Bachelor’s Thesis

Energy and Environmental Engineering

2025

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Underwater noise from the construction phase of offshore wind parks

TURKU AMK

TURKU UNIVERSITY OF APPLIED SCIENCES

Bachelor’s Thesis | Abstract

Turku University of Applied Sciences

Energy and Environmental Engineering

2025 | 34 pages

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Underwater noise from the construction phase of offshore wind parks

The potential for offshore wind energy as part of the energy transition is growing rapidly. The construction phases of offshore wind farms generate harmful underwater noise, but its effects on the marine environment have not been fully understood.

The aim of this thesis was to gather current knowledge through a literature review on the noise levels during the construction phases of offshore wind parks and the effects of underwater noise on the marine environment. Based on the literature review, an assessment was conducted on the construction phase impacts on the marine environment of the Eolus Offshore Finland Oy’s Navakka Offshore AB wind park project.

Underwater noise can affect marine animals by masking important environmental sounds and communication and by causing hearing damage and behavioral changes, as well as physical injuries. The nature and levels of underwater noise vary depending on the construction phase. Pile driving and explosions generate impulsive noise, while increased vessel traffic raises continuous low-frequency noise throughout the construction process. At its most severe, underwater noise can lead to direct or indirect mortality of marine animals. However, mitigation measures can reduce construction phase noise levels and minimize its impact on the marine environment.

Keywords:

offshore wind energy, underwater noise, marine construction, environmental impacts

Opinnäytetyö AMK | Tiivistelmä

Turun ammattikorkeakoulu

Energia- ja ympäristötekniikka

2025 | 34 sivua

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Vedenalainen melu merituulipuiston rakentamisvaiheesta

Merituulivoiman hyödyntäminen osana energiamurrosta on voimakkaassa kasvussa. Merituulipuistojen rakennusajan työvaiheista syntyy haitallista vedenalaista melua, jonka vaikutuksia meriympäristöön ei kuitenkaan ole tutkittu vielä kattavasti.

Työn tavoitteena oli kerätä kirjallisuuskatsauksen avulla tämänhetkinen tieto merituulipuiston rakennusvaiheen eri melutasoista ja vedenalaisen melun vaikutuksista meriympäristöön. Kirjallisuuskatsauksen tuloksien pohjalta arvioitiin Eolus Finland Oy:n Navakka-merituulivoimahankkeen mahdollisia rakennusaikaisia vaikutuksia meriympäristöön.

Vedenalainen melu voi vaikuttaa merieläimiin peittämällä tärkeitä ympäristön ääniä ja kommunikaatiota, aiheuttaa kuulovaurioita ja muutoksia käyttäytymisessä, sekä fyysisiä vammoja. Vedenalaisen melun luonne ja tasot vaihtelevat rakennusvaiheen mukaan. Paalutuksesta ja räjäytyksistä syntyy impulsiivista melua, kun taas lisääntynyt laivaliikenne nostaa matalataajuisempaa jatkuvaa melua koko rakennusprosessin ajan. Vakavimmillaan vedenalainen melu voi johtaa merieläinten kuolemaan suoraan tai välillisesti. Lievennyskeinoilla voidaan kuitenkin vähentää rakennusvaiheiden meluhaittoja ja pienentää niiden vaikutuksia meriympäristöön.

Asiasanat:

merituulivoima, vedenalainen melu, rakentaminen merialueella, ympäristövaikutukset

Table of contents

Abbreviations and glossary

Frequency weighting	Adjusting the sound frequencies to match the sensitivity of the receiver's hearing (NPL 2014, 16).
Peak sound pressure	Maximum sound pressure for a period of time, expressed in pascals (Pa) (NPL 2014, 12).
RMS	Root mean square sound pressure, an acoustic metric that describes the average sound pressure over a time period, measured in pascals (Pa). (NPL 2014, 12.)
SEL	Sound Exposure Level represents the sound exposure expressed in decibels, using a reference value of 1µPa²s (NPL 2014, 18).
Sound exposure	Describes the total amount of sound energy received in a given time in units of pascal squared seconds ($Pa^2 \cdot s$) (NPL 2014, 13).
SPL	Sound Pressure Level is a measure of sound pressure expressed in decibels, using a reference value of 1µPa (NPL 2014, 17–18).

Introduction

In the ongoing energy transition, the focus is now on renewable energy sources, with increasing attention being turned towards offshore wind energy. Finland aims to significantly increase its electricity production from renewable energy sources, supporting both the EU's 2050 climate neutrality target and Finland's more ambitious goal of carbon neutrality by 2035. (Ministry of Economic Affairs and Employment 2024, 7,11.) While the environmental impacts of onshore wind energy have been more studied, the impact of offshore wind farms and its effect on marine environment is still understudied and not fully understood. The impulsive and continuous noise produced during the construction period and in the operational phase should be further studied in order to understand its impact on the underwater environment and identify potential negative effects.

