FISH & INVERTEBRATES

What you should know:

- Climate change is causing oceans to warm. This warming can cause sea level rise and can cause some fish species move to different areas, both of which have widespread ecosystem impacts and impacts to fish and ocean invertebrate species.
- Higher concentrations of carbon dioxide (CO_2) in the atmosphere also makes the oceans more acidic, which makes it difficult for shellfish to build strong shells and puts several types of marine life at risk.
- Offshore wind activities during different phases of project development can have different impacts on fish and species of marine invertebrates (e.g., zooplankton, shellfish, squid). While the impact is temporary, species that live on or just below the ocean floor can be heavily impacted by seabed disturbances during construction. Localized changes to habitat surrounding offshore wind turbines or cables can also have variable impacts.
- Species that communicate using sound can be affected by noise generated during construction (i.e., vessel traffic and pile-driving activities). Technology applications and installation methods can reduce the intensity of noise and mitigate these effects.
- Electromagnetic fields (EMFs) from unprotected submarine power cables can cause short-term changes in behavior in some species. However, these cables are typically buried or protected by rock, which reduces the intensity and localized effects of EMF.
- Construction and development best practices are used to mitigate potential negative effects, and new techniques are being developed to better address these issues. In addition, restorative measures can be taken to return habitats to their original state, and the artificial reef effects of turbine structures often improve localized biodiversity and ecosystem health.

Spotlight Question: How much does EMF affect fish and invertebrates?

Submarine power cables generate electromagnetic fields (EMFs) during the operation of offshore wind farms. Depending on the type and amount of electrical current a cable carries, the cable design, and the proximity of an organism to a cable, EMF emitted by a submarine power cable can have variable impacts on marine life that occupy habitats along a cable route. Alternating-current (AC) and direct-current (DC) power cables that may be used in offshore wind projects produce EMF at different magnitudes and frequencies (Normandeau Associates et al., 2011). Responses to EMF may occur because of exposure, however, an organism must have the sensory ability to detect the EMF produced by these cable types and be close enough to the EMF source. Bottom-dwelling species are likely to be more susceptible to EMF effects than those further up in the water column (CSA Ocean Sciences Inc. & Exponent, 2019). Submarine power cables are thus buried, when practicable, to reduce the potential impacts of EMF by increasing the distance between the EMF source and the organisms present in the vicinity of a cable (Figure 1). To read more about the sea floor and water column, visit Coastal and Marine Habitats.

Some fish and invertebrate species make use of either electric (electrosensitive) or magnetic (magnetosensitive) signals (along with other senses) to locate food, habitats, and spawning areas. These include species such as salmon, eel, sturgeon, tuna, sharks, skates, rays, and lobster (CSA Ocean Sciences Inc. & Exponent 2019). For an organism to sense the EMF emitted by the inter-array or export cables used in offshore wind projects, the intensity and frequency must overlap with that which can be detected by a given electro- or magnetosensitive organism (U.S. Offshore Wind Synthesis of Environmental Effects Research [SEER], 2022a). Some species of fish and invertebrates have been found to be able to detect electric fields up to 25 Hz, which makes detection of an EMF from a DC cable generally operating at a frequency of 10 Hz possible. The detection of an EMF from an AC cable, typically operating at a frequency of 60 Hz, is much less likely (SEER, 2022a).

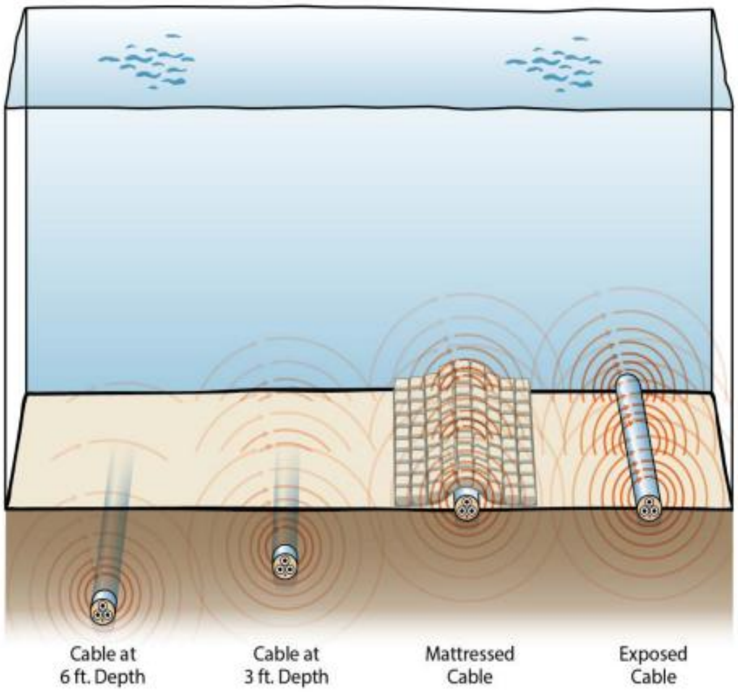

Figure 1. Offshore wind farms cables are typically buried to 6 feet. This figure illustrates the qualitative electromagnetic field (EMF) decay with distance from an undersea power cable from different cable placement scenarios (CSA Ocean Sciences Inc. & Exponent, 2019).

Potential effects of EMF on benthic and demersal fish and invertebrate species can include behavioral responses, altered movement patterns, and physiological effects (Taormina et al., 2018). Temporary alterations in behavior and movement patterns in response to undersea DC power cable EMFs have been observed in sturgeon, skates, and lobster (Wyman et al., 2023; Hutchison et al., 2018). Wyman et al. (2023) noted varied evidence of green sturgeon behavioral responses to EMF from a subsea DC cable, however, no strong negative effects on migratory behavior or success were found. Similarly, Hutchison et al. (2018) reported that biologically significant alterations in movement patterns of both the American lobster and little skate occurred within the cable EMF zone, but that the cable did not act as a barrier to the movements of either species. For marine invertebrates, a synthesis by Albert et al. (2020) reported that temporary behavioral and physiological effects from both AC and DC EMF exposure can occur in crustaceans, echinoderms, molluscs, and polychaetes, but any impacts from these changes at the population level are unidentified.

