Effects of Noise Emissions from Offshore Wind Turbines on the Marine Environment

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Abstract

The pursuit of Offshore Wind Energy (OWE), integral to the German government's ambitious renewable energy goals raises concerns about the environmental impact of noise emissions on marine life. This paper delves into the theoretical background of Offshore Wind Turbine (OWT) noise, exploring its various phases from the survey to decommission. It examines the types and causes of noise emissions, their effects on marine wildlife and potential mitigation measures. Highlighting the regulatory framework in Germany, the paper emphasises the need for nuanced approaches to balance renewable energy objectives with marine ecosystem preservation.

Keywords: Offshore Wind Turbines, Noise Emissions, Marine Wildlife, Environmental Regulations, Mitigation Measures

1 Introduction

The German government has taken significant steps in promoting OWE as a crucial component of the global energy transition. Enacted through the OWE Act, the government aims to achieve a minimum installed capacity of 30 gigawatts by 2030, almost twice as much as the current capacity and 70 gigawatts by 2045 [1]. The pursuit of OWE presents a viable path for sustainable power, but it raises environmental concerns, particularly regarding noise from Offshore Wind Farm (OWF) activities. Such begs the question: *What impact do noise emissions from Offshore Wind Turbines have on marine wildlife?* This paper explores the theoretical background of OWT noise and its impact on marine wildlife. It examines various phases from survey to decommission and delve into types and causes of noise emissions, their effects on wildlife and potential mitigation measures. Achieving a harmonious coexistence between renewable energy objectives and marine ecosystem preservation demands a nuanced understanding and proactive solutions.

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2 Theoretical Background

2.1 Significance of the Topic

OWF activities, along with other sources of underwater noise, can harm marine wildlife by affecting their physiology and behaviour. The impact depends on factors like intensity, frequency, distance and duration of the noise, as well as the animals' hearing ability, distribution and habitat use [2]. Marine species heavily rely on sound as their primary sense for communication, navigation and survival [3]. Human-generated noise often overlaps with natural ocean sounds, posing a challenge for marine wildlife (cf. Fig. 1) [3].

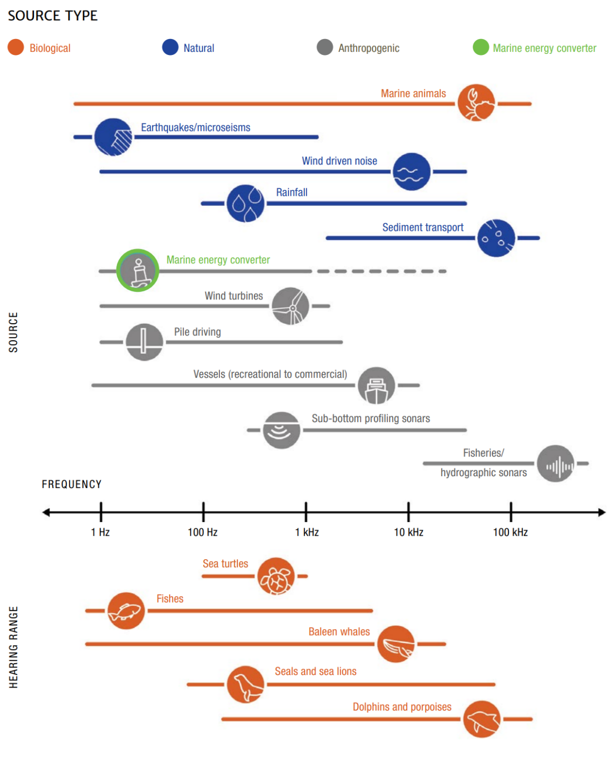

Fig. 1: An overview of biological, natural physical and anthropogenic noises in marine environments and the hearing ranges of marine animals [4], adapted from [3]

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2.2 Acoustic Background

Sound travels at 1,500 m/s in the sea, five times faster than in the air [5]. Acoustic signals consist of sound pressure and particle movement [5]. Sound pressure, measured in Pascals (Pa) or micro Pascals (μPa), is a scalar quantity [5]. A distinction must be made between different parameters. The Sound Pressure Level (SPL) (in dB re 1 μPa) measures the sound pressure at a specific point and time [6]. The Sound Exposure Level (SEL) (in dB re 1 $\mu Pa^2 \cdot s$) represents the cumulative exposure to sound over a specified period [6]. Additionally, the Peak Sound Pressure Level (LPeak) (in dB re 1 μPa) indicates the maximum sound pressure reached during an event, irrespective of its duration [6].

