, B. (2017, September 29). What America's First Offshore Wind Farm Can Teach Us About Saving Birds. Retrieved November 25, 2019, from https://earther.gizmodo.com/what-americas-first-offshore-wind-farm-can-teach-us-abo-1818965886.

Besio, G., and Losada, M. A. "Sediment Transport Patterns at Trafalgar Offshore Windfarm" Ocean Engineering 35.7 (2008): 653-65. Web.

Dafforn, K.A., Johnston, E.L. & Glasby, T.M. (2009) Shallow moving structures promote marine invader dominance. Biofouling, 25, 277–287.

Dai, K., Gao, K., & Huang, Z. (2017). Environmental and Structural Safety Issues Related to Wind Energy. In Wind Energy Engineering (pp. 475-491). Academic Press.

Dierschke, V., Furness, R. W., & Garthe, S. (2016). Seabirds and offshore wind farms in European waters: Avoidance and attraction. Biological Conservation, 202, 59-68.

Drewitt, A. L., & Langston, R. H. (2006). Assessing the impacts of wind farms on birds. Ibis, 148, 29-42.

Harding, G., Harding, P., & Wilkins, A. (2008). Wind turbines, flicker, and photosensitive epilepsy: Characterizing the flashing that may precipitate seizures and optimizing guidelines to prevent them. Epilepsia, 49(6), 1095-1098.

Ingebrigsten, C. O., & Froese, M. (2018, July 6). A quieter way to construct offshore turbine foundations. Retrieved from https://www.windpowerengineering.com/a-quieter-way-to-construct-offshore-turbine-foundations/.

Kaldellis, J. K., & Zafirakis, D. (2011). The wind energy (r) evolution: A short review of a long history. Renewable energy, 36(7), 1887-1901.

Kastelein, R. A., Verboom, W. C., Muijsers, M., Jennings, N. V., & Van der Heul, S. (2005). The influence of acoustic emissions for underwater data transmission on the behaviour of harbour porpoises (Phocoena phocoena) in a floating pen. *Marine Environmental Research*, *59*(4), 287-307.

Kikuchi, R. (2010). Risk formulation for the sonic effects of offshore wind farms on fish in the EU region. Marine Pollution Bulletin, 60(2), 172-177.

Konstantinidis, E. I., & Botsaris, P. N. (2016, November). Wind turbines: current status, obstacles, trends and technologies. In IOP Conference Series: Materials Science and Engineering (Vol. 161, No. 1, p. 012079). IOP Publishing.

Krone, R., Dederer, G., Kanstinger, P., Krämer, P., Schneider, C., & Schmalenbach, I. (2017). Mobile demersal megafauna at common offshore wind turbine foundations in the German Bight (North Sea) two years after deployment-increased production rate of Cancer pagurus. Marine environmental research, 123, 53-61.

Lacroix, Denis, and Sylvain Pioch. “The Multi-use in Wind Farm Projects: More Conflicts or a Win-win Opportunity?” Aquatic Living Resources 24.2 (2011): 129-35. Print.

Lagardare, J. P. (1982): Effects of noise on growth and reproduction of Crangon crangon in rearing tanks. Marine Biology 71: 177-185.

Langhamer, O. (2012). Artificial reef effect in relation to offshore renewable energy conversion: state of the art. The Scientific World Journal, 2012.

Offut, G. C. (1970): Acoustic stimulus perception by the American Lobster Homarus americanus. Experentia 26: 1276-1278.

Packard, A., Kalsen, H. E. & Sand, O. (1990): Low frequency hearing in cephalopods. Journal of Comparative Physiology 166: 501-505.

Simon, T., Joyeux, J. C., & Pinheiro, H. T. (2013). Fish assemblages on shipwrecks and natural rocky reefs strongly differ in trophic structure. Marine environmental research, 90, 55-65.

Smallwood, K. S. (2013). Comparing bird and bat fatality ‐ rate estimates among North American wind ‐ energy projects. Wildlife Society Bulletin, 37(1), 19-33.

Taormina, B., Bald, J., Want, A., Thouzeau, G., Lejart, M., Desroy, N., & Carlier, A. (2018). A review of potential impacts of submarine power cables on the marine environment: Knowledge gaps, recommendations and future directions. Renewable and Sustainable Energy Reviews, 96, 380-391.

Thomsen, F., Lüdemann, K., Kafemann, R., & Piper, W. (2006). Effects of offshore wind farm noise on marine mammals and fish. Biola, Hamburg, Germany on behalf of COWRIE Ltd, 62.

Tricas, T., & Gill, A. B. (2011). Effects of EMFs from Undersea Power Cables on Elasmobranchs and Other Marine Species.

University of Rhode Island. (2018, December 17). Bubble Curtain. Retrieved November 25, 2019, from https://dosits.org/galleries/audio-gallery/anthropogenic-sounds/bubble-curtain/.

Vella, G., Rushforth, I., Mason, E., Hough, A., England, R., Styles, P., ... & Energy, S. (2001). ASSESSMENT OF THE EFFECTS OF NOISE AND VIBRATION FROM OFFSHORE WIND FARMS ON MARINE WILDLIFE ETSU W/13/00566/REP.

Zhou, L., Tian, Y., Roy, S. B., Thorncroft, C., Bosart, L. F., & Hu, Y. (2012). Impacts of wind farms on land surface temperature. Nature Climate Change, 2(7), 539.

Zucco, C., Wende, W., Merck, T., Köchling, I., & Köppel, J. (2006). Ecological research on offshore wind farms: International exchange of experiences. Part A: Assessment of Ecological Impacts. Bonn.