In an assessment of the effects of EMF from renewable energy cables and devices on the marine environment, Gill and Desender (2020) concluded that biological or ecological effects associated with subsea power cables range from weak to moderate at the EMF intensities associated with marine renewable energy, though further research is still necessary. In a review of potential EMF impacts from undersea power cables on commercial and recreational fish species, CSA Ocean Sciences Inc. and Exponent (2019) found that bottom-dwelling fish were more likely to encounter EMF, with skates having the greatest potential for exposure. However, no evidence of negative impacts from EMF was found for any of the fishery species studied.

While research on EMF in the marine environment continues to progress, EMF detection ranges are not well known for many species (SEER, 2022a). As such, EMF detection or exposure thresholds for marine organisms cannot be established by regulatory agencies. However, consensus based on the available research referenced above generally concludes that any potential effects from EMF generated by offshore wind farms would be minor to negligible at the individual and population levels. To minimize any potential effects of EMF on marine organisms, best management practices adopted by offshore wind developers during export and inter-array cable installation include cable burial, the use of cable protection (rock or concrete blankets) when cable burial is insufficient, and industry standard cable shielding. These measures reduce the amount of EMF that enters the surrounding environment to very minimal levels that individuals may detect, but that are unlikely to affect the health of individuals or population status of marine species.

Key Species

There are different types of fish and invertebrate species that occupy the offshore areas where wind energy projects may be sited. Benthic and demersal species are fish and invertebrates strongly associated with the seafloor; utilizing various seafloor habitats for feeding, spawning, or protection (e.g., skates, flounder, sea scallops, lobster). Pelagic species are those fish and invertebrates that are mostly found in the water column and either migrate long distances or drift with currents (e.g., tuna, sharks, squid, plankton). Plankton (microscopic to < 4 mm organisms that drift with currents) often includes the larval stages of many fish and invertebrate species that have been spawned in, or transported to, the offshore pelagic environment.

Key species found in the Northeast U.S. Outer Continental Shelf (OCS), where a majority of U.S. offshore wind development is planned, have been defined to include fish and invertebrates of commercial and ecological importance. These also include species of cultural importance, particularly those relevant to Tribal Nations. Commercially harvested species such as the Atlantic cod and Atlantic sea scallop, protected species such as Atlantic salmon and Atlantic sturgeon, and ecologically important forage species such as sand lances occur within the Northeast OCS marine ecosystem (Hare et al., 2016), This indicates a potential overlap of these species' distributions with planned wind energy areas off the East Coast.

Two important statutes that focus on the protection and management of species and habitat in the marine environment are the Endangered Species Act (ESA) of 1973 and the Magnuson-Stevens Fishery Conservation and Management Act. The ESA provides a framework to conserve and protect endangered and threatened species and their habitats, both domestically and abroad. NOAA Fisheries (a division of the National Oceanic and Atmospheric Administration [NOAA]) is responsible for the protection, conservation, and recovery of more than 160 endangered and threatened marine and anadromous species under the ESA. The Magnuson-Stevens Fishery Conservation and Management Act is the primary law that governs marine fisheries management in U.S. federal waters. Because offshore wind farm infrastructure is located in coastal areas, state agencies also have a review and management role via the Coastal Zone Management Act and other regulations. For a summary of the role of federal and state jurisdictions with respect to offshore wind, review this Congressional Research Service summary report (CRS, 2023).

Climate Change Effects

Some of the most extreme cases of rise in ocean temperatures due to climate change are projected to occur in waters off the Northeast U.S. (Saba et al., 2016). A major impact of climate change on the world's oceans has been the redistribution of marine organisms. Thermal habitat modeling conducted by Morley et al. (2018) on over 600 marine species, including fish and invertebrates, found that many species are projected to experience future shifts, with distribution moving poleward to cooler waters. Geographic shifts in species distributions can have economic implications, from regional changes in fisheries catch composition (Cheung et al., 2013) to ecological implications when food web dynamics are altered through the introduction or removal of key species (Pörtner & Peck, 2010).

Hare et al. (2016) conducted an assessment on the vulnerability of 82 marine fish and invertebrate species to climate change on the Northeast OCS. Fish species that were found to have very high vulnerability to the effects of climate change included Atlantic salmon, American shad, blueback herring, hickory shad, shortnose sturgeon, alewife, rainbow smelt, Atlantic sturgeon, and winter flounder. Invertebrates with very high climate vulnerability included ocean quahog, bay scallop, and Eastern oyster. Results in Hare et al. (2016) indicate that these species have the highest risk of altered abundance or productivity from the projected climate change impacts over the next three decades. Among ocean ecosystems studied in the region, the Gulf of Maine has experienced some of the fastest rates of warming over the last two decades. This warming has lead the Gulf of Maine to lose some of its subarctic characteristics, causing a decline in stocks of important prey species (e.g., copepods and euphausiid shrimp) and commercially important species near the southern limit of their distribution range (e.g., Northern shrimp, Atlantic cod, and Southern New England American lobster) (Pershing et al., 2021).

In addition, negative climate change impacts include a decrease in shellfish fishery yields due to ocean acidification (Hare et al., 2016). Increased concentrations of CO_2 in the ocean causes it to become more acidic leading to reduced availability of calcium for shell formation in marine organisms. Ocean acidification also eats away at the minerals used by oysters, clams, lobsters, shrimp, coral reefs, and other marine life to build their shells and skeletons. Thus, making these structures thinner or harder to maintain and reducing energy for other life functions like finding food or reproduction (Fabry et al., 2008; Cooley et al., 2015). For more on the effects of ocean acidification on marine life, see the National Oceanic Atmospheric Administration’s (NOAA) webpage on ocean acidification.

Offshore Wind Effects

Any activity that affects the ocean surface, water column, currents, or seafloor has the potential to affect fish and invertebrate species. Offshore wind installation and operation may cause disturbances, via seabed preparation and cable installation, the presence of structures in the water, intakes and discharges, light, and, as is discussed in this section’s Spotlight Question.

Sound

Underwater sound can cause impacts by producing both sound pressure and particle movement. Sounds can be impulsive (usually louder/higher energy, intermittent, and short-term) or continuous (usually softer/lower energy, ongoing, and long-term) (Popper et al., 2022). These types of sound can vary widely in intensity and affect organisms in different ways. Sound sources related to offshore wind (Figure 2) include:

- acoustic site surveys and sediment coring used to investigate the seafloor during site assessment;
- installation sound during foundation pile driving;
- operational sound from rotation and vibration of the wind turbines and;
- sound from the dismantling of wind farm components during decommissioning (Mooney et al., 2020; SEER, 2022b).