2.3 Environmental Regulations of Noise Emissions from Offshore Wind Turbines

The noise protection standard for impact sound in Federal Maritime and Hydrographic Agency (BSH) approval documents, determined since 2008, is specified as a dual criterion. Within a 750 m radius from the pile-driving location, the following thresholds must not be surpassed [2, 7]:

- Sound Exposure Level (SEL)[1] of 160 dB re 1 $\mu Pa^2 s$
- Peak level (LPeak)[2] of 190 dB re 1 μPa

Since 2011 it has been compulsory to implement noise abatement systems to meet the specified noise mitigation values in the German Exclusive Economic Zone of the North and Baltic Seas, because without proper measures, the measured values at a distance of 750 m from the source would be up to 183 dB re 1 $\mu Pa^2 \cdot s$ (SEL) and 205 dB re 1 μPa (LPeak). [6]

The third OWE Ordinance, in addition to previously stated requirements, mandates specific measures in section seven to mitigate noise emissions during the foundation, installation and operation of OWTs. The ordinance requires noiseless work methods during facility foundation and installation. This involves following the state of the art and considering the prevailing circumstances. Additionally, the ordinance emphasises the imperative for deterrent measures against marine animals. Furthermore, it obligates project proponents to choose construction methods that are operationally soundproof according to contemporary standards, explicitly prohibiting detonations. Also, each foundation type, like Monopiles or Jackets, has a designated maximum ramming duration (Monopiles: 180 min, Jackets: 140 min). Section eight emphasises compliance with the 'Concept for the Protection of Harbour Porpoises from Sound Exposures during the Construction of Offshore Wind Farms in the German North Sea' (2013). This requires project proponents to coordinate piling activities with concurrent OWF developments in the North Sea's exclusive economic zone. All of these requirements serve to ensure compliance with the prohibition of killing and injuring species and the prohibition of disturbance under the German Federal Nature Conservation Act (Section 44(1)(1) and (2)). [7]

In the United States and the United Kingdom, similar guidelines are followed, drawing from technical recommendations provided by the National Oceanic and Atmospheric Administration [8] and Southall et al. (2019) [9]. These guidelines incorporate frequency-weighted parameters tailored to different species [6].

3 Noise Emissions of Offshore Wind Turbines

In the case of OWTs and their noise emissions, various phases of the wind turbine project need to be considered. This includes site surveys, the construction phase, the operational phase and the decommissioning phase (cf. Fig. 2). [10]

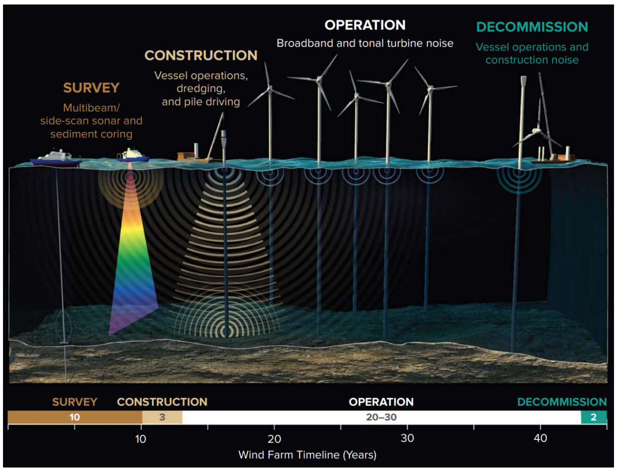

Fig. 2: Acoustic life of an Offshore Wind Farm area, including during site surveys, construction, operation and decommissioning [5]

3.1 Survey Phase

3.1.1 Types and Causes of Noise Emissions

The survey phase involves geophysical profiling with multibeam and side-scan sonar, mapping the seabed.

[1] Sound Exposure Level in dB re 1 μPa^2 s; dB = Decibel; re = in reference to; 1 μPa = 1 Micro Pascal; 1 μPa^2 s = 1 Micro Pascal squared * second; the reference level for water is 1 μPa.

[2] Peak Sound Pressure Level in dB re 1 μPa; dB = Decibel; re = in reference to; 1 μPa = 1 Micro Pascal; 1 μPa^2 s = 1 Micro Pascal squared * second; the reference level for water is 1 μPa.

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Special sensors, cameras, sampling and seismic systems can be used to characterise the benthos (depth, morphology, sediment, geology and biology). Examples for seismic systems are echosounders and sparkers. Echosounders have depth limitations (< 2–20 m) and a 240-250 dB re 1 μPa source level, offering a 2-22 kHz frequency range and 5-15 cm vertical resolution. For deeper grounds (100 m to 1 km), sparkers with 222 dB re 1 μPa source level are used (40 Hz to 1.5 kHz, 20 cm to 10 m vertical resolution). It should be noted that seismic airguns are rarely used in the survey phase of OWTs, which is why they are not discussed any further. [5]