Underwater noise is known to be capable of disrupting the communication of fish and marine mammals, which can lead to disturbance and changes in their behavior. Species that rely on sound when locating food also suffer from the harmful effects of noise pollution. Strong impulsive noise, such as from pile driving, may even cause physical damage, such as temporary or permanent hearing loss. (OSPAR 2009, 26–27; Tougaard 2021, 7–8.)

The thesis has been commissioned by Eolus Offshore Finland Oy, a renewable energy project developer with offshore wind projects in the Baltic Sea. Eolus states that it is committed to identifying and reducing the negative impacts of offshore wind energy on the marine environment and to raising awareness of these impacts in the Baltic Sea region. (Eolus n.d.).

This thesis examines the underwater noise generated during offshore wind farm construction and its impacts on the marine environment through a literature review

The four main research questions identified:

1. What are the expected noise levels from the planned activities?

2. How does the underwater noise change during the different stages of offshore wind farm construction?

Various stages produce different kind of noise, with intense impulsive noise often occurring at the beginning of the construction process. Marine traffic during the construction and operational phases also causes noise pollution

3. What are the environmental impacts of the generated noise?

By examining the noise levels and quality, it can be estimated whether they have effects on the surrounding marine environment and its inhabitants. This analysis helps to identify the potential construction stages causing noise disturbance that may require addressing.

4. How can the effects of noise be mitigated? What are the best available techniques and relevant methods to reduce the negative impact in marine environment?

The research consists of two main parts: a literature review and a case study. The literature review summarizes the current knowledge on underwater noise and its environmental impacts during the construction of offshore wind farms. The case study section applies these findings to evaluate the expected noise levels and environmental impacts of the planned Eolus offshore wind project in the Baltic Sea.

Underwater sound and noise

Underwater soundscapes include both harmless sounds and potentially harmful noise, and it's important to understand the difference between these terms. TG-Noise (2019, 6) defines underwater “sound” as acoustic energy that naturally occurs in marine environments without harmful effects. The term “noise”, in contrast, is used specifically when acoustic energy disturbs marine life or their habitats.

2.1 Marine soundscape

The underwater soundscape is formed from many different sources. Natural sounds are produced by wind, ice movement and the activity of marine life, with marine mammals and other species actively contributing to this acoustic environment. Marine animals rely on sound as a vital tool for survival and communication. They use acoustic signals not only for interaction between individuals, but also for finding food, navigating their environment, and detecting predators. (NOAA 2024; NOAA 2016.) Human activities generate underwater noise into the marine environments. According to the International Maritime Organisation (IMO) (2023, 1), commercial shipping is the primary source of underwater noise. In addition, activities such as underwater construction and sonar use contribute significantly to anthropogenic noise in marine environments (NOAA 2016).

Noise can be divided into continuous noise and short, impulsive noise. Continuous noise is generated by natural and anthropogenic sources (TG-Noise 2019, 6). Continuous anthropogenic noise is produced mainly by shipping, but also from operation of offshore wind farms. Impulsive noise is mainly created by underwater construction activities such as pile driving and explosions (HELCOM 2023a, 84).

2.2 Underwater sound measurements

Measuring underwater noise in marine environments follows specific methods and guidelines. In the Baltic Sea, HELCOM provides monitoring guidelines for both continuous and impulsive noise. The monitoring requirements in the Baltic Sea include specific frequency ranges that account for marine mammals' hearing ranges. Measurements are conducted using hydrophones and associated rigs. Guidelines also include specific instructions for hydrophone installation to avoid unwanted noise radiation and disturbance. (HELCOM 2019, 2–5.)

For continuous noise, HELCOM (2019, 8) recommends presenting data as either full-bandwidth or third-octave frequency Sound Pressure Level (SPL). UK's National Physical Laboratory (NPL) guides that continuous noise is measured using time-averaged Sound Pressure Level (SPL) and Sound Exposure Level (SEL) is used for both continuous and impulsive noise. Continuous noise requires longer, fixed measurement periods, while impulsive noise focuses on individual events or pulses. SEL measurements adjust frequency to match the receiving animal's hearing sensitivity. Impulsive noise measurements include peak sound pressure level, showing the highest pressure during measurement, and peak-to-peak level, indicating the range between lowest and highest pressures. (NPL 2014, 18, 21–22.)

