Marine Research Programme

Marine Institute - Research for Policy Awards Call 2023

Topic - Underwater Noise

Guidance for Monitoring and Reporting of Underwater Noise

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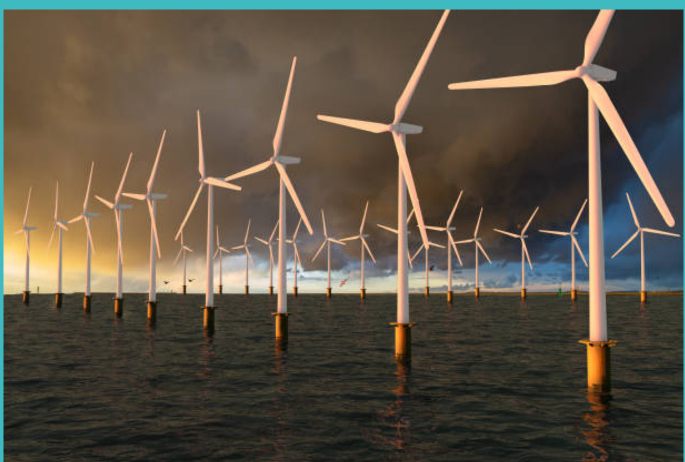

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Underwater Noise Guidance for ORE

Guidance for Monitoring and Reporting of Underwater Noise

BD01923002

Revision 03

Marine Institute Research for Policy Awards

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Reviewed	John Breslin	18/06/2024

This project (Grant-Aid Agreement No. RPA/23/02/02) is carried out with the support of the Marine Institute under the Marine Research Programme, and funded by the Government of Ireland.

Revision History

Revision no	Revision Text	Initials	Date
01	Issued for Review	RC	19/06/2024
02	Issued for Release	RC	20/09/2024
03	DHLGH logo removed	RC	28/10/2024

Acknowledgements

BlueWise Marine is thankful to the following organisations that have gently provided their valuable views on the topics studied in this report during the Stakeholder Consultation phase: Parkwind, Codling, SSE, Statkraft, ESB / Orsted, HydroTwin (Portugal), IWDG and NPWS.

Glossary

AA	Appropriate Assessment
ABP	An Bord Pleanála
ADD	Acoustic Deterrent Devices
ATU	Atlantic Technological University
BWM	BlueWise Marine
DECC	Department of Environment, Climate and Communications
DHLGH	Department of Housing, Local Government and Heritage
EC	European Commission
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
EU	European Union
HRA	Habitats Regulations Assessment
ICES	International Council for the Exploration of the Seas
IEC	International Electrotechnical Commission
IMO	International Maritime Organisation
ISO	International Standards Organisation
IWDG	Irish Whale and Dolphin Group
JRC	Joint Research Centre
MAC	Maritime Area Consent
MARA	Maritime Area Regulatory Authority
MI	Marine Institute
MMO	Marine Mammal Observer
MRIA	Marine Renewables Industry Association
MSFD	Marine Strategy Framework Directive
NAS	Noise Abatement Systems
NGO	Non-Governmental Organisation
NIS	Natura Impact Statement
NPWS	National Parks and Wildlife Service
O&M	Operations and Maintenance
ORE	Offshore Renewable Energy
OREDP	Offshore Renewable Energy Development Plan
ORESS	Offshore Renewable Electricity Support Scheme
OTEC	Ocean Thermal Energy Conversion
OWF	Offshore Wind Farm
SAM	Static Acoustic Monitoring
SEA	Strategic Environmental Assessment
SI	Statutory Instrument
TSO	Transmission System Operator
UAN, URN	Underwater Acoustic Noise, Underwater Radiated Noise

UNCLOS	United Nations Convention on the Law of the Sea
WEI	Wind Energy Ireland

Table of Contents

1 Executive summary

This document is the first technical deliverable of the study carry out to address the topic "Underwater Noise guidance for Offshore Renewable Energy (ORE) developers", under the Marine Institute's Research for Policy Awards 2023. The study has been split into two sections, both approached under the ORE perspective. The first addresses the monitoring and reporting of underwater acoustic noise, the subject of this document. The second section covers mitigation measures and thresholds for underwater noise and is presented in a separate deliverable.

The methodology used in the study was based on a desktop review of literature on the topic (grey and peer-reviewed), as well as of regulations (national, regional and international levels) applicable to the management of UAN in offshore developments. A review and analysis of best practices in jurisdictions other than Ireland, as well as consultation of relevant stakeholders, has also been undertaken.

Following a brief introduction to the subject of monitoring and reporting of underwater acoustic noise (UAN), and some definitions of terminology, the report first presents the context, referencing a scope already pre-defined, of UAN generated by human activities during the various stages of ORE developments (pre-construction, construction, operation and decommissioning). It followed from this review that the most impactful activity during these stages is pile-driving, that is, the installation of fixed infrastructure in the seabed through mechanical percussion (or vibration) at the surface by specialised vessels.

An analysis of regulations, guidelines and best practices followed in other countries was then presented. This included reference countries in the North and Baltic Seas, two areas with well-established ORE developments spanning several decades, such as the UK, Germany, Denmark and the Netherlands, as well as countries where ORE is currently undergoing considerable development, as in the United States and New Zealand. The analysis was completed with an overview of existing and future international standards, regional and international regulations (such as the European Union's Marine Strategy Framework Directive, or international agreements such as OSPAR) and also international (basic and applied) research projects on the matter of underwater acoustic noise. This latter review was coupled with a systematic search and review of the rich technical and scientific literature carried out to date on underwater noise and its impacts on marine life, especially on marine mammals. All along these tasks, a consultation of a range of stakeholders, including ORE developers, an SME specialised in underwater noise services, a state agency for protection of wildlife and a non-governmental organisation focused on marine mammals, was also carried out.

These reviews enabled the identification of common grounds and of different approaches to UAN management across the most representative places on the globe where human economic development (at least, in the offshore sector) has been paired with a nature conservation imperative, which usually results in more or less strict measures for environmental impact management. and a selection of recommended approaches and UAN monitoring and reporting measures applicable to the Irish ORE context.

Generally speaking, there are two main approaches to UAN management followed across the countries reviewed: one based on "**source and thresholds**" and another based on "**receiver and exposure**". The first (*source and thresholds*) is followed in countries like Germany, Denmark and Belgium. It uses a representative marine mammal species with the worst possible known effect from UAN, assuming that effects on hearing thresholds or to auditory organs are the most damaging (currently the harbour porpoise, since it presents the wider hearing frequency range and uses the highest frequencies for communication and awareness among all marine mammals), and assigns one or several maximum thresholds of Sound Exposure Level or Sound Pressure Level at pre-determined distances from anthropogenic sources (typically pile-driving during ORE construction stage), based on the assurance that these thresholds guarantee minimum or no disturbance to the representative species (and, presumably, even less to other species).

Regulations under this UAN management approach require OWF developers to actively monitor underwater sound produced during the construction of OWF. In most cases, monitoring of UAN produced during the operation and, in some cases, the decommissioning stages of the developments is also required. This is accompanied by requirements to keep the sound levels below a predetermined threshold, that varies among countries, through whatever noise mitigation or abatement measures necessary.

The second approach (*receiver and exposure*) is followed in countries like New Zealand, France, and the UK (for the time being). This approach requires a solid knowledge of the presence or absence of certain species (the receivers) in the ORE development area, of the effects of UAN on them, and of the sound propagation characteristics of the intended activity (either modelled or empirical) to predict exposure levels for each species (or group of species) likely to be affected by the future development. It then further requires that *surveillance* is kept at all times during the activity to ensure that, whenever a certain species is present in the area of the development, or in its surroundings to a certain distance (typically determined as the point at which the anthropogenic noise levels are indistinguishable from ambient sound levels), the sound source is mitigated or even completely terminated. For example, pile-driving being the most powerful sound source, this may mean shutting down piling while the "receivers" are known to be in the area.

The advantages and disadvantages of both approaches were then reviewed, from the viewpoint of the conservationist "precautionary principle" widely taken as fundamental. However, excessively precautious measures may have serious economic impacts on the developments for being too restrictive, and a fine balance must be sought.

Ultimately, as suggested by the New Zealand's Technical Working Group on Biologically Relevant Sound Levels (DOC, 2016e), and along the lines also suggested in recent work on impacts of UAN (e.g., Southall *et al*., 2021), perhaps the best approach is to combine the virtues of both, by managing the source level or frequency structure at the source through noise abatement systems (where predicted as necessary), and by reducing or eliminating effects at the receiver(s) through mitigation measures such as soft starts, shutdown or power-down thresholds, while keeping robust monitoring activities (e.g., Marine Mammal Observation combined with Passive Acoustic Monitoring).

Following all the analyses described above and detailed in the text, given the current practices in several jurisdictions, the current applicable legislation and the concerns of stakeholders, some recommendations on UAN monitoring and reporting for consideration in the Irish OWF context were formulated. Since, at the time of writing this report, there is no indication of which approach the Irish State will ultimately follow regarding UAN management (one of the above-mentioned general approaches, or a mixed balance of both), the guidance summarised below should be understood as recommendations on possible avenues for both regulators and OWF developers, without specifying a preference for any particular approach.

Development stage	**Recommendation**	
Pre-construction	**Use existing data to inform any assumption of acoustic baselines when preparing EIS/NIS for OWF developments**. If surveys are asked by regulators at this stage, **Standard IEC TS 62400-40:2019** can help.	
Construction	Monitoring	*S&T*: UXO Removal: **JNCC guidelines for minimising the risk of disturbance and injury to marine mammals whilst using explosives** (JNCC, 2021) and the new **JNCC draft guidelines for minimising the risk of injury to marine mammals from unexploded ordnance clearance in the marine environment** (JNCC, 2023b). Pile-driving: **ISO 18406:2017.**
		R&E: Use **combination of visual surveillance by MMO (at daytime) and acoustic surveillance by PAM, at all times.** Helpful guidance: **JNCC guidance for the use of Passive Acoustic Monitoring in UK waters for minimising the risk of injury to marine mammals from offshore activities** (JNCC, 2023a). **Report of the Marine Mammal**

Development stage	Recommendation	
		Observer/Passive Acoustic Monitoring Requirements Technical Working Group (DOC, 2016a). Additional recommendation for developers: **continuous review of advances in PAM systems.** Additional recommendation for regulators: **no specific PAM system or manufacturer mentioned in guidelines or regulations.**
	Reporting	*If UAN monitoring required*: Use **standard ISO 18406:2017**, eventually complemented by specifications of the **MSFD technical guidelines** (TG NOISE, 2014). Weekly reports prepared following **OSPAR requirements** (OSPAR, 2016) or regulator-provided templates. Data sent to international data banks such as ICES.
Operations	Monitoring	**Be compliant with either MSFD, or (*if explicit in the project consent*) with any consent conditions regarding UAN monitoring.** Helpful guidance: **Monitoring Guidance for Underwater Noise in European Seas** (TG NOISE, 2014). **Standard IEC TS 62400-40:2019. CEMP Guidelines for Monitoring and Assessment of loud, low and mid-frequency impulsive sound sources in the OSPAR Maritime Region** (OSPAR, 2017). **Literature on UAN monitoring related to OWF.**
	Reporting	Same as for “Construction”, but no weekly reports (replace by annual or bi-annual reports).
Decommissioning	Monitoring	Same as for “Construction”.
	Reporting	Same as for “Construction”.

Note: “S&T”: Source and Thresholds. “R&E”: Receivers and Exposure

2 Introduction

2.1 Background

The offshore renewable energy (ORE) landscape has undergone significant growth and development during the last decade, particularly in the domain of offshore wind energy. This sector, alongside other offshore renewable technologies, assumes a critical role in diversifying Ireland's energy mix, mitigating greenhouse gas emissions, and achieving sustainable energy objectives.

Offshore wind energy has seen significant growth worldwide. Numerous projects have entered, or are entering, operation and many more are in planning and development. Technological advancements, such as larger and more efficient turbines, contribute to increased energy production and cost competitiveness. This increase in offshore wind projects has been happening not only in European countries, with the United Kingdom, Germany, Denmark, and the Netherlands at the forefront, but also in other regions, including Asia (especially in China and Taiwan), the United States, and Australia. On the other hand, emerging technologies such as floating wind turbines are gaining attention as a promising technology, allowing deployment in deeper waters where traditional fixed-bottom turbines may not be feasible. Several pilot projects and demonstration sites are exploring the potential of floating wind farms.

In addition to wind energy, other ORE technologies have also seen some progress. This is the case of tidal and wave energy, ocean thermal energy conversion (OTEC), floating solar and hybrid systems. Tidal energy harnesses kinetic energy from the tidal movements of water masses; pilot projects and small-scale commercial installations have been exploring the feasibility of tidal energy as a reliable and predictable source, with mixed success. Wave energy converters aim to capture energy from ocean waves and convert it into electricity. While still in the early stages of development, several countries are investing in wave energy research and projects, with a few projects close to commercial sustainability. OTEC systems leverage the temperature difference between warm surface waters and cold deep waters to generate electricity. Most projects are still in the experimental phase, but OTEC holds long-term potential. Finally, floating solar energy is beginning to make the transition from their traditional field of application in inland waters, lakes or reservoirs into the coastal or open seas; however, most offshore floating solar projects are also still experimental. More recently, some projects have been exploring hybrid systems that combine multiple renewable energy technologies, such as combining offshore wind with tidal, wave, or floating solar energy.

All the above developments are important and significant for Clean Energy transition goals, by contributing to reducing carbon emissions and thus leading to a low-carbon energy system, as well as for Energy Security through diversification of energy production sources, and for job creation and economic growth. In addition, they are an excellent ground for technological innovation, promoting advancements in materials, design, and operation and maintenance practices. Many countries, including Ireland, have set ambitious targets for offshore wind capacity, signalling a strong commitment to the expansion of offshore renewables. Ongoing research, innovation, and international collaboration are critical for overcoming challenges and unlocking the full potential of offshore renewable energy.

One of the major challenges facing ORE developments is the potential for environmental impacts and the balancing of renewable energy development with environmental conservation. In this context, concerns related to anthropogenic underwater noise and its impacts on marine ecosystems, including their soundscapes, must be addressed (see Figure 1).