3.1.2 Effects on the Marine Wildlife

While active acoustic benthic surveys are common, the impact of echosounders and related technologies on marine wildlife remains insufficiently explored. Sonar systems, operating at frequencies often undetectable by aquatic organisms, have limited effects [11, 12]. Extensive research on mid-frequency active (MFA) sonar in the 1-7 kHz range has been conducted, yet echosounders and chirp sonars lack comprehensive studies [5]. Clupeids exhibit sensitivity to mid-frequency sonar, but MFA sonar experiments on adult herring reveal no significant behavioural responses [13]. Limited MFA sonar studies suggest marginal effects on fish hearing, with no observed impacts on rainbow trout and minimal, inconsistent shifts in auditory thresholds for channel catfish [12]. One study acknowledges potential hearing loss induced by low-frequency sonar at high SPLs (193 dB re 1 μPa) [11]. Its impacts on invertebrates remain unexplored [14]. Ship noise (130-200 dB re 1 μPa [15]) during site surveys, despite its intermittent nature, can mask communication signals of haddock, cod and other taxa, inducing physiological stress, impairing foraging and predator responses in fish and invertebrates [16]. The intermittent nature of vessel noise is a key factor in elevating stress-related responses [17]. While harmful effects on marine mammals are unlikely, their exposure to noise levels above the background could induce behavioural changes in sensitive species (cf. Fig. 3) [15, 18].

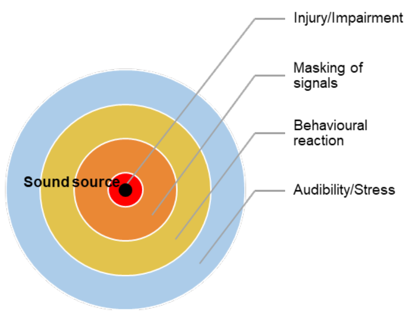

Fig. 3: The different effects of noise on marine mammals, adapted from [19, 20]

3.2 Construction Phase

3.2.1 Types and Causes of Noise Emissions

OWTs can be categorised based on foundation types (cf. Fig. 4), which is crucial for determining installation methods [21].

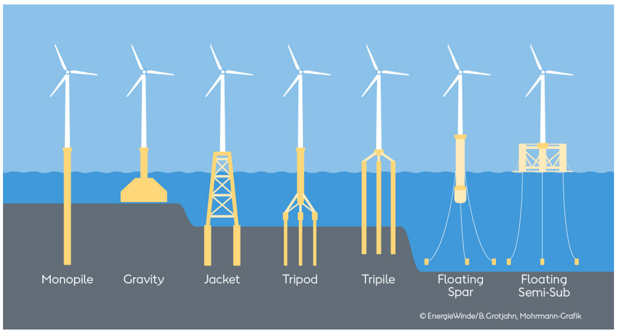

Fig. 4: Different types of foundations of Offshore Wind Turbines [22]

The selection of foundation types, such as Monopiles and Tripod systems, depends on site conditions. Monopile foundations, characterised by a single steel tube, emerge as the most frequently employed and cost-effective solution for OWTs (cf. Fig. 5). For larger turbines positioned farther offshore, there is a growing preference for Jacket and Tripod systems. [5]

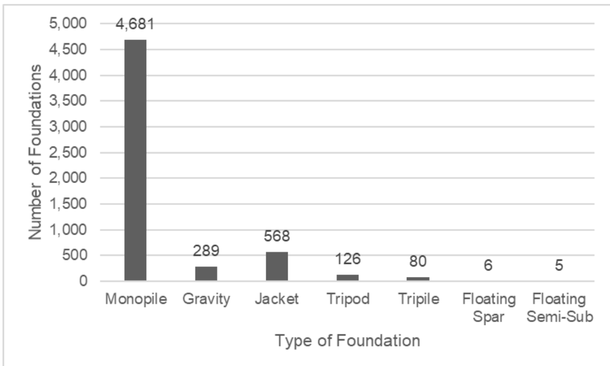

Fig. 5: All foundations installed with and without grid connection by the end of 2020 in Europe, adapted from [23]

The construction phase of OWFs typically spans one to three years and raises ecological concerns, primarily due to the substantial noise generated during the installation of foundations using impact or vibrational hammers [5, 24]. During the foundation installation LPeaks result at 220 dB re 1 μPa at 10 m and 200 dB re 1 μPa at 300 m from (0.75 m and 5 m diameter) piles [25]. The primary energy is concentrated below 500 Hz, extending beyond 1 kHz [5]. This aligns with the auditory bandwidth of marine species, potentially impacting underwater ecosystems (cf. Fig. 6) [5].

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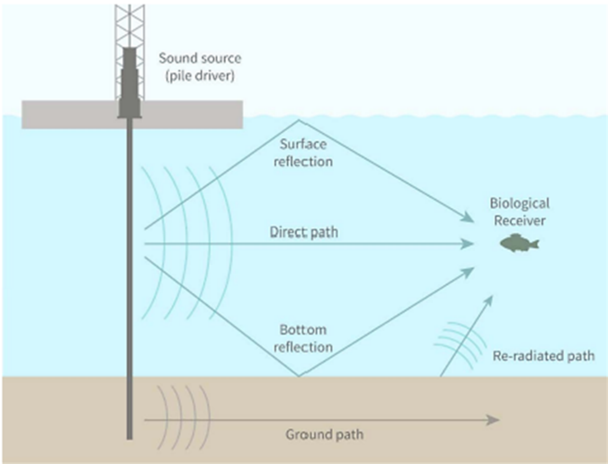

Fig. 6: Sound propagation paths associated with pile-driving [26], adapted from [27]

