Impacts of Noise from Wind Farm Construction and Installation on Large Whales
A *Brief S*ummary

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Right whales, and other large cetaceans such as humpback, fin and minke whales, are of particular concern regarding the construction and operation of wind turbines because of the relatively low frequency at which they vocalize (Madsen et al. 2006). Baleen whales produce sounds in the frequency range of 10 Hz to 10 kHz, whereas toothed whales produce sounds in the frequency range of 1 to 150 kHz (Richardson et al. 1995). Right whales vocalize in a frequency range of 50 Hz to 2 kHz (Parks & Tyack 2005), with most sounds made between 200 Hz and 900 Hz (Vanderlaan et al. 2003). These frequencies are generally higher than those typical of fin whale vocalizations, but lower than those of humpback whale vocalizations (Clark et al. 2009). Right and other baleen whales use sound for communication, navigation and foraging (Richardson et al. 1995; Tyack 1998; Parks et al. 2007). It is therefore important to understand the impacts of sounds from wind turbine construction and operation on whales, when zoning the marine environment for wind energy development.

Four zones of noise impact on marine mammals have been defined and widely cited: the zone of audibility, the zone of responsiveness, the zone of masking and the zone of injury (Richardson et al. 1995). Audibility refers to the threshold at which a source noise is just detectable to a whale. Responsiveness refers to the whale changing its behavior in response to the source noise. Masking refers to the addition of the source noise to ambient noise that makes whale vocalizations less likely to be detected by conspecifics or other species; this has been defined as an increase by 3 dB re 1 µPa (RMS) of ambient noise (Madsen et al. 2006). Injury refers to source noise characterized by sound pressure high enough to cause direct physical harm or loss of auditory senses; injury-level sound pressure has been identified at 180 dB re 1 µPa (RMS) above ambient noise levels for cetaceans (NMFS 2003). This figure is under debate because it does not take into consideration whether the sound is transient or continuous (Madsen et al. 2006). Further, an experiment showed that a dolphin suffered injury from noise at the 160 dB re 1 µPa (RMS) level (Nachtigall et al. 2003). It is illegal by both state and federal law to “take” a North Atlantic right whale without a permit to do so; a “take” includes harassment (MMPA; ESA) and therefore all of the zones of noise impact listed above, except for the zone of audibility, represent potentially illegal interference with right whales.

A certain level of ambient background noise exists in the ocean, some of which is anthropogenic and some naturally occurring (Nedwell & Howell 2004). Ambient noise at different frequencies comes from different sources. For example, ambient noise between 200 Hz and 50 kHz fluctuates with changing sea state, due to sound from wind, wave action and bubble formation (Knudsen 1948). Contribution of background noise from distant shipping tends to fall around 100 Hz (Wenz 1962). Figure 1 shows the distribution of ambient sound frequencies (Hz) and sound pressure (dB re 1 µPa (RMS)) (Wenz 1962; Nedwell & Howell 2004). In addition to ambient noise, background noise must be considered. Background noise refers to noise sources such as local shipping and boat traffic, and any noise produced locally by marine life, humans and/or man-made structures in the water (Nedwell & Howell 2004).

Lastly, water depth and bottom type must be considered for evaluating potential impacts of wind turbines on the acoustic environment. Sound can only propagate through water if the wavelength is less than or equal to 4 times the water depth; for soft sediment bottom types the cut-off frequency is often higher (Madsen et al. 2006).