Understanding underwater noise effects, particularly on fish, requires studying particle motion and vibration. These factors significantly affect marine life, but current technology cannot measure them reliably. (NPL 2014, 10.) Future monitoring guidelines will likely include new measurement technologies as research develops.

2.3 Regulatory framework of underwater noise

International and EU regulations form the foundation for underwater noise management in marine environments. At the international level, United Nations

Convention on the Law of the Sea (UNCLOS) provides the framework for protecting marine environments from anthropogenic impacts, while IMO's Marine Environment Protection Committee offers non-binding guidelines for reducing vessel noise (UNCLOS, 26; IMO 2023).

The Marine Strategy Framework Directive (MSFD) (2008/56/EC) sets requirements for European Union Member States regarding underwater noise management. According to the directive's qualitative descriptors for good environmental status: "The introduction of energy, including underwater noise, must be at levels that do not adversely affect the marine environment." (European Parliament and Council, 2008.) The European 2017 Commission Decision (2017/848, 65–66) distinguishes between impulsive noise (D11C1) and continuous low-frequency noise (D11C2), requiring Member States to set appropriate threshold values. In the Baltic Sea region, HELCOM coordinates regional cooperation between coastal countries and the EU, developing monitoring guidelines and research initiatives (HELCOM n.d.).

Member States are responsible for setting their own regulatory frameworks and there are differences in the implementations across the Baltic Sea region. Germany and Denmark have implemented specific regulations for offshore wind farm construction noise. German regulations (BMU 2013 as cited in Brandt et al. 2018, 215) set strict noise control requirements during pile driving, the SEL_{05} (Sound Exposure Level exceeded during 5% of piling time) must stay within 160 dB re 1 $\mu Pa^2 s$ at a distance of 750 meters. In addition, marine mammals must be deterred from the area using acoustic deterrent devices before piling begins, and operations must start gradually (Brandt et al. 2018, 215). Finland is still in the research phase. In its action plan, proposal number 13, the Ministry of Economic Affairs and Employment (2024, 39) proposes to “launch studies on the impact of offshore wind energy on migratory fish, marine mammals, migratory birds and bats”.

The Danish framework differs in that it takes into account cumulative effects of pile driving and species specific safety distances. For the Baltic Sea, these distances extend beyond 10 km for harbour porpoises, but remain below 750 m for seals. Unlike Germany's unweighted thresholds, Danish guidelines implement frequency-weighted SEL values that vary based on frequency and target species, making direct comparisons between the two approaches challenging. (Tougaard & Mikaelsen 2023, 9–10, 14, 18.)

2.4 Environmental impacts of underwater noise

2.4.1 General effects of underwater noise on marine life

Assessing the impact of underwater noise is challenging because individual responses vary widely (Tougaard et al. 2021, 7). The way animals respond to noise varies with age, sex and hunger state (OSPAR 2009, 26; Russell et al. 2016). At the population level, effects are particularly difficult to measure because it's difficult to separate natural disturbances from anthropogenic disturbances (Tougaard et al. 2021, 7).

2.4.2 Masking effects

Ambient noise can mask important underwater sounds, disrupting both communication between individuals and echolocation abilities. This disrupts essential behaviors like foraging and mother-offspring bonding. In severe cases, animals may struggle to find food or detect predators, which can be fatal. (OSPAR 2009, 26.)

2.4.3 Behavioral responses

Noise can cause changes in animal behavior, ranging from mild to severe reactions. These responses vary based on individual characteristics including age, gender, and typical behavior patterns. Recurring noise disturbances affect animals' time management, as the time spent avoiding noise reduces the time available for essential activities such as resting and feeding (Tougaard 2021, 7).

The complexity of behavioral responses makes it difficult to assess disturbance, especially at the population level. This challenge complicates the development of noise regulations based on behavioral effects (OSPAR 2009, 26–27; Tougaard 2021, 7–8). Population-level assessments focus on measuring how underwater noise affects both the number of animals and the extent of habitat affected. Key factors include the distance from the noise source, the location of the disturbance and the duration of exposure (Tougaard 2021, 8).

2.4.4 Hearing damage

Hearing loss affects the ability of marine mammals to detect predators and to communicate with others. Damage occurs as temporary threshold shift (TTS) or permanent threshold shift (PTS). TTS allows hearing to recover within hours or days, while PTS results in irreversible hearing loss at certain frequencies. (OSPAR 2009, 27.) Repeated exposure to even low levels of TTS can also lead to PTS (Skjellerup et al. 2015, 3).