Additionally, a pile-driving operation can take 157 min required 7,000 blows of the hammer. Predicting effects is challenging due to the dynamic nature of acoustic pulses during propagation. LPeaks at 205 dB re 1 μPa at 100 m, yet signals remain detectable up to 70 km. Close to the source (1 km), the initial waveform peak lasts 10 ms, but at 40 km, durations extend to 200 ms, indicating a less impulsive nature of signals at greater distances. This complexity is amplified by additional noise sources like vessel movements, trenching, dredging, drilling and scour protection laying within 1 km of the turbine site. [28]

3.2.2 Effects on the Marine Wildlife

Numerous studies have investigated construction noise, notably pile-driving, in aquatic ecosystems. Results, spanning various methods and species, reveal a spectrum of effects from severe physical injury to minimal impact. For instance, hybrid striped bass experienced multiple injury types when exposed to simulated pile-driving signals, with injury numbers and severity increasing with fish size (cf. Fig. 7) [29]. In Lake sturgeon and Nile tilapia, injuries occurred at lower SELs (204 dB re 1 $\mu Pa^2 \cdot s$), intensifying at higher levels (216 dB re 1 $\mu Pa^2 \cdot s$) [30]. Comparative studies highlight greater vulnerability in fish with physoclistous swim bladders (closed structures not connected with digestive tract) compared to physostomous swim bladders (open structures connected with digestive tract) [29, 30]. European seabass displayed physiological and behavioural effects, including disrupted schooling structures and increased swimming speeds at 154 dB re 1 $\mu Pa^2 \cdot s$ [31]. Also, they demonstrate heightened swimming speeds and depths, decreased inter-fish distances, increased startle responses and a tendency to move away from the sound source at exposure levels ranging from 200 Hz to 1 kHz and a mean SPL of 180–192 dB re 1 μPa [32]. Certain fish species, like sheepshead and flatfish, minimally

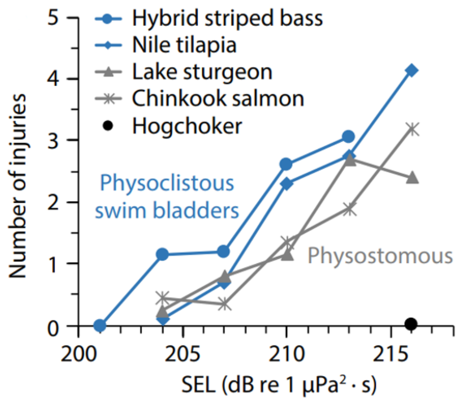

Fig. 7: Barotrauma effects on marine species exposed to pile-driving noise [5], adapted from [29, 30]

respond to noise from activities such as pile-driving [33, 34]. Limited research on invertebrates highlights potential negative effects on species like hermit crabs and blue mussels due to simulated pile-driving and sediment vibrations [35, 36].

Marine mammals face potential hearing loss, for cetaceans at 5 m and pinnipeds at 20 m and temporary at 10 m respectively 40 m within the pile-driving operation [28]. If noise levels at 100 m are below safe limits (166 dB re 1 $\mu Pa^2 \cdot s$), there is no indicating damage beyond this distance for these types [28]. Harbour porpoises may experience behavioural disturbances up to 70 km, with strong avoidance reactions up to 20 km [28]. Pinnipeds are affected within a 14 km zone [28]. Bottlenose dolphins and minke whales may show disturbances at 50 and 40 km, respectively [28]. Acoustic deterrent devices and gentle approaches can cause a significant directional movement away from the sound source before pile-driving [37].

3.3 Operation Phase

3.3.1 Types and Causes of Noise Emissions

The underwater sound generated during the operation of an OWE system mainly comes from rotating machine parts like rotor blades, gearbox and generator (cf. Fig. 8) [38]. These components cause vibrations in the nacelle and tower structure, propagating beneath the waterline and emitting underwater sound [38]. The SPLs can range from 111 to 123 dB re 1 μPa ($<$ 1 kHz) at 100 m, contingent on wind and rotation speed [39]. These sounds, inclusive of those from ships and transformers, can extend over several kilometers [5]. Turbine size influences the noise and different foundation types may have varied acoustic impacts [5]. With a lifespan of 20-30 years [5], the emissions persist at least for a long time and pose challenges for marine animals. Current noise mitigation methods may be unsuitable due to prolonged operational times and relatively low noise levels [5].