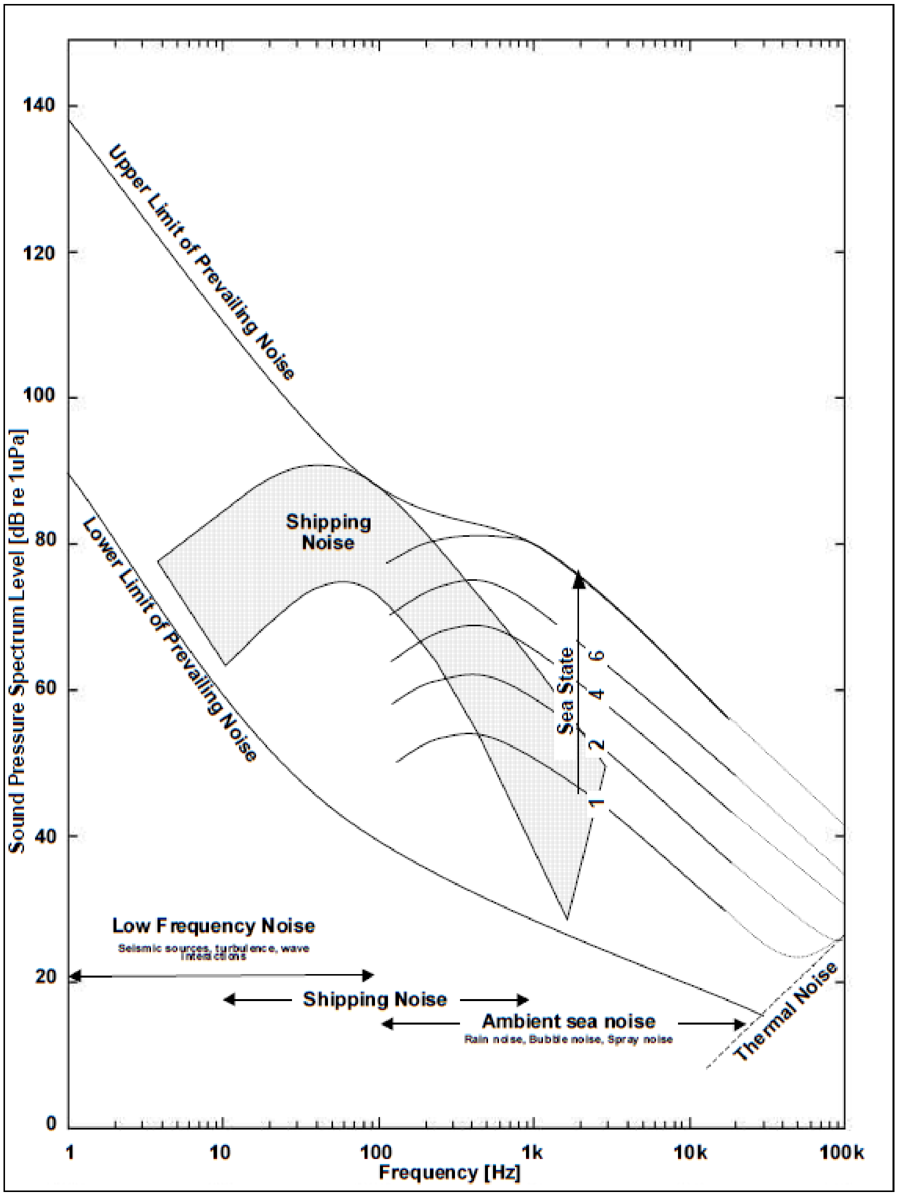

Figure 1. The composition of ambient ocean noise; from Nedwell & Howell 2004; adapted from Wenz 1962.

The different phases of wind energy facility development are characterized by different noise sources. Initial surveys will increase small boat traffic in an area, adding to background noise. Construction of the facilities includes larger and more sustained ship traffic, turbine installation, dredging and other activities. Turbine operation introduces sound and vibration over prolonged periods while the facility is in use. Finally, decommissioning of the facilities again increases background noise from large vessel traffic, and noise sources from any removal of equipment. This review will focus on construction and operation of wind energy facilities, though the initial and final phases of the wind farm life-cycle should also be considered.

Noise from the installation of turbine bases depends upon the type of base to be used. For monopile bases, noise varies based upon size of the monopile, the sediment type, and the force required to drive the monopile into the seafloor (Rodnkin & Reyff 2004). One example from a large pile-driving unit resulted in noise with a frequency concentration below 500 Hz and sound pressure levels above 300 dB re 1 µPa (RMS) at 100 m distance (Anonymous 2001). Another instance recorded the driving of a 4-meter monopile into the seafloor at above 200 dB re 1 µPa (RMS) at 1 meter, with a frequency concentration between 100 and 1000 Hz (McKenzie-Macon 2000). It usually takes several hours to drive one monopile, and strikes are usually at an interval of around 1 strike per second (Madsen et al. 2006).

There have been no studies to date on the direct effects of pile-driving on right whales. The most equivalent information available is data on the reactions of bowhead whales to airgun shots underwater. The studies suggest that right whales (closely related to the bowhead whale) will avoid airgun shots (similar to the strike of a hammer on a monopile) at a distance of approximately 20 km and sound pressure above 120 dB re 1 µPa (RMS) (Richardson et al. 1999). Given the intensity of source sound during pile-driving, and the avoidance behavior observed in other large baleen whales (in this case bowhead) in reaction to underwater airgun noise, the installation of monopiles is of critical concern to the acoustic environment for right and other large whales, as it will likely cause injury at close proximities and responsiveness at up to 20 km away.