2.4.5 Other physical effects

The physical impacts of noise extend beyond the auditory organs. Marine mammals and fish can suffer severe physical injuries from large pressure changes, which can be lethal. Observed injuries in marine mammals include internal bleeding, expansion of brain chambers, and organ damage. Studies have shown that particularly vulnerable areas are the liver, lungs, and auditory system. The damages can include broken bones in the middle ear and bleeding in internal organs. (Ketten 2004, 5.) Similarly, Popper et al. (2014) found that pressure changes can harm fish with swim bladders. Quick pressure changes make swim bladders move rapidly, which can damage nearby tissues or rupture the swim bladder. These injuries can kill fish immediately or weaken them, making them easier prey or more vulnerable to diseases. (Popper et al. 2014, 15–17.)

2.5 Setting threshold values

Studies on the effects of underwater noise have attempted to provide more accurate information on threshold values for adverse effects in marine animals. Due to the complexity of estimating these effects, setting exact thresholds is not always possible (Kastelein et al. 2013, 2291). Tougaard et al. (2022, 4260) note that the results are partly cautious and that more supporting data are needed to set threshold values.

It has been proposed by Southall et al. (2007) to categorise marine mammals into hearing frequency groups for use in setting noise exposure criteria, due to their different auditory capabilities. According to this classification system, harbour porpoises are classified as very high frequency (VHF) cetaceans with a corresponding auditory weighting function. Seals are categorised as phocid carnivores in water (PCW) and phocid carnivores in air (PCA), also with corresponding auditory weighting functions. (Southall et al. 2007.)

2.5.1 HELCOM indicator species in the Baltic Sea

The assessment of thresholds requires the identification of specific indicator species for monitoring. For the Baltic Sea, HELCOM (2023b, 8–9) has identified a set of indicator species to assess the impact of underwater noise on the status of the Baltic Sea. These species were selected based on their noise sensitivity and available hearing information, ensuring regional representation with at least one seal species present in each Baltic Sea sub-region.

Indicator species defined by HELCOM (2023b, 9):

- Marine mammals:
  - Harbor porpoise (*Phocoena phocoena*)
  - Ringed seal (*Pusa hispida*)
  - Grey seal (*Halichoerus grypus*)
  - Harbor seal (*Phoca vitulina*)
- Fish species:

- Herring (*Clupea harengus*)
- Cod (*Gadus morhua*)

2.5.2 Treshold categories

The Level of Onset of Biologically Adverse Effects (LOBE) depends on the hearing characteristics and sensitivity of the indicator species. LOBE can be estimated from various effects, including masking effects, behavioral disturbances, habitat loss due to displacement and physiological changes, such as hearing impairment. (HELCOM 2023b, 10)

For continuous noise, HELCOM (2023b, 11) has defined specific evaluation frequencies and thresholds. Seals and harbor porpoises are evaluated at 500 Hz with thresholds of 110 and 109 dB re 1 μPa SPL respectively, while fish species are assessed at 125 Hz with a threshold of 110 dB re 1 μPa SPL.

Dominance means the reduction in the communication range of individuals due to vessel noise. This is determined by comparing the combined levels of background noise and ship-generated noise with background noise alone. A level above 20 dB is considered critical as it can reduce the maximum communication range of species by up to 90%. (HELCOM 2023b, 11.)

NMFS (2018, 18) has established frequency-weighted TTS values for marine mammals. Harbor porpoises (VHF cetaceans) have a cumulative SEL threshold of 153 dB re 1 $\mu Pa^2 s$, while seals (phocid pinnipeds) have a threshold of 181 dB re 1 $\mu Pa^2 s$. However, Tougaard et al. (2022, 4260) note that these values require further examination, particularly regarding TTS at low frequencies for seals and high frequencies for harbor porpoises. According to Kastelein et al. (2013, 2291), PTS levels are estimated by adding 15-20 dB to TTS onset levels, as direct PTS studies in natural environments are not conducted for ethical reasons.

2.6 Current status of underwater noise in the Baltic Sea

HELCOM's Third Holistic Assessment (HOLAS 3) examines the state of the Baltic Sea, including an analysis of underwater noise. Noise levels in the Baltic Sea have been evaluated in relation to the risks they pose to selected indicator species. (HELCOM 2023a, 81.) As part of the BIAS project, soundscape maps of underwater noise levels in the Baltic Sea have been studied and produced. (BIAS n.d.)

The EU Technical Group on Noise (TG-Noise) recommends in the HELCOM assessment of good environmental status that excessive continuous noise levels should be limited to 20% of the assessed area. The assessment combines median total sound pressure measurements with evaluations of anthropogenic noise increases compared to the natural soundscape. These measurements are species specific, with marine mammals being assessed in the 500 Hz decidade band and fish in the 125 Hz decidade band. (HELCOM 2023b, 3, 11.)