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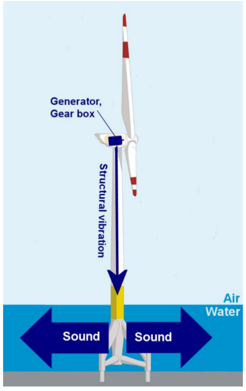

Fig. 8: Schematic representation of the entry of machine noise into the water [38]

3.3.2 Effects on the Marine Wildlife

Operational noise from OWFs has varying effects on fish. While direct physical injury is unlikely due to moderate noise levels, long-duration exposure may induce temporary threshold shifts, affecting fish communication, foraging and predator detection [5]. Studies in Sweden indicate a negative correlation between fish abundance and local noise levels, with reduced catches at higher noise levels [40]. Behavioural responses differ; some fish show increased catchability near turbines when not operating, while others, like tagged cod in a Belgian OWF, exhibit no change [41]. Studies dismiss the possibility of killing or injuring marine mammals due to temporary or permanent threshold shifts (TTS and PTS) [9]. Other studies affirm these findings with minimal impacts like reacting to avoidance or disruptive effects [42]. Also new gearless OWTs generate lower-frequency tones with reduced amplitudes compared to geared OWTs [38]. This decreases for instance the likelihood of detection by porpoises (cf. Fig. 9) [38]. OWTs may have a more notable impact in regions with minimal background noise and limited ship activity [39].

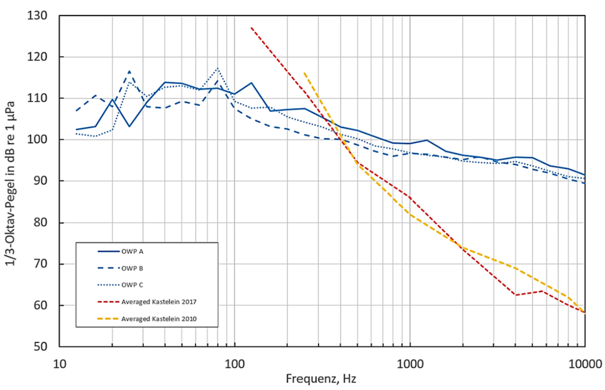

Fig. 9: Harbour porpoise hearing thresholds vs. operational noise at 100 m from three turbines (OWP = OWT) [38], created from [43, 44]

3.4 Decommission Phase

3.4.1 Types and Causes of Noise Emissions

Decommissioning involves the removal of turbines, foundations, cables and other structures, which can have a significant impact. One of the few studies found that the SPL, when cutting a steel pylon during OWF decommissioning, can be high (198.7-199.8 dB re 1 μPa) at a 10-50 m distance. The predominant portion of this sound energy fell within the frequency range of 250 Hz to 1 kHz. [45]

3.4.2 Effects on the Marine Wildlife

Research on the impact of OWF decommissioning on marine wildlife is limited as decommissioning is still in its early stages. The effects on marine wildlife are difficult to predict, but there is the potential for disturbance such as masking, displacement, physiological stress and other factors, particularly in habitats around OWF piles or foundations while decommissioning. [5]

4 Measures to Minimise Noise Emissions

Recognising the significance of environmental sounds and minimising human-made noise impacts is crucial for the economy, national security and maintaining a balance with the ocean's essential role [3].

In general, noise mitigation involves two main categories: primary measures (Noise Mitigation Systems) aim to reduce impulsive noise during foundation structure installation through source strength reduction or alternative, low-noise methods. Secondary measures (Noise Abatement Systems) focus on minimising impulsive pile-driving noise in water. Experience from 21 offshore wind projects shows that three effective secondary noise abatement systems are in use: Noise Mitigation Screen (IHC-NMS), Hydro Sound Damper (HSD) and Big Bubble Curtain (BBC and Double BBC), which have successfully reduced noise levels by approximately 17 dB re 1 μPa in water depth 25-40 m. The combination of near-pile and far-pile protection systems enables a reduction of $\geq$ 20 dB re 1 μPa up to a depth of 40 m. Technical requirements and site-specific adaptations are important. The spectral sound reduction varies depending on the system and frequency range. A sound-optimised pile-driving process can achieve additional reductions. [6]

Koschinski and Lüdemann (2011, 2013, 2020) overview sound protection and alternative foundations, highlighting innovations like AdBm and Blue-Piling for reduced noise and environmental impact. Suction Bucket, Floating Foundation and ongoing research on Vibro-Piling are discussed. [46–48]

5 Knowledge Gaps and Research Needs

- Survey Technologies: Impacts of current-use seismic sources on marine wildlife
- Alternative Foundations: Research technologies to reduce noise and environmental impact
- Long-term Noise Effects: Study continuous operational noise on marine wildlife
- Operational Noise Effects: On early developmental stages in various species
- Decommissioning Impact: Evaluate OWF decommissioning, particularly noise
- Decommissioning Practices: Evaluate adherence to environmental regulations

6 Conclusion

In conclusion, while the German government's push for OWE signifies a positive step in the global transition to sustainable power, the question arises: *What impact do noise emissions from Offshore Wind Turbines have on marine wildlife?* This paper has illuminated environmental concerns related to noise emissions from OWTs. The examination of various project phases reveals complex issues impacting marine wildlife, necessitating robust environmental regulations. Existing German standards are discussed, emphasising the importance of nuanced approaches and mitigation efforts such as bubble curtains. Despite progress, challenges persist, particularly in understanding the decommission phase impacts on marine mammals, fish and invertebrates. The paper calls for ongoing research, comprehensive strategies and a balanced approach to ensure the coexistence of renewable energy goals and marine ecosystem preservation. Future advancements and collaborative efforts will be crucial for refining mitigation measures and addressing knowledge gaps in this evolving sector.