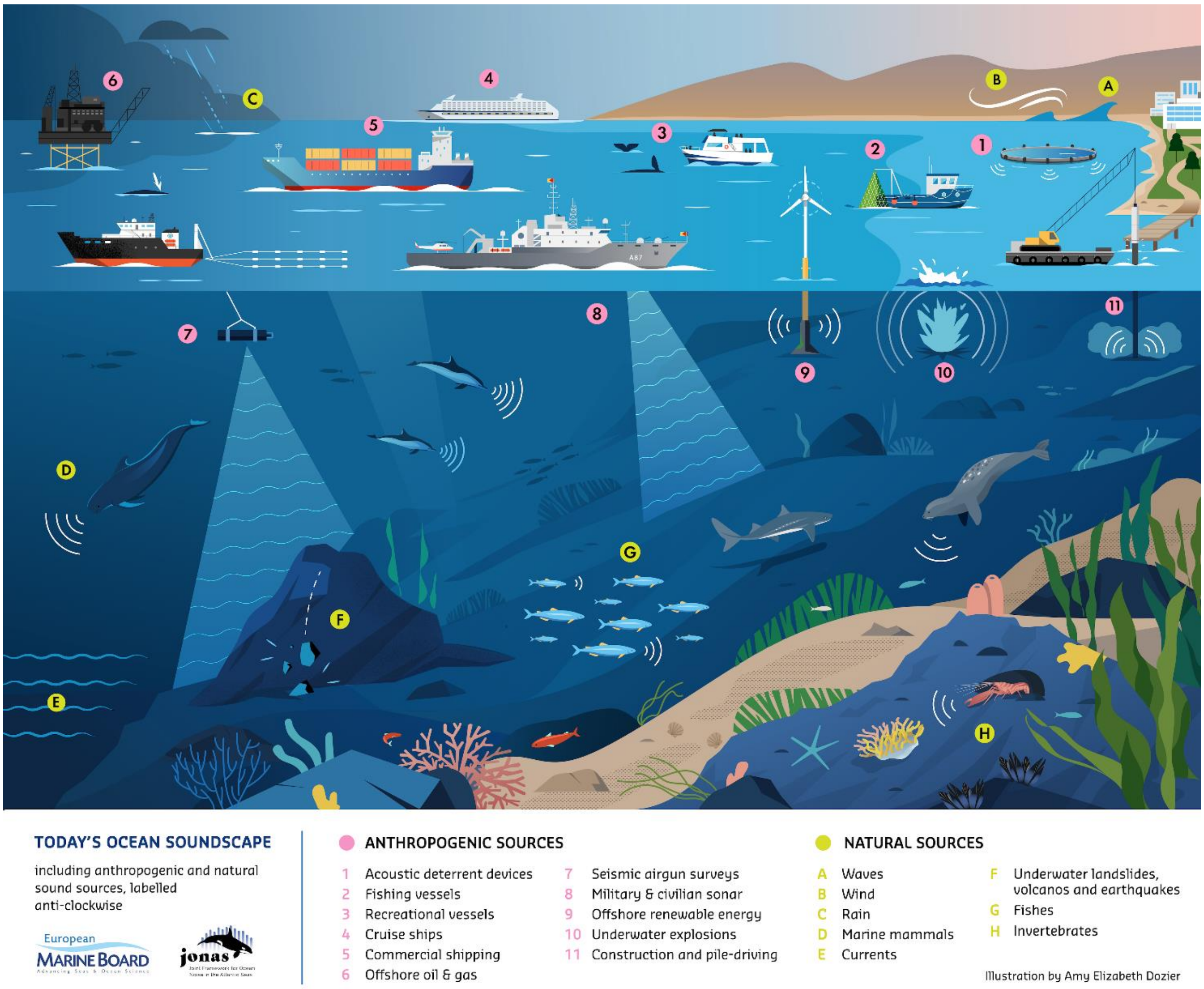

Figure 1 - An illustration of the ocean soundscape (image credit: the JONAS project[1])

For this reason, the Marine Institute's Research for Policy Awards, in its topic 2 (*Guidance for the management of impulsive and continuous noise for Offshore Renewable Energy development in Ireland*), addresses the need to study and develop practical guidance for the management of underwater noise in Irish waters, in compliance with national regulations and European obligations under the applicable Directives, and based on European best practices. The need for

[1] Illustration by Amy Dozier, in Thomsen, F., Mendes, S., Bertucci, F., Breitzke, M., Ciappi, E., Cresci, A. Debusschere, E., Ducatel, C., Folegot, F., Juretzek, C., Lam, F-P., O'Brien, J., dos Santos, M. E. (2021) *Addressing underwater noise in Europe: Current state of knowledge and future priorities*. Kellett, P., van den Brand, R., Alexander, B., Muniz Piniella, A., Rodriguez Perez, A., van Elslander, J., Heymans, J. J. [Eds.] Future Science Brief 7 of the European Marine Board, Ostend, Belgium. ISSN: 2593-5232. ISBN: 9789464206104. DOI: 10.5281/zenodo.5534224

this study and the guidance requirement has been put forward by the Department of Housing, Local Government and Heritage (DHLGH).

A scoping document for the study has been prepared and delivered to the Marine Institute and DHLGH in February 2024 (document *BD01923001-01 – Scope and Problem Description*).

The deliverables of this study comprise:

- The above mentioned Scope and Problem Description document (Deliverable D1).
- A review and summary of procedures and technical specifications for compliant underwater acoustic noise monitoring and reporting eventually applicable to Irish ORE developments (Deliverable D2, this document), and
- A review and summary of "do not exceed" criteria, thresholds and mitigation measures for underwater acoustic noise generated by ORE developments (Deliverable D3).

2.2 Objective

The objective of this document is to present the rationale, and develop a summary of guidance and technical specifications for measuring, monitoring and reporting underwater noise in the context of Irish ORE developments (deployment, operation and decommissioning of technologies), in line with the latest industry standards, best practices in other jurisdictions, and national regulations and European Union (EU) directives.

3 Definitions

Sound in the ocean is a complex phenomenon, and its study has led to different characteristics, properties and units being defined over time which, in turn, has led to confusion and difficulty in comparing results from experiments and research. The International Standards Organisation (ISO) has published a standard for acoustic properties (ISO 18405:2017 Underwater Acoustics – Terminology) (ISO, 2017), which will be used in this study for uniformity. Another useful source of nomenclature and definitions in underwater acoustics, in reality a summary of the ISO standard, is the paper by Ainslie *et al*. (2021), and the material with definitions available online (e.g., *Electropedia* by the EIC[2]). Appendix B contains a very brief introduction to underwater sound and the properties and units used in this report.

4 Context

Offshore renewable energy projects typically comprise several phases. These could include:

1. Pre-feasibility and Site Selection: This phase involves initial assessments to identify suitable offshore locations for renewable energy projects, considering factors such as wind or wave resources, water depth, proximity to existing infrastructure, environmental impact and regulatory constraints.
2. Feasibility Studies and Permitting: Once potential sites are identified, feasibility studies are conducted to assess technical, economic and environmental feasibility. This phase also involves obtaining necessary permits and approvals from regulatory authorities.
3. Design and Engineering: During this phase, detailed engineering designs are developed for the offshore renewable energy infrastructure, including wind turbines, wave energy converters, or tidal turbines, as well as associated support structures such as foundations and substations.
4. Procurement and Construction: The procurement process involves selecting suppliers, contractors, and equipment necessary for construction. Construction activities include the installation of offshore structures, laying of cables, and other infrastructure required for power generation and transmission.
5. Operations and Maintenance: Once construction is complete, the offshore renewable energy project enters the operations phase. This involves the ongoing monitoring, maintenance, and management of the infrastructure to ensure optimal performance and reliability over the project's operational lifetime, which can span several decades.
6. Decommissioning: At the end of the project's operational life, decommissioning activities are undertaken to safely remove and dispose of offshore infrastructure, restore the site

[2] https://www.electropedia.org/iev/iev.nsf/welcome?openform

to its original condition, and manage any environmental impacts associated with decommissioning.

The above common project phases have different implications in what concerns impact on the environment, especially in terms of the generation of underwater acoustic noise (UAN[3]). In the context of this study, phases 1 to 3 in the list above will be grouped into a **pre-construction stage**, and phases 4, 5 and 6 will constitute the **construction stage**, the **operations stage**, and the **decommissioning stage**, respectively.

4.1 Development Stages

4.1.1 Pre-construction stage

Site investigation surveys (geophysical and geotechnical) may take place during this stage of the development. Typical data collection activities include acquisition of bathymetric data (morphology of the ocean bottom), geotechnical data (composition and structure of the bottom, sediment layers, rock substrates, etc.), environmental characteristics (ocean current, waves, wind), archaeological data, biological activity in the survey area, among other.

These activities usually require passive acoustic monitoring (PAM) of the soundscape of the future development area, usually targeted at the detection of marine mammals. It may be advisable at this stage to conduct wider (i.e., not limited to marine mammals) baseline noise passive assessments to understand the ambient noise levels before construction, if knowledge of this baseline is not yet available. Other studies, such as developing predictive acoustic propagation computer models adjusted to the environmental conditions at the site, may be undertaken to help predict noise propagation during construction to minimize impact on marine life.

[3] "Underwater Acoustic Noise" is preferred in this document over "Underwater Radiated Noise", as is often seen in studies of underwater acoustics, since "radiated noise" may refer to not just acoustic noise (e.g., electromagnetic noise is also radiated underwater from varied sources).

Developers typically work closely with regulatory agencies, environmental experts, and stakeholders to plan and tailor future mitigation measures to the specific context of each offshore renewable energy project, such as employing marine mammals observers (MMO) and soft start and ramp up procedures during surveys and OWF construction, etc. (for details on mitigation measures please refer to document *BD01923003-01 Underwater Acoustic Noise Thresholds and Mitigation Measures Guidance*).

4.1.2 Construction stage

This is the development stage during which most of the underwater acoustic noise is generated. In this stage, continuous marine operations and maritime construction works take place. Typical maritime works could include:

- Foundation Installation: This involves the installation of foundations for offshore wind turbines, wave energy converters, or tidal turbines. Foundations can vary depending on the water depth and seabed conditions and may include monopiles, jackets, tripods, or floating structures. Drilling of the rocky substrate and pile driving are common installation techniques used (see section 5.2 for typical noise levels generated by pile driving).
- Mooring Systems: Floating offshore wind and wave energy projects require mooring systems to anchor the floating structures to the seabed. Mooring system installation involves the deployment of anchors (embedment or placement) and mooring lines to secure the floating structures in place.
- Turbine Installation: Offshore wind farms require the installation of wind turbines, which involves the use of specialised vessels equipped with cranes to transport and install the turbines onto their foundations. Tidal and wave energy projects also require the installation of turbines or devices onto their support structures.
- Substation Installation: Offshore renewable energy projects often include offshore substations to collect and transform the electricity generated by the turbines before transmission to shore. Installation of these substations involves maritime construction work, including foundation installation and substation platform installation.
- Cable Installation: Subsea cables are used to connect offshore renewable energy infrastructure, such as turbines and substations, to each other and to onshore grid

connections. Cable installation involves laying and burial of cables on the seabed using specialised vessels and equipment.

In addition to the above, other sources of acoustic energy in the marine environment of the development site arise from continuous vessel traffic from specialised vessels (transport of crews, jack-up barges, transport of materials, survey vessels, etc.).

During this stage, underwater acoustic monitoring may be required with real-time monitoring (of sound generated and possibly mitigated, or monitoring of presence of certain marine life) to detect and respond to unexpected increases in noise levels.

4.1.3 Operations stage

Underwater acoustic noise generated in this stage is mainly due to inspection and specialised maintenance vessels, noise generated by the energy conversion devices themselves (note that some devices can be acoustically characterised prior to deployment following applicable standards), noise generated by mooring systems in the case of floating structures, and by the interaction of the environment (wind, waves, currents) with the newly installed structures.

Noise generated by wind turbines can propagate into the marine environment through the foundations or floating structures. The internal machinery and equipment within wave and current energy conversion devices generate noise directly in the water column. In general, the level of sound emitted during the operation of offshore wind farms is relatively similar to ambient noise levels at several hundred meters from the farms (see Figure 2 and Figure 3), although this may change in the future with the growing size and power of installed turbines, the combined effect of several large turbines and a possible tendency to cluster OWF in regions with limited maritime space available (see, for example, Tougaard, Hermannsen and Madsen, 2020).

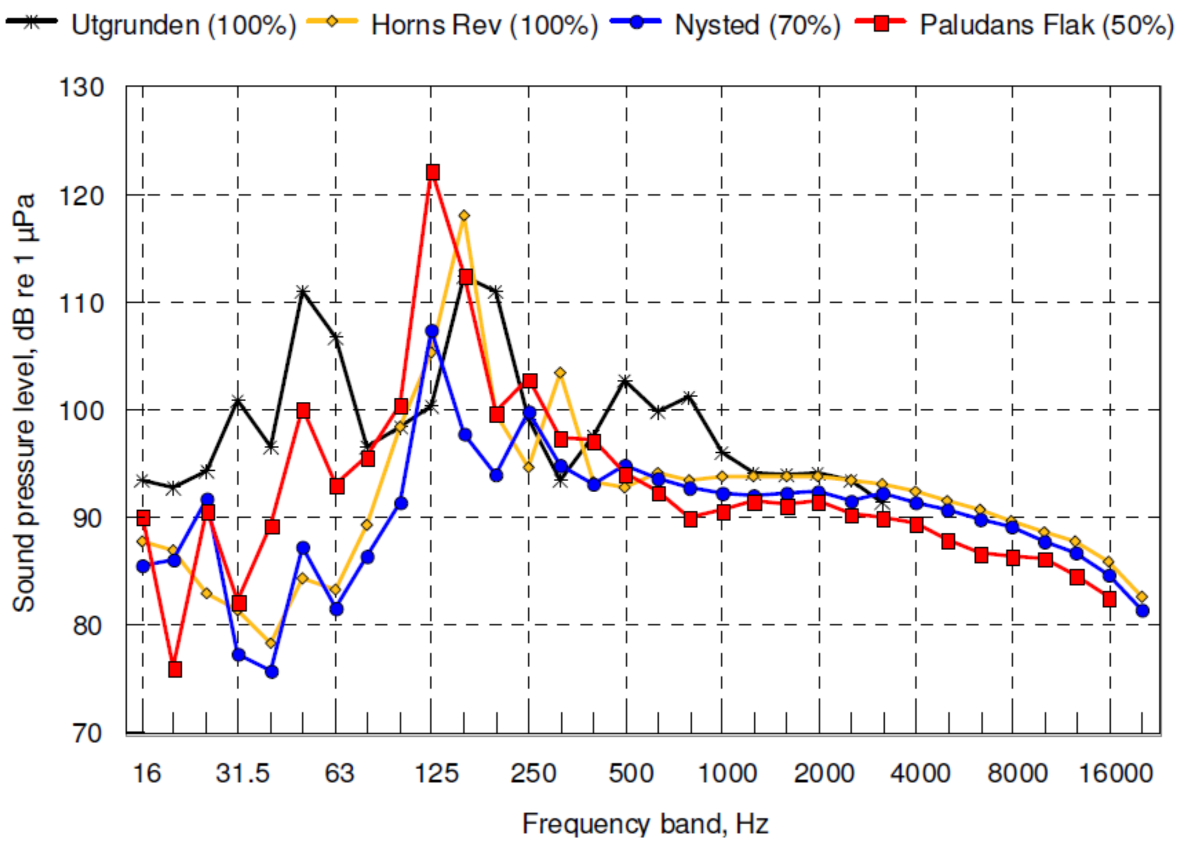

Figure 2 - Third-octave spectra of noise radiated from offshore wind turbines off Denmark, at 100m (Image Source: Diederichs *et al.*, 2008**)**

In this stage, developers may implement (or continue to operate) ongoing underwater acoustic monitoring to assess the continued impact of operational noise and, together with results from emerging scientific knowledge, develop and implement innovative technologies and practices to reduce underwater noise, such as implementing adaptive management strategies that allow for adjustments to operational activities. On the other hand, the UAN monitoring activities may be explicitly stated as required conditions for consenting.

4.1.4 Decommissioning stage

In this stage, decommissioning activities are undertaken to safely remove and dispose of the infrastructure. This may involve the removal of energy conversion devices, turbines, demolition and removal of foundations, cables, and other equipment, as well as site remediation and environmental restoration. This stage is thus similar to the construction stage in terms of the amount of maritime work and marine operations undertaken, but with lower expected levels of generated noise as, in principle, there shouldn't be any pile driving activity.

5 Soundscapes

A soundscape is understood as the collection of sounds and their sources present in an environment and their spatial, temporal and frequency attributes (ISO, 2017). Therefore, it encompasses both natural and human-made sounds and can vary widely depending on factors such as location, time of day, weather conditions and human activity. In the context of marine environments, a soundscape includes sounds produced by marine life, such as vocalisations of marine mammals and sounds generated by fish and invertebrates. Additionally, it includes natural non-biological ambient sounds such as waves, wind, and geological activity (see Figure 3). When perceived by receivers, the soundscape becomes their "auditory scene", which can vary among receivers depending on their acoustic sensing abilities (Ainslie *et al.*, 2021).