Pile-driving is of particular concern because it is widely used for turbine base installation and because it may cause acute negative effects in cetaceans (Madsen et al. 2006). Other activities that may be associated with the construction of wind turbines include: drilling, dredging, gravity support structure installation, rock laying, trenching, and turbine support structure installation. There is insufficient information to document the source noise from gravity support structure installation, rock laying, trenching, and turbine support structure installation. The noise data associated with pile-driving, drilling and dredging activities are summarized from Nedwell & Howell (2004) in Table 1.

Activity	Dominant Frequency	Sound pressure (dB re µPa)	Distance (m)
Pile-driving	100-1000 Hz	approx. 200	1
Drilling	1-5 Hz	approx. 120	115-259
Dredging	20-1000 Hz	approx. 140	200

Table 1. summary of turbine construction activities and characteristics of their associated noise (summarized from Nedwell & Howell 2004); these data summarize a limited sample size and are by no means exhaustive; exact noise levels are highly variable depending on equipment, bathymetry, substrate and other environmental conditions.

Wind turbine operation also creates noise that may affect right whales and other cetaceans. Noise from operating turbines can reach a marine mammal through an initially waterborne, airborne, or substrate-borne path. Aerodynamic vibrations caused by the rotating blades travels through the air before reaching the water and then the animal. Vibrations from the structure itself will enter the water directly. Vibrations from the nacelle (the housing for the energy generating components of the turbine) will depend upon mechanical refinement and construction, and will transmit down the structure, becoming waterborne noise, as well as through the air. Vibration from this source may increase over time as the mechanical components wear. Vibrations transmitting from the base of the turbine must propagate through sediment before becoming waterborne; therefore these noise levels also depend upon substrate composition. Generally, sounds produced from operating turbines are harmonics of the rotational frequency of the blades (Nedwell & Howell 2004).

Due to the factors outlined above, there is great variation in the noise produced from operating turbines. Only a few studies have been conducted on operational turbine noise and each has a number of caveats (Nedwell & Howell 2004). The results of these studies are summarized in Table 2. There have been very limited numbers of studies of baleen whales' reactions to low frequency noise, comparable to that emitted from an operating turbine. One study showed that North Atlantic right whales will react to a modulating alert sound at 500 to 4500 Hz at a receiving sound pressure of 134 to 148 dB re 1 µPa (RMS) (Nowacek et al. 2004). Another study showed that bowhead whales react to playbacks of noise at sound pressure as low 110 dB re 1 µPa (RMS) (Richardson et al. 1995). A review paper concluded that North Atlantic right whales may respond to wind turbine operational noise at distances up to a few kilometers away, in a quiet habitat (Madsen et al. 2006).

Location	Turbine power	Foundation type	Wind speed (m/s)	Peak frequency (Hz)	Sound pressure (dB re µPa)	Distance (m)	dB above background noise	notes	Citation
Sweden offshore	220 kW	unknown	6 12	16 8 and 16	102 113 (for 16 Hz)	100	unknown	16 Hz noise remained similar levels above background noise regardless of wind speed	Westerberg 1999
Denmark offshore	450 kW	Concrete gravity	13	25	119	20	33	noise up to 400 Hz documented	Degn 2000
Sweden offshore	550 kW	Steel monopile	13	160	95	20	25	noise at background levels at 63 and 630 Hz	Degn 2000

Table 2. Summary of known operational turbine noise data from Nedwell & Howell (2004).

Based upon limited current information regarding noise from the installation and operation of offshore wind turbines, it appears that the greatest acoustic risk to right whales and other large whales comes from the installation of wind turbines compared with their operation (Madsen et al. 2006; Nedwell & Howell 2004). It is advisable to enact time-of-year restrictions for the construction and decommissioning of wind turbines; decommissioning requires activities that produce similarly acute, high pressure sounds as does installation (Nedwell & Howell 2004). It seems that the amount of noise produced by the operation itself is highly variable depending upon the turbine type and construction; this noise appears to be more likely to alter behavior of large whales, rather than injure them. It should be noted, however, that some recorded frequencies of operating turbines do fall within the vocalization range of the North Atlantic right whale and that cumulative effects of operational noise are unknown.

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