HELCOM (2023c, 13–14) addresses impulsive noise through time based criteria. Short-term impulsive noise must not exceed LOBE levels in more than 20% of the habitat of indicator species during a single day, while long-term impulsive noise, measured over a year, must not exceed LOBE levels in more than 10% of the habitat.

Monitoring data from the Baltic Sea show varying effects on different species and areas. Continuous noise levels, measured by median total sound pressure, remain acceptable for both fish and marine mammals. Compared to the natural soundscape, the masking thresholds for fish were exceeded in nine out of seventeen assessment areas, without reaching behavioral disturbance levels. Marine mammals appear to be less affected, with all measurements below critical levels, suggesting that shipping noise remains at acceptable levels. The impulsive noise measurements also reached the criteria for good environmental status. (HELCOM 2023b, 3–4, 15–19; 2023c, 42.)

Construction of offshore wind parks

3.1 Underwater noise from wind energy construction

Underwater noise is generated by all the different stages of offshore wind energy construction and the nature of the noise generated varies between the different stages of construction. Geophysical surveys are needed before construction to examine the project area. The construction usually starts with foundation installation or cable laying. During these phases, there are also seabed preparations such as dredging, explosions and drilling. All these activities and increased vessel traffic in the area generate underwater noise. (Nedwell & Howell, 2004, 5.) There is currently limited research on the different construction phases and their impacts. As a result, many environmental impacts are still unclear and more studies are needed to understand the full impact of these activities.

3.2 Geophysical survey

Before construction begins, acoustic and geophysical surveys are conducted to determine turbine and cable locations, identify explosive munitions requiring clearance, and assess seabed characteristics for specific construction requirements. Different types of seismic sonar can be used depending on the characteristics of the site. These systems provide data on the subsurface structure at varying depths of the seabed.

Multibeam, echosounder and chirp sonar can be used to survey shallower subsurface layers (2-30 meters below the seabed). These produce source levels of 200-220 dB re 1 μPa, 240-250 dB re 1 μPa and 212 dB re 1 μPa respectively. Boomers or sparkers with a source level of 215-222dB re 1μPa can be used in deeper subsurface layers. (Mooney et al. 2020, 86.) Airguns represent an even higher intensity source, producing levels of 260-262 dB re 1 μPa (peak-to-peak) (OSPAR Commission 2009, 25).

Sivle et al. (2012, 1084) studied the effects of sonar on fish and found that sonars operating at 1–7 kHz frequencies produced SPL up to 176 dB re 1 μPa and SEL up to 181 dB re 1 μPa². Their study showed no behavioral disturbance in Atlantic herring at these levels. The study by Popper et al. (2007, 630, 632) also showed no mortality or tissue damage when low and mid-frequency sonar was used on fish. There was some evidence of TTS, but this describes as worst case scenario.

Studies have shown that the use of airguns can lead to stranding and even mortality of cetaceans (Gordon et al. 2003, 18). Effects may also be indirect, as any changes in the behaviour and presence of prey species will affect the feeding patterns of cetaceans and consequently their fitness. Both harbour seals and grey seals have shown strong avoidance behaviour in response to airgun noise. (Gordon et al. 2003, 26–27).

3.3 Installation of foundations

Monopiles are the most common method of foundation installation. Other popular methods are jacket and tripod foundations. Pile driving is used in all of these foundation installations. (Mooney et al. 2020, 85.) The installation of jacket foundations involves more phases, resulting in a longer construction time and longer periods of noise pollution (Jiang 2021, 6–7). Foundation installation through piling generates strong impulsive noise. The noise levels from piling are difficult to predict due to varying site-specific factors. Water depth, seabed characteristics, and pile properties all affect the generated noise levels. Even within the same site, factors such as bottom sediment composition and used hammer energy can vary during the piling process. (NPL 2014, 62; Mooney et al. 2020, 88.) According to OSPAR Commission (2009, 25), the noise from piling reaches levels of 228 peak dB re 1 μPa.

Alternative methods exist to foundations that require piling. Gravity-based foundations rely on their own weight to stabilise, using heavy fill (Nedwell & Howell 2004, 5; Mooney et al. 2020, 85). Elomatic engineering company describes an alternative float foundation system, which stabilises by excavating the seabed rather than using piles. According to their assessment, this design allows for onshore installation of both the foundation and turbine before installation at sea, reducing the need for large installation vessels. For cases where piling is necessary, they state that self-dredging piling provides an alternative to traditional pile driving, potentially eliminating the need for hammering and producing noise levels comparable to normal dredging operations. (Välitalo, H., personal communication 20.11.2024.)