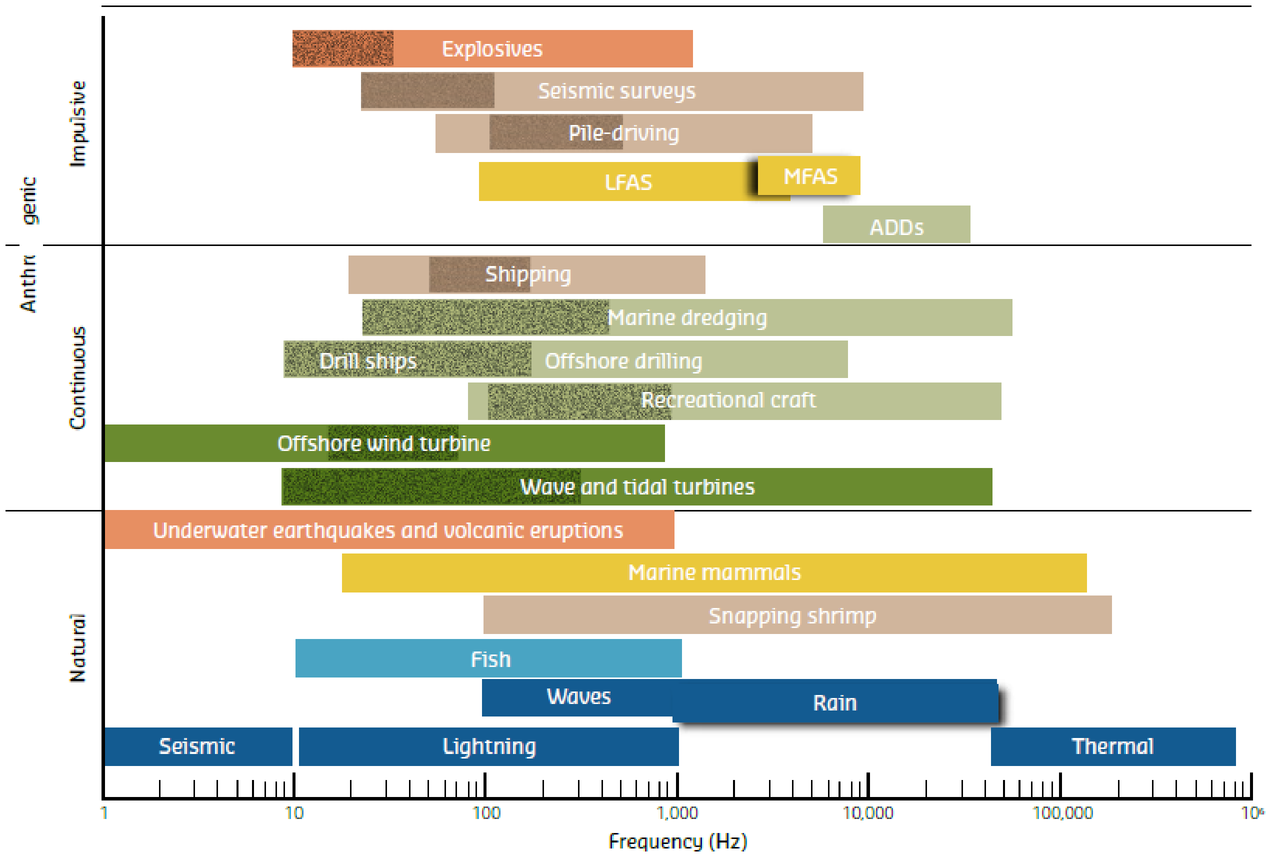

Figure 3 - Comparison of typical sound sources in the ocean. Order (from top to bottom) within each category rank the sound level, and colours allow for comparison among categories. LFAS, MFAS – Low and Medium Frequency Active Sonars, respectively. ADD – Acoustic Deterrent Device. ***(Image source: EMB, 2021)***

Soundscapes vary between shallow and deep waters due to differences in physical characteristics, biological activity and human influence. Some factors contributing to these variations include depth and seabed composition (more attenuation and refraction/diffraction in shallow depths), biological activity (higher closer to the coast), human activities (shallow water environments are often more heavily influenced by human activities) and oceanographic conditions (with greater variability expected in shallow water environments). This said, it is expected that most ORE developments will take place in relatively shallow waters (that is, less than 200m deep), although future developments (e.g., floating solar or floating wind) may be installed in deeper waters.

When considering soundscapes and their importance as a component of ecosystems, it is also advisable to consider the relevance of instantaneous levels of sounds versus trends in the soundscape. Previous knowledge of soundscapes, also commonly called “ambient noise”, is needed as a baseline against which to determine the changes in noise levels resulting from human activities. In the case of ORE developments, a baseline should be established, or known, before activity takes place because the new soundscape created by the presence of the development may impact marine life. The need for baseline data is consequently increasingly mentioned in policy papers and in guidelines (e.g., the *Offshore Renewable Energy Policy Position* by Fair Seas (Fair Seas, 2024), the Irish Whale and Dolphin Group *Policy On Offshore Windfarm Development Paper* (IWDG, 2020) in or DECC’s guidelines (DECC, 2018a,b), among other), although not explicitly in regulations (at least, not In Ireland).

Even though they can have significant temporary impact on marine habitats, instantaneous sources of high-powered sound are not relevant for the establishment of a soundscape, whereas an increase (or decrease) of the levels of other sound sources, such as shipping or underwater installations, or natural marine life sounds, may with time have a more significant cumulative effect. With this in mind, several regulations (e.g., the EC’s Marine Strategy Framework Directive (MSFD), or the UK’s Joint Nature Conservation Committee (JNCC)) establish the need to measure or monitor “continuous” and “impulsive” acoustic noise derived from human activities, including ORE developments (see section 6 for details on these regulations).

5.1 Continuous Noise

Continuous underwater noise sources are those that produce steady or relatively constant sound emissions over time, without abrupt changes or interruptions. These sources can include both natural phenomena and human activities. Typical sources include:

- Oceanic Background Noise: Natural processes such as wind, waves, and currents generate continuous background noise in the ocean. Wind-driven waves produce surface agitation, generating a broad spectrum of noise frequencies. This background noise is typically more pronounced in coastal areas and can vary with weather conditions and sea state.

- Biological Activity: Biological organisms, including marine mammals, fish, and invertebrates, contribute to continuous underwater noise through vocalizations, feeding and other behaviours. Marine mammals, such as whales and dolphins, produce a variety of vocalizations for communication and navigation, while fish and invertebrates may generate noise through movement and feeding activities.

- Geological Processes: Geological activities such as underwater earthquakes, volcanic eruptions, and submarine landslides can generate continuous noise in the ocean. These processes produce low-frequency seismic signals that can propagate over long distances and contribute to the ambient noise background.

- Shipping and Maritime Traffic: Vessel traffic, including commercial shipping, cargo vessels, and recreational boating, generate continuous noise in the ocean through engine propulsion, propeller cavitation and hydrodynamic interactions with the water. Shipping noise is typically characterized by low to mid-frequency components and can be particularly pronounced in shipping lanes and busy maritime routes.

- Offshore Industrial Activities: Offshore industrial activities can produce continuous noise from machinery and underwater equipment. These activities can introduce anthropogenic noise into marine environments, impacting local acoustic conditions and marine life.

- Underwater Anthropogenic Sources: Other anthropogenic sources, such as underwater communication devices, and underwater vehicles, can generate continuous noise emissions in the ocean. These sources typically operate within specific frequency bands and may produce steady or modulated signals for navigation, detection and communication purposes.

In particular, the result of increasing shipping intensity or vessel activity on the marine environment is an increasing pressure on marine life in the form of rising levels of continuous anthropogenic underwater noise. Whereas instantaneous values are of short duration and fairly easily adapted to by marine life (provided, of course, proper mitigation measures are taken in the case of anthropogenic sound sources), current underwater noise monitoring guidelines advise to measure the *long-term trends* in the overall noise levels in the frequency bands where ship noise is most prevalent.

Shipping noise covers a broad range of frequencies, typically spanning from low to mid frequencies. The specific frequency bands can vary depending on factors such as the type of vessel, engine design, and operational conditions. However, shipping noise is generally characterized by dominant frequency components within the following frequency bands:

- Low Frequencies (10 Hz to 1 kHz): Shipping noise often contains significant energy in the low-frequency range, typically below 1 kHz. This frequency band is particularly important for large vessels, such as cargo ships, container ships, and tankers, which produce low-frequency noise due to the operation of their propulsion systems, including diesel engines and propellers. Low-frequency noise can propagate over long distances in the ocean and can have significant implications for marine life, including marine mammals, fish, and invertebrates.

- Mid Frequencies (1 kHz to 10 kHz): Mid-frequency noise is also prevalent in shipping noise, with dominant components typically ranging from 1 kHz to 10 kHz. This frequency band can be associated with various sources on ships, including engine noise, machinery, and hydrodynamic interactions between the hull and water. Mid-frequency noise can have important implications for marine organisms, including communication, navigation, and foraging behaviours.

- Higher Frequencies (>10 kHz): While less dominant compared to low and mid frequencies, shipping noise may also contain energy in higher frequency bands, exceeding 10 kHz. These higher frequencies can arise from various sources onboard vessels, including pumps, ventilation systems, and mechanical components. While less significant for long-range propagation, higher-frequency noise can still influence local acoustic environments and marine life, particularly in coastal areas and shallow water environments (Mustonen *et al.*, 2019).

Noise from shipping (here understood as the result of the operation of specialised vessels in the area of the ORE development – a wind farm, a wave farm, etc.) is expected to be present in all stages of the ORE development, including the planning (in this case, vessel noise generated during site investigation surveys). However, it will be during the operation stage, in which vessels are expected in the area on a daily basis, that shipping noise in the area will have larger cumulative effect over the lifespan of the development and thus contribute to trends in continuous UAN in the area (on this aspect of future trends, see, for instance, Tougaard *et al*., 2020).

The MSFD has set guidelines for continuous acoustic noise monitoring mostly derived from shipping and its possible impacts on marine mammals (1/3 octave bands centred at 63Hz and 125 Hz; details in section 6).

5.2 Impulsive Noise

Impulsive underwater noise refers to *short-duration*, *transient* sound events characterized by rapid changes in pressure (see also the definition in the *MSFD Technical Subgroup on Underwater Noise*, TG NOISE, 2013). These short-duration sounds, of which nearly instantaneous sounds such as explosions or airgun bursts are an example, can arise from various natural and anthropogenic sources in the marine environment. Fishes and marine mammals may suffer a range of potential effects from exposure to intense underwater sound generated by anthropogenic activities such as pile driving, sonars or seismic survey equipment, or underwater blasting (Southall *et al*. 2021).

The frequency content of impulsive underwater noise can vary depending on the source and the characteristics of the sound event. However, impulsive noises typically exhibit a broad spectrum of frequencies, with significant energy across a broad frequency range, typically spanning from low to mid-high frequencies. The specific frequencies most expected for human activity can vary depending on the source and the nature of the impulsive event:

- Pile Driving: Pile driving activities associated with offshore construction projects can generate impulsive noise with dominant frequency components in the low to mid frequencies, typically ranging from a few hundred hertz to several kilohertz. The exact frequency content can depend on factors such as the size and type of pile, the driving technique, and the characteristics of the surrounding environment. Typical sound pressure levels depend on the pile driving technique used and size and diameter of the pile; SPL in excess of 200dB re 1uPa were measured at 750m of unmitigated pile driving in an OWF in the Baltic Sea (Juretzek, Schmidt and Boethling, 2021).

- Seismic Surveys: Seismic surveys, used for oil and gas exploration and geological research, involve the use of airguns to generate impulsive sound pulses. These pulses typically have dominant frequency components in the low to mid frequencies, ranging from tens of hertz to a few kilohertz. The specific frequency content can vary depending on factors such as the airgun array configuration, pulse duration, and water depth.

- Underwater Explosions: Explosive detonations, such as those used in military exercises or demolition activities, can generate impulsive noise with energy distributed across a broad frequency range, from low to high frequencies. The specific frequency content of underwater explosions can vary depending on factors such as the explosive charge size, depth of detonation, and surrounding water conditions.

- Sonar Operations: Active sonar systems used for navigation, detection, and communication purposes can emit impulsive pulses of sound with dominant frequency components spanning from low to high frequencies. The frequency content of sonar pulses can vary depending on the type of sonar system, the operational frequency band, and the transmission parameters.

- Geophysical and geotechnical surveys: these surveys, very common if not a standard on ORE developments, use sound in many forms to collect information about the marine environment which is critical for the design and safe and efficient operation of the ORE devices and infrastructures. A recent survey of techniques, frequencies and acoustic power utilised in these surveys has recently been published by Wind Energy Ireland (Wind Energy Ireland, 2023).

The MSFD, motivated by the achievement of good environmental status of European waters, has set guidelines for monitoring impulsive noise in the frequencies that are known to be used by marine mammals (low and mid-frequency band from 10 Hz to 10 kHz; details in section 6).

6 Relevant Regulatory Frameworks

Due to the known and unknown impacts of UAN on the marine environment, and following a general aim of preserving and protecting marine life and their habitats, several regulatory frameworks to better understand and eventually mitigate the effects of anthropogenic sound in the ocean have been produced, at national, regional and international levels. These currently comprise an elaborate set of codes of practice, instructions, laws, guidelines, regulations, policies, etc. aimed at monitoring sound produced by human activities in several maritime sectors, including ORE, which means making measurements of underwater sound.

Underwater acoustic noise measurements can be designed and made to satisfy several requirements. For instance, measurements of underwater sound during pile driving activities may be designed to achieve one or more of the following objectives (ISO 18406:2017):

- measurement at a fixed location to monitor the source output for comparison with other percussive pile driving events;

- measurement to assess the accuracy of predictions made in environmental impact assessments, environmental impact statements, or environment statements;
- measurement at ranges that allow comparison with a normative threshold level, for example, where specific impact criteria are expected to be exceeded;
- measurement at specific sites which are regarded as sensitive because of the presence of specific species of aquatic fauna;
- measurement in order to derive a source output metric, which can be compared with other sources and used in noise mapping and prediction of "impact zones".

Clear guidelines aligned to regulations are needed during the development phase of ORE projects so that developers can plan for, and collect, the required data either in advance of (e.g., baseline data collection) or during construction activities (for mitigation). A review of current National and International regulations is provided below to ensure the development of guidance and technical specifications for measuring, monitoring and reporting underwater noise is in line with the latest industry standards, best practices in other jurisdictions, national regulations and European Union (EU) directives.

6.1 In Ireland

The Irish regulations landscape concerning ORE developments is undergoing some changes and updates. At the time of writing this report, the most recent national regulations that conform to EU directives transposed to National legislation require ORE developers to undertake an Environmental Impact Statement (EIS) due to the national Act (and amendments) enforcing the EU's Environmental Impact Assessment Directive 2014/52/EU, and also a Nature Impact Statement (NIS) due to the national Acts enforcing the Habitats Directive 92/43/EEC and the Birds Directive 2009/147/EC, in case there is a likelihood of a significant effect on a Natura 2000 Site. These two Statements inform an Environmental Impact Assessment (EIA) and an Appropriate Assessment (AA), respectively, from competent authorities. The "Guidance on EIS and NIS preparation for ORE projects" (DCCAE, 2017) offers non-statutory guidance to assist ORE developers in the preparation of these statements.