7 Outlook

As the OWE sector continues to expand globally, proactive research and collaborative efforts are crucial to refine noise mitigation measures and address knowledge gaps. Ongoing technological advancements will play a pivotal role in minimising the impact of noise emissions on marine ecosystems. A balanced approach that harmonises renewable energy development with environmental conservation is essential. The call for continued research underscores the commitment to achieving sustainable coexistence between offshore wind energy objectives and the preservation of marine wildlife.

References

[1] D. Bundesregierung. "Mehr Windenergie auf See" (2023). accessed on 15.11.2023. URL: https://www.bundesregierung.de/breg-de/schwerpunkte/klimaschutz/windenergie-auf-see-gesetz-2022968.

[2] B. für Seeschiffahrt und Hydrographie. "Underwater sound" (2020). accessed on 20.11.2023. URL: https://www.bsh.de/EN/TOPICS/Offshore/Environmental_assessments/Underwater_sound/underwater_sound_node.html.

[3] A. Scholik-Schlomer. "Where the Decibels Hit the Water: Perspectives on the Application of Science to Real-World Underwater Noise and Marine Protected Species Issues". *Acoustics Today* 11.3 (2015), pp. 36–44.

[4] A. E. Copping and L. G. Hemery. *OES-Environmental 2020 State of the Science Report: Environmental Effects of Marine Renewable Energy Development Around the World.* 2020, p. 70. DOI: 10.2172/1632878.

[5] T. A. Mooney, M. H. Andersson, and J. Stanley. "Acoustic impacts of offshore wind energy on fishery resources". *Oceanography* 33.4 (2020), pp. 82–95. DOI: 10.5670/oceanog.2020.408.

[6] M. A. Bellmann, J. Brinkmann, A. May, T. Wendt, S. Gerlach, and P. Remmers. *Underwater noise during the impulse pile-driving procedure: Influencing factors on pile-driving noise and technical possibilities to comply with noise mitigation values.* Technical Report. Supported by the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), FKZ UM16 881500. Commissioned and managed by the Federal Maritime and Hydrographic Agency (BSH), Order No. 10036866. itap GmbH, 2020, p. 137.

[7] B. für Seeschifffahrt und Hydrographie. *Dritte Verordnung zur Durchführung des Windenergie-auf-See-Gesetzes.* 3. Gesetzblatt oder andere relevante Informationen. 2023, p. 48.

[8] N. M. F. Service. *Revisions to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts.* NOAA Technical Memorandum NMFS-OPR-59. U.S. Dept. of Commerce, NOAA, 2018, p. 167.

[9] B. L. Southall, J. J. Finneran, C. Reichmuth, P. E. Nachtigall, D. R. Ketten, A. E. Bowles, W. T. Ellison, D. P. Nowacek, and P. L. Tyack. "Marine mammal noise exposure criteria: Updated scientific recommendations for residual hearing effects". *Aquatic Mammals* 45.2 (2019), pp. 125–232. DOI: 10.1578/AM.45.2.2019.125.

https://doi.org/10.25974/ren_rev_2024_09
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[10] A Müller and C Zerbs. "Offshore-Windparks-Messvorschrift für Unterwasserschallmessungen: Aktuelle Vorgehensweise mit Anmerkungen". *Bundesamt für Seeschifffahrt und Hydrographie ", BSH, Hamburg* (2011), p. 35.

[11] A. N. Popper, M. B. Halvorsen, A. Kane, D. L. Miller, M. E. Smith, J. Song, P. Stein, and L. E. Wysocki. "The effects of high-intensity, low-frequency active sonar on rainbow trout". *Journal of the Acoustical Society of America* 122.1 (2007), pp. 623–635. DOI: 10.1121/1.2735115.

[12] M. B. Halvorsen, D. G. Zeddies, W. T. Ellison, D. R. Chicoine, and A. N. Popper. "Effects of mid-frequency active sonar on hearing in fish". *The Journal of the Acoustical Society of America* 131.1 (2012), pp. 599–607. DOI: 10.1121/1.3664082.

[13] L. Doksæter, N. O. Handegard, O. R. Godø, P. H. Kvadsheim, and N. Nordlund. "Behavior of captive herring exposed to naval sonar transmissions (1.0–1.6 kHz) throughout a yearly cycle". *The Journal of the Acoustical Society of America* 131.2 (2012), pp. 1632–1642. DOI: 10.1121/1.3675944.

[14] D. M. Hudson, J. S. Krumholz, D. L. Pochtar, N. C. Dickenson, G. Dossot, G. Phillips, E. P. Baker, and T. E. Moll. "Potential impacts from simulated vessel noise and sonar on commercially important invertebrates". *PeerJ* 10 (2022), p. 19. DOI: 10.7717/peerj.12841.