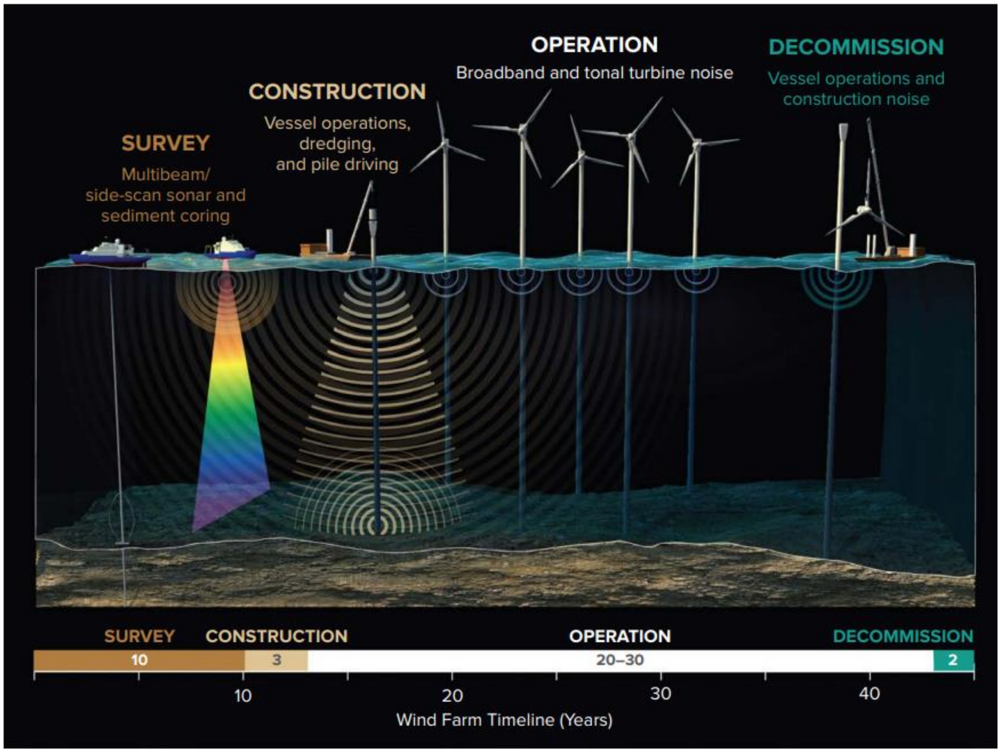

Figure 2. Sources of underwater sound during key phases of offshore wind development (Mooney et al., 2020).

The most intense underwater sound from offshore wind development occurs from impact pile driving. Effects of this intense, impulsive noise on fish and invertebrates can include behavioral changes, physiological injury, and, depending on a species' noise tolerance threshold, mortality (Mooney et al., 2020). Impacts of sound on fish vary depending on a fish's ability to detect sound pressure, the acoustic sensory organ used, and the distance from the sound source (Popper et al., 2014). Impacts from underwater sound diminish with distance from the sound source as seen in Figure 3 (Mooney et al., 2020). Fishes that have swim bladders (i.e., most bony fishes) are more susceptible to injury than those without, as these fishes generally have lower sound pressure thresholds and wider frequency ranges of hearing (Popper et al., 2014; Mooney et al., 2020). Physiological injuries in fish caused by intense, impulsive noise include auditory hair cell loss (Mooney et al., 2020) and damage to hearing tissues and other organs (Popper & Hastings, 2009).

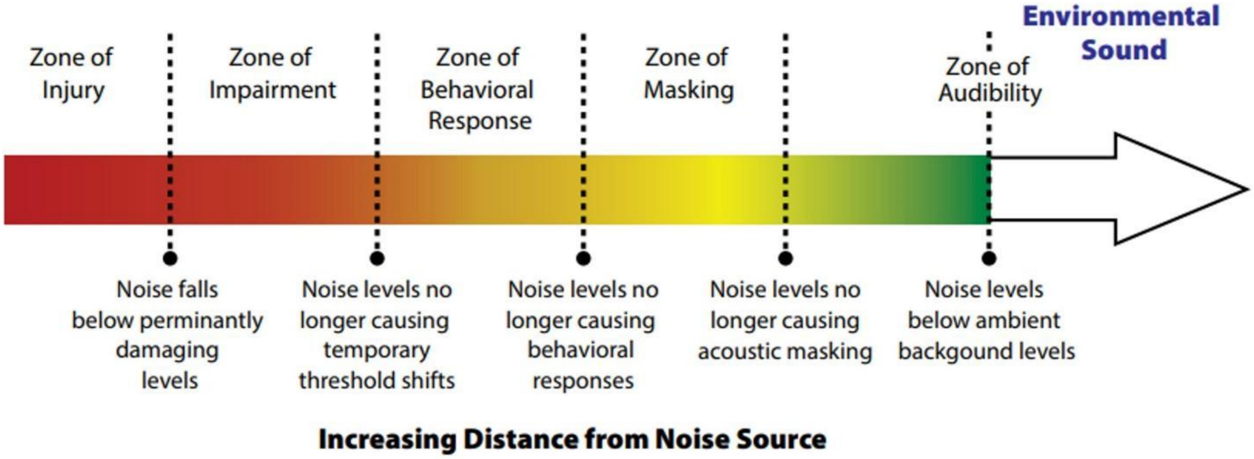

Figure 3. Potential effects of underwater sound with distance from sound source (Mooney et al., 2020).

The low-amplitude sound generated during the operation of wind turbines is not expected to cause physiological injury to aquatic organisms due to its lower sound pressure levels (ICF, 2021). However, continuous sounds, such as vessel noise and turbine operation noise, have the potential to mask auditory cues used by some fish (e.g., biological cues used by soniferous fish such as Atlantic cod during spawning). Masking communication at specific frequencies could disrupt activities such as foraging or breeding (Mooney et al., 2020). To minimize the effects of sound on marine organisms, offshore wind developers use multiple mitigation techniques, including:

- technologies to muffle sound during pile driving, such as bubble curtains, isolation casings, and hydro sound dampeners,
- soft starts for pile driving, where the gradual increase in hammer blow energy allows mobile species to leave the area, and
- time of year restrictions that do not allow sound generating activities such as pile driving when sensitive marine life is present in the project area (SEER, 2022b).