Pile driving has been the most studied aspect of offshore wind farm construction. Studies have shown that species differ in their sensitivity to impulsive pile-driving noise, with harbour porpoise being notably more sensitive than seals. (Tougaard 2021, 21, 24 25–26).

Research on the response of seals to pile driving varies in its findings, though available studies are limited. In Alaska, ringed seals showed minimal response to pile driving, with 39% showing no reaction to sounds averaging 151 dB re 1 μPa. However, the seals may have habituated to noise during the previous months of construction on the island, or some might have already fled the area. (Blackwell et al. 2004, 2350, 2355.) Harbour seals at the Wash and Moray Firth showed stronger avoidance behavior, staying 14-25 km away from pile driving sites (Russell et al. 2016, 1647; Bailey et al. 2010, 894). While these studies also considered potential habituation to construction noise, the role of individual characteristics in noise response remains unclear. The monitoring data during the construction period did not indicate immediate negative effects on seal population growth, though longer-term studies would be needed to fully understand the potential impacts. (Russell et al. 2016, 1649.)

Research on harbour porpoises to pile driving noise has mainly examined behavioral disturbance. In the Moray Firth, porpoises reacted more strongly than seals, avoiding areas up to 20 km from pile driving sites. The pile driving noise remained detectable at 10 kHz frequency up to 70 km away before reaching ambient noise levels. (Bailey et al. 2010, 894–895.) In German Bight, porpoise detections decreased hours before pile driving began due to increased vessel traffic, with negative effects starting at 143 dB SEL_{05} (Brandt et al. 2018, 222, 229). At Horns Reef I, Tougaard et al. (2009, 13–14) found no signs of porpoises habituating to pile driving noise. While porpoises clearly avoided the area within a 20 km radius, the actual response zone may extend even further.

In fish, pile driving can cause tissue damage that may affect survival or lead directly to death. Fish can also suffer hearing damage and have behavioural changes as a result of pile driving noise. (Popper & Hastings 2009, 45.)

3.4 Seabed modification

The installation of offshore wind farms requires modifications to the seabed along cable routes and at turbine foundation sites. The necessary preparation methods depend on the seabed conditions. For float foundations, soft sediments require plowing and removal of weak materials, while hard seabed areas can be levelled using gravel beds instead of blasting to reduce environmental impact (Välitalo, H., personal communication 20.11.2024).

Dredging is necessary for both cable laying and foundation preparation. It generates noise levels that also vary depending on the characteristics of the seabed. According to the OSPAR Commission (2009, 25), dredging noise levels range from 168-186 dB re 1 µPa rms. Harder and more compacted sediments require more force to excavate, resulting in higher noise levels. In some cases, the seabed must be blasted or hammered before dredging can proceed (CEDA 2011, 25–26).

Studies on dredging noise impacts on marine mammals and fish are limited. Southall et al. (2007) suggested that dredging noise levels are generally low enough not to cause severe physical damage to marine mammals. The main concerns are behavioral disturbances and potential masking rather than hearing impairment. Hearing damage could occur only if individuals remain in immediate proximity to dredging operations for long periods of time (CEDA 2011, 25–27).

If explosions are necessary during the construction phase, noise levels depend on the amount of explosives used and environmental factors such as water depth. Explosions are impulsive, short-duration noise sources that can reach extremely high sound pressure levels of 272-287 dB re 1 µPa (zero to peak) (The OSPAR Commission 2009, 38, 41–42). In the Baltic Sea area, safe construction may require clearing old explosives (Nord Stream 2009, 3).

The pressure waves and underwater noise from explosions can be lethal or cause severe injuries to fish and marine mammals (Koschinski 2011, 81). In fish, pressure changes can cause swim bladder rupture when individuals are close to explosions (Fan et al. 2004, 18). In a study by Ketten (2004), the effects of explosions were examined through post-mortem examinations of twenty porpoises and dolphins. The study found that pressure waves from explosions caused severe trauma in organs such as the liver, lungs, and auditory system. The examined specimens showed internal hemorrhaging, damaged liver tissue, fractures in the middle ear structures, and expansion of brain chambers. These extensive internal injuries can be fatal. (Ketten 2004, 5.)

Drilling produces relatively low noise levels compared to other construction phases. OSPAR Commission (2009, 25) has estimated drilling operations to produce sound pressure levels of 145-190 rms dB re 1 µPa. Research on the impacts of drilling noise on marine life is also limited. Moulton et al. (2003) studied the effects of underwater construction noise on ringed seals during the construction of an oil production island in Alaska using aerial surveys. Although the construction included drilling, there was no reduction in the number of seals in the area. (Moulton et al. 2003, 12, 15.)