[15] C. Erbe, S. A. Marley, R. P. Schoeman, J. N. Smith, L. E. Trigg, and C. B. Embling. "The effects of ship noise on marine mammals—A review". *Frontiers in Marine Science* 6 (2019), p. 21. DOI: 10.3389/fmars.2019.00606.

[16] J. A. Stanley, S. M. Van Parijs, and L. T. Hatch. "Underwater sound from vessel traffic reduces the effective communication range in Atlantic cod and haddock". *Scientific Reports* 7.1 (2017), p. 12. DOI: 10.1038/s41598-017-14743-9.

[17] L. E. Wysocki, J. P. Dittami, and F. Ladich. "Ship noise and cortisol secretion in European freshwater fishes". *Biological Conservation* 128.4 (2006), pp. 501–508. DOI: 10.1016/j.biocon.2005.10.020.

[18] D. Cholewiak, A. I. DeAngelis, D. Palka, P. J. Corkeron, and S. M. Van Parijs. "Beaked whales demonstrate a marked acoustic response to the use of shipboard echosounders". *Royal Society open science* 4.12 (2017), p. 15.

[19] C. Audoly and C. Rousset. "European project for achieving quieter oceans by shipping noise footprint reduction". *Proceedings of Meetings on Acoustics*. Vol. 21. 1. AIP Publishing. 2014, p. 15. DOI: 10.1121/1.4877560.

[20] W. J. Richardson, C. R. Greene Jr., C. I. Malme, and D. H. Thomson. *Marine Mammals and Noise*. San Diego: Academic Press, 1995, p. 576. ISBN: 0-12-588441-9. DOI: 10.1016/C2009-0-02253-3.

[21] Z. Jiang. "Installation of offshore wind turbines: A technical review". *Renewable and Sustainable Energy Reviews* 139 (2021), p. 21. DOI: 10.1016/j.rser.2020.110576.

[22] Energiewinde. "Gebohrt, nicht gehämmert" (2023). accessed on 17.11.2023. URL: https://energiewinde.orsted.de/trends-technik/offshore-wind-fundamente-gebohrt-deme-herrenknecht-frankreich.

[23] WindEurope. "Offshore Wind in Europe: Key Trends and Statistics 2020". 1 (2021), p. 38.

[24] National Academies of Sciences, Engineering, and Medicine and others. "Atlantic Offshore Renewable Energy Development and Fisheries: Proceedings of a Workshop—in Brief" (2018), p. 12.

[25] P. G. Reinhall and P. H. Dahl. "Underwater Mach wave radiation from impact pile driving: theory and observation". *The Journal of the Acoustical Society of America* 130.3 (2011), pp. 1209–1216. DOI: 10.1121/1.3614540.

[26] C. Pyć, Z. D., S. Denes, and M. Weirathmueller. "Supplemental Information for the Assessment of Potential Acoustic and Non-acoustic Impact Producing Factors on Marine Fauna during Construction of the Vineyard Wind Project". 3 (2018), p. 84.

[27] P. David Buehler, R. Oestman, J. Reyff, K. Pommerenck, and B. Mitchell. *Technical Guidance for Assessment and Mitigation of the Hydroacoustic Effects of Pile Driving on Fish*. Report CTHWANP-RT-15-306.01.01. California Department of Transportation, 2015, p. 533.

[28] H. Bailey, B. Senior, D. Simmons, J. Rusin, G. Picken, and P. M. Thompson. "Assessing underwater noise levels during pile-driving at an offshore wind farm and its potential effects on marine mammals". *Marine Pollution Bulletin* 60.6 (2010), pp. 888–897. DOI: 10.1016/j.marpolbul.2010.01.003.

[29] B. M. Casper, M. B. Halvorsen, F. Matthews, T. J. Carlson, and A. N. Popper. "Recovery of Barotrauma Injuries Resulting from Exposure to Pile Driving Sound in Two Sizes of Hybrid Striped Bass". *PLoS ONE* 8.9 (2013), p. 12. DOI: 10.1371/journal.pone.0073844.

[30] M. B. Halvorsen, B. M. Casper, F. Matthews, T. J. Carlson, and A. N. Popper. "Effects of Exposure to Pile-Driving Sounds on the Lake Sturgeon, Nile Tilapia, and Hogchoker". *Proceedings of the Royal Society B* 279.1748 (2012), pp. 4705–4714. DOI: 10.1098/rspb.2012.1544.

[31] J. E. Herbert-Read, L. Kremer, R. Bruintjes, A. N. Radford, and C. C. Ioannou. "Anthropogenic Noise Pollution from Pile-Driving Disrupts the Structure and Dynamics of Fish Shoals". *Proceedings of the Royal Society B* 284.1863 (2017), p. 9. DOI: 10.1098/rspb.2017.1627.

[32] Y. Y. Neo, J. Hubert, L. Bolle, H. V. Winter, C. Ten Cate, and H. Slabbekoorn. "Sound Exposure Changes European Seabass Behaviour in a Large Outdoor Floating Pen: Effects of Temporal Structure and a Ramp-Up Procedure". *Environmental Pollution* 214 (2016), pp. 26–34. DOI: 10.1016/j.envpol.2016.03.075.