In addition to the above guidance, DECC has also published, in 2018, guidelines to assist developers in carrying out marine baseline ecological assessments and monitoring activities (DECC 2018a,b). These guidelines cover most environmental aspects required in the preparation of EIS and NIS and, of relevance to this study, they contain requirements to observe and monitor the acoustic energy released into the environment by ORE developments, with a particular focus on potential effects on marine mammals. A "baseline survey" and a "monitoring" phase are described, as detailed in section 9.1.

The ORE industry in Ireland closely follows a set of guidelines published by the National Parks and Wildlife Service (NPWS) in 2014, the "Guidance to Manage the Risk to Marine Mammals from Man made Sound Sources in Irish Waters" (NPWS, 2014). At the time of writing this study, these guidelines are under review and a draft of the new text is still unknown.

6.2 In Other Jurisdictions

6.2.1 United Kingdom

In the United Kingdom, the Joint Nature Conservation Committee (JNCC) published several guidelines applicable to ORE developments to ensure their compliance with existing legislation, namely the Environment Act 2021, the Habitats Regulations (enacted before Brexit) and several other pieces of legislation. The UK government is currently working on an Offshore Wind Environmental Improvement Package (OWEIP), composed of legislation to support the accelerated deployment of offshore wind. The OWEIP will help to reduce offshore wind consenting time in the UK from up to four years to one year, whilst ensuring meeting environmental commitments.

The JNCC guidelines were primarily developed with marine mammals conservation and the offshore oil and gas industry in mind, but have been further expanded to include other offshore industries and maritime activities such as those typical in ORE (e.g., offshore wind farms, tidal energy, etc.). JNCC's guidelines are focused on noise abatement and mitigation of risk of injury to marine mammals and, thus, they are more relevant for the part of this work addressing mitigation and thresholds (Deliverable *BD01923003-01 Underwater Acoustic Noise Thresholds and Mitigation Measures Guidance*). Nevertheless, the most relevant guidelines are listed below:

- JNCC guidelines for minimising the risk of injury to marine mammals from geophysical surveys (seismic survey guidelines) (JNCC, 2017).
- Statutory nature conservation agency protocol for minimising the risk of injury to marine mammals from piling noise (JNCC, 2010).
- JNCC guidance for the use of Passive Acoustic Monitoring in UK waters for minimising the risk of injury to marine mammals from offshore activities (JNCC, 2023a).
- JNCC guidelines for minimising the risk of disturbance and injury to marine mammals whilst using explosives (JNCC, 2021).

The UK's Marine Management Organisation (MMO) has also published a set of guidelines for ORE developers in 2012. These have been commissioned to the Centre for Environment, Fisheries & Aquaculture Science (CEFAS) and contain guidance to assist developers, environmental consultants, regulators, decision makers and consultees in the design, review and implementation of environmental data collection and analytical activities associated with all stages of ORE developments, and especially for offshore wind farms:

- MMO/CEFAS Guidelines for data acquisition to support marine environmental assessments for ORE projects (CEFAS, 2012).

The above guidelines are similar to those published in Ireland by DECC, but with further information covering the subsequent stages of ORE developments.

In Scotland, NatureScot (formerly Scottish Natural Heritage) maintains a Handbook on EIA, with guidance similar to that available in DECC's guidelines. Scotland has its own country-specific authorities in relation to the offshore area:

- Environmental Impact Assessment Handbook V5 (NS, 2018).

In Wales, a document has recently been published with a comprehensive and excellent review of the different disturbance thresholds that have been used in previous EIA and Habitats Regulations Assessment (HRA), both in the UK and elsewhere, for a variety of different sound sources in the context of OWF developments, and the risks they may present to marine mammals (Sinclair *et al.*, 2023). The report concludes with a recommendation to authorities to prepare three sets of guidelines, since no specific guidance exists in the UK relating to UAN thresholds and how to use them.

- Regulatory Guidance document – containing not only legislation and regulations, but also needed important definitions such as “disturbance” or “significant”, approaches on noise management, etc.
- Threshold guidance document – definitions and usage of thresholds for UAN.
- Population guidance document – to maintain updated information on marine mammals populations and the conservation policies affecting them and maritime infrastructure.

Until the above recommendations are followed, general non-statutory guidance available in the UK from the MMO and JNCC is followed by the Licensing Authorities (either the MMO, the Crown Estate, or the Crown Estate Scotland) when considering requisites for issuing OWF marine licenses (other consents must be secured as well, such as planning licenses, which may be local or national). Depending on the specific case under consideration, some requirements may be added to the license holder during the construction and the operation phases. The general process regarding marine licenses and UAN is described below, for each significant project stage:

Construction. The Licence Holder must undertake measurements of the noise generated by the installation of foundation pieces. Measurements need to be taken at various distances for the first few foundation pieces (minimum of four) including during the ‘soft start’ procedure. The specification for these measurements should be agreed with the Licensing Authority, through consultation with CEFAS and Natural England or other appropriate body, at least four months before the construction work commences. The results of these initial measurements should be processed, and a report submitted to the Licensing Authority within six weeks of the installation of the first foundation piece. Assessment of this report by the Licensing Authority will determine whether or not any further noise monitoring is required. Should noise levels be significantly in excess of those predicted during the Environmental Impact Assessment process then further pile installation will not occur without the consent of the Licensing Authority.

Operation. The Licence Holder must develop plans for subsea noise and vibration from the turbines to be assessed and monitored during the operational phase of the wind farm. Before completion of the construction phase, the Licence Holder must supply a specification to the Licensing Authority of how it proposes to measure subsea noise and vibration. These measurements must be taken at various frequencies across the sound spectrum at a selection of locations immediately adjacent to, and between turbines within the array, and outside the array at varying distances.

A typical measurement plan for monitoring piling noise during construction employs two fixed noise monitoring buoys to measure the entire piling sequence, including “soft start” if this mitigation measure is being used. Typically, these buoys are deployed at about 1.5 and 3 km from the pile, with two hydrophones each at about 2.5 and 7.5 m from the seabed. Additional measurements are taken from a vessel at various ranges from the pile, ideally at increasing range along a predetermined transect with a relatively flat bathymetry. Typical distances chosen are 250 m, 500 m, 750 m, 1 km, 1.5 km, 2 km, 3 km, 5km, 7.5 km, etc., depending on time. Two hydrophones are deployed, one below mid-water column and one close to mid-water column. These range dependent measurements are taken to estimate source characteristics.

For details on recommended practice for underwater noise measurement and measuring systems in the UK please see the National Physical Laboratory’s “Good Practice Guide for Underwater Noise Measurement” (NPL, 2014).

6.2.2 Denmark

In 2022, the Danish Energy Agency published guidelines concerning underwater noise in relation to the construction of offshore wind farms in Danish waters:

- Guideline for underwater noise (Installation of impact or vibratory driven piles) (DEA, 2022).

These guidelines, first published in 2016, used to focus only on the effects of pile driving or drilling on permanent impact to marine mammals (permanent hearing thresholds), but have recently been updated with the inclusion of other impacts and other receptors (e.g., behavioural disturbance of marine mammals, introduction of frequency weighting principles and acoustic criteria according to auditory groups), using the most recent learnings from research.

Construction. The guidelines establish thresholds for a number of marine species, and it is the responsibility of the concession holder to determine which and how many of the species shall be considered as possibly affected in their OWF development, based on the presence or absence of the species in the concession area. They also require monitoring and evaluation of the cumulative sound exposure level (SEL_{cum}) for each foundation over the entire installation period, with a maximum integration time of 24 hours.

The above requirements may be achieved through a so-called *Prognosis* assessment, using modelling or semi-empirical estimations of sound levels, with specific guidance on several model and environmental parameters to be considered. In the case of semi-empirical estimations, actual acoustic measurements in the future OWF site are required using artificial sound sources, in order to acquire reference data.

The results of the Prognosis must be verified by limited field measurements. This can be done before or during piling (if done before the actual piling, an artificial equivalent source must be used and justified), placing, at minimum, hydrophones at 750m, 1000m, 1500m, 2000m from the source (further distances are recommended as well). Details on how to perform the measurements and the processing of data are also provided in the guidelines.

In addition, the guidelines require measurements of background (ambient) noise, to be undertaken when sound from pile driving is not present, intended for subsequent correction of measurements taken during construction, including contributions from relevant support vessels. The hydrophone deployment depth shall be the same as for the measurements during pile installation. The background noise shall be analysed as root-mean-square sound pressure level (SPL_{rms}) with an averaging time of 60s. Measurements shall be taken over a minimum of 10 minutes, and the 60s averaging blocks need not be contiguous. The background noise shall be reported as unweighted 1/3-octave band spectra based on minimum, maximum, median (50% exceedance), and mean and standard deviation of SPL_{rms}.

6.2.3 Germany

In Germany, the regulatory authority (the Bundesamt für Schifffhart und Hydrographie – BSH) is responsible for developing and publishing guidelines and statutory compliance measures to mitigate the effects of underwater acoustic noise generated by offshore wind farms developments. Currently, the main guides and regulations include:

- Offshore wind farms - Measuring instruction for underwater sound monitoring. Current approach with annotations. Application instructions (BSH, 2011).
- Prediction of underwater sound. Minimum requirements for documentation (BSH, 2013a).
- Measuring Specification for the Quantitative Determination of the Effectiveness of Noise Control Systems (BSH, 2013b).

The first document in the list above contains precise instructions on how to measure, monitor and report UAN in offshore project areas; the last two documents focus on required mitigation measures and thresholds (currently, Sound Exposure Level (SEL) below 160 dB ref 1µPa^2.s at 750m, and Peak Sound Pressure Level (SPL_{PEAK}) below 190 dB ref 1µPa at 750m), and on how to document sound modelling and mitigation measures informing EIS and NIS for future projects.

Another useful document describes the current underwater acoustic noise regulations in place in Germany, with practical considerations for developers:

- Assessment Effects Offshore Wind Energy Technical Report (BSH, 2019).

Requirements for sound monitoring and reporting in Germany are applicable at each stage of the OWF development.

Pre-construction. Background noise measurements have to be carried out before construction starts. Measurements must be carried out for three wind classes, which correspond to sea state 1 (without rainfall) and, with regard to average and nominal capacity, also to the wind farm's power range. The exact measuring sites must be coordinated with the licensing authority 12 weeks in advance considering project-specific and site-specific needs. For evaluating the measurements, equivalent SPL values (in dB re 1µPa) are generated, frequency-resolved in 1/3-octave bandwidths, with an averaging time of 5 seconds.

Construction. In the construction phase, monitoring measurements must be executed during high-noise activities (e.g., deterrent measures, use of vibrators, pile driving). For each type of foundation and each installation method used in a wind farm, a complete registration of the noise caused by the foundation work must be performed at least once, with measurements done ideally during the installation of the first foundation of its kind. All measures for sound protection (e.g., deterrent measures, soft-start, pile-drive vibrations, quenching water, hydro sound absorbers, coffer dam, etc.) must be supervised by sound measurements. The measuring sites are to be located at distances of 750 m and 5 km to the foundation structure, and also in the closest nature reserve if it is more than 5 km away from the project site. Typical sequences of the sound pressure history shall be represented with the equivalent continuous SPL at the beginning, at half time and at the completion of the relevant building project. Furthermore, the single event sound exposure level (SEL) and the peak sound pressure level (SPL_{peak}) shall be given for impulsive installation methods (e.g., piling).

Operation. Control measurements must be done in the surroundings of the OWF, in close agreement with the licensing authority, in its operation phase. Conditions under three power ranges (low, medium and nominal power) are to be recorded, on a random basis at positions inside the wind farm, and sound measurements must be carried out at approximately 100 m from the nearest sound source. Additionally, measurements must be performed in the nearest nature reserve, provided that it is not more than 4 km away from the project site, in which case a sound measurement at 4 km distance to the wind farm must be carried out alternatively. For comparison, equivalent SPL values (in dB re 1µPa) must be generated, frequency-resolved in 1/3-octave bandwidths, with an averaging time of 5 seconds.

6.2.4 France

In France, the main source of guidance on underwater acoustic noise monitoring and mitigation is a document published in 2020 by the French Ministry for Ecological Transition listed below:

- Recommendations to limit the impacts of manmade underwater acoustic emissions on marine wildlife (MTE, 2020).

This document contains guidance on assessing and mitigating UAN during the various phases of offshore developments, including ORE, Oil and Gas, as well as in other marine and maritime activities such as fishing, aquaculture, research, shipping, cable laying, mining, coastal protection, etc. The recommendations on UAN assessment define almost exclusively the utilisation of acoustic prediction models based on localised expected or known sources. The document includes "summary fact sheets" with useful guidance on mitigation (to be developed in deliverable *BD01923003-01 UN Thresholds and Mitigation Measures Guidance for ORE*).

6.2.5 Belgium

There are specific guidelines for ORE developers in Belgium regarding maximum values for underwater acoustic noise, similar to those followed in Germany:

- Omschrijving van Goede Milieutoestand en vaststelling van Milieudoelen voor de Belgische mariene wateren. Kaderrichtlijn Mariene Strategie – Art 9 & 10 (Anonymous, 2012).

According to these guidelines, mitigation measures, if needed, to ensure noise levels remain below the required threshold (currently, SPL 185 dB ref 1µPa at 750m) and adequate underwater noise monitoring must be proposed at EIS stage by the developer. On the other hand, Belgian environmental researchers have done dedicated surveys to assess underwater noise caused by Offshore Wind Farms in Belgian waters, in the different stages of their life cycle (except decommissioning), which have resulted in some good reference papers in the evolving topic of ORE-related underwater noise, such as Norro *et al*., 2010, and Rumes *et al*., 2016.

6.2.6 The Netherlands

ORE developments in The Netherlands follow the guidance developed by the Netherlands Organisation for Applied Scientific Research (TNO) on behalf of the Ministry of Infrastructure and the Environment, Directorate-General for Water Affairs, in 2011. The results of the intense study TNO performed on the occasion, including input from experts from several European countries and also the US, consisted of two main documents:

- Standard for measurement and monitoring of underwater noise, Part I: physical quantities and their units (TNO, 2011a).
- Standard for measurement and monitoring of underwater noise, Part II: procedures for measuring underwater noise in connection with offshore wind farm licensing (TNO, 2011b).

The latter document contains the standard that ORE developers must follow in The Netherlands' offshore waters. It includes requirements for monitoring of UAN during two specific activities: impact pile driving in the construction phase and operational wind farms.

Pile driving: The aim is to both gather data for future studies of the distribution of piling noise on the North Sea, which are needed for environmental impact assessment studies for OWF development in the Dutch Economic Zone, and to monitor compliance with any threshold set in the marine licenses. Licensing decision requires measurements with a "permanent" noise measurement system, plus a "ship-based" measurement system along transects, with hydrophones at various depths, to get a good overview of the spatial characteristics of the noise. Measurements have to be carried out 'during piling activities' and have to include the ambient noise between the piling activities. Transects should extend to distances at which the piling noise can no longer be "distinguished from the ambient noise". Special attention is required for transects in the direction of the Dutch coastal zone. The measurement plan has to be approved by the licensing authority, who will judge whether the measurements provide sufficient detail for modelling the spatial distribution of UAN.

Operation of the wind farm. The aim is to determine the long-term averaged SPL and the Zero-to-Peak Sound Pressure Level (SPL_{z-p}) of transients. This noise has to be monitored continuously, during the first year of operation of the wind farm, by permanent measurement systems installed in the OWF and in an area around it up to a distance where the noise can no longer be "distinguished from the ambient noise". The systems should operate during all-weather conditions.

TNO, 2011b also includes the necessary conditions that a UAN "Measurement Plan" must abide by to guarantee the above requirements, including guidance on hydrophone calibration and deployment, distances, depths to be considered, environmental conditions to be recorded, data processing, etc.