Up-and-coming mitigation technologies for noise effects are discussed in the Mitigation Innovations section below.

Seabed Preparation and Cable Installation

Undersea export cables deliver energy from substations located within the offshore wind farm to substations that connect to the local power grid, while inter-array cables connect turbines to each other. Each wind farm has a designated export cable corridor a few hundred meters wide where cables could be installed (Figure 4).

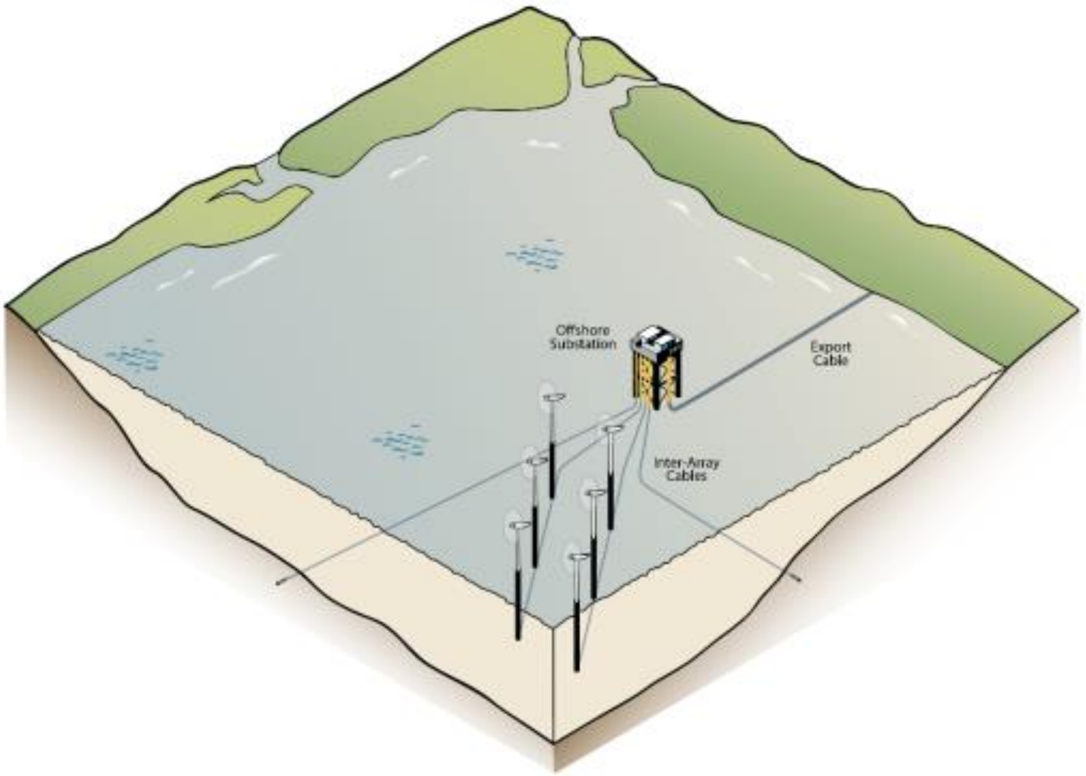

Figure 4. Components of a typical offshore wind energy project (CSA Ocean Sciences Inc. & Exponent, 2019).

Within these corridors developers conduct detailed seafloor mapping to understand the sediments and species present, as the installation of undersea cables can have impacts. Seabed preparation and cable installation activities such as dredging, boulder clearance, trenching, cable burial, and the use of cable protection can disturb habitats, convert habitats from soft-bottom to hard-bottom or vice versa, cause sediment transport and deposition, and cause mortality to fish and invertebrate larvae through entrainment during dredging (unintentional removal of organisms by the suction field created by hydraulic dredgers). While direct impacts to fish and invertebrates may occur during seabed preparation and cable installation, benthic habitat recovery is expected to occur post-construction as documented in habitat disturbance studies in soft-sediment habitats (Dernie et al., 2003), in dredging in the English Channel (Desprez, 2000), in bottom trawling off California (de Marignac et al., 2008), and in the installation and operation of the Block Island Wind Farm in Rhode Island waters (HDR, 2020).

Offshore wind farm developers use best management practices to minimize and monitor impacts to the seafloor during preparation and cable installation, such as:

- cable micro-siting (small siting adjustments) to avoid complex and sensitive habitats,
- relocating boulders to similar boulder habitats and depositing dredged material to areas with similar sediment composition to promote species recolonization,
- employing detailed modeling to assess sediment transport and turbidity impacts (i.e., the amount of suspended sediment particles in the water), and
- conducting benthic habitat and fisheries monitoring surveys to monitor recovery after construction and compare to baseline conditions.

Sand waves and other soft-bottom benthic features on the OCS of the Middle Atlantic Bight are naturally dynamic structures formed by wind-waves and storm-driven currents during sediment mobility events (Dalyander et al., 2013) As such, post-construction recovery of soft-sediment habitats is usually achieved on relatively short timescales due to the dynamic nature of sediments (HDR, 2020). Since the sediment is mobile and habitat is ever-changing, the benthic communities present are generally early colonizers adapted to disturbance. Where disturbing complex habitats cannot be avoided, the recovery of more stable hard-structure-oriented communities could take many years to return to their former composition. Where new hard surfaces are introduced (e.g., cable protection), soft-bottom habitats will be functionally converted to hard-bottom for the life of the project and monitoring of new marine organisms inhabiting these structures would be done instead of assessing recovery.

Presence of Structures in the Water

Hard surfaces and static structures introduced into the marine environment can affect seafloor and water column ecological communities through changes in seabed habitats, artificial reef effects, local current flow alterations, species distribution shifts, and the introduction of invasive species. To learn more about sea floor and water column impacts visit [Coastal and Marine Habitats](#).