[33] J. D. Iafrate, S. L. Watwood, E. A. Reyier, D. M. Scheidt, G. A. Dossot, and S. E. Crocker. "Effects of Pile Driving on the Residency and Movement of Tagged Reef Fish". *PLoS ONE* 11.11 (2016), p. 17. DOI: 10.1371/journal.pone.0163638.

[34] D. Wilber, D. Carey, and M. Griffin. "Flatfish Habitat Use near North America's First Offshore Wind Farm". *Journal of Sea Research* 139 (2018), pp. 24–32. DOI: 10.1016/j.seares.2018.06.004.

[35] L. Roberts and M. E. Laidre. "Finding a Home in the Noise: Cross-modal Impact of Anthropogenic Vibration on Animal Search Behaviour". *Biology Open* 8.7 (2019), p. 7. DOI: 10.1242/bio.041988.

[36] L. Roberts, S. Cheesman, T. Breithaupt, and M. Elliott. "Sensitivity of the Mussel *Mytilus edulis* to Substrate-borne Vibration in Relation to Anthropogenically Generated Noise". *Marine Ecology Progress Series* 538 (2015), pp. 185–195. DOI: 10.3354/meps11468.

[37] I. M. Graham, D. Gillespie, K. C. Gkikopoulou, G. D. Hastie, and P. M. Thompson. "Directional hydrophone clusters reveal evasive responses of small cetaceans to disturbance during construction at offshore windfarms". *Biology Letters* 19.2 (2023), p. 6. DOI: 10.1098/rsbl.2022.0101.

[38] M. A. Bellmann, T. Müller, K. Scheiblich, and K. Betke. *Experience Report on Operational Noise - Cross-Project Evaluation and Assessment of Underwater Noise Measurements from the Operational Phase of Offshore Wind Farms.* Report 3926. Funded by the German Federal Maritime and Hydrographic Agency, Funding No. 10054419. itap, 2023, p. 101.

[39] J. Tougaard, L. Hermannsen, and P. T. Madsen. "How loud is the underwater noise from operating offshore wind turbines?" *The Journal of the Acoustical Society of America* 148.5 (2020), pp. 2885–2893. DOI: 10.1121/10.0002453.

[40] L. Bergström, F. Sundqvist, and U. Bergström. "Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community". *Marine Ecology Progress Series* 485 (2013), 199–210. DOI: 10.3354/meps10344.

[41] H. V. Winter, G. Aartsw, and O. A. van Keeken. *Residence Time and Behaviour of Sole and Cod in the Offshore Wind Farm Egmond aan Zee (OWEZ).* Tech. rep. Institute for Marine Resources & Ecosystem Studies, 2010, p. 50.

[42] A. Rose, M Brandt, R. Vilela, A. Diederichs, A. Schubert, V. Kosarev, G. Nehls, M Volkenandt, V Wahl, A Michalik, **et al.**. "Effects of noise-mitigated offshore pile driving on harbour porpoise abundance in the German Bight 2014-2016 (Gescha 2)". *Report by IBL Umweltplanung GmbH* (2019), p. 204.

[43] R. A. Kastelein, L. Hoek, C. A. de Jong, and P. J. Wensveen. "The effect of signal duration on the underwater detection thresholds of a harbor porpoise (Phocoena phocoena) for single frequency-modulated tonal signals between 0.25 and 160 kHz". *The Journal of the Acoustical Society of America* 128.5 (2010), pp. 3211–3222. DOI: 10.1121/1.3493435.

[44] R. A. Kastelein, L. Helder-Hoek, and S. Van de Voorde. "Hearing thresholds of a male and a female harbor porpoise (Phocoena phocoena)". *The Journal of the Acoustical Society of America* 142.2 (2017), pp. 1006–1010. DOI: 10.1121/1.4997907.

[45] N. Hinzmann, P. Stein, J. Gattermann, J. Bachmann, and G. Duff. "Measurements of hydro sound emissions during internal jet cutting during monopile decommissioning". *COME-Conference on Maritime Energy 2017-Decommissioning of Offshore Geotechnical Structures, 28.-29. März 2017 in Hamburg, S. 139.* Vol. 161. 2017, p. 22.

[46] S. Koschinski and K. Lüdemann. "Stand der Entwicklung schallminimierender Maßnahmen beim Bau von Offshore-Windenergieanlagen". *Studie im Auftrag vom Bundesamt für Naturschutz (BfN)* (2011), p. 88.

[47] S. Koschinski and K. Lüdemann. "Development of noise mitigation measures in offshore wind farm construction". *Commissioned by the Federal Agency for Nature Conservation* (2013), p. 102.

[48] S. Koschinski and K. Lüdemann. "Noise mitigation for the construction of increasingly large offshore wind turbines". *Technical Options for Complying with Noise Limits; The Federal Agency for Nature Conservation: Isle of Vilm, Germany* (2020), p. 40.