6.2.7 New Zealand

In 2013, the New Zealand's Department of Conservation issued the "Seismic Surveys Code of Conduct" establishing the basis for protection of marine mammals from seismic survey activity. Although the code deals specifically with marine mammals and is meant to regulate seismic surveys, other marine infrastructure developers have been observing the same guidance, including when pile driving activity is required as in OWF developments.

The code was reviewed in the period 2015-2016, following feedback received from a variety of stakeholders. The review work was carried out by nine technical subgroups composed by representatives from the state, maritime industry (especially O&G) and academia, among others. These groups submitted reports on different topics regulated in the Seismic Surveys Code of Conduct in 2016. The most relevant for this study, along with the Code, are listed and referenced below:

- 2013 Code of Conduct for Minimising Acoustic Disturbance to Marine Mammals from Seismic Survey Operations (DOC, 2013).

- Report of the Marine Mammal Observer/Passive Acoustic Monitoring Requirements Technical Working Group (DOC, 2016a).
- Report of the Marine Mammal Impact Assessments/Marine Mammal Mitigation Plans Technical Working Group (DOC, 2016b).
- Report of the Marine Mammal Observer/Passive Acoustic Monitoring Observer Data Technical Working Group (DOC, 2016c).
- Report of the Non-Standard Surveys Technical Working Group (DOC, 2016d).
- Draft report of the Biologically Relevant Sound Levels Technical Working Group (DOC, 2106e).

The latter report remains in draft form since it was not possible to reach consensus within the technical working group in relation to a final text; nonetheless, it contains useful information in particular on thresholds and mitigation of UAN, as well as a good discussion on UAN management approaches that can be extrapolated for use in the OWF case.

It is interesting to note that the New Zealand code exempts so-called “Level 3” surveys from any of its obligations regarding monitoring and mitigation of UAN to avoid possible effects on marine mammals. Level 3 surveys include all surveys that utilize low power sub-bottom profiling, such as single, small airguns, sparkers, boomers and Sub-Bottom Profilers, which are typically employed in site investigation surveys and considered to be within the noise levels of commercial shipping in New Zealand. However, during the revision of the code carried out in 2016 there were concerns raised about potential impact from specific equipment such as low-frequency, high-power multi-beam echosounders (DOC, 2016d).

Another interesting note is that, for Level 2 surveys (which use medium power high-resolution seismic survey systems), properly trained crew members of the *survey vessel* may be used to fill in the obligation to carry a MMO onboard during the survey, thus waving the necessity to engage independent MMO (required only in high-power, high-resolution Level 1 surveys).

General rules in New Zealand allow for nighttime operations with continuous PAM surveillance, complemented by MMO surveillance at daytime. PAM surveillance requirements and technical specifications are clearly defined in the code and further discussion and guidance is available in DOC, 2016. PAM surveillance is not mandatory for Level 2 surveys but, on the other hand, these may be restricted to operate only at daytime unless a few strict conditions are met before twilight.

6.2.8 United States

The United States have a complex body of regulations regarding nature conservation, both at federal and state level. These include the Marine Mammal Protection Act, the Endangered Species Act, the National Marine Sanctuaries Act, and the Magnuson-Stevens Fishery Conservation and Management Act, all of them with provisions to protect habitats and certain species that ORE developers and licensing authorities must observe. A recent strategy document has been published that contains summary guidance useful to ORE developers, as well as directions for upcoming UAN monitoring standard developments, and unified legislation. This document, developed by the Bureau of Ocean Energy Management (BOEM) and the National Ocean and Atmospheric Administration – Fisheries (NOAA), is called "BOEM and NOAA Fisheries North Atlantic Right Whale and Offshore Wind Strategy" (BOEM-NOAA, 2024) and adds to NOAA's own Ocean Noise Strategy Roadmap (NOAA, 2016). Although it targets the protection of cetaceans, it includes a summary of current (and future) requirements that can be applied to safeguard other marine species as well. In accordance with the latest documents, the main references for ORE developments in the USA are listed below:

- BOEM and NOAA Fisheries North Atlantic Right Whale and Offshore Wind Strategy (BOEM-NOAA,2024).
- NOAA Ocean Noise Strategy Roadmap (NOAA, 2016).
- Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing – Version 2.0 (NOAA, 2018).

These three documents, plus the above mentioned four Acts, set out the framework for UAN management that is followed by regulatory and consenting authorities in the US. In practice, ORE developers prepare their EIAs for planning applications by using the guidance, other tools made available by NOAA and their own modelling efforts to estimate impacts of UAN on marine life, especially (but not only) on marine mammals. For example, ORE developers must provide rationale or evidence that UAN levels at 1,000 m of a piling operation will fall below the Level A (injury) thresholds set for Low-Frequency Cetaceans (LFC) in NOAA, 2018, currently set at SPL_{PEAK} less than 219 dB re 1µPa, or $SEL_{CUM\text{-}24h}$ less than 183 dB re $1µPa^2.s$ (this document is currently being reviewed, with the review due for release in July 2024)[4]. The regulatory or consenting authority will then decide, on a case-by-case basis and using the same guidance, whether the assessment of underwater noise impacts made by the developer is reasonable, or whether monitoring measures must be taken to ensure that OWF construction and operating noise levels are within the NOAA thresholds, in which case monitoring of UAN will be done using applicable standards.

6.3 Other regulations

Since UAN is a transboundary pollutant, according to the definition of “pollutant” that can be found in the United Nations Convention on the Law of the Sea (UNCLOS)[5] and because certain UAN frequencies can travel large distances in the ocean environment, it would be natural that efforts to monitor and mitigate the effects of anthropogenic UAN should be made in a cooperative and coordinated manner among countries. However, the preceding subsections have shown that there are different approaches and regulations regarding UAN from country to country. In this section, regional or globally applicable regulations or guidance of eventual relevance to Ireland are explored.

[4] More on thresholds in deliverable *BD01923003-01 UN Thresholds and Mitigation Measures Guidance for ORE*
[5] Article 1, Point 1.(4) of the UNCLOS define "pollution of the marine environment" as the “introduction by man, directly or indirectly, of substances or energy into the marine environment, including estuaries, which results or is likely to result in such deleterious effects as harm to living resources and marine life, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of sea water and reduction of amenities

6.3.1 MSFD (Descriptor 11)

This European Marine Strategy Framework Directive establishes UAN monitoring requirements to the European Union Member States under Descriptor 11 (Noise/Energy) of Good Environmental Status: "Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment" (MSFD, 2008). The descriptor has two indicators, defined as follows according to the impulsive or continuous nature of the noise:

- Indicator 11.1.1 *Distribution in time and place of loud, low, and mid frequency impulsive sounds*: Proportion of days and their distribution within a calendar year over areas of a determined surface, as well as their spatial distribution, in which anthropogenic sound sources exceed levels that are likely to entail significant impact on marine animals measured as Sound Exposure Level (in dB re 1µPa^2.s) or as peak sound pressure level (in dB re 1µPa_{peak}) at one metre, measured over the frequency band 10 Hz to 10 kHz.
- Indicator 11.2.1 *Continuous low frequency sound*: Trends in the ambient noise level within the 1/3 octave bands 63 Hz and 125 Hz (centre frequency) (re 1µPa RMS; average noise level in these octave bands over a year) measured by observation stations and/or with the use of models if appropriate.

It is relevant to note that the original proposal for Descriptor 11 included levels for impulsive sound (originally, only sounds exceeding SEL of 183 dB re 1 µPa^2s @ 1m or SPL_{PEAK} of 224 dB re 1 µPa @ 1m would need recording) and for continuous sound (the original aim was to keep noise at the 1/3 octave bands centred at 63 Hz and 125 Hz below 100 dB re 1 µPa rms). These levels were removed from the final form of the descriptor since it became obvious that it would not be possible to respect the continuous noise threshold in busy shipping lanes, and that not enough information on impulsive sounds would be collected by imposing a minimum level for recording (Erbe, 2013).

Guidelines to monitor UAN under Descriptor 11 have been developed by the MSFD Technical Group on Underwater Noise (TG Noise):

- Monitoring Guidance for Underwater Noise in European Seas, Part II: Monitoring Guidance Specifications (TG NOISE, 2014), published as a Joint Research Centre (JRC) report.

It should be noted that the choice of the frequency bands stated in the above indicators was informed by the best knowledge of underwater acoustic noise at the time of their development. In fact, the frequency band from 10 Hz to 10 kHz includes most of the known hearing ranges of many marine species, both fishes and mammals, and it makes sense thus to monitor impulsive noise in this range since it has been shown that high levels of impulsive acoustic energy in the environment can cause damage to marine animals, in very specific situations. On the other hand, chronic exposure to low frequency continuous noise in the 63 and 125 Hz bands (i.e., those usually originating in sources like shipping) has been shown to cause auditory masking and other effects in fish and marine mammals, like induced stress. However, recent research has shown that other frequencies and types of sound (or sound-related phenomena, like water particle motion) may also cause impacts in marine animals, which suggests that monitoring of underwater sound should not be confined to these two indicators (see ,for instance, Wind Energy Ireland, 2023).

As mentioned, the above guidelines and requirements are intended to monitor whether (acoustic) Good Environmental Status (GES) is maintained in the European seas. However, on one hand, monitoring as suggested in these guidelines does not guarantee GES in or near OWF and, on the other, they are not compulsory (that is, they are an obligation of the EU Member States that can be passed on to economic operators at sea but, so far, this has not been the case). Nonetheless, the guidelines constitute a good reference should monitoring of UAN during OWF developments become compulsory, in the absence of other specific guidelines or standards. It should be noted, also, that the implementation of the overall MSFD across Europe is currently under review, which could entail changes in the above documents at some point.

In 2017, the European Commission decided on criteria and methodologies to set thresholds for GES in European waters via the Commission Decision 2017/848 (MSFD, 2017), of which an extract relevant for Descriptor 11 is presented in Appendix A. In line with the objectives of the MSFD (achieving and maintaining GES) and the above-mentioned Commission Decision, the Technical Group on Underwater Noise, working at JRC, has more recently developed further material to that purpose, comprised of thresholds for onset of biological adverse effect to marine life (LOBE). This work is similar to that performed and published by NOAA (see section 6.2.8) and will be further detailed in deliverable *BD01923003-01 Underwater Acoustic Noise Thresholds and Mitigation Measures Guidance*.

6.3.2 ISO Standards

Standards on underwater acoustics were first developed in 2017 and revised in 2022 by the ISO Technical Committee 43 (*Acoustics*), Subcommittee SC 3 (*Underwater acoustics*), comprising experts on underwater acoustics from several countries around the world. TC43 developed work in standards for "Measurement of underwater sound from ships" (SC3 Working Group 1), "Underwater Acoustic Terminology" (SC3 Working Group 2), "Measurement of radiated noise from pile driving" (Standard ISO18406, developed by SC3 Working Group 3), "Standard-target method for calibrating active sonars" (SC3 Working Group 4), "Measurement and modelling of underwater ambient sound" (SC3 Working Group 5) and "Aquatic bioacoustics" (SC3 Working Group 6).

Each of the above WG has produced, or will produce, a standard on their respective topic. The most relevant for ORE developers are (both published and in draft form):

- ISO 18405:2017 Terminology, published in 2017 and revised in 2022.
- ISO 18406:2027 Measurement of radiated underwater sound from percussive pile driving, published in 2017 and revised in 2022.
- ISO/DIS (Draft International Standard) 7605 Measurement of underwater ambient sound, due for publication in 2025.
- ISO/FDIS (Final Draft International Standard) 7447 Underwater acoustics — Measurement of radiated underwater sound from percussive pile driving — In-situ determination of the insertion loss of barrier control measures underwater, due for publication in 2025.

Other standards in this series may become relevant when published, such as the standard on Bioacoustics and related observations; the standards on *Underwater Sound from Ships* may also be relevant in certain applications, although they are perhaps more relevant for the shipping and ship-building industries.

Of the list above, the existing ISO 18406:2017 should be used whenever ORE developers are required to monitor UAN effectively generated during their pile driving operations (currently not the case in Ireland) and in the absence of other statutory regulations. The standard includes specifications for the instrumentation to be used in the measurements, for their deployment (a standard distance of 750m to the source has been specified similarly to current practice in Europe), for the configuration of the measurements, for data processing and for reporting of results, including how to treat uncertainty and what ancillary data should be recorded as well.

6.3.3 DNV and Bureau Veritas

Both DNV and Bureau Veritas offer services and classifications for underwater noise radiated from vessels:

- Underwater Radiated Noise (URN), Rule Note NR 614 DT R02 E (BV, 2018).
- DNV Silent Class notation (for vessels)

These rules, along with DNV's "RU-OU" and "OS" series of rules, apply mostly to OWF structures design and engineering, and to vessels, and do not cover underwater noise radiated by the structures of from OWF construction or operation and, therefore, will not be further considered in this work.

6.3.4 Baltic Sea – HELCOM

The Helsinki Commission (Baltic Marine Environment Protection Commission, of which all Baltic Sea countries are members), or HELCOM, has published guidance on monitoring of continuous noise in the ocean. These guidelines (listed below) are an expanded version of the MSFD regulations on Descriptor 11, including higher frequency bands (in the range up to 20 kHz) intended not only to collect information on frequencies used by most marine mammals besides those masked by shipping, but also to collect data useful for future analysis of eventual impact of sound on other marine life:

- HELCOM Guidelines for monitoring continuous noise (HELCOM, 2021).

HELCOM countries utilise the JRC MSFD guidance to monitor and register impulsive noise (see section 6.3.1). HELCOM shares the International Council for the Exploration of the Sea's (ICES) Impulsive Noise registry with OSPAR (below).

6.3.5 OSPAR Commission

The OSPAR Commission (the governing body of the Convention for the Protection of the Marine Environment of the North-East Atlantic, of which Ireland is a signatory party) maintains numerous guidelines on many aspects of environmental monitoring that include UAN, both continuous (ambient) and impulsive noise. The list below shows some guidelines relevant for this work:

- OSPAR Coordinated Environmental Monitoring Programme (CEMP) (OSPAR, 2016).
- CEMP Guidelines for Monitoring and Assessment of loud, low and mid-frequency impulsive sound sources in the OSPAR Maritime Region (OSPAR, 2017).
- CEMP Guidelines for the candidate indicator on ambient underwater noise (OSPAR, 2021).

The OSPAR convention imposes some obligations from signatory parties, including the contribution to a database of man-made acoustic energy input in the North-East Atlantic region, through monitoring and periodic reporting. Although not yet explicitly included in any internal regulation, to our knowledge, these requirements may be transposed to ORE developers at some stage (for instance, by requiring them to monitor and register impulsive sound sources during some stages of the development to the OSPAR Impulsive Underwater Noise Registry, managed by ICES (ICES, 2024).

6.3.6 ASCOBAN

ASCOBAN stands for "Agreement on the Conservation of Small Cetaceans of the Baltic, Northeast Atlantic, Irish and North Seas", of which Ireland is a Non-Party Range State (that is, a non-signatory state whose maritime space is included in the geographical coverage of the agreement), and functions under the United Nations. The organisation has been looking at the potential effects of OWF in the region covered by the agreement, with several conferences and advisory meetings held on the topic of underwater noise effects on small cetaceans and looking in particular at the effect of noise generated by OWF:

- Offshore Wind Farms and Marine Mammals: Impacts & Methodologies for assessing impacts (ASCOBAN, 2008).
- Concept for the Protection of Harbour Porpoises from Sound Exposures during the Construction of Offshore Wind Farms in the German North Sea (ASCOBAN, 2014).