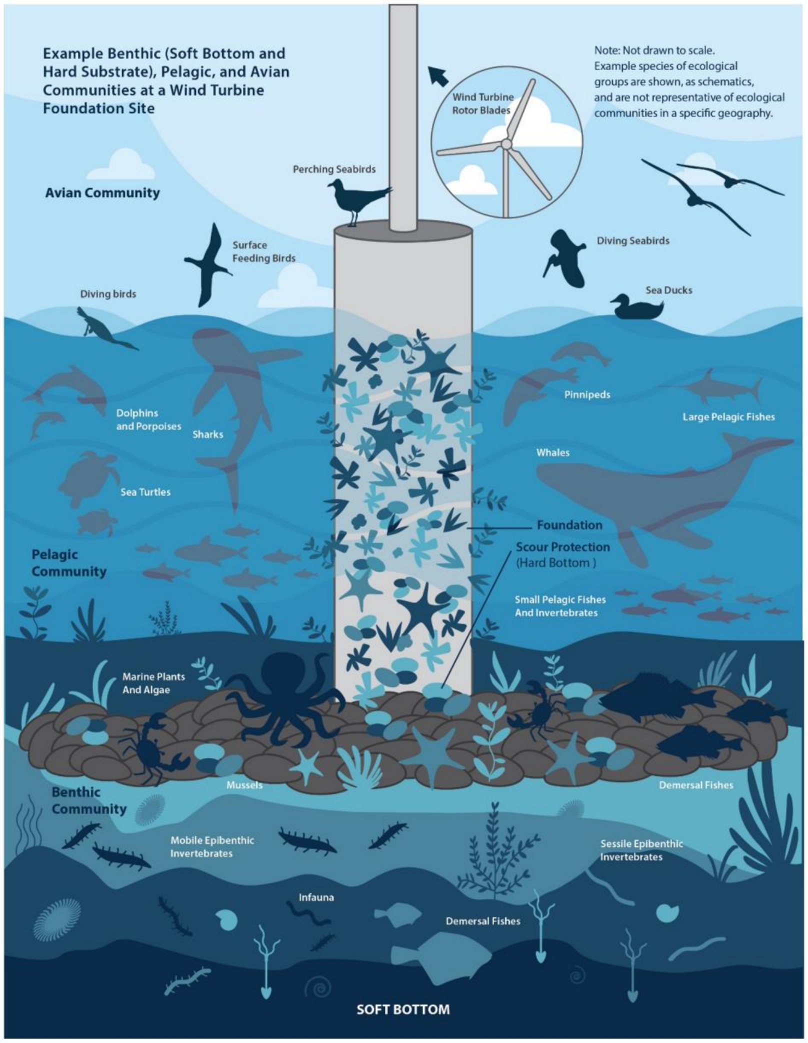

Figure 5. Habitats created by offshore wind farm foundation (ICF, 2021).

Turbine foundations are often protected from the potential weakening effects of moving water through the deposit of large rock piles around the base of turbine foundations, called scour protection. The addition of new hard substrates from turbine foundations and scour protection converts previously soft-bottom substrate (i.e., sandy or muddy sediments of fine grain sizes) into hard-bottom complex substrate (i.e., pebbly, cobbly, or boulder habitat with large grain sizes that provide structural habitat that attracts some species). Conversion of benthic habitat from soft to hard-bottom likely changes nearby benthic communities (Figure 5) since some species prefer hard-bottom while others prefer soft-bottom habitats. Over time attached organisms, such as mussels, barnacles, anemones, and algae, colonize the introduced hard substrates creating new habitats, food webs, and species-interaction pathways around wind farms (De Mesel et al., 2015). A synthesis study on this reef effect of offshore wind farms by Degraer et al. (2020) noted that increased species densities, biological diversity, and biomass have been observed in the soft-bottom communities nearest the turbine foundation. A meta-analysis on finfish abundance at offshore wind farms by Methratta and Dardick (2019), observed an almost universal increase in the abundance of benthic and demersal fish species. Although the reef effect is often considered a net positive, there is the possibility of negative impacts on certain species. If the wind farm area becomes too much of a fishing hot spot or acts as an ecological trap (where a population occupies a suboptimal habitat) there could be decreases in stock size (Vandendreisecche et al., 2013; Reubens et al., 2013). Additionally, turbine foundations can act as a stepping stone for invasive species, which may lead to the displacement of native species of commercial or ecological importance (Kerckhof et al., 2016). More on the reef effect can be found in Mitigation Innovations below, and in Recreational and Commercial Fishing.

Changes in water movement around offshore wind turbines may also affect the local incidence of larval fish and invertebrate species that settle out of the water column onto benthic substrates. Changes in these patterns could potentially affect the availability of food to species higher up the food chain (ICF, 2021). Research funded by the Bureau of Ocean Energy Management (BOEM) has been conducted to better understand the effects of changes in hydrodynamics on larval distribution or settlement due to offshore wind development (Johnson et al., 2021) and more research on the topic is forthcoming. Usually, added structure from offshore wind development is considered to have a net neutral or positive effect on affected ecosystems, primarily from the artificial reef effect (English et al., 2017). However, the level of benefit or impact may vary by species and location (ICF, 2021), and each study area needs to be evaluated to fully understand the potentially short and long-term impacts of the presence of structures in the water column. For offshore wind impacts on ocean hydrodynamics, see the spotlight question in Coastal and Marine Habitats.

Intakes and Discharges

Offshore substations in and near lease areas collect electricity from nearby turbines and relay it to onshore facilities through export cables. Although most early projects are not expected to use high-voltage direct-current (HVDC) converter stations, some current and future offshore substations may employ these types of converter stations which, in turn, will require the use of cooling water intake systems (CWIS). Fish and invertebrate species near these CWIS may be injured or experience mortality from impingement and entrainment within seawater intake pipes. Impingement takes place when organisms are trapped against intake screens by the force of the water passing through the cooling water intake structure. Entrainment occurs when organisms are drawn through the cooling water intake structure into the cooling system. Eggs and larval life stages are the most susceptible to entrainment. Design intake flow at offshore wind converter station CWIS can range between 7 to 10 million gallons per day with a typical intake velocity of 0.5 feet per second (in compliance with EPA velocity-based guidelines on impingement).