3.5 Power transmission and cable installation

The wind farm construction requires cable installation between individual turbines and from the production area to the mainland. The installation method depends on seabed characteristics. Underwater noise during cable installation is primarily caused by the vessels required for the operation rather than the installation itself. (Nedwell et al. 2012, 2.)

3.6 Vessel traffic

The construction of offshore wind farms requires extensive vessel traffic during all phases of construction. Increased vessel traffic begins before the actual construction phase during site surveys and continues throughout the construction period (Mooney et al. 2020, 83). Vessels generate continuous low frequency noise, primarily from propeller cavitation. Low frequency sounds propagate further than high frequency sounds in water. (OSPAR Commission 2009, 50.) As a result, vessel noise and its impact on the marine environment affects a wider area compared to high-frequency and impulsive noise sources. According to the OSPAR Commission (2009, 25, 51–52), construction vessels produce source levels of 160-180 rms dB re 1 μPa. Foundation installation alone can require multiple vessels per turbine, using either one large installation vessel or three smaller vessels (Välitalo, H., personal communication 20.11.2024). Bailey et al. (2010, 891) found that increased vessel traffic during the construction phase of the Moray Firth offshore wind farm raised the ambient noise level to 138 dB re 1 μPa within a 1 km of the wind farm area.

Studies have shown that Baltic ringed seals react to vessel noise by occasionally diving deep when vessels are nearby, which is characteristic of an escape response. No other reactions have been observed, suggesting that seals may become habituated to vessel noise (Prawirasasra et al. 2011, 211). According to OSPAR Comission (2009, 54), shipping noise won’t cause direct injury to marine mammals.

Fish hear and produce sounds at low frequencies that can overlap with ship noise. This noise reduces the ability of fish to detect environmental sounds, which can increase their risk of predation. Ship noise affects fish most by masking their communication and environmental awareness (OSPAR Commission 2009, 56). HELCOM (2023a, 3) uses this masking effect as an indicator when assessing continuous noise levels and their environmental impact in the Baltic Sea.

3.7 Mitigation

Underwater noise from construction activities and its impacts can be mitigated. One approach is to use construction methods that generate less noise. When this is not feasible, various barriers can be used to reduce noise propagation. For pile driving, bubble curtains have been shown by research to significantly reduce noise spread into the environment. (Dähne et al. 2017, 222.) For impulsive noise from explosions and pile driving, animals can be deterred from the area using acoustic deterrent and scarer devices. Additionally, it is recommended to monitor animal presence during operations and postpone noise-generating activities when necessary. However, the operations may still cause fish mortality, which can attract marine mammals. Therefore, dead fish should be removed by trawling. (Nord Stream 2009, 35-37) Dähne et al. (2017, 223) note that the use of deterrent devices may negatively impact marine animals through habitat loss.

Noise impacts of the Navakka Offshore AB

4.1 Description of the project

The focus of this study is Eolus' offshore wind park project Navakka Offshore AB, located off the coast of Merikarvia in the Bothnian Sea, 30 kilometers off the Finnish coast. The offshore wind park is currently in the planning phase, with the planned project area of 670 km² and a planned total capacity of 1500 MW. The construction phase is expected to begin in the early 2030s and will last approximately two years. Two offshore wind farm projects have been zoned in the surrounding area, and seven others are in the preliminary planning phase. According to the environmental impact assessment report (EIA) of the project, water depths in the area range from 32 to 115 meters. The seabed varies from moraine to clay-mud sediment (EIA 2023, 17, 86, 92).

For the assessment of underwater noise impacts, the EIA identifies several important species in the area. The most visible species in the Navakka project area are herring schools. The presence of harbor porpoises is considered rare but possible, while no seal rookeries have been observed in the area, and the movement of grey seals and Baltic ringed seals is considered occasional (EIA 2023, 11–12). However, the scientific assessment by HELCOM (2023a, 59) considers both grey seals and Baltic ringed seals are present in the area. The EIA findings on harbor porpoises are further supported by HELCOM's assessment

4.2 Noise-generating construction phases and their assessment

4.2.1 Geophysical surveys

Geophysical surveys will be used to plan Navakka’s cable routes and turbine locations. The seismic sources used in these surveys can cause strong avoidance behavior in marine mammals and could theoretically result hearing damage to fish.