The latter document is both a summary and a reference document for the guidelines currently in use in Germany, covered in section 6.2.3, and includes the definition of the "Sound Protection Concept" based on a single species (harbour porpoise) which underpins the German guidelines. The above documents, although they contribute to understand thresholds and their relevance to marine mammals conservation, do not contain specific guidance concerning monitoring and reporting of UAN. Nonetheless, ASCOBANS maintain a repository of data on several environmental pressures, including UAN, to which member states report annually and that could be a good source of data for the preparation of EIS/NIS.

7 Recent research projects on UAN

This section contains key points from several recent and relevant research projects on the subject of monitoring and reporting of UAN only, funded by the EU through different programmes. Out of the many research actions found in the literature review, the most relevant and recent are briefly analysed below. It should be noted that findings from research and literature review on the topic of UAN are especially relevant to what concerns setting thresholds and investigating the effectiveness of noise mitigation measures, developed in deliverable *BD01923003-01 Underwater Acoustic Noise Thresholds and Mitigation Measures Guidance*.

7.1 JOMOPANS

This Interreg Northwest Europe (NWE) project (titled "Joint Monitoring Programme for Ambient Noise North Sea"), completed in June 2021, developed a framework for an operational joint monitoring programme for ambient noise in the North Sea. The project created the tools necessary for managers, planners, and other stakeholders to incorporate the effects of ambient noise in their assessment of the environmental status of the North Sea, and to evaluate measures to improve the environment. This includes, among other miscellaneous results and reports, the following:

- "How loud is the underwater noise from operating offshore wind turbines?" (Tougaard *et al*., 2020), in which measurements of ambient noise in the North Sea have shown that operational OWF turbines produce noise about 10 dB to 20 dB lower than pre-existing ambient underwater noise. However, the authors caution about eventually higher cumulative levels of future larger turbines and wind farms.
- Standard for "Terminology for ocean ambient noise monitoring" (Robinson and Wang, 2021).
- "Standard for Data Processing of Measured Data" (Ward *et al*., 2021).
- "JOMOPANS Measurement Guidelines" (Fischer *et al*., 2021).

The final three documents in the list above contain a set of guidelines that, in the absence of other more recent or localised guidelines – since these were developed for the North Sea – may provide useful information and guidance to ORE developers required to perform measurements of underwater sound, and to regulators in the Irish context.

7.2 JONAS

This Interreg Atlantic Area (AA) project (titled *Joint Framework for Ocean Noise in the Atlantic Seas*), completed in 2022, had similar goals to JOMOPANS. However, it focused on the Atlantic ocean and aiming at supporting EU member states in meeting the MSFD requirements. In practice, the project conducted studies to make: 1) a Noise Risk Assessment, whereby monthly noise and risk maps to support better planning and decision-making in EU Member States were produced. These maps were based on the spatial modelling of noise characteristics and the distributions of key sensitive species; 2) Five ocean noise case studies, in which the impacts and effects of acoustic pollution, including ship quieting methods, seismic survey operations, offshore wind energy devices, and acoustic deterrent devices in aquaculture where examined, and 3) a Noise Visualisation Platform (the JONAS Virtual Research Environment)[6], an online noise visualisation platform designed to make technical material more accessible.

In addition to the above, and besides several research papers, JONAS produced useful tools such as PAMguide[7] and PAM2Py[8], which are software tools designed to harmonise and simplify the processing of underwater acoustic data and common indicators for noise levels.

7.3 SATURN

This Horizon 2020 EU-funded project, still underway, will examine 1) which sounds pose the greatest threat to aquatic species and how they are produced and propagated; 2) the short and long-term effects of Underwater Radiated Noise on invertebrates, fish, and marine mammals; and 3) the most promising options for reducing the negative impacts of Underwater Radiated Noise. The project will also develop and progress standards for terminology and methodology across all disciplines working on Underwater Radiated Noise, producing recommendations for effective underwater sound management.

The project is focused on noise from shipping, trying to cover knowledge gaps in the understanding of impacts of this type of underwater noise. As such, it may have limited direct

[6] https://indico.egi.eu/event/5882/contributions/16788/attachments/14852/19168/Jonas%20VRE.pdf
[7] https://sourceforge.net/projects/pamguide/
[8] http://www.siplab.fct.ualg.pt/proj/jonas/pam2py.shtml

application on ORE developments, except perhaps on better informing assessments of potential impacts during the operation phase of the OWF.

7.4 PURE WIND

This recent project, titled "Impact of sound on marine ecosystems from offshore wind energy", is funded by JPI-Oceans (contributions from each Member State participating in the consortium). Due for completion in late 2025 or 2026, it aims to address the knowledge gaps on the impact of operational OWF, by expanding existing knowledge of underwater radiated noise and the biological consequences of OWF developments in the operational phase.

The project hopes to quantify key features of radiated noise from fixed and floating OWF, to increase understanding and simulate cumulative effect of OWF clusters on radiated noise, helping to identify sensitive habitats in cross-basin soundscapes. The project will also identify spatial and qualitative use of OWF sites by top predators, and study the impacts of the related noise on zooplankton behaviour. These efforts will advance the knowledge of acute and cumulative effects of the operational noise of OWF across pelagic food webs. Thus, PURE WIND will develop knowledge and tools for integration of all aspects of noise production and propagation from operational OWF. This will facilitate assessment of planned offshore wind expansion for marine spatial planning and environmental impact.

Finally, the project will synthesise knowledge and best practices from EU and international experiences with fixed offshore wind installations and transfer this into the development of policy, mitigation, and regulation for floating offshore wind development within national, EU and international frameworks.

Given the above descriptions, it is expected that the results of the project should be highly valuable to the ORE developer and regulator communities; unfortunately, results are not yet currently publicly available for consultation.

8 Stakeholder consultation

This work included a simplified stakeholder consultation phase, during which interviews with ORE developers, one environmentalist organisation, one environmental services company (based in Portugal and with the goal of assessing the current legislation in Portugal and whether it would be relevant for the study – as it turned out, there are no current guidelines for anthropogenic UAN in Portugal), and one state agency responsible for nature conservation and protection were carried out. The following organisations accepted invitations to meet online:

- Parkwind
- Codling
- SSE
- Statkraft
- HydroTwin (Portugal)
- IWDG
- NPWS

In addition to the above, meetings were held with Wind Energy Ireland to discuss several aspects of the work, as well as granting access to a briefing note (WEI, personal communication, 2024) prepared by WEI providing an "Industry perspective on the challenges and consequences for projects by adopting the German noise threshold-based approach in Irish waters".

In a general sense, the representatives from the ORE industry that have been consulted presented similar views. The following are the main points conveyed by industry to this study:

- Concern with changes in UAN-related compulsory requirements or guidance introduced after the project has started (for instance, after submission of planning applications, or at any time during the pre-construction phase), which would mean a need to incur in unplanned costs.
- Concern with Ireland adopting strict requirements on monitoring and reporting of UAN levels in OWF (all project phases) that could render projects too costly or financially

unfeasible, given the tight financial margins they usually operate in. This could happen, for instance, if Ireland adopted a "Source and Thresholds" approach to UAN management (see section 9 for considerations in this respect), similar to that used in Germany and other countries, as a result of the ongoing review of UAN management guidelines.

- Concern that new or revised requirements could ask for the use of UAN abatement methods (Noise Abatement Systems, or NAS) that are too costly or not practicable in the Irish context. This could render ongoing projects either non-compliant, or economically unfeasible, or both, if any alternative measures proposed by developers are not acceptable to the regulatory authorities.
- Concern that the current requirement to have Marine Mammal Observers on board for most activities (e.g., drilling, pile driving, or geophysical surveys), which effectively means that only daytime operations are allowed, will not be waived for planned ORE developments in Ireland. This could be achieved by accepting other techniques (e.g., PAM or Acoustic Deterrent Devices - ADD) to assess presence, or deter presence, of marine mammals in the vicinity of the developments during those activities. While daytime-only operations mean that pile driving or geophysical surveys may need to extend for longer periods than if carried out day round, potentially increasing the cumulative exposure level for species present in the region, it is also acknowledged that not all animals (even marine mammals) vocalise and can thus be captured in PAM systems, which increases the risk of undetected presence (it could be argued, as well, that MMO on the other hand also only see those animals that surface and, therefore, the "false-negative" risk could well end up being equivalent for both MMO and PAM).
- Concern that new guidance will be based on research or existing guidance developed for shallower waters, different environmental conditions, and different marine species than those found in deeper Irish waters where some ORE developments will take place, leading to likely unsuitability of any strict requirements on monitoring or mitigation of UAN in Ireland.
- General concern over the current uncertainty (at the time of writing this document) regarding future rules and requirements on UAN for ORE developments in Ireland. In fact,

some key documents are reportedly being revised which will bring unknown changes in requirements.

In general, the developers listed further above would favour a dialogue-based agreement between the developer and the State concerning potential UAN impacts of their developments and the mitigation measures (if any required) proposed for implementation. A "species / location specific, case-by-case" approach to this problem would be preferred compared to a scenario where OWF developers would be required to keep UAN levels under rigid preset thresholds (depending on the development phase) applicable across the board, with little or no flexibility for adaptation.

The above consensual position among Irish ORE developers contrasts with the position of one of the main Irish non-governmental organisations working on environmental protection, and specifically on the protection of Irish marine mammals, the IWDG. This organisation, which has developed extensive and extremely relevant work in the acoustic soundscape of Ireland and on the effect of sound on marine mammals, besides a thorough mapping of their populations in Ireland, is currently reviewing their policy paper (IWDG, 2020), with no expected major changes; however, IWDG tends to favour the German-type of approach (see section 9) based on thresholds, which they think is best aligned with a "precautionary approach" to dealing with the problem of increased anthropogenic UAN in the absence of sufficient data for informed decisions. IWDG thinks that the tendency observed in the successive reviews of the JNCC guidelines in the UK also shows a convergence towards the German solution.

On the other hand, NPWS, who are also reviewing their existing guidelines (NPWS, 2014) with publication expected for Fall 2024, have hinted that they favour a "species/location case-by-case" approach, and this could be reflected in their revised text with more specific and clear guidance (for instance, clarifying that impact should be taken at population level – as, for instance, is done in The Netherlands – and not at individual level). NPWS would also prefer an open dialogue between regulators and ORE developers, as seen in other European countries, with a view to find the most consensual solution to monitoring and mitigating risks for marine life. They do not anticipate the creation of further SACs or Natura sites for marine mammals, but there could be new protection zones for other species in the future (in line with the ongoing Marine Spatial Planning deployment). While NPWS stated that they are considering the use of PAM and ADD in addition to MMO, the exact definition of these and other aspects of the revised guidelines remains unclear until their publication.

9 Recommendations on monitoring and reporting of UAN

Monitoring and reporting of UAN in the OWF context mainly depends on the UAN management approach that governments follow in their maritime spaces, through regulatory authorities, to balance nature conservation concerns and regulations against the need to develop economic and social well-being (in the present case, the need to decarbonise electricity generation and guarantee "green" energy supply to its citizens and economy). As described in section 6, established practice in this regard throughout the world can be grouped into two broad approach types for UAN management: one based on "**source and thresholds**" and another based on "**receiver and exposure**" (DOC, 2016e).

The "*source and thresholds*" approach is followed in countries like Germany, Denmark and Belgium. This approach uses research performed mostly on marine mammals, selects a representative species with worst possible known effect from UAN, assuming that effects on hearing thresholds or to auditory organs are the most damaging (currently the harbour porpoise, since it presents the wider hearing frequency range and uses the highest frequencies for communication and awareness among all marine mammals), and assigns one or several maximum thresholds of SEL or SPL at pre-determined distances from anthropogenic sources, based on the assurance that these thresholds guarantee minimum or no disturbance to the representative species.

The most powerful source of UAN during OWF developments is, without doubt, pile-driving, and hence attention is focused on this activity (Sinclair *et al.*, 2023). Therefore, regulations under this UAN management approach require OWF developers to actively monitor underwater sound produced during the construction of OWF. In most cases, monitoring of UAN produced during the operation and, in some cases, the decommissioning stages of the developments is also required. This is accompanied by requirements to keep the sound levels below a predetermined threshold, that varies among countries, through whatever noise mitigation or abatement measures necessary.

The "*receiver and exposure*" approach is favoured in countries like New Zealand, France, and the UK (for the time being). This approach requires a solid knowledge of the presence or absence of certain species (the receivers), of the effects of UAN on them, and of the sound propagation characteristics of the intended activity (or a modelled alternative in case any of this knowledge is incomplete) to predict exposure levels for each species (or group of species) likely to be affected by the future development. It then further requires that surveillance is kept at all times during the activity to ensure that, whenever a certain species is present in the area of the development, or in its surroundings to a certain distance (typically determined as the point at which the anthropogenic noise levels are indistinguishable from ambient sound levels), the sound source is mitigated or even completely terminated. For example, pile-driving being the most powerful sound source, this may mean shutting down piling while the "receivers" are known to be in the area.

There are advantages and disadvantages in both approaches. From a regulator perspective, the hard-set thresholds approach is easier to enforce since it requires certain fixed rules to be followed, regardless of their practical implementation or effectiveness, and in practice applying a precautionary approach to the problem of nature conservation and protection. Thus, this approach can be considered safer for the environment, as long as the thresholds are set correctly[9] and can be effectively respected or enforced. However, it does not take into account whether the representative species (or species) are actually present in the development area during the noise-generating activities, thereby requiring developers to commit time and resources which may be unnecessary. This approach also requires a thorough understanding of UAN effects on marine life, and tends to neglect other species in favour of marine mammals, or of a particular marine mammal. It is important to note that the research on which this approach is based can lead to severe errors in the prediction of effects of UAN on marine life (mammals), due to the variability created by differences between species and between individuals, by

[9] More on thresholds and mitigation in deliverable *BD01923003-01 Underwater Acoustic Noise Thresholds and Mitigation Measures Guidance*.

different situational contexts, and by varying temporal and spatial scales, among other, as proven by recent research (Southall *et al*., 2021).

The receiver-based approach seems, at first glance, able to circumvent the disadvantages of a hard-set threshold approach, by allowing for flexibility and (presumably) efficiency without completely brushing "precaution" aside when viewed from a conservationist point of view. From a regulator perspective, its enforcement does not present particular challenges. However, this approach means that *surveillance* while conducting the noise-generating activities becomes of utmost importance, and the most effective way of doing this is not yet consensual. Taking the most common case of avoiding impacts on marine mammals, the usual requirement to have an MMO permanently on site typically means that nighttime operations are not allowed, and PAM is not yet widely accepted as an effective way to ensure absence of marine mammals in the vicinity of the development (although it could be argued that both PAM and MMO methods may have similar probability of "false negatives"). Nonetheless, as mentioned in section 8, this approach seems to be the preferred one among the OWF developers consulted in this study.

Ultimately, as suggested by the New Zealand's Technical Working Group on Biologically Relevant Sound Levels (DOC, 2016e), and along the lines suggested in recent work on impacts of UAN (e.g., Southall *et al*., 2021), perhaps the best approach is to combine the virtues of both, by managing the source level or frequency structure at the source through noise abatement systems (where predicted as necessary), and by reducing or eliminating effects at the receiver(s) through mitigation measures such as soft starts, shutdown or power-down thresholds[10], while keeping robust monitoring activities (e.g., MMO combined with PAM).

Given the above considerations, the current practices in several jurisdictions, the current applicable legislation (of which the MSFD, the EIA and the Habitats Directives are the most relevant in Europe) and the concerns of stakeholders, the following sections present some recommendations on UAN monitoring and reporting for consideration in the Irish OWF context.