Depending on the configuration of the offshore substation, potential impacts can be minimized by restricting CWIS intake velocities, running a single pump during operations, and using variable frequency drives. A modeling study looking into the CWIS entrainment impact on larval dispersal and population dynamics in coastal power plants (White et al., 2010) found minimal effects on the population densities of benthic marine organisms except when the population had been heavily depleted by other factors. The power plant CWIS water intake volume modeled by White et al. (2010) was in the 2 billion gallons per day range which is many orders of magnitude greater than CWIS water withdrawal rates of potential offshore wind converter stations (7 to 10 million gallons per day). While this indicates a minimal entrainment impact from offshore wind converter station operations, more research is needed in assessing the differences in coastal versus offshore effects. In a synthesis review of impingement and entrainment impacts on fish populations caused by CWIS in both marine and freshwater ecosystems, Barnthouse (2013) concluded that such impacts were generally small in comparison to more predominant causes of fish population impairment and ecosystem degradation, including the impacts of overfishing, habitat destruction, pollution, and invasive species.

In addition, as a result of the CWIS cooling process, heated effluent (liquid waste) is released back into the environment at a maximum discharge temperature of 90°F (32.2°C), which may have adverse effects on fish and invertebrates nearby. The area of disturbance from heated effluent varies with local hydrodynamics and the design of the CWIS, but the extent of the thermal plume is generally limited to the immediate vicinity of the HVDC converter station. Modeling studies have been employed by offshore wind developers that plan to use these types of converter stations (e.g., Sunrise Wind, LLC and SouthCoast Wind, LLC) and results have indicated that the warmer HVDC converter station outflow will have minimal effects on surrounding habitats and associated species (Middleton & Barnhart, 2022). Potential impacts to surrounding sea water as part of the use of a converter station CWIS are required to be permitted through the EPA's National Pollutant Discharge Elimination System (NPDES) system.

As previous studies focus mainly on nearshore coastal, estuarine, and riverine ecosystems, identifying and monitoring the environmental impacts of offshore converter stations will be necessary once these facilities are commissioned.

Artificial Light

In accordance with Federal Aviation Administration (FAA) and U.S. Coast Guard (USCG) lighting standards, wind turbine generators and offshore substations will be outfitted with appropriate markings and lighting to prevent collisions with vessels and aircrafts. Work vessels transiting to and from offshore wind farm project areas would also make use of artificial lighting outside of daylight hours. Potential impacts on pelagic fish and invertebrates from artificial lighting at night may include changes in localized movement patterns due to light attraction or avoidance, shifts in distributions in response to altered movement patterns, and behavioral shifts (Marangoni et al., 2022). The degree to which these effects occur is highly dependent on the duration of exposure to light and the depth of light penetration from the ocean surface. Unlike constant light sources, which have been shown to affect behavior and movement (Longcore & Rich, 2004), light sources on wind turbines and work vessels are intermittent and unlikely to provide continuous light-related impacts on fish and invertebrates.

Mitigation Innovations

While some effects may be unavoidable, all potential impacts from an offshore wind project are evaluated within a mitigation framework. The aim is to avoid, minimize, or mitigate adverse effects as much as is feasible.

Sound

As the introduction of noise to the underwater environment can be one of the most harmful effects, many mitigation efforts focus on reducing sound impacts. Recent innovations in isolation casings that minimize noise during pile-driving activities include the IQIP Integrated Monopile Installer (Integrated Monopile Installer - IQIP) and the AdBm Technologies Noise Mitigation System (Technology – AdBm Technologies). The IQIP Integrated Monopile Installer is a double-wall steel casing with a bubble curtain between the casing and the pile that has been tested to reduce noise from pile driving by 13 to 16 decibels (Koschinski & Lüdemann, 2020). The AdBm Technologies Noise Mitigation System surrounds the pile with large arrays of Helmholtz resonators (used to dampen sound) in the form of custom injection-molded blocks that trap air bubbles that absorb sound (Wochner, 2019). On its own, this system can reduce pile driving noise levels by 7 to 8 decibels and can reach 14 to 15 decibels of noise attenuation when used in tandem with bubble curtains (Elzinga et al., 2019). This constitutes about an eight percent reduction in pile-driving noise using a reference sound pressure level of 200 decibels for the pile-driving activity (Reinhall & Dahl, 2011). While underwater sound levels produced during pile driving can vary depending on substrate characteristics, depth, pile diameter, and size of impact hammer, multiple noise abatement systems may also be employed to ensure that noise thresholds are not exceeded during pile-driving activities.

Seabed

Cable protection materials, like EConcrete ECO Mats, have been developed to promote colonization of benthic marine organisms. These interlocking mats are made of ECOncrete Admix and have complex surface textures meant to facilitate colonization (Offshore Applications – ECOncrete (econcretetech.com)). In comparison to smooth-surface concrete blocks, Sella et al. (2021) found increased richness and diversity of nonmobile/attached benthic species and a higher abundance of mobile species where ECOncrete ECO Mats were used. Such innovations can offset some of the habitat disturbance impacts of cable installation.

Reef Effect

Add-on structures that attach to offshore wind turbine foundations have also been developed to promote reef growth, act as shelter for benthic organisms, or provide ecosystem support to specific species through their nature-inclusive designs. Nature-inclusive designs refer to design-integrated add-ons to offshore wind infrastructure (e.g., wind turbine foundation and scour protection) that create suitable habitat for native species or communities (Hermans et al., 2020). Recent add-on structural innovations include the Reef Ball Foundation Layer Cake (Layer Cakes – Reef Innovations) and the Witteven + Bos Cod Hotel (Nature-inclusive designs for offshore wind farms | Witteveen+Bos). In a study of fish colonization on artificial reef structures in the Caribbean, Hylkema et al. (2020) found that fish abundance, biomass, and species richness were significantly higher on artificial reef structures compared to sandy bottom control sites and that the Layered Cake structure type supported the highest fish abundance and fish biomass among reef structures tested (i.e., reef balls and rock piles). The Cod Hotel (Hermans et al., 2020) was designed specifically to accommodate Atlantic cod in North Sea offshore wind farms using a steel gabion basket filled with perforated steel tubes and monitoring funnels. These add-on structures are expected to increase the biomass of Atlantic cod and other fish species around wind turbine foundations by providing spaces that offer shelter for different life stages of fish and increase the abundance of prey items such as small crustaceans.

An excellent resource for learning more about up-and-coming mitigation and monitoring technologies was developed by Working Together to Resolve Environmental Effects of Wind Energy (WREN) and is accessible through the Pacific Northwest National Laboratory's TETHYS website: Wind Energy Monitoring and Mitigation Technologies Tool | Tethys (pnnl.gov).