4.2.2 Seabed preparations

Explosions and munition clearance create loud, impulsive noise that generate pressure waves. These are particularly harmful to all marine animals present in the Navakka project area and create a significant risk. No impacts on marine mammals or fish have been observed directly from underwater noise generated from dredging operations, and the noise generated from these operations is mainly associated to vessel activities.

The use of explosives should be avoided in the construction process if possible and to mitigate the impacts of munitions clearance, animals should be deterred to a safety zone and their presence monitored throughout the operation. Explosions and munition clearance should be scheduled with consideration for the life cycle stages of local marine species. Underwater noise can disrupt breeding behavior and reproduction, and as Popper & Hastings (2009, 49) note, it can also affect with fish migration patterns.

4.2.3 Foundations and turbine Installation

The EIA program outlines that the wind turbines will primarily be installed on seabed foundations and therefore possible foundation methods include monopile foundations, gravity-based foundations and jacket foundations. Ice conditions in the Baltic Sea can limit the use of jacket foundations and in deeper waters, where these traditional methods are not feasible, anchored floating turbines are an option. (EIA 2023, 27, 47.)

Pile driving generates impulsive noise and is one of the major noise-producing phases, causing severe impacts on marine animals through tissue and hearing damage. If pile driving is used in the Navakka construction, the risks to harbor porpoises are considered low due to their rare presence in the area. For Baltic ringed seals and grey seals, the impacts are higher due to at least occasional presence. Fish species are considered to be most affected by noise, due to their abundance in the area. If a gravity based foundation is used instead of pile driving, the noise levels are expected to be lower. The impacts from these mainly involve possible behavioral changes in fish, grey seals, and Baltic ringed seals.

Underwater noise can be reduced by selecting foundation methods that avoid impact pile driving. Where pile driving is necessary, bubble curtains should be considered as a noise mitigation measure. Animals can also be deterred from the area, and it is important to ensure they have sufficient time to flee from the site.

Construction phases generating loud noise should be scheduled with consideration for the life cycle stages of local marine species. Underwater noise can disrupt breeding behavior and reproduction, and as Popper & Hastings (2009, 49) note, it can also affect fish migration patterns.

4.2.4 Power transmission and cable Installation

Cables can either be laid directly on the seabed or need to be installed in the seabed (EIA 2023, 28). Seabed modification for cable routes may require dredging and potentially explosives. While cable installation itself does not generate noise, the operation produces vessel-related noise.

4.2.5 Vessel traffic

During the construction of offshore wind farms, vessel traffic is a continuous source of low-frequency noise. The impacts of vessel traffic are widespread and continue throughout the life cycle of the offshore wind farm. Given the extended construction period, vessel traffic is likely to be Navakka's most significant source of underwater noise, potentially causing the greatest disturbance to marine animals.

Section 3.5 addresses the impact of shipping noise on indicator species. While harbor porpoises are rarely present in the project area and face minimal risk, grey seals and Baltic ringed seals face moderate impacts. These impacts are most evident when vessels operate in seal foraging areas, where increased traffic can disrupt feeding and affect the animals' general condition. Although seals can gradually adapt to construction and vessel noise, habituation in the project area cannot be assumed. Fish populations may face more severe consequences, as low-frequency noise can mask their essential acoustic signals. This dual effect of masking and behavioural change can impact individual fitness and survival.

Mitigation measures focus on the selection and design of vessels used in the project. When selecting vessels for Navakka's construction, preference can be given to those that generate lower noise levels. Operations requiring heavy vessel traffic should be scheduled with consideration for the life cycle stages of local marine species. Underwater noise can disrupt breeding behavior and reproduction, and as Popper & Hastings (2009, 49) note, it can also affect fish migration patterns.

Conclusion

There are still gaps in research on the effects of underwater noise. Although it is difficult to assess certain impacts, setting thresholds for underwater noise would be crucial to minimizing negative environmental effects. The construction of offshore wind farms generates both continuous and impulsive noise, which can cause severe direct or indirect injuries to marine animals. Since mandatory threshold values have not yet been set, construction should utilize precautionary methods that generate less noise emissions whenever possible.

To better understand the impact of underwater noise on the marine environment during the construction of offshore wind farms, noise level monitoring and impact assessment should be an integral part of the construction process. This will also allow to react to observed noise levels with appropriate mitigation measures. Monitoring can also help to identify construction phases that need further development and contribute to the development of more effective protection methods.

Environmental impact assessments and measures of wind park construction should also take into account other planned projects in the surrounding areas and their combined underwater noise emissions and impacts on sub-basin level. Overall, the increased vessel traffic over a larger produces long-term continuous noise that may affect the good environmental state of the Baltic Sea.

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