[10] *Ibidem*

Since, at the time of writing this report, there is no indication of which approach the Irish State will follow regarding UAN management, which will be determined by the final form of the ongoing review of important guidelines (namely, the review of NPWS, 2014), the guidance below should be understood as recommendations on possible avenues for both regulators and OWF developers, without specifying a preference for any particular approach.

9.1 Monitoring

The recommendations in this section have been separated by development stage (section 4.1).

Pre-construction

This is when EIS and planning applications are prepared. Current (non-compulsory) guidance in Ireland (DECC, 2018a) points towards usage or establishment of a baseline, assumed to be also an *acoustic baseline*, against which to measure any eventual effects of the OWF during and after construction. In practice, developers do not usually engage in the determination of this baseline through field-based surveys; instead, they rely on historical data or best estimates of existing ambient noise levels at their proposed development site, and then use acoustic modelling to estimate effects of expected activities.

Baseline surveys require several years, or decades, of observations to be meaningful, especially when the bio-acoustic components of ecosystems are at play and trends in UAN are the main objective (TG NOISE, 2014). For instance, MSFD guidelines mention annual averages to describe levels of continuous sound (a good proxy for ambient noise baselines). Current guidance in Ireland mentions three years (and a minimum of two years) of year-round acoustic deployments (DECC, 2018a,b) or, in other words, 2 or 3 data points in time. This is likely to be insufficient for UAN baselines, and it is questionable whether any requirement to determine acoustic baselines at this stage of the development should be passed on to OWF developers because such long term commitment is incompatible with the time scales of OWF developments and of their licensing process. It seems therefore that this should be a task more suitable for the State, through the appropriate state laboratories or third level institutions (in fact, it is part of the state's responsibilities under the MSFD, descriptor 11 (MSFD, 2008)).

In any case, the surveillance and mitigation measures foreseen in guidance or regulations should be enough to adequately protect marine animals in the development areas, regardless of whether they are part of the baseline or deviating from it. Therefore, the most sensible **recommendation for ORE developers is to use existing data to inform any assumption of acoustic baselines when preparing EIS/NIS for OWF developments**. Regulators should *clarify any ambiguity in current regulations or guidelines that may lead developers to think that a requirement for acoustic baseline field surveys exists*. The State should endeavour to make all existing data available to users, including acoustic data collected during high-resolution seismic surveys. As an option, the State might enforce license or application fees to partially contribute to the research and long-term monitoring required to establish baselines of use to all.

If, regardless of the above recommendation, surveys to establish baselines are indeed required from developers in Ireland, it is noted that instrument and deployment requirements for determination of baselines may differ from those used in the measurement of actual sound originated in OWF developments. **Standard IEC TS 62400-40:2019** (although developed for the acoustic characterisation of wave and current energy conversion devices) may be useful for guidance in this regard.

Construction

Any compulsory requirement to monitor sound generated by OWF developments in this stage will ultimately depend on the approach for UAN management that the Irish State decides to implement, as discussed in the previous section, following revision of current guidelines (that is, revision of NPWS, 2014). Currently, there is no specific requirement in Ireland (note that DECC 2018a,b do not cover the construction phase and only list a set of potential stressors in this stage that could impact marine mammals). However, the following guidance is available and applicable to each of the approaches.

Source-threshold approach. Should sound levels be required to be monitored during construction of OWF, in which the most impactful activities are pile-driving and old unexploded ordnance (UXO) removal by explosion (the latter may be applicable in Ireland but is highly dependent on location), then the following guidance may be used:

- UXO removal: **JNCC guidelines for minimising the risk of disturbance and injury to marine mammals whilst using explosives** (JNCC, 2021) and the new **JNCC draft guidelines for minimising the risk of injury to marine mammals from unexploded ordnance clearance in the marine environment** (JNCC, 2023b).
- Pile-driving: **ISO 18406:2017**

Receiver-exposure approach. In this case, surveillance is an important task that must be continuously performed. It is recommended to use a **combination of visual surveillance by MMO (during daytime) and acoustic surveillance by PAM, at all times**. This would allow continuous operations and eventually minimise costs and duration of the activities. The following guidance may be relevant for regulators in Ireland in this case:

- **JNCC guidance for the use of Passive Acoustic Monitoring in UK waters for minimising the risk of injury to marine mammals from offshore activities** (JNCC, 2023a).
- **Report of the Marine Mammal Observer/Passive Acoustic Monitoring Requirements Technical Working Group** (DOC, 2016a).
- **ISO 18406:2017** (in case the developer decides, or is required by regulators, to survey UAN produced during pile-driving, as well).

OWF developers should state which PAM system they intend to use and its main characteristics[11]. It is also recommended that **continuous review of advances in PAM systems is followed as a standard** (see, for example, Diviacco *et al.*, 2021), to make sure that the most adequate system

[11] For instance, in 2016 a New Zealand report (DOC, 2016a) defined PAM as *the use of calibrated hydrophone arrays with full system redundancy to estimate bearing and distance of vocalising cetaceans* [to at least 1 km to 1.5 km from sources]. *The arrays incorporate appropriate hydrophone elements (1 Hz – 180 kHz range) and [sound] data acquisition card technology for sampling relevant frequencies (to 360 kHz) used by New Zealand cetacean species, and are coupled with appropriate observations by software-aided monitoring and listening by a qualified PAM operator skilled in bioacoustic analysis, and computer system specifications capable of running appropriate PAM software effectively*. Any system providing the above functions would be compliant.

is used on a case-by-case basis, and that **no specific PAM system or manufacturer is mentioned in guidelines or regulations** so as not to bind ORE developers to anything that may be inappropriate for their specific development.

Operation

The post-construction phase is covered in existing guidelines in Ireland (DECC, 2018a,b), in which the use of Static Acoustic Monitoring (SAM) is mentioned as a technique that can be used for post-construction monitoring surveys. Here, SAM is understood as similar to PAM, with the exception that is does not require real time processing by a specialist, as during construction, and the measuring equipment can be stationary, self-powered with adequate storage.

An argument for monitoring in this stage of the development is made in DECC, 2018a, section 4.1 (page 14). There, it is correctly stated that "monitoring provides the information necessary to evaluate the impacts on the receiving environment over the lifecycle of the project". Furthermore, "monitoring and mitigation commitments set out in consent design documentation, and including an EIS or NIS, will be considered to form part of the project from a consent perspective. In addition, monitoring and mitigation may form explicit conditions on consent(s) for a project. Therefore, *it is incumbent on the developer to ensure that these commitments are met to ensure compliance* with the project consent(s) and to avoid enforcement action." This clearly sets a requirement to monitor UAN generated by the OWF in the Operational stage, but *only* if it is an explicit condition on consent and, supposedly, to monitor the effectiveness of any required mitigation measures and that explicit "thresholds" are observed and complied with.

The DECC guidelines do not attempt to establish thresholds for stress indicators, but do state that they should be in line with "existing values agreed either nationally, at regional seas level (e.g., Celtic Sea) or at EU level". With this in mind, the recommendation for UAN monitoring in the Operational stage is then to **either be compliant with MSFD, or (*if explicit in the project consent*) to be compliant with any consent conditions on UAN monitoring**. The following guidance documents may be useful in both cases:

- **Monitoring Guidance for Underwater Noise in European Seas** (TG NOISE, 2014). This publication was developed to guide EU Member states towards compliance with MSFD requirements.
- **Standard IEC TS 62400-40:2019.** Although developed for the acoustic characterisation of wave and current energy conversion devices the standard has useful information on deployment of instruments for long-term observations
- **CEMP Guidelines for Monitoring and Assessment of loud, low and mid-frequency impulsive sound sources in the OSPAR Maritime Region** (OSPAR, 2017).
- **Literature on UAN monitoring related to OWF**, such as Lindseth and Lobel, 2018, or Pangerc *et al.*, 2016.

Decommissioning

This stage of the ORE development may be regulated by specific conditions in the project consent documentation, in which case it must follow those requirements, or be considered similar to the "Construction" stage, in which case it should follow the same guidance.

It should be noted that the systematic literature review carried out in this study did not identify any relevant paper dedicated to the topic of UAN management during decommissioning of OWF, perhaps due to the relatively few projects that have reached this stage (7 projects in Europe as of 2021, such as the 5 MW capacity / 11 turbine Vindeby project in Denmark[12]) or perhaps because the works involved in the decommissioning may be considered less impactful to marine life than the construction itself.

9.2 Reporting

Reporting of UAN only makes sense in those cases when monitoring is compulsory (see section 9.1). Therefore, there are three stages of the ORE development lifecycle during which reporting of UAN may need to be done in different forms.

[12] https://www.spinergie.com/blog/impact-wind-farm-decommissioning

Construction

If UAN monitoring is required in this stage, the recommendation is to follow the **ISO 18406:2017 standard** specifications for reporting of UAN. These could be checked or complemented by the specifications set forth in the **MSFD technical guidelines** (TG NOISE, 2014), particularly in what concerns impulsive UAN. Weekly reports should be prepared and delivered to the competent authority, and data made available to international data banks such as ICES (ICES, 2024), in this case using the **OSPAR requirements** to communicate data (OSPAR, 2016), or using templates provided by the relevant agencies, prescribing the content of the reports. Weekly reports may focus on information required to demonstrate compliance, if this is required in the monitoring.

Operations

Reporting of UAN in this stage should be similar to those in the “Construction” stage, with the exception that weekly reports are no longer necessary. Annual or bi-annual reports should be sufficient to check for tendencies against historical data or baselines, especially in what concerns trends in continuous UAN at the frequencies generated by the operating turbines and maintenance/inspection vessels.

Decommissioning

The same recommendations for UAN reporting as for “Construction”.

10 Conclusions

This study has looked extensively into the topic of UAN monitoring and reporting in the context of ORE developments, by searching existing literature, considering current regulations and legislation, and analysing practices observed in other jurisdictions. For reasons that are obvious in the Irish case, focus has been put on wind energy (offshore wind farms) as the main driver for research in this study; on the other hand, research related to OWF is one of the dominant topics in the underwater acoustics literature and in assessments of regulations mostly found in technical reports (along with the equivalent research related to seismic geophysical surveys for the Oil and Gas industry and the protection of marine mammals).

The conclusions of the work carried out, which must be considered jointly with the recommendations set forth in the accompanying deliverable *BD01923003-01 UN Thresholds and Mitigation Measures Guidance for ORE*, are summarised below.

1. UAN management approaches differ considerably from country to country. However, these approaches may be grouped into two broad types:
   a. "*Source and Thresholds*", in which hard-set UAN thresholds are defined and enforced for certain maritime activities (e.g., pile-driving) based on a worst case scenario and available research. This approach requires mitigation (and possibly abatement) of UAN and monitoring measures in place to guarantee compliance.
   b. "*Receiver and Exposure*", in which each maritime activity is analysed from the viewpoint of potential impact of generated UAN on marine species likely present in the area, mitigation measures are defined, and active surveillance is established at all times to assess whether, when and how mitigation (and possibly abatement) of UAN must be activated.

   Current Irish guidelines are more inclined towards the latter. The ongoing revision of practical guidance to manage UAN in activities typical of ORE developments (NPWS, 2014) will define which approach Ireland will ultimately follow. The general tendency of recent research is to point towards the latter given its greater flexibility, although it may require substantial dialogue between ORE developers and regulatory and consenting authorities.

2. The recommendations for Monitoring and Reporting of UAN depend on the approach taken, as shown in the table below (*S&T* means Source and Threshold, *R&E* means Receiver and Exposure, both explained above). Full explanation of the table is found in section 9.

Development stage	Recommendation	
Pre-construction	**Use existing data to inform any assumption of acoustic baselines when preparing EIS/NIS for OWF developments**. If surveys are asked by regulators at this stage, **Standard IEC TS 62400-40:2019** can help.	
Construction	Monitoring	*S&T*: UXO Removal: **JNCC guidelines for minimising the risk of disturbance and injury to marine mammals whilst using explosives** (JNCC, 2021) and the new **JNCC draft guidelines for minimising the risk of injury to marine mammals from unexploded ordnance clearance in the marine environment** (JNCC, 2023b). Pile-driving: **ISO 18406:2017.**
		R&E: Use **combination of visual surveillance by MMO (at daytime) and acoustic surveillance by PAM, at all times.** Helpful guidance: **JNCC guidance for the use of Passive Acoustic Monitoring in UK waters for minimising the risk of injury to marine mammals from offshore activities** (JNCC, 2023a). **Report of the Marine Mammal Observer/Passive Acoustic Monitoring Requirements Technical Working Group** (DOC, 2016a). Additional recommendation for developers: **continuous review of advances in PAM systems** Additional recommendation for regulators: **no specific PAM system or manufacturer mentioned in guidelines or regulations**

Development stage	Recommendation	
	Reporting	*If UAN monitoring required*: Use **standard ISO 18406:2017**, eventually complemented by specifications of the **MSFD technical guidelines** (TG NOISE, 2014). Weekly reports prepared following **OSPAR requirements** (OSPAR, 2016) or regulator-provided templates. Data sent to international data banks such as ICES.
Operations	Monitoring	**Be compliant with either MSFD, or (*if explicit in the project consent*) with any consent conditions regarding UAN monitoring.** Helpful guidance: **Monitoring Guidance for Underwater Noise in European Seas** (TG NOISE, 2014). **Standard IEC TS 62400-40:2019. CEMP Guidelines for Monitoring and Assessment of loud, low and mid-frequency impulsive sound sources in the OSPAR Maritime Region** (OSPAR, 2017). **Literature on UAN monitoring related to OWF.**
	Reporting	Same as for "Construction", but no weekly reports (replace by annual or bi-annual reports).
Decommissioning	Monitoring	Same as for "Construction".
	Reporting	Same as for "Construction".

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Appendix A – Extract of Commission Decision 2017/848

Descriptor 11

Introduction of energy, including underwater noise, is at levels that do not adversely affect the

marine environment

Relevant pressures: Input of anthropogenic sound; Input of other forms of energy

Criteria, including criteria elements, and methodological standards

<table>
<tr><th>Criteria elements</th><th>Criteria</th><th>Methodological standards</th></tr>
<tr><td>Anthropogenic impulsive sound in water</td><td>D11C1 — Primary

The spatial distribution, temporal extent, and levels of anthropogenic impulsive sound sources do not exceed levels that adversely affect populations of marine animals.

Member States shall establish threshold values for these levels through cooperation at Union level, taking into account regional or subregional specificities.</td><td rowspan="2">Scale of assessment:
• Region, subregion or subdivisions.
Use of criteria:
• The extent to which good environmental status has been achieved shall be expressed for each area assessed as follows:

(a) for D11C1, the duration per calendar year of impulsive sound sources, their distribution within the year and spatially within the assessment area, and whether the threshold values set have been achieved;
(b) for D11C2, the annual average of the sound level, or other suitable temporal metric agreed at regional or subregional level, per unit area and its spatial distribution within the assessment area, and the extent (%, km2) of the assessment area over which the threshold values set have been achieved.

The use of criteria D11C1 and D11C2 in the assessment of good environmental status for Descriptor 11 shall be agreed at Union level. The outcomes of these criteria shall also contribute to assessments under Descriptor 1.</td></tr>
<tr><td>Anthropogenic continuous low-frequency sound in water.</td><td>D11C2 — Primary

The spatial distribution, temporal extent and levels of anthropogenic continuous low-frequency sound do not exceed levels that adversely affect populations of marine animals.