References

- Albert, L., Deschamps, F., Jolivet, A., Olivier, F., Chauvaud, L., & Chauvaud, S. (2020). A current synthesis on the effects of electric and magnetic fields emitted by submarine power cables on invertebrates. Marine Environmental Research, 159, 104958.
- Barnthouse, L.W. (2013). Impacts of entrainment and impingement on fish populations: A review of the scientific evidence. Environmental Science and Policy, 31, 149–156.
- Cheung, W. W., Watson, R., & Pauly, D. (2013). Signature of ocean warming in global fisheries catch. Nature, 497(7449), 365–368.
- Congressional Research Service (CRS) (2023). Offshore wind energy development: Legal framework. R40175
- Cooley, S. R., Rheuban, J. E., Hart, D. R., Luu, V., Glover, D. M., Hare, J. A., & Doney, S. C. (2015). An integrated assessment model for helping the United States sea scallop (*Placopecten magellanicus*) fishery plan ahead for ocean acidification and warming. PloS ONE, 10(5), e0124145.
- CSA Ocean Sciences Inc. and Exponent. (2019). Evaluation of potential EMF effects on fish species of commercial or recreational fishing importance in Southern New England. U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Headquarters, Sterling, VA., OCS Study BOEM 2019-049. 59 pp.
- Dalyander, P. S., Butman, B., Sherwood, C. R., Signell, R. P., & Wilkin, J. L. (2013). Characterizing wave- and current-induced bottom shear stress: U.S. middle Atlantic continental shelf. Continental Shelf Research, 52, 73–86.
- de Marignac, J., Hyland, J., Lindholm, J., DeVogelaere, A., Balthis, W. L., & Kline, D. (2008). A comparison of seafloor habitats and associated benthic fauna in areas open and closed to bottom trawling along the central California continental shelf. NOAA Marine Sanctuaries Conservation Series ONMS-09-02. Silver Spring, MD.
- De Mesel, I., Kerckhof, F., Norro, A., Rumes, B., & Degraer, S. (2015). Succession and seasonal dynamics of the epifauna community on offshore wind farm foundations and their role as stepping stones for non-indigenous species. Hydrobiologia, 756(1), 37–50.
- Degraer, S., Carey, D. A., Coolen, J. W., Hutchison, Z. L., Kerckhof, F., Rumes, B., & Vanaverbeke, J. (2020). Offshore wind farm artificial reefs affect ecosystem structure and functioning: A synthesis. Oceanography, 33(4), 48–57.
- Dernie, K. M., Kaiser, M. J., Richardson, E. A., & Warwick, R. M. (2003). Recovery of soft sediment communities and habitats following physical disturbance. Journal of Experimental Marine Biology and Ecology, 285–286, 415–434.
- Desprez, M. (2000). Physical and biological impact of marine aggregate extraction along the French coast of the eastern English Channel: Short and long-term post-dredging restoration. ICES Journal of Marine Science, 57(5), 1428–1438.
- Elzinga, J., Mesu, A., van Eekelen, E., Wochner, M., Jansen, E., & Nijhof, M. (2019). Installing offshore wind turbine foundations quieter: A performance overview of the first full-scale demonstration of the AdBm underwater noise abatement system. Paper presented at the Offshore Technology Conference (OTC), Houston, TX
- English, P. A., Mason, T. I., Backstrom, J. T., Tibbles, B. J., Mackay, A. A., Smith, M. J., & Mitchell, T. (2017). Improving efficiencies of National Environmental Policy Act Documentation for offshore wind facilities case studies report. U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs, Sterling, VA., OCS Study BOEM 2017-026.

- Fabry, V. J., Seibel, B. A., Feely, R. A., & Orr, J. C. (2008). Impacts of ocean acidification on marine fauna and ecosystem processes. ICES Journal of Marine Science, 65, 414–432.
- Gill, A. B., & Desender, M. (2020). Risk to animals from electromagnetic fields emitted by electric cables and marine renewable energy devices. In A. E. Copping & L. G. Hemery (Eds.), OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES), 86–103.
- Hare, J. A., Morrison, W. E., Nelson, M. W., Stachura, M. M., Teeters, E. J., Griffis, R. B., et al. (2016). A vulnerability assessment of fish and invertebrates to climate change on the Northeast U.S. Continental Shelf. PLoS ONE, 11(2), e0146756.
- Hylkema, A., Debrot, A.O., Osinga, R., Bron, P.S., Heesink, D.B., Izioka, A.K., Murk, A.J. (2020). Fish assemblages of three common artificial reef designs during early colonization. Ecological Engineering. 157, 105994.
- HDR. (2020). Benthic and epifaunal monitoring during wind turbine installation and operation at the Block Island Wind Farm, Rhode Island — project report. Final report to the U.S. Department of the Interior, Bureau of Ocean Energy Management, Office of Renewable Energy Programs. OCS Study BOEM 2020-044 (1&2).
- Hermans, A., Bos, O. G., & Prusina, I. (2020). Nature-inclusive design: A catalogue for offshore wind infrastructure: Technical report. Technical report no. 114266/20-004.274, Witteveen+Bos.
- Hutchison, Z. L., Sigray, P., He, H., Gill, A. B., King, J., & Gibson, C. (2018). Electromagnetic field (EMF) impacts on elasmobranch (shark, rays, and skates) and American lobster movement and migration from direct current cables. U.S. Department of the Interior, Bureau of Ocean Energy Management, Sterling, VA, OCS Study BOEM 2018-003.
- ICF. (2021). Comparison of environmental effects from different offshore wind turbine foundations. U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Headquarters, Sterling, VA., OCS Study BOEM 2021-053.
- Johnson, T. L., van Berkel, J. J., Mortensen, L. O., Bell, M. A., Tiong, I., Hernandez, B., Snyder, D.B., Thomsen, F., & Svenstrup Petersen, O. (2021). Hydrodynamic modeling, particle tracking and agent-based modeling of larvae in the U.S. Mid-Atlantic Bight. U.S. Department of the Interior, Bureau of Ocean Energy Management, Lakewood, CO., OCS Study BOEM 2021-049.
- Kerckhof, F., De Mesel, I., & Degraer, S. (2016). Do wind farms favour introduced hard substrata species. Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Environmental impact monitoring reloaded, 61-75.
- Koschinski, S. & Lüdemann, K. (2020). Noise mitigation for the construction of increasingly large offshore wind turbines. Report by Marine Stewardship Council. Report for German Federal Agency for Nature Conservation: Bundesamt für Naturschutz (BfN).
- Longcore, T., & Rich, C. (2004). Ecological light pollution. Frontiers in Ecology and the Environment, 2, 191–198.
- Marangoni, L.F.B., Davies, T., Smyth, T., Rodríguez, A., Hamann, M., Duarte, C., Pendoley, K., Berge, J., Maggi, E., & Levy, O. (2022). Impacts of Artificial Light at Night (ALAN) in marine ecosystems–A review. Global Change Biology, 28, 5346–5367.
- Methratta, E. T., & Dardick, W. R. (2019). Meta-analysis of finfish abundance at offshore wind farms. Reviews in Fisheries Science & Aquaculture, 27, 242–260.
- Middleton, P., & Barnhart, B. (2022). Supporting National Environmental Policy Act documentation for offshore wind energy development related to high voltage direct current cooling systems. U.S. Department of the Interior, Bureau of Ocean Energy Management Washington DC., OCS Study BOEM 2022-023.