Member States shall establish threshold values for these levels through cooperation at Union level, taking into account regional or subregional specificities.</td></tr>
</table>

Specifications and standardised methods for monitoring and assessment

1. For D11C1 monitoring:

   a) Spatial resolution: geographical locations whose shape and areas are to be determined at regional or subregional level, on the basis of, for instance, activities listed in Annex III to Directive 2008/56/EC (MSFD, 2008).

   b) Impulsive sound described as monopole energy source level in units of dB re 1 µPa^{2}s or zero to peak monopole source level in units of dB re 1µPa @1m, both over the frequency band 10 Hz to 10 kHz. Member States may consider other specific sources with higher frequency bands if longer-range effects are considered relevant.

2. For D11C2 monitoring:

   Annual average, or other suitable metric agreed at regional or subregional level, of the squared sound pressure in each of two '1/3-octave bands', one centred at 63 Hz and the other at 125 Hz, expressed as a level in decibels in units of dB re 1 µPa, at a suitable spatial resolution in relation to the pressure. This may be measured directly, or inferred from a model used to interpolate between, or extrapolated from, measurements. Member States may also decide at regional or subregional level to monitor for additional frequency bands.

Criteria relating to other forms of energy input (including thermal energy, electromagnetic fields and light) and criteria relating to the environmental impacts of noise are still subject to further development.

Units of measurement for the criteria:

— D11C1: Number of days per quarter (or per month if appropriate) with impulsive sound sources; proportion (percentage) of unit areas or extent in square kilometres (km^2) of assessment area with impulsive sound sources per year.

— D11C2: Annual average (or other temporal metric) of continuous sound level per unit area; proportion (percentage) or extent in square kilometres (km^2) of assessment area with sound levels exceeding threshold values.

Appendix B – Brief overview of Underwater Sound

Sound in the ocean is acoustic energy propagating as compressive (longitudinal) waves, that is, waves in which the particles that compose the medium oscillate about a rest position in the direction of wave propagation, with origin at some sound source. With sound, this means that, while the wave propagates, there are alternating regions of compression and decompression along the propagation path and particles in the medium move back and forth.

The usual parameters to describe waves apply to sound: amplitude, wavelength, direction of propagation, frequency and phase. Wavelength and frequency are related to the speed of wave propagation, which in turn depends on properties of the medium. In the ocean, the velocity of sound depends mostly on temperature, salinity and pressure (i.e., the major variables controlling density and, hence, what is known as “acoustic impedance” – the measure of the ease with which a sound wave propagates through a particular medium). The average speed of sound in seawater is about 1,500 m/s.

As sound waves propagate in a medium, such as seawater, or from one medium to another (e.g., from seawater into sediments), the acoustic energy released at the source suffers several physical processes, usually grouped in three main groups: i) *absorption*, in which some energy is lost to the environment due to friction or viscosity; ii) *reflection*, in which some energy is reflected at the interface of two regions with different acoustic properties, and iii) *refraction*, in which energy is transmitted from one medium to another. Reflection and refraction can both make the direction of propagation of the incoming energy (wave) change; depending on the wavelength and the nature of the interface between propagating media, reflection and refraction can occur in multiple directions (which is known as “scatter”), some of which back to the source (backscatter). Scatter can also take place while the sound wave propagates in a medium that contains very small particles in suspension, as it is common in seawater.

Due to the above[13], the acoustic energy released at the source will decrease with distance to the source and its direction will vary[14]. Since the velocity of sound waves ultimately depends on the density of the medium, slight variations in density will cause reflection and refraction to occur, to some greater or lesser extent (this is, of course, most noticeable in the interface between air and sea, and at the seabed, where significant variations of density are present in the respective propagating media). Therefore, an inverse problem can be stated and solved to determine properties of the propagating media, if measurements of acoustic energy at several points along the propagation path(s) are made (at least two, one source and one receiver, but multiple sources and receivers can be used – with increased complexity). This is, in simple terms, the principle behind all scientific acoustic instruments used in marine surveys.

Measurement of sound.

A sound wave has an **amplitude** equal to the maximum distance a particle is displaced from rest. The more energy in the sound wave, the larger the amplitude. Amplitude can also be defined for the variations in pressure – the pressure amplitude being the maximum pressure relative to that at rest. The **wavelength** of a wave is the distance between two successive compressions ("crests") or the distance the wave travels in one cycle of vibration (in meter). The **frequency** of a sound wave is the rate of oscillation or vibration of the wave particles (in Hertz, or cycles per second). The **phase** (in radians) can be described as how far in the cycle a wave is, at a given location and at a reference time; phase is important in the way that waves interact with each other. These four parameters completely describe a sound wave. In addition, for sound waves propagating in a geographical space, the **direction of propagation** can also be defined in relation to the vertical and to the geographical north (i.e., elevation/depression and azimuth).

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[13] Other factors, such as loss due to geometrical spreading of the energy released, also come into play. The so-called Sonar Equation usually considers a "Transmission Loss" factor that encompasses absorption, scattering and geometrical spreading in a single loss term.

[14] The propagation of sound is a complex phenomenon, treated here simplistically to allow for easier understanding. The effects of diffraction and multi-path propagation are beyond the scope of this appendix, as well as boundary effects. All can lead either to decreased or increased sound amplitude locally.

Sound speed

It is the velocity of wave propagation. In single-frequency (monochromatic) waves, speed is the ratio of wavelength and frequency. The average sound speed in the ocean is 1,500 m/s.

Sound pressure

Pressure is force per unit area, with unit pascal (Pa). Sound pressure is the force exerted by a sound wave in a unit area of propagating medium. Since the waveform varies in time, represented by sinusoidal oscillations for simplicity, it is necessary to define what pressure is being used; several options exist, the most used being peak or peak-to-peak (the difference between the minimum and maximum pressure from static pressure – in the absence of a sound wave) for impulsive sound, and root mean square (RMS) of the pressure variation over a full cycle for continuous sound.

The instantaneous sound pressure (p(t)) can be related to the density of the medium (ρ), the instantaneous velocity of the oscillating particles (v(t)), and the speed of sound in the medium (c).

$$p(t) = \rho c v(t) \quad \text{(Pa)}$$

Sound Intensity

The intensity of a wave is power per unit area in the direction of propagation, in watt per meter squared. The intensity of a sound wave is related to its pressure amplitude squared by the following relationship:

$$I = (\Delta p)^2 / 2\rho c \quad (\text{W/m}^2)$$

The quantity “ρc” is called the *acoustic impedance* of the medium.

Sound Intensity Level

Sound intensities exist in a very large range of values. For instance, the human ear can detect sound intensities from $1\text{x}10^{-12}$ W/m^2 to $1\text{x}10^{2}$ W/m^2 (the latter already causing damage to the ear). Therefore, it is more useful to define a logarithmic scale for sound intensity, the sound intensity level:

$$SIL = 10 \log_{10}(I/I_0) \quad \text{in decibel (dB)}$$

The reference intensity I_0 is $1\text{x}10^{-12}$ W/m^2 (in the air). Thus, the SIL is the intensity of a given sound relative to a reference level, in this case, the threshold for human hearing in the air.

Sound Pressure Level

The same rationale applies to sound pressure, and a Sound Pressure Level can be defined which is much more useful than sound pressure itself:

$$SPL = 20\ \log_{10}(p/P_0)\quad \text{(dB)}$$

where $P_0 = 1\times10^{-6}$ Pa (or 1 µPa) is the reference pressure in the ocean, and 20×10^{-6} Pa (or 20 µPa) in air. This reference pressure is taken as the root mean squared (RMS) pressure measured at a standard distance of 1 m from the source.

Note that it is important to explicitly state the reference pressure (or intensity) when indicating SPL or SIL, although it has nearly become a standard to use the above references (that is, ref. 1 µPa @ 1 m in the ocean, and ref. 20 µPa @ 1 m in air).

There are also significant differences between the perception of sound in water and in air. For instance, the SPL for the same sound pressure in air and in the ocean differ by 26 dB:

$$SPL_{water} - SPL_{air} = 20\log_{10}(P_{0\,air}/P_{0\,water}) = 20\log_{10} 20 = 26\ dB$$

$$SPL_{water} = SPL_{air} + 26\ dB$$

Further, due to the difference in acoustic impedance between air and water (the acoustic impedance in water being about 3600 times greater than in air), there is an additional ~36 dB difference when considering the SIL in air and water for the same sound pressure:

$$10\ \log_{10} 3600 = 35.5\ dB$$

Therefore:

$$SIL_{water} = SIL_{air} + 62\ dB$$

The above relationship may be useful when trying to compare, in practical terms, the sound perceived by a diver (or a marine animal) if exposed to the same sound out of the water. For example, the sound produced by a humpback whale, whose SPL can reach about 180 dB (ref. 1 µPa @ 1 m), would be as loud as a pneumatic chipper at a distance of 2 m or a loud rock concert (about 120 dB), if the whale produced the same sound in air. Viewed from another perspective, this relationship indicates that **sounds of similar intensities (in air and in water) are technically described by much higher SPL in water than in air**. To a less informed person, this can give the false impression that sounds are much louder in water than they are in air.

Most acoustic equipment used in ocean surveying is commonly specified in terms of SPL or of power emitted at the source. When SPL is used, often there's no indication of whether it refers to peak, or peak-to-peak, or RMS pressure. The relations between peak, peak to peak and RMS sound pressure levels can be easily found, since (assuming a sinusoidal wave pattern for the sound pulse) $P_{RMS=}\left(1/\sqrt{2}\right)P_{PEAK}$ and $P_{RMS}=(1/2\sqrt{2})P_{P-P}$, which give:

$$SPL_{RMS}=20\log_{10}\left(\left(\frac{1}{\sqrt{2}}\right)P_{PEAK}/P_0\right)=20\left(\log_{10}(P_{PEAK}/P_0)+\log_{10}\left(\frac{1}{\sqrt{2}}\right)\right)=SPL_{PEAK}-3dB$$

$$SPL_{RMS}=SPL_{P-P}-9dB$$

These relations hold for sinusoidal waves of constant amplitude throughout the duration of the signal. Impulsive sound can vary significantly from this, as the amplitude of the sound pulse decreases over time (i.e., the RMS value of these signals will be smaller than indicated above).

Sound exposure level

When considering impacts from exposure to sound, it is useful to introduce another quantity that takes into account the amount of time a receiver is subject to a specific sound. Sound sources can be continuous or intermittent, with the latter further divided in impulsive and non-impulsive[15]. Impulsive sources are usually taken as those in which a sound is emitted for no longer than a few milliseconds.

Continuous sounds, even sounds with relatively low SPL, can produce effects in marine life after some time of exposure (e.g., low frequency, continuous shipping noise may cause habituation, or change of behaviour in animals). On the other hand, impulsive sound of very high intensity but very short duration can cause significant damage to life if the receiver is close enough to the source (e.g., the sound produced by an underwater explosion will produce a very short by very high SPL that will likely kill sound-sensitive animals in the explosion's near field). The quantity Sound Exposure (E) integrates the sound pressure squared over the period of time of the sound duration:

$$E=\int_{t-\Delta t}^{t+\Delta t}p(t)^2\,dt,\quad (\mathrm{Pa}^2.\mathrm{s})$$

If a reference sound exposure is quantified using a reference pressure (P_0) and a standard sound duration T_0, then the quantity Sound Exposure Level (SEL) is defined as

$$SEL=10\log_{10}(E/E_0)\quad \text{in dB, where } E_0=T_0.{P_0}^2$$

[15] These categories are generally followed in regulations on environmental status and monitoring. For instance, the Marine Strategy Framework Directive (MSFD) considers different monitoring requirements for impulsive and for continuous sound sources in the ocean, in terms of maximum desired levels and frequency bins to monitor.

The reference sound exposure can vary among applications, but it has become accepted to use 1 $\mu Pa^2.s$ in the ocean (that is, the reference sound pressure and a standard sound duration of 1 s).

SEL can be used to compare the effect of sounds of different intensities. It also allows to infer or estimate changes in impacts of sound with changes in the source. For instance, a survey vessel generates less noise if she moves slower (SPL decreases) but SEL may actually increase as the ship will take more time to cover the same distance.

Under certain assumptions, a relation can also be found between SPL and SEL. Note that the expressions for both are similar and use the same references. If the sound is emitted in a single strike pulse (SEL_{SS}), then the following relation can be easily obtained:

$$SEL_{SS} = SPL + 10\log_{10}(T) ,$$

with "T" de duration of the pulse in seconds. In the case of a series of identical pulses of equal duration and equal sound pressure levels, then a cumulative SEL (SEL_{CUM}) can be estimated as

$$SEL_{CUM} = SEL_{SS} + 10\log_{10}(N),$$

in which N is the number of pulses. In this case, the interval between pulses should also be considered when analysing impacts, in addition to frequency and other factors, because hearing cavities and sensors can recover in between pulses.

Particle motion

A quantity that has recently received attention from the research community in terms of impact on hearing physiology of fish is *particle motion* or *particle velocity*. As mentioned above, the propagation of a compressive sound wave means the particles that compose the medium oscillate in the direction of wave propagation about a rest position. The particles' displacement is a function of amplitude (power or pressure variation) and frequency of the wave:

$$\xi(t) = \frac{p(t)}{2\pi f\rho c}\sqrt{1 + \left(\frac{\lambda}{2\pi r}\right)^2}$$

This expression is valid away from boundaries, and it reduces to $\xi(t) = {p(t)}/{2\pi f\rho c}$ in the far field of the source, where the distance to the source (r) is large enough to consider a plane wave. For reference, a 10 kHz wave with a SPL of 100 dB re 1 µPa will generate particle displacements of about 1.04x10^{-12} m, or roughly 1 pm, in the far field of the source, with peak velocities of about 10 nm/s and peak accelerations in the order of 600 µm/s^2.

Once the displacement is known, velocity and acceleration can be computed. Hearing systems can be sensitive to any of these processes, but mostly to acceleration.

It is possible to define log-scaled dB levels for particle displacement, velocity and acceleration, using the reference values of 1 pm, 1 nm/s and 1 µm/s^2, respectively. For instance, the particle velocity level (PVL) is given by:

$$PVL = 20\ \log_{10}(v/v_0), \quad \text{in dB ref 1 nm/s}$$

In studies of impacts of sound on marine life, particle velocities should ideally be measured with adequate equipment since the approximations used to compute PVL from SPL (based on the relation $I = p.v$) result in an underestimation of particle velocity levels (Jansen et al., 2019, Farina, 2018), especially for low frequencies (below 1 kHz).

Sound attenuation in the ocean

As mentioned further above, attenuation of sound intensity as it propagates in seawater depends on several factors, among which interaction with boundaries, absorption in the medium, scattering, and geometrical spreading from the source. Modern sound propagation models use physical principles for each of these terms to compute the changes in intensity and in direction as a sound wave propagates.

For quick estimates in practical applications in which the distance to the source is not too large (that is, in which it can be considered that absorption is much smaller that geometrical spreading), simple models of geometrical spreading can provide a first approximation to the variation of sound levels with distance to the source. It is common to use either spherical or cylindrical spreading (the former for point sources away from boundaries, the latter more appropriate for point sources in shallow water).

In spherical spreading, and using the assumption that the absorption in the medium is negligible, the power radiated in all directions from the source remains more or less the same, that is,

$$P = 4\pi r^2 I = P_0 = 4\pi r_0^2 I_0 \rightarrow I = I_0(r_0^2/r^2)$$

In other words, the intensity decreases with the inverse of the squared distance to the source. The attenuation level in sound intensity, or Transmission Loss (TL), is then given by (using a reference r_o of 1 m):

$$TL_{sph} = -10\log_{10}(I/I_0) = 20\log_{10}(r)$$ in dB, (*r* in meter from the source)

For cylindrical spreading, the variation in sound intensity is proportional to the inverse (horizontal) distance to the source, and it is easy to show that:

$$TL_{cyl} = 10\log_{10}(r)$$ in dB, (*r* in meter from the source)

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