- Mooney, T. A., Andersson, M. H., & Stanley, J. (2020). Acoustic impacts of offshore wind energy on fishery resources. Oceanography, 33(4), 83–95.
- Morley, J. W., Selden, R. L., Latour, R. J., Frolicher, T. L., Seagraves, R. J., & Pinsky, M. L. (2018). Projecting shifts in thermal habitat for 686 species on the North American continental shelf. PLoS ONE, 13(5), e0196127.
- Normandeau Associates, Exponent, Tricas, T., & Gill, A. (2011). Effects of EMFs from undersea power cables on elasmobranchs and other marine species. U.S. Dept. of the Interior, Bureau of Ocean Energy Management, Regulation, and Enforcement, Pacific OCS Region, Camarillo, CA., OCS Study BOEMRE 2011-09.
- Pershing, A.J., Alexander, M.A., Brady, D.C., Brickman, D., Curchitser, E.N., Diamond, A.W., et al. (2021). Climate impacts on the Gulf of Maine ecosystem: A review of observed and expected changes in 2050 from rising temperatures. Elementa: Science of the Anthropocene 9(1), 1–18.
- Popper, A. N., & Hastings, M. C. (2009). The effects of anthropogenic sources of sound on fishes. Journal of Fish Biology, 75(3), 455–489.
- Popper, A. N., Hawkins, A. D., Fay, R. R., Mann, D. A., Bartol, S., Carlson, T. J., et al. (2014). Sound exposure guidelines for fishes and sea turtles: A technical report prepared by ANSI-Accredited Standards Committee S3/S1 and Registered with ANSI. ASA Press and Springer Press, New York.
- Popper, A. N., Hice-Dunton, L., Jenkins, E., Higgs, D. M., Krebs, J., Mooney, A., et al. (2022). Offshore wind energy development: Research priorities for sound and vibrations effects on dish and aquatic invertebrates. The Journal of the Acoustical Society of America. 151(1), 205-215.
- Pörtner, H. O., & Peck, M. A. (2010). Climate change effects on fishes and fisheries: Towards a cause-and-effect understanding. Journal of Fish Biology, 77, 1745–1779.
- Reinhall, P. G., & Dahl, P. H. (2011). Underwater mach wave radiation from impact pile driving: Theory and observation. The Journal of the Acoustical Society of America, 130(3), 1209–1216.
- Reubens, J. T., Braeckman, U., Vanaverbeke, J., Van Colen, C., Degraer, S., & Vincx, M. (2013). Aggregation at windmill artificial reefs: CPUE of Atlantic cod (*Gadus morhua*) and pouting (*Trisopterus luscus*) at different habitats in the Belgian part of the North Sea. Fisheries Research, 139, 28-34
- Saba, V. S., Griffies, S. M., Anderson, W. G., Winton, M., Alexander, M. A., Delworth, T. L., et al. (2016). Enhanced warming of the northeast Atlantic Ocean under climate change. Journal of Geophysical Research: Oceans, 121, 118–132.
- Sella, I., Hadary, T., Rella, A., Riegl, B., Swack, D., & Perkol-Finkel, S. (2021). Design, production, and validation of the biological and structural performance of an ecologically engineered concrete block mattress: A Nature-Inclusive Design for shoreline and offshore construction. Integrated Environmental Assessment and Management, 18(1), 148–162.
- Taormina, B., Bald, J., Want, A., Thouzeau, G., Lejart, M., Desroy, N., & Carlier, A. (2018). A review of potential impacts of submarine cables on the marine environment: Knowledge gaps, recommendations, and future directions. Renewable and Sustainable Energy Reviews, 96, 380–391.
- U.S. Offshore Wind Synthesis of Environmental Effects Research (SEER). (2022a). Electromagnetic field effects on marine life. Report by National Renewable Energy Laboratory and Pacific Northwest National Laboratory for the U.S. Department of Energy, Wind Energy Technologies Office.
- U.S. Offshore Wind Synthesis of Environmental Effects Research (SEER). (2022b). Underwater noise effects on marine life associated with offshore wind farms. Report by National Renewable Energy Laboratory and Pacific Northwest National Laboratory for the U.S. Department of Energy, Wind Energy Technologies Office.

- Vandendriessche, S., Reubens, J., Derweduwen, J., Degraer, S. & Vincx, M. (2013). Offshore wind farms as productive sites for fishes. Royal Belgian Institute of Natural Sciences, Brussels, pp.153-161.
- White, J. W., Nickols, K. J., Clarke, L., & Largier, J. L. (2010). Larval entrainment in cooling water intakes: Spatially explicit models reveal effects on benthic metapopulations and shortcomings of traditional assessments. Canadian Journal of Fisheries and Aquatic Science, 67, 2014–2031.
- Wochner, M. (2019). Pile driving noise reduction approaches. The Journal of Ocean Technology, 14(3), 146–147.
- Wyman, M. T., Kavet, R., Battleson, R. D., Agosta, T. V., Chapman, E. D., Haverkamp, P. J., Pagel, M. D., & Klimley, A. P. (2023). Assessment of potential impact of magnetic fields from a subsea high-voltage DC power cable on migrating green sturgeon, *Acipenser medirostris*. Marine Biology, 